Sabine and Neches Rivers and Sabine Lake Bay Basin and Bay Expert Science Team

Environmental Flows Recommendations Report

Final Submission to the Sabine and Neches Rivers and Sabine Lake Bay Basin and Bay Area Stakeholder Committee, Environmental Flows Advisory Group, and Texas Commission on Environmental Quality

November 30, 2009

http://www.sratx.org/BBEST/RecommendationsReport/

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November 2009

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Environmental Flows Advisory Group

The Honorable Allan Ritter, Co-presiding Officer,
Environmental Flows Advisory Group

Mark R. Vickery, P.G., Executive Director,
Texas Commission on Environmental Quality

Jerry Lynn Clark, Chairman,
Sabine and Neches Rivers and Sabine Lake Bay Basin and Bay Stakeholder Committee

Dear Senator Averitt, Congressman Ritter, Mr. Vickery, and Mr. Clark:

For your consideration, the Sabine and Neches Rivers and Sabine Lake Bay Basin and Bay Expert Science Team (Sabine-Neches BBEST) hereby submits its final report pursuant to its charge under Senate Bill 3 (80th R, 2007), including environmental flow recommendations with rationale. The Sabine-Neches BBEST members have reached consensus on these recommendations.

Respectfully submitted,

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ENVIRONMENTAL FLOWS RECOMMENDATION REPORT

Final Submission to the Sabine and Neches Rivers and Sabine Lake Bay Basin and Bay Area Stakeholder Committee, Environmental Flows Advisory Group, and Texas Commission on Environmental Quality

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EXECUTIVE SUMMARY

The Sabine and Neches Rivers and Sabine Lake Bay Basin and Bay Expert Science Team (Sabine-Neches BBEST) was appointed by the Sabine and Neches Rivers and Sabine Lake Bay Basin and Bay Area Stakeholders Committee (Sabine-Neches BBASC) under Senate Bill 3 (Texas Legislature 2007), the third in a series of three omnibus water bills related to the State of Texas meeting the future needs for water. Under its SB 3 charge, the Sabine-Neches BBEST used the "best available science" to develop environmental flow analyses and recommend flow regimes for the Sabine and Neches Basins and the Sabine-Neches Estuary. These recommendations are provided to the Sabine-Neches BBASC, Texas Environmental Flows Advisory Group (EFAG), and the Texas Commission on Environmental Quality (TCEQ).

The Sabine-Neches BBEST held twelve monthly meetings and several workshops beginning with its initial meeting on December 8, 2009. To accomplish this task the Sabine-Neches BBEST established subcommittees for:

- gaging
- hydrology
- biology
- water quality
- geomorphology
- Recommendations Report preparation.

Two consulting firms were retained to provide modeling and research in addition to extensive committee/subcommittee work. The meetings were an open process that benefited from participation and contributions from the resource agencies – TCEQ, Texas Water Development Board (TWDB) and Texas Parks and Wildlife Department (TPWD), environmental groups such as the National Wildlife Federation (NWF), and the public.

The Sabine-Neches BBEST believes the body of work presented and discussed in the Recommendations Report (Report) has enabled it to move the Texas environmental flows process forward and to address the charge to develop environmental flow analyses and recommend an environmental flow regime in a positive manner within the limited time frame and full recognition of the best science available. The Report is comprised of:

- a Preamble, which outlines the charge, goal and objectives;
- Summary of Recommendations, Recognitions and Rationale, which highlights the report findings;
- Basins and Bay Descriptions and Current Conditions, which describes the Sabine River Basin (Texas and Louisiana), the Neches River Basin, Sabine Lake Estuary (Sabine-Neches Estuary, Texas and Louisiana); Regional Water Planning (SB 1 ongoing process), and Sabine-Neches Study Area Unique Issues;
- Texas Environmental Flows Science Advisory Committee (SAC) which provided guidance documents for this process as well as overall direction, coordination, and consistency from the broader state perspective;

- Discipline Reports from the four disciplines – hydrology, biology, water quality and geomorphology;
- Development of Environmental Flows Recommendations/Recognitions/Unresolved Issues which includes instream flow regime application, environmental flow matrices for selected stream flow gages, and inflows to Sabine-Neches Estuary; and
- Appendices which includes the full body of work and references that the Report is based on.

The SAC, an objective body of experts tasked to advise and make recommendations to the Environmental Flows Advisory Group, provided valuable assistance to the Trinity-San Jacinto BBEST and Sabine-Neches BBEST as the two initial BBESTs. To date, the SAC, composed of members with expertise in a number of technical fields including hydrology, hydraulics, water resources, aquatic and terrestrial biology, geomorphology, geology, water quality, and computer modeling, has developed six technical guidance documents for BBEST use. These are as follows:

- Geographic Scope of Instream Flow Recommendations;
- Use of Hydrologic Data in the Development of Instream Flow Recommendations for the Environmental Flows Allocation Process and the Hydrology-Based Environmental Flow Regime (HEFR);
- Fluvial Sediment Transport as an Overlay to Instream Flow Recommendations for the Environmental Flows Allocation Process;
- Methodologies for Establishing a Freshwater Inflow Regime for Texas Estuaries Within the Context of the Senate Bill 3 Environmental Flows Process;
- Nutrient and Water Quality Overlay on Hydrology-Based Instream Flow Recommendations; and
- Essential Steps for Biological Overlays in Developing Senate Bill 3 Instream Flow Recommendations.

Unfortunately, the Sabine-Neches BBEST was unable to take full advantage of all guidance documents since the SAC's development timeline coincided with the Sabine-Neches BBEST timeline. However, the SAC member performing as liaison to the Sabine-Neches BBEST assisted the group by providing the initial drafts of works in progress to allow the process to move forward. This resulted in an evolving process through the twelve months with the Report reflecting a transition of understanding from SAC guidance to the Sabine-Neches BBEST, to its consultants' work, its subcommittees' reports, input from the resource agencies, and the NWF studies. This input and work influenced the understanding and progress along the twelve month timeline. The final Report reflects the evolving and transitional understanding as the year unfolded and additional information and data was brought into the process.

Decision Tree – To help follow this process from start to finish, the Sabine-Neches BBEST developed a DECISION TREE (Figure 4, page 8). The Decision Tree traces the decisions made throughout the process. The decision tree was instrumental in tracking decisions and pathways and the concept should be of great value to future BBESTs.

During the course of the past year, the Sabine-Neches BBEST recognized its recommendation charge required further clarity. Taking its charge from the "theoretical" to the "practical", the Sabine-Neches BBEST was able to make some specific environmental flow recommendations, while in other cases (for example overbank flows), the group agreed to recognize (recognition) the ecological value of such flows but not recommend them. The Sabine-Neches BBEST was able to move forward with the environmental flow process by agreeing that some issues, due to the severe time constraint and limitations of available science would remain 'unresolved issues'. These unresolved issues would need 'future studies' and, ultimately, as envisioned by the SB 3 process, 'adaptive management' to resolve. Thus, over time, the path forward became:

1. Recommendations;
2. Recognitions;
3. Unresolved Issues;
4. Future Studies; and
5. Adaptive Management.

Recommendations and Recognitions

The following recommendations and recognitions are presented in the Report with qualifying language and in some cases remain unresolved issues that will need future study and adaptive management to determine if particular flow components need to be altered. The recommendations and recognitions are presented in the Report with supporting rationale based on information and data summarized from a substantial body of work in the appendices and noted references. They are summarized as follows:

Recommendations:

1. Recommendation 1: Definition of a Sound Ecological Environment.
   The Sabine-Neches BBEST recommends the SAC definition that it adopted (see Section 1.2.4, page 11) for sound ecological environment.
2. Recommendation 2: The Current Conditions of the Sabine and Neches Rivers and the Sabine-Neches Estuary are Sound.
3. Recommendation 3: Acknowledge that Flows in the Sabine and Neches Rivers and Inflow to the Sabine-Neches Estuary will Change Over Time.
4. Recommendation 4: Future Study, Data Gathering, and Adaptive Management are Necessary to Determine Whether or not Changes in Environmental Flows will Maintain a Sound Ecological Environment.
5. Recommendation 5: Applicable Hydrologic Conditions for the Entire Season are Defined on the Basis of an Assessment of Hydrologic Conditions of Storage in Selected Reservoirs at the Beginning of the First Day of the Season Thereby Recognizing Both Drought Persistence and Practical Operations.
6. Recommendation 6: Subsistence Flows.
   The Sabine-Neches BBEST recommends adoption of the seasonal subsistence flows from MBFIT /HEFR, unless:
   i. the seasonal value is less than the summer value in which case the summer value is adopted by default, and

ii. MBFIT/HEFR failed to calculate a value (this occurred usually for winter) in which case the lowest recorded flow value for that season at that gage was adopted by default.

Translation of seasonal subsistence flows into environmental flow standards and permit conditions should not result in more frequent occurrence of flows less than the recommended seasonal subsistence values as a result of the issuance of new surface water appropriations or amendments.

7. Recommendation 7: Base flows.

   Seasonal base flows represent thresholds for environmental protection based on current scientific understanding of fluvial and estuarine ecosystems. As new studies and monitoring information become available, these base flow thresholds may be revised.

8. Recommendation 8: High Flow Pulses.

   Seasonal high flow pulses have recognized ecological benefits and are recommended for protection with certain reservations associated with environmental and operational liability risks.

9. Recommendation 9: Fluvial Matrices Inflow Recommendations are Adequate to Maintain a Sound Ecological Environment in the Sabine-Neches Estuary.

   Recognizing that the Sabine-Neches Estuary is a system in transition (Tatum 2009) and that the Sabine-Neches Estuary receives the freshwater inflows determined by the flow component recommendations for the Sabine-Ruliff, Neches-Evadale, and Village Creek gages (as well as other inflows), the Sabine-Neches BBEST recommends that these inflows are adequate to maintain a sound ecological environment in the Sabine-Neches Estuary.

Recognitions

1. Recognition 1: Overbank Flows Have Recognized Ecological Benefits but are not Recommended.

   Overbank flows may cause extensive damage to private property and endanger the public. Therefore the Sabine-Neches BBEST recognizes the ecological benefits of these events, but cannot recommend such events be produced.

2. Recognition 2: Toledo Bend Reservoir FERC Relicensing.

   The relicensing of the Toledo Bend Project is ongoing at this time. The relicensing will recognize the Project's primary use as a water supply project with the capability of generating hydroelectric power. Since no major changes in operations are planned, a maintenance flow will continue to be maintained from the spillway.

3. Recognition 3: Sabine River Compact.

   The major purposes of the Sabine River Compact are to provide for the equitable apportionment between the States of Louisiana and Texas of the waters of the Sabine River and its tributaries. Texas retains free and unrestricted use of the water of the Sabine River and its tributaries above the Stateline, subject only to the provisions that the minimum flow of 36 cfs must be maintained at the Stateline. All free water (free water means all waters other than stored water) and stored water in the Stateline reach, without reference to origin, will be divided equally between the two states.

4. Recognition 4: Cutoff Bayou.
   Environmental flows as well as the diversions for the water supply canal system in Texas are adversely affected by migration of channel flow to the Old River Channel in Louisiana during low and average flow conditions.

Basins and Bay Descriptions and Current Conditions

The Study Area defined for the Sabine-Neches BBEST is the Sabine River Basin and the Neches River Basin with each having a watershed of approximately 10,000 square miles with the total drainage of some 20,000 square miles being received by the Sabine-Neches Estuary. Detail descriptions and maps are found in the Report and supporting appendices and references. SB 1 Regional Water Planning for this area is presented in Regions I, D and C plans since the geographic footprint extends into all three regions. SB 2, or Texas Instream Flow Program (TIFP), studies include only the lower Sabine River from Toledo Bend Reservoir to tidal. (The State of Louisiana owns half the flow in this stateline reach, but does not have a program similar to SB 2). Unique aspects of the Study Area include:

1. Texas/Louisiana (stateline flows, water supply reservoir and estuary);
2. Texas State Water Quality Flows (Texas – 7Q2/Louisiana – 7Q10);
3. SB 2 priority study – lower Sabine River;
4. Toledo Bend Reservoir Project Joint Operations – Federal Energy Regulatory Commission relicense of Toledo Bend hydropower facility;
5. Sabine River Compact which provides for equitable apportionment of waters between Texas and Louisiana;
6. Lower Neches River Saltwater Barrier - minimum flow requirement;
7. Cutoff Bayou – migration of water to Louisiana's Old Sabine River channel affecting environmental flows and water supply users in Texas; and
8. USACE proposed deepening of existing ship channel through the Sabine-Neches Estuary to upstream ports.

Discipline Reports

The Sabine-Neches BBEST Subcommittees submitted reports –on the disciplines of hydrology, biology, water quality and geomorphology – key components identified by the TIFP Technical Overview.

Hydrology – The Hydrology Subcommittee benefited from outside consultant work which prepared three memoranda:

1. Analysis of Sabine-Neches BBEST Stream Gages;
2. Hydrology-Based Environmental Flow Regime (HEFR) Analyses for Sabine-Neches BBEST; and
3. Water Availability Analyses for Sabine-Neches BBEST.

The subcommittee worked with the consultant in the preparation of these memos and used this baseline work to develop flow regime matrices for each of the selected gages for use by the other disciplines.

Biology – The Biology Subcommittee assisted in the selection of representative focal species for the two river basins and the estuary, and also worked with an outside consultant to prepare reports on Fluvial Focal Species and Estuarine Focal Species. The flow regime matrix produced by the HEFR statistical analyses of the historical stream gage records was used to evaluate the available biological information for the focal species related to subsistence flows, base flows, high flow pulses, and overbank flows. Using SAC guidance, the estuarine ecosystem evaluation was enhanced with the NWF analysis of habitat suitability for key estuarine species under alternative flow regimes. Changes to the estuary including the ship channel, intracoastal waterway, and secondary channels into the marshes were discussed along with a need for habitat restoration in marshes in Texas and Louisiana. Adaptive management as envisioned by the SB 3 process was considered along with the need for future studies to address the unresolved issues in the Report.

Geomorphology (Sediment Transport) – The Geomorphology Subcommittee, utilizing SAC guidance, worked with the TWDB to address sediment transport in the Study Area. The TWDB has conducted studies of sediment transport and geomorphologic characterization within Texas river systems and most recently has worked with Dr. Jonathan Phillips of the University of Kentucky to conduct studies in the lower Sabine River as part of the SB 2 study. TWDB modeling was undertaken for each of the gages as well to determine how these systems are functioning. Estuary sediment delivery was also considered.

Water Quality – The Water Quality Subcommittee evaluated water quality as an overlay application in environmental flows. Water quality is an important aspect of environmental flow recommendation development. Available water quality was compiled and evaluated for the study area along with water quality standards, flow and water quality relationships, and the integration of water quality into environmental flow recommendations.

Development of Environmental Flows Recommendations/ Recognitions/ Unresolved Issues

As illustrated in the Report's Decision Tree (Figure 4, page 8), the decision process and statistical analyses created, in effect, a statistical river which resulted in HEFR output matrices for each of the twelve gages (six in the Neches Basin and six in the Sabine Basin). These are listed with descriptions of each location and the corresponding matrix (for example – HEFR Matrix for Big Sandy Creek near Big Sandy) which presents the numbers associated with these decisions on a seasonal basis (Sabine-Neches BBEST selected Jan-Mar for winter, Apr-Jun for spring, and so on) for subsistence, base, high flow pulses and overbank flows with qualifying language regarding the interpretation of these flow components. For base flows, seasonal numbers were generated for dry, average and wet conditions which were arbitrarily chosen to be 25th /50th /75th percentiles.

The Sabine-Neches BBEST developed an example application of a flow regime to focus on key elements of a HEFR output matrix and considerations in order to understand how such flow regimes might be applied to new surface water appropriations and/or diversions. The group's understanding of potential flow regime application is summarized in a series of examples for Big Sandy Creek near Big Sandy, Texas.

The Sabine-Neches Estuary current status is summarized from the discipline reports, appendices, and reference documents. The SAC guidance, Sabine Lake history, State Methodology, percent inflow schematic documenting inflows (from the Sabine River, the Neches River, and coastal inflows), and HEFR as an estuary inflows recommendation tool are presented. The USACE's project to deepen the ship channel includes extensive studies. Hydrodynamic salinity modeling, water supply planning using the 2007 Texas Water Plan (Texas Water Development Board. 2007) data modeling current and future water use (50 year) conditions, and marsh habitat mitigation/restoration in Texas and Louisiana are included.

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1 PREAMBLE

The Sabine and Neches Basin and Sabine Lake Bay Expert Science Team (Sabine-Neches BBEST) is pleased to provide this *Environmental Flows Recommendation Report* to the Sabine and Neches Rivers and Sabine Lake Bay Basin and Bay Area Stakeholder Committee (Sabine-Neches BBASC), Texas Environmental Flows Advisory Group (EFAG), and the Texas Commission on Environmental Quality (TCEQ). The Sabine-Neches BBEST fully understands its primary charge for developing environmental flow analyses and arriving at these final recommendations, as well as the constraints on making this determination. The Sabine-Neches BBEST believes the body of work discussed herein has enabled it to move the Texas environmental flows process forward and to address this charge in a very positive manner, in full recognition of the best science available and limited time frame. The Sabine-Neches BBEST has worked very hard over the past twelve months to provide this *Environmental Flows Recommendations Report* within the allotted time frame with recommendations and supporting rationale that will lay the necessary groundwork for the Sabine-Neches BBASC to balance environmental flows with the needs of the people of Texas in the Sabine and Neches River Basins and the Sabine-Neches Estuary (Sabine Lake) area with full recognition of the State of Louisiana's co-ownership of Toledo Bend Reservoir and the portion of the Lower Sabine River that forms the state line (see Section 3.5, page 36).

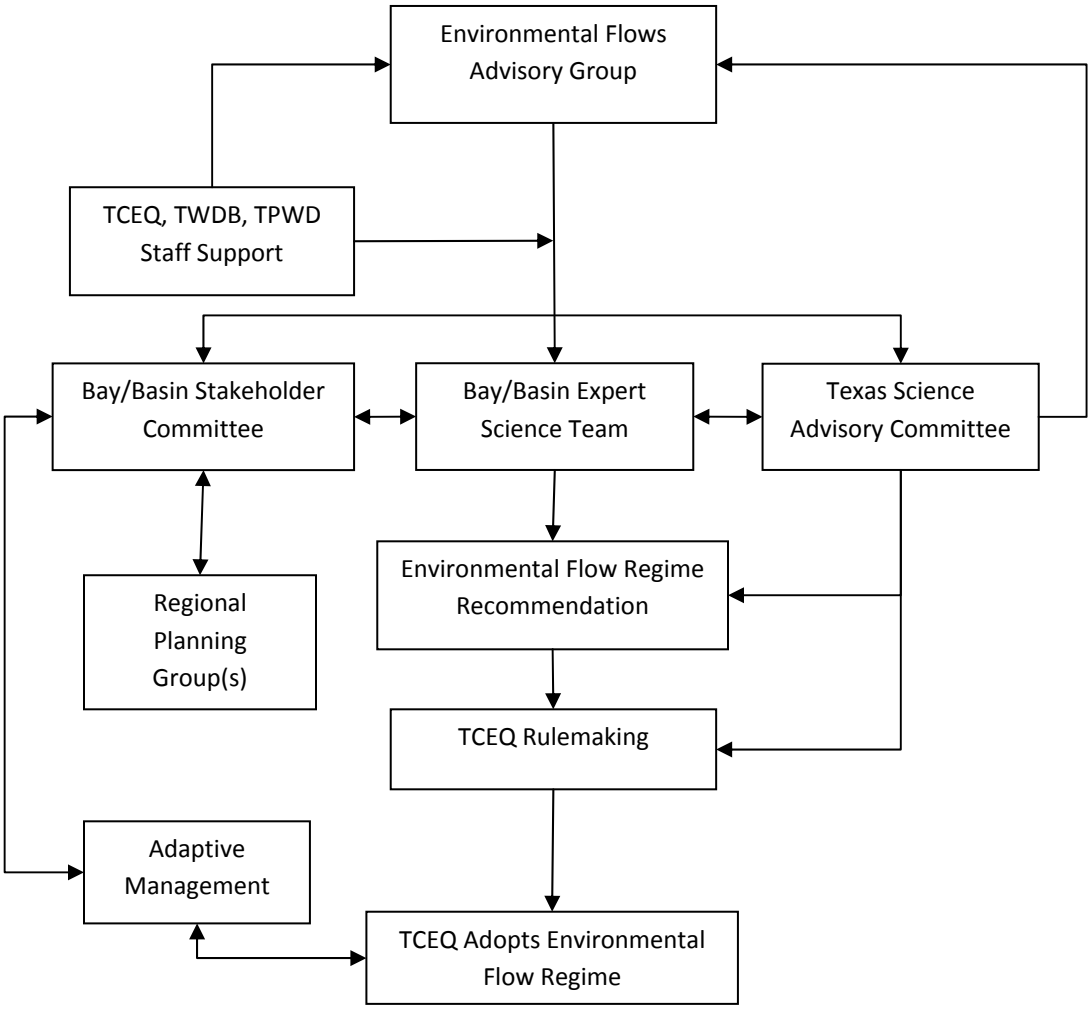
1.1 SENATE BILL 3

Texas lawmakers passed Senate Bill 3 (SB 3) in the 2007 80th Regular Session of the Texas Legislature. SB 3 is the third in a series of three omnibus water bills related to the State of Texas' meeting the future needs for water. Senate Bill 1 (SB 1) established a "bottom-up" approach to water resource planning. The Senate Bill 2 (SB 2) instream flow program was established in recognition of the lack of data to determine how much water is needed for the environment. SB 3 created a basin-by-basin process (see Figure 1, page 2) for developing recommendations to meet the instream flow needs of rivers as well as freshwater inflow needs of affected bays and estuaries and required TCEQ to adopt the recommendations in the form of environmental flow standards. Such standards will be utilized in the decision-making process for new water right applications and in establishing an amount of unappropriated water to be set aside for the environment. (Texas Legislature 2007)

Prior to SB 1, SB 2, and SB 3, Texas law recognized the importance of balancing the biological soundness of the state's rivers, lakes, bays, and estuaries with the public's economic heath and general well-being. The Texas Water Code (TWC) requires the TCEQ, while balancing all other interests, to consider and provide for the freshwater inflows necessary to maintain the viability of Texas' bay and estuary systems in TCEQ's regular granting of permits for the use of state waters. Unfortunately, even though Texas has long been the leading state at documenting existing and historical flows, the information needed to determine the instream flows and freshwater inflows needed to support ecologically sound river and bay systems is limited. Prior to SB 3, the balancing of the effect of authorizing a new use of water with the need for that water to maintain a sound ecological

system was done on a case-by-case basis as part of the water rights permitting process. This resulted in an enormous roadblock for the SB 1 water planning process.

FIGURE 1. SB 3 ENVIRONMENTAL FLOW PROCESS



(Environmental Flows Advisory Committee 2006)

1.2 SABINE-NECHES BBEST

The Trinity and San Jacinto Rivers and Galveston Bay system and the Sabine and Neches Rivers and Sabine Lake Bay system are the priority river basin and bay systems of the state for the purpose of developing environmental flow regime recommendations and adopting environmental flow standards. Therefore, the Sabine-Neches BBEST is one of two initial basin and bay expert science teams in Texas.

In accordance with SB 3, the Sabine-Neches BBEST members were appointed by the Sabine-Neches BBASC (Texas Commission on Environmental Quality 2008a). Table 1 provides a list of the Sabine-Neches BBEST members and the Sabine-Neches BBASC representatives that nominated them. The Sabine-Neches BBEST held twelve monthly meetings and several workshops beginning with its initial meeting on December 8, 2009. During the course of this time, the Sabine-Neches BBEST established subcommittees for:

- Gaging
- Hydrology
- Biology
- Geomorphology (sediment transport)
- Water Quality
- Recommendations Report Preparation

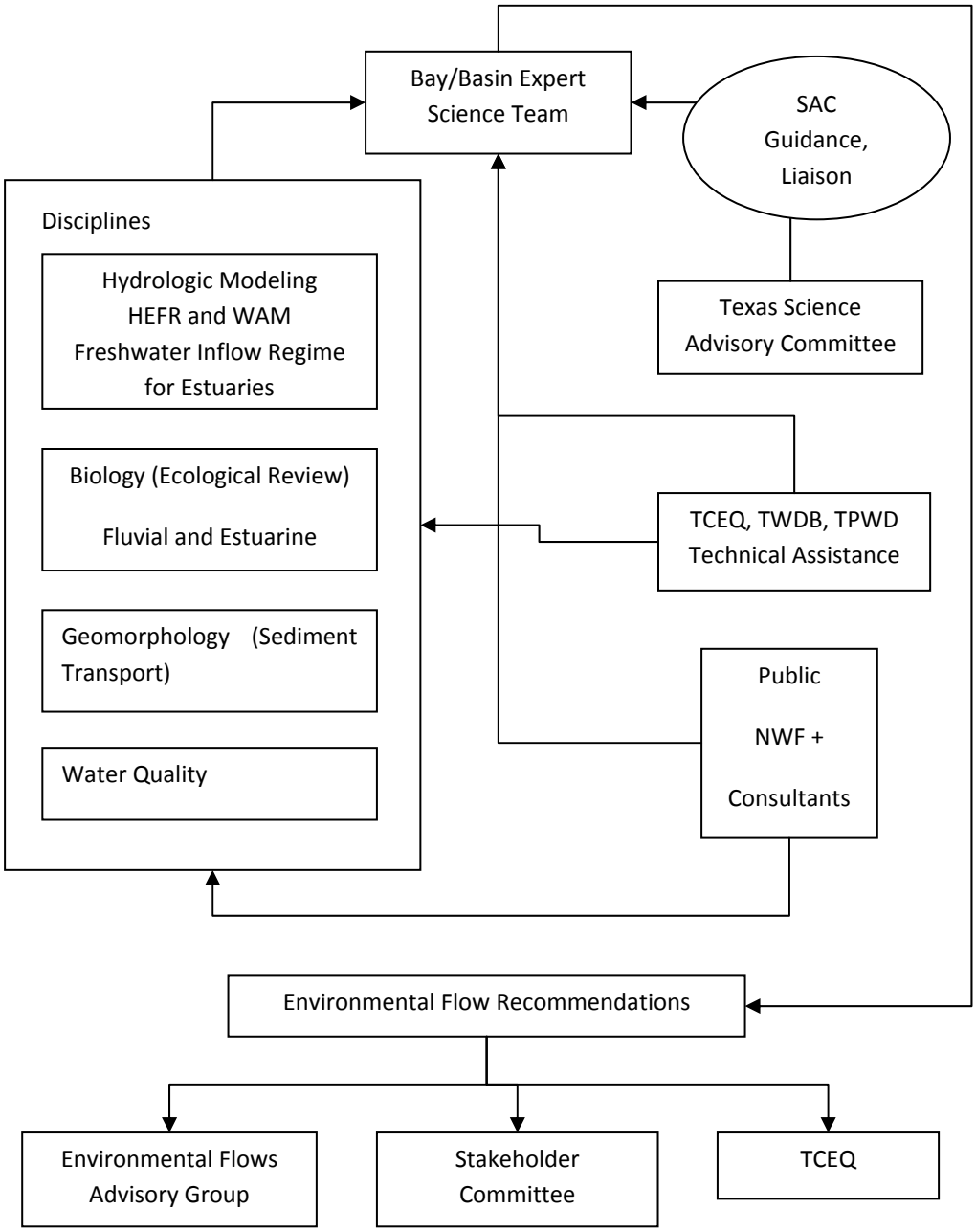
Subcommittee work has included numerous meetings and conference calls in addition to the monthly meetings as the Sabine-Neches BBEST has moved forward to define the available science in the study area shown in Figure 5 on page 25. The Sabine-Neches BBEST meetings were an open process that benefited from the resource agencies -- TCEQ, Texas Water Development Board (TWDB) and Texas Parks and Wildlife Department (TPWD), environmental groups such as the National Wildlife Federation (NWF), and the public. All the contributions of these have been constructive to the process (conceptualized in Figure 2, page 5) and have been carefully considered.

To assist the subcommittees, the Sabine-Neches BBEST retained the services of Freese-Nichols, Inc., (FNI) and BIO-WEST, Inc., for hydrologic modeling and ecological review, respectively.

TABLE 1. SABINE-NECHES BBEST MEMBERSHIP

Member	Affiliation	Nominated by
Graham, Gary	G.E. Walker & Associates, L.L.C.	Jerry Clark
Hall, Scott (Co-Chair)	Lower Neches Valley Authority, General Manager	Robert Stroder
Harrel, Richard	Lamar University, Clean Air & Water, Inc.	Bruce Drury and Robert Stroder
Hunt, Rex H.	Alan Plummer Associates, Inc., Principal	Kelley Holcomb
Kelley, J. Roger	LBG, Inc., General Manager - Environmental	Ken Dickson
McBroom, Matthew	Stephen F. Austin State University, Assistant Professor	Baker Pattillo
McCullough, Jack D.	Stephen F. Austin State University, Research Scientist	Baker Pattillo
Parkhill, David L.	AECOM Water, Vice President	Jerry Clark
Tatum, Jack W. (Chairman)	Sabine River Authority of Texas, Water Resources Manager	Jerry Clark
Vaugh, Samuel Kent	HDR Engineering, Vice President	Monty D. Shank
Winemiller, Kirk	Texas A&M University, Professor	David Roemer

FIGURE 2. SABINE-NECHES BBEST PROCESS



1.2.1 Primary Charge

The Sabine-Neches BBEST Primary Charge is taken directly from SB 3 (Texas Legislature 2007):

> ***Primary Charge*** *to the Texas Environmental Flows Bay Basin and Science Expert Science Team (BBEST) is found in SB3, Section 11.02362 (m). "Each basin and bay expert science team shall* ***develop environmental flow analyses*** *and a recommended* ***environmental flow regime*** *for the river basin and bay system for which the team is established through a collaborative process designed to achieve a consensus." In developing the analyses and recommendations, the science team must consider all reasonably available science, without regard to the need for the water for other uses, and the science team's recommendations must be based solely on the best science available.*

SB 3 defines an **"environmental flow analysis**" as the "application of a scientifically derived process for predicting the response of an ecosystem to changes in instream flows or freshwater inflows."

SB 3 defines **"environmental flow regime"** as "a schedule of flow quantities that reflects seasonal and yearly fluctuations that typically would vary geographically, by specific location in a watershed, and that are shown to be adequate to support a sound ecological environment and to maintain the productivity, extent, and persistence of key aquatic habitats in and along the affected water bodies."

1.2.2 Accomplishment of Primary Charge and Decision Tree

The two components of the Sabine-Neches BBEST's Primary Charge under SB 3, develop environmental flow analyses and develop a recommended environmental flow regime, could be considered independently: develop environmental flow analyses then use the resulting analyses to recommend an environmental flow regime (Figure 3, below). However, the Sabine-Neches BBEST found them to be tightly coupled and accomplished both components of the Primary Charge together through an iterative process of decision making that is shown in Figure 4. Sabine-Neches BBEST Decision Tree.

1.2.3 Recommendation Report Evolution

The Sabine-Neches BBEST Recommendations Report is composed of a main body, which is a summary of the BBEST process, the study area, the work that was done in the development of recommendations; and the appendices, which include the full text of reports that were assembled through the process. Work reflected in the appendices was done throughout the twelve months the Sabine-Neches BBEST had to finish its charge and reflects a transition of understanding. Opinions and recommendations by the discipline report authors were generally agreed upon by consensus of the Sabine-Neches BBEST. ***The body of this Environmental Flows Recommendations Report is intended to be an assembly of the information that best reflects the consensus of the Sabine-Neches BBEST at the time the Recommendations Report was written.***

FIGURE 3. SABINE-NECHES BBEST - ACCOMPLISHMENT OF PRIMARY CHARGE

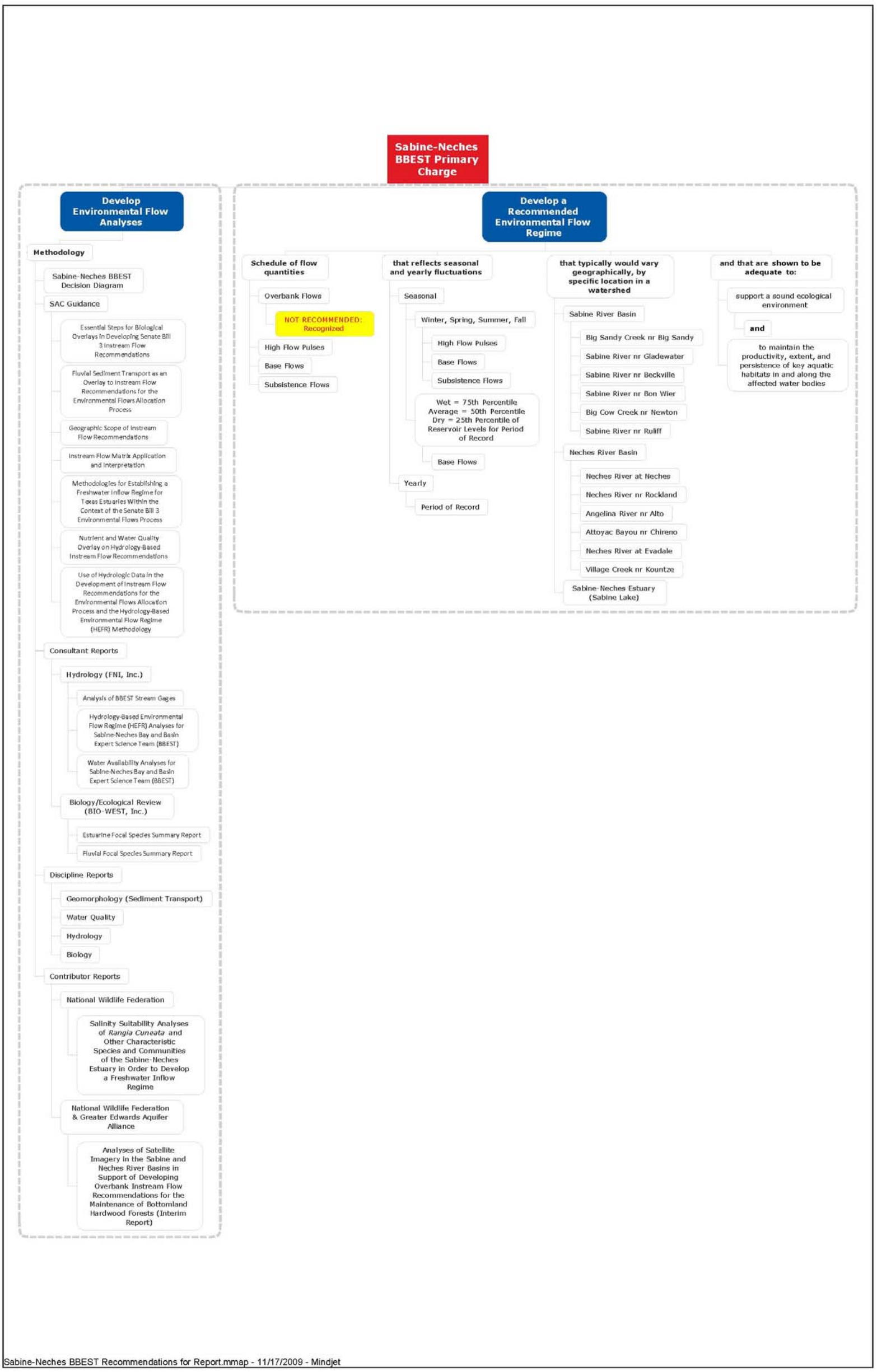
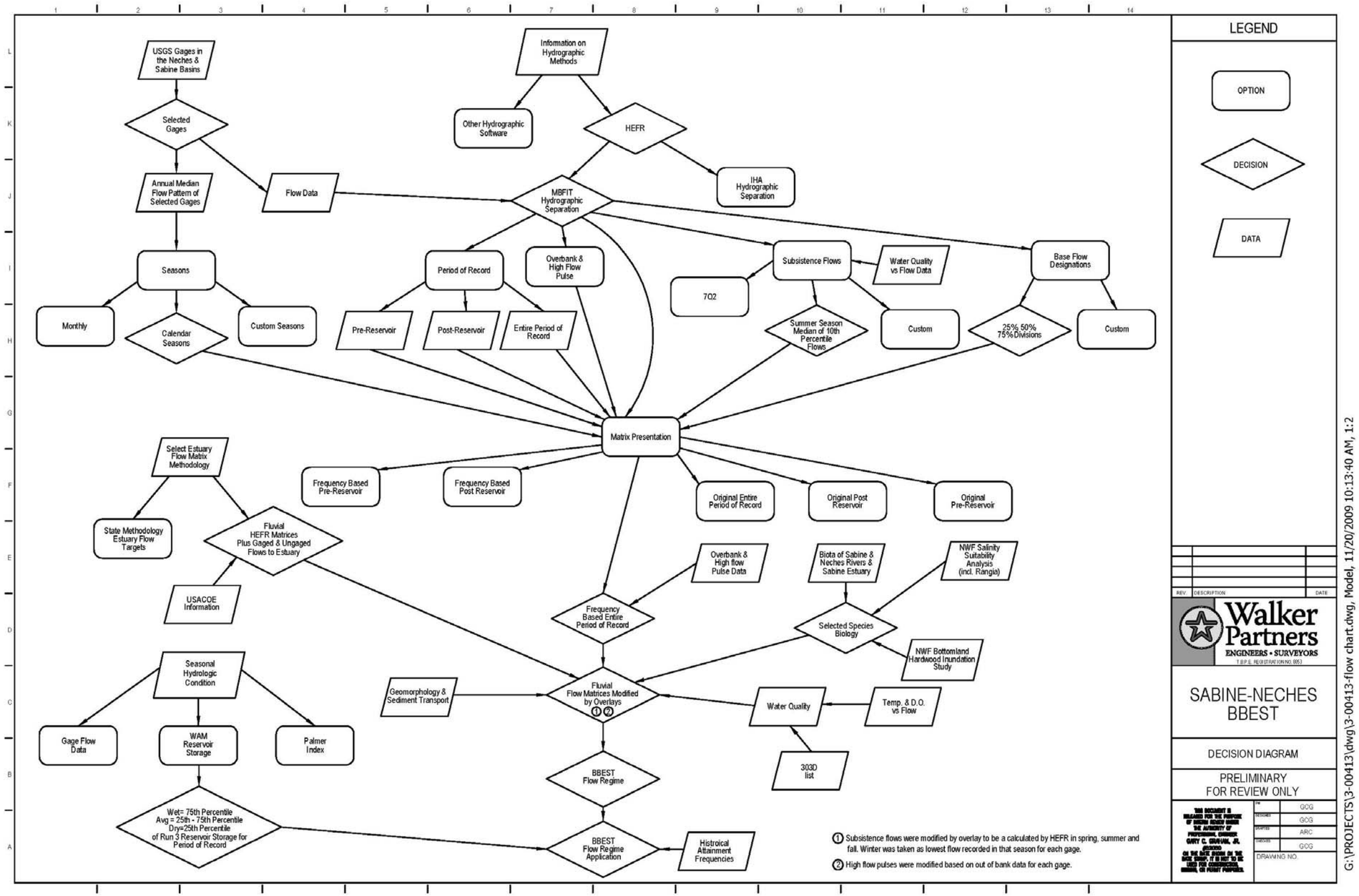


FIGURE 4. SABINE-NECHES BBEST DECISION TREE



1.2.4 Sound Ecological Environment

SB 3 did not define "sound ecological environment"; therefore, the Sabine-Neches BBEST adopted the definition of "sound ecological environment" stated by the Texas Environmental Flows Science Advisory Committee (SAC) in its "Methodologies for Establishing a Freshwater Inflow Regime for Texas Estuaries Within the Context of the Senate Bill 3 Environmental Flows Process" (SAC 2009d):

> *A **sound ecological environment** is one that:*
>
> - *sustains the full complement of native species in perpetuity,*
> - *sustains key habitat features required by these species,*
> - *retains key features of the natural flow regime required by these species to complete their life cycles, and*
> - *sustains key ecosystem processes and services, such as elemental cycling and the productivity of important plant and animal populations.*

(SAC 2009d) further notes:

Underlying each of these is the need to establish relationships between elements of the environment, including flows, and the native species and their functions.

1.2.5 Goal

> *The goal of the Sabine-Neches BBEST is to maintain a **sound ecological environment** in the Sabine and Neches Basin and the Sabine-Lake Estuary as defined above.*

1.2.6 Objectives

> *Objectives: To meet the Criterion of a **sound ecological environment***
>
> - *Characterize system hydrology and hydraulics*
> - *Examine status of geomorphic processes within the system*
> - *Characterize system water quality*
> - *Evaluate biological communities*
> - *Define the influence and relationship of other riverine environmental components relative to biology of the system*

The "Texas Instream Flow Studies: Technical Overview" (Texas Commission on Environmental Quality 2008b) provided the basis for these objectives.

1.2.7 Instream Flow Regime Components

Variations in the magnitude, frequency, duration, timing, and rate of change of stream flows are all critical components of a natural flow regime (Poff, Allan et al. 1997). Variability in stream flow is manifested to stream biota as a change in habitat availability. Consequently, the life histories of stream fishes and other aquatic organisms are adapted to the seasonal and interannual variability of low, base, and high flow components. Hydrologic pattern and variability are therefore key determinants of aquatic community structure and stability (Poff and Ward 1989; Richter, Baumgartner et al. 1996; Poff, Allan et al. 1997; Dilts, Leonard et al. 2005).

Alterations to a natural flow regime may result in decreased richness, diversity, and abundance of aquatic species inhabiting lotic systems. While the elimination of high flows can result in reduced species densities and community diversity (Robinson, Clarkson et al. 1998), stable flow regimes that lack seasonal and interannual variability may favor generalist and non-native species (Tyus, Brown et al. 2000). In addition, seasonal and interannual flow variability may benefit native species that have developed life history strategies in response to natural flows. Thus, providing a flow regime based on the natural flow paradigm should provide ecological benefits in stream systems (Dilts, Leonard et al. 2005).

To date, most instream flow recommendations in Texas have used a single "minimum" flow standard, which may vary by month and location (see discussion on Lyons Method in Section 5.1 Hydrology, below). Conversely, instream flow recommendations based on a flow regime concept, such as the regime concept found in SB 3, consist of multiple flow regime components, or levels, with specific characteristics. Following the recommendation of the National Research Council (National Research Council Committee 2005), and consistent with "Scientific Principles for Definition of Environmental Flows" (Maidment, Montagna et al. 2005) , the Texas Instream Flow Program[1] (TIFP) (Texas Commission on Environmental Quality 2008b) uses a framework that consists of a set of four components of a flow regime intended to support a sound ecological environment. These instream flow regime components and their definitions as adopted by the Sabine-Neches BBEST are described in Table 2. Instream Flow Regime Components Definitions, below.

[1] Senate Bill 2, 77th Texas Legislature, 2001

TABLE 2. INSTREAM FLOW REGIME COMPONENTS DEFINITIONS

Component	Definition
Overbank Flows	the component of an instream flow regime that represents infrequent, high flow events that exceed the normal channel. These flows maintain riparian areas and provide lateral connectivity between the river channel and active floodplain. They may also provide life-cycle cues for various species.
High Flow Pulses	the component of an instream flow regime that represents short-duration, in-channel, high flow events following storm events. These flows maintain riparian areas and provide lateral connectivity between the river channel and active floodplain. They may also provide life-cycle cues for various species.
Base Flows	the component of an instream flow regime that represents normal flow conditions (including variability) between precipitation events. Base flows provide a range of suitable habitat conditions that support the natural biological community of a specific river sub-basin.
Subsistence Flows	the component of an instream flow regime that represents infrequent, naturally occurring low flow events that occur for a seasonal period of time. They maintain sufficient water quality and provide sufficient habitat to ensure organism populations capable of recolonizing the river system once normal, base flows return.

The instream flow regime flow regime components are discussed in more detail in Section 5.1.4, Instream Flow Regime Components (page 45).

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2 SUMMARY OF RECOMMENDATIONS, RECOGNITIONS, AND RATIONALE

SB 3 established an aggressive schedule for determining environmental flow standards in Texas' river basins and bay systems. (Texas Water Code § 16.059 (Vernon 2008)). The BBESTs are to develop a flow regime recommendation. These recommendations must consist of a schedule of flow quantities, reflecting seasonal and yearly fluctuations that may vary by location. The SB 3 schedule does not allow for the development of multi-year site-specific instream flow studies to determine the ecological flow needs mandated by SB 2. Instead, SB 3 requires that environmental flow standards be predicated upon the best science and data currently available and intends that adaptive management be employed to refine the flow standards in the future. The timing constraints in SB 3 dictate that "desktop methods" be utilized which are primarily based on statistical evaluations of historical flows and therefore establish the flows that have occurred rather than a determination of the flows that are needed to support a sound ecological environment.

The immediate task for developing the flow standards required under SB 3 is to identify an environmental flow regime at particular locations on a stream that will support a sound ecological environment and maintain the productivity, extent, and persistence of key aquatic habitats. The extent to which such an environmental flow regime conforms to the basic structure of that being proposed for application in the TIFP studies is an important consideration. Incorporating the results of TIFP studies into SB 3 environmental flow regimes may be greatly facilitated if the initial environmental flow regime recommendations are consistent with the TIFP flow regime components.

2.1 RECOMMENDATIONS

SB 3 charged each BBEST with recommending an environmental flow regime. While the Sabine-Neches BBEST has met its SB 3 charge, its recommendations are not limited to an environmental flow regime only. Defining *recommendation* as "a course of action that is recommended as advisable", the Sabine-Neches BBEST was very careful to limit its recommendations to those flow regimes for which the group agreed that implementation is advisable. For those environmental flow regime components it did not deem advisable for implementation, the Sabine-Neches BBEST *recognized*, or acknowledged, the ecological benefits of the component.

Following are nine recommendations adopted by the Sabine-Neches BBEST regarding an environmental flow regime for the Sabine and Neches Basins and the Sabine-Neches Estuary. Each recommendation includes a brief summary of the rationale associated with the recommendation.

2.1.1 RECOMMENDATION 1: DEFINITION OF A SOUND ECOLOGICAL ENVIRONMENT

The Sabine-Neches BBEST recommends the SAC definition that it adopted (see Section 1.2.4, page 9) for **sound ecological environment**.

Rationale The Sabine-Neches BBEST recognizes that the ecology of the rivers and estuaries in Texas is a dynamic system, in that what exists today differs from what existed in the past. Further, current ecological conditions will naturally change over time under the forces of nature and other external influences (hurricanes, floods, ship channel deepening, land use changes, etc.) unrelated to and unaffected by instream flows. Therefore, while instream flow regimes may have a direct and immediate influence on the ecologic system of the rivers and estuaries, mankind does not have the ability to fully control these systems or render them static.

2.1.2 Recommendation 2: The Current Conditions of the Sabine and Neches Rivers and the Sabine-Neches Estuary are Sound

Rationale Appendix XII-1 summarizes Sabine and Neches Basin water quality impairments appearing on the 2008 Texas 303(d) List.[2] None of the segments including the 12 gages are listed as impaired for any water quality parameter that would be significantly affected by the level of environmental flow in the stream at the gage, or by future diversions of water from the stream at these locations. The Sabine-Neches Estuary is generally sound, exhibiting good overall water quality and diverse fish and wildlife communities (see Section 6.2.3, page 141) despite the influence that the Sabine-Neches Waterway (SNWW) and Gulf Coast Intracoastal Waterway (GIWW) have on salinity in the estuary. Also, although no other specific instream flow studies have been completed in the Sabine-Neches Basins, the Sabine-Neches BBEST evaluation of biological/ecological responses to flow variation was greatly aided by data collected over broader spatial and temporal scales (Evans and Noble 1979; Moriarty and Winemiller 1997; Bonner and Runyan 2007; Bart 2008) and other studies summarized in (BIO-WEST 2009b).

2.1.3 Recommendation 3: Acknowledge That Flows in the Sabine and Neches Rivers and Inflows to The Sabine-Neches Estuary will Change Over Time

Rationale The Sabine-Neches BBEST acknowledges that the flow regimes recommended herein are based upon analysis of historical streamflow gages at specific locations and that the current state of the environment is sound. Furthermore, the Sabine-Neches BBEST acknowledges that over time, changes in utilization of existing water rights, and issuance of future water rights, climate change, land use changes, and other outside factors will undoubtedly change stream flows from those seen in the past. Consequently, the Sabine-Neches BBEST believes that the flow regime matrices provided in this report are representative of a flow regime necessary to support a sound ecological environment but by no means do they represent the only flow regime that could do the same.

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[2] TCEQ, 2008 Texas Water Quality Inventory and 303(d) List, http://www.tceq.state.tx.us/compliance/monitoring/water/quality/data/08twqi/twqi08.html, retrieved November 7, 2009

2.1.4 Recommendation 4: Future Study, Data Gathering, and Adaptive Management are Necessary to Determine Whether or Not Changes in Environmental Flows will Maintain a Sound Ecological Environment

Rationale SB 3 envisions an adaptive management process for revisiting the environmental flow standards and environmental flow set-asides derived through the TCEQ rulemaking procedure. The SB 3 adaptive management process envisions that additional data, information, and studies will be necessary to make informed decisions regarding future changes to environmental flow recommendations. The on-going TIFP studies and Toledo Bend Project Federal Energy Regulatory Commission (FERC) Relicensing will provide useful information, but more research will be needed. In particular, dependence upon hydrology-based environmental flow recommendations, which is required to meet the aggressive time frames specified in SB3, highlights the need for future adaptation of the adopted flow standards. While application of the pre- and post-biological overlay process and other overlay disciplines can substantively improve the hydrology-based recommendations, future refinements and validation will accrue only from the use of new and better science developed through the adaptive management process.

2.1.5 Recommendation 5: Applicable hydrologic conditions for the entire season are defined on the basis of an assessment of hydrologic conditions of storage in selected reservoirs at the beginning of the first day of the season thereby recognizing both drought persistence and practical operations

Rationale The Sabine-Neches BBEST considered instantaneous or cumulative flow, Palmer Drought Severity Indices, and reservoir storage as potential means of defining hydrologic conditions. The Sabine-Neches BBEST chose hydrologic conditions at any specific location to be defined on the basis of cumulative storage in major reservoirs located upstream and the frequency of occurrence of such storage subject to full use of authorized water rights (TCEQ Run3). Wet, average, and dry are represented by 25th, 25th – 75th, and 75th percentile conditions.

2.1.6 Recommendation 6: Subsistence Flows

The Sabine-Neches BBEST recommends adoption of the seasonal subsistence flows from MBFIT /HEFR, unless:

1. ***the seasonal value is less than the summer value in which case the summer value is adopted by default, and***
2. ***MBFIT/HEFR failed to calculate a value (this occurred usually for winter) in which case the lowest recorded flow value for that season at that gage was adopted by default.***

Translation of seasonal subsistence flows into environmental flow standards and permit conditions should not result in more frequent occurrence of flows less

than the recommended seasonal subsistence values as a result of the issuance of new surface water appropriations or amendments.

Rationale **H**ydrology-**B**ased **E**nvironmental **F**low **R**egime (HEFR; Opdyke 2009; SAC 2009f) outputs were used to estimate subsistence flows based on historical streamflow data and manipulation of the **M**odified **B**ase **F**low **I**ndex with **T**hreshold (MBFIT; Opdyke 2009) option. Historical streamflows represent a sound ecological environment, and this recommendation is consistent with the subsistence flow definition of the component of an instream flow regime that represents infrequent, naturally occurring low flow events that occur for a limited period of time (Table 2, page 11). See Section 5.2.2.1, page 63, for more detailed discussion of the biological overlay evaluation of subsistence flows.

Subsistence flows lower or higher than those recommended for the basins could be justified if sufficient water quality data were available for evaluation. It is important, therefore, to prioritize additional sampling trips to better characterize water quality conditions during extreme low flow periods; and, as such, additional water quality study (e.g. TCRP Special Studies) at low and subsistence flow is recommended.

After review of Environmental Protection Agency (EPA) DFLOW biologically-derived low flow statistics documentation[3] (i.e., 4B3, or more generally xBy) and sources on hydrologically derived low flow statistics (i.e., 7Q2, 7Q10, or more generally xQy), the Sabine-Neches BBEST concluded that none of these methods determine what the ecological subsistence flow should be for a specific stream. 7Q2 in particular has a two-year expected return period which is frequent and isn't consistent with the adopted definition of subsistence flow. Some BBEST members supported use of the 5th percentile as the subsistence flow criterion due its current widespread support within the environmental flows arena. Recent studies and reviews have concluded that the 5th percentile marks a significant point below which already stressful conditions in the river change rapidly. Hence, the Sabine-Neches BBEST acknowledges that new studies and findings may warrant revision of these subsistence flow thresholds (Recommendation 6).

2.1.7 Recommendation 7: Base Flows

Seasonal base flows represent thresholds for environmental protection based on current scientific understanding of fluvial and estuarine ecosystems. As new studies and monitoring information become available, these base flow thresholds may be revised.

Rationale For the Sabine-Neches BBEST ecological analysis, the HEFR base flows for dry-year (25th percentile of upstream reservoir storage for period of record), average-year (25th – 75th percentile of upstream reservoir storage for period of record), and wet-year (75th

[3] DFLOW: A Tool for Low Flow Analysis | Water Quality Models and Tools | US EPA, http://www.epa.gov/waterscience/models/dflow/, retrieved November 3, 2009

percentile of upstream reservoir storage for period of record) estimates from each gage were compared with our information on the ecology of focal species (BIO-WEST 2009a, Appendix VIII) and, when appropriate, findings from the BIO-WEST instream flow study of fishes in the lower Colorado River (BIO-WEST 2008a). Adoption of base flow benchmarks for dry years (low precipitation years when reservoir pools are low), average years, and wet years (high precipitation years when reservoir pools are high) was deemed critical for protecting populations of aquatic organisms within the various diverse habitat guilds.

2.1.8 Recommendation 8: High Flow Pulses

Seasonal high flow pulses have recognized ecological benefits and are recommended for protection with certain reservations associated with environmental and operational liability risks.

Seasonal in-channel high flow pulses with historical frequencies of two smaller-magnitude pulses (defined by the frequency-based method in HEFR as 2-per season) and one larger magnitude pulse (defined as 1-per season) were calculated using the frequency-based method in HEFR. Under average or wet hydrologic conditions (Recommendation 5), up to two pulses would be passed each season for the needs of a sound ecological system. A single larger magnitude in-channel pulse must be passed when produced by precipitation and runoff under wet hydrologic conditions. Two pulses, smaller-magnitude seasonal pulses, must be passed when produced by precipitation and runoff under average hydrologic conditions. Under dry hydrologic conditions (Recommendation 5) during spring and summer (defined in this instance as Spring: March – May; and Summer: June–August), one of the smaller-magnitude pulses must be passed during each season for critical ecological functions, including cues for synchronized fish spawning, passive transport of fertilized eggs and larvae into retention zones, and resuspension of silt. This latter recommendation assumes high flow pulses of the prescribed magnitude and duration to be naturally rare events based on the historical record. Other flows exceeding these environmental pulse targets would be eligible for impoundment or diversion. There would be no memory (carry over) between seasons and no requirement for a storage project to create any flow pulses not delivered by natural precipitation and runoff in the watershed.

Translation of seasonal pulse flows of specified frequencies into environmental flow standards may result in frequencies of occurrence of high flow pulses that are lower than historical frequencies as a result of the issuance of new surface water appropriations or amendments. This reduced frequency of occurrence is deemed a crudely calculated environmental risk at this time, subject to review as new studies and information become available. The Sabine-Neches BBEST recommends further evaluation of the ecological functions of alternative categories of in-channel high flow pulses having lower magnitudes but greater frequencies of occurrence. The ecological functions of small but more frequent high flow pulses can be critical, especially during spring spawning seasons, and under Recommendation 8, these are not protected for support of a sound ecological environment.

At several reference gage locations, winter and spring high flow pulses with historical frequencies of one (1) per season approach were deliberately limited to peak flow rates

associated with the approximate bankfull stage condition. Hence, extreme caution is warranted in the passage of high flow pulses to ensure that concomitant downstream runoff does not cause overbank flooding, particularly under wet hydrologic conditions. This potential liability is deemed an acceptable operational risk at this time, subject to BBASC review, logical translation of pulse flows into environmental flow standards and permit conditions by TCEQ, and indemnification of present and future water rights holders operating in accordance with permit conditions specifying high flow pulses.

Rationale As discussed in Section 5.1.4, Instream Flow Regime Components, high flow pulses serve to maintain important physical habitat features and connectivity along a stream channel. And as discussed in Section 5.2.2.3, High Flow Pulses and Overbank Flows, the Sabine-Neches BBEST evaluated HEFR-derived pulse flows in the context of available ecological information and concluded that certain categories of high flow pulses need protection (2-per-season and 1-per-season; see Section 6.2 for specific recommendations). Available hydrologic, biologic, geomorphologic, water quality data, and professional judgment suggest that these recommended pulses are currently perceived that they may be adequate to provide high in-channel flows of short duration, recruitment events for organisms, lateral connectivity, channel and substrate maintenance, limitation of riparian vegetation encroachment, and in-channel water quality restoration after prolonged low flow periods as necessary for long-term support of a sound ecological environment. However, the Sabine-Neches BBEST recognizes that, within certain stream segments, high flow pulses of certain magnitudes might pose potential liability issues (for example, prescribed high flow pulse releases from a reservoir project could exacerbate flooding caused by uncontrollable rainfall events downstream from the project).

2.1.9 Recommendation 9: Fluvial Matrices Inflow Recommendations are Adequate to Maintain a Sound Ecological Environment in the Sabine-Neches Estuary

Recognizing that the Sabine-Neches Estuary is a system in transition (Tatum 2009) and that the Sabine-Neches Estuary receives the freshwater inflows determined by the flow component recommendations for the Sabine-Ruliff, Neches-Evadale, and Village Creek gages (as well as other inflows[4]), the Sabine-Neches BBEST recommends that these inflows are adequate to maintain a sound ecological environment in the Sabine-Neches Estuary.

Rationale

1. The Sabine-Neches Estuary, like all coastal estuarine ecosystems, is spatially heterogeneous, physically and biologically dynamic, and highly complex owing to

[4] Ungaged inflows and gaged inflows at Pine Island Bayou and Cow Bayou that were not included in this analysis.

interactions among numerous environmental variables, manipulations by man, and diverse species spanning a range of salinity tolerances and ecological niches.

2. The Sabine-Neches Estuary, which includes Sabine Lake, is highly influenced by over 100 years of man-made alterations which have and continue to influence the estuary's current salinity structure (see Section 6.2.3, page 141).
3. The U.S. Army Corps of Engineers (USACE) is currently completing the Sabine-Neches Waterway Feasibility Study – a feasibility study for deepening the existing Sabine-Neches Waterway in Sabine Lake. The study includes a Hydrodynamic-Salinity Model and an analysis of Hydrologic Units in existing marshes/cypress-tupelo swamps in both the Texas and Louisiana portions of the Sabine-Neches Estuary for mitigation and habitat restoration related to the incremental changes of the proposed modifications to the Sabine-Neches Waterway.
4. The Sabine-Neches Estuary is generally sound, exhibiting good overall water quality and diverse fish and wildlife communities (Tatum 2009). The Sabine-Neches Estuary receives more freshwater than all other estuaries on the Texas Gulf Coast (see Table 17, page 143) and provides enough freshwater to Sabine Lake for the focal species studied there (NWF 2009). Sediment transport and concentration are within a range that is indicative of a sound ecological environment (Section 5.3, page 86); and
5. The Sabine-Neches BBEST's fluvial-derived environmental flow recognitions fall within the range of values that should provide sufficient freshwater inflows to maintain a sound ecological environment in the Sabine-Neches Estuary under the estuary's current geomorphologic configuration (Section 5.2.3 Estuarine Ecosystem Realm, page 72).

2.2 Recognitions

2.2.1 Recognition 1: Overbank Flows Have Recognized Ecological Benefits but are not Recommended

Overbank flows may cause extensive damage to private property and endanger the public. Therefore the Sabine-Neches BBEST recognizes the ecological benefits of these events, but cannot recommend such events be produced.

Rationale Overbank flows are infrequent, high flow events greater than bankfull that result in the inundation of the adjacent floodplain habitats. Overbank flows are ecologically important and can beneficially restructure the channel and floodplain, recharge groundwater tables, deliver nutrients to riparian vegetation, and connect the channel with floodplain habitats that provide additional food for aquatic organisms. By providing linkages with the stream channel and wetland areas, overbank flows contribute to the creation of waterbird habitat and breeding grounds, fish community diversity, invertebrate colonization, and provide for significant carbon returns to the river. Inclusion of overbank flows as part of a regulatory requirement will be subject to considerations of ecological benefit and issues of liability and the practicality of managing such flows (Texas Parks and Wildlife Department 2008). The Sabine-Neches BBEST recognizes that legal challenges may arise including liability for the damage resulting from managing for environmental flows

that must be addressed (Dyson, Bergkamp et al. 2003), especially as relates to overbank flows. Because of the potential for legal challenge, property damage, and most importantly the threat to human life, the Sabine-Neches BBEST agrees that implementation of overbank flows should remain within the domain of nature.

2.2.2 Recognition 2: Toledo Bend Reservoir FERC Relicensing

The relicensing of the Toledo Bend Project is ongoing at this time. The relicensing will recognize the Project's primary use as a water supply project with the capability of generating hydroelectric power. Since no major changes in operations are planned, a maintenance flow will continue to be maintained from the spillway.

Rationale There are no major revisions proposed for the operations of the Toledo Bend Project during the relicensing that is currently underway and will be completed in September 2013. Under the existing license, the Project maintains a continuous discharge from the spillway of the dam with a minimum flow established by the license. While the Pre-Application Document (PAD), submitted in September 2008, outlines a small hydroelectric unit for the spillway, it is simply to extract the energy from the currently required spillway discharge.

A series of aquatic studies are underway downstream of the dam and will be used to determine if current operation of the Project has an adverse impact upon the Sabine River. These studies will be completed prior to submitting the Application of the new license in September 2011.

2.2.3 Recognition 3: Sabine River Compact

The major purposes of the Sabine River Compact are to provide for the equitable apportionment between the States of Louisiana and Texas of the waters of the Sabine River and its tributaries. Texas retains free and unrestricted use of the water of the Sabine River and its tributaries above the Stateline, subject only to the provisions that the minimum flow of 36 cfs must be maintained at the Stateline. All free water (free water means all waters other than stored water) and stored water in the Stateline reach, without reference to origin, will be divided equally between the two states.

Rationale Under the Sabine River Compact, there is a minimum flow requirement of 36 cfs at the Stateline. According to the USGS, this equilibrates to 22 cfs at the Beckville Gage (USGS 08022040). The SRA-TX releases 6 cfs from Lake Tawakoni and 4 cfs from Lake Fork as its prorated share of the Compact Stateline requirement. "Stateline" means the point on the Sabine River where its waters in downstream flow first touch the states of both Louisiana and Texas.

2.2.4 Recognition 4: Cutoff Bayou

Environmental flows as well as the diversions for the water supply canal system in Texas are adversely affected by migration of channel flow to the Old River Channel in Louisiana during low and average flow conditions.

Rationale The historic flow distribution between the Texas and Louisiana channels occurring near Cutoff Bayou (river mile 29.3) is changing. Since Hurricane Rita, the flow split, historically measured as close to 50/50, has been determined to be closer to 70 to 80 percent flow to the Old River channel in Louisiana and 20 to 30 percent flow to the Texas Stateline reach. The hydrologic flow conditions in the lower Sabine River Basin are complexly interrelated. That is evidenced by the historic and present flow distribution between the Texas and Louisiana channels occurring near Cutoff Bayou. Recent observations indicate that during low flow conditions, distribution appears to favor Louisiana with greater quantities of water. If recently observed trends were to continue, there is potential for flow during normal flow, and especially during low flow, conditions to be essentially eliminated in the Sabine River within Texas below Cutoff Bayou. These conditions may establish the Old River in Louisiana as the sole conveyance channel to the Gulf of Mexico through that reach. (AECOM 2009)

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3 Basins and Bay Descriptions and Current Conditions

The Study Area defined for the Sabine-Neches BBEST, the Sabine and Neches Rivers, and Sabine-Neches Estuary (Sabine Lake), are shown on Figure 5 (page 25).

3.1 Sabine River Basin

The Sabine River originates in Texas northeast of Dallas and flows southeast towards Logansport, Louisiana, then south to Sabine Lake. The crescent-shaped basin is 48 miles across at its widest point and over 300 miles in length from its headwaters to its mouth at the northeast end of Sabine Lake (580 river miles). All or part of twenty-one Texas counties and seven Louisiana parishes are in the Sabine Basin. The total drainage area of the Basin is 9,756 square miles, with 7,396 square miles (76 percent) in Texas and 2,360 square miles (24 percent) in Louisiana. The Sabine River Authority of Texas (SRA-TX), the Sabine River Authority, State of Louisiana (SRA-LA), and the Sabine River Compact Administration (SRCA) (Sabine River Compact Administration 2008) all have responsibilities relating to the waters of the Sabine Basin. (Sabine River Authority of Texas 1999)

SRA-TX is authorized to store water in the upper Sabine Basin in Lake Tawakoni and Lake Fork, and in the lower Sabine Basin in Toledo Bend Reservoir. SRA-TX and SRA-LA jointly own and operate Toledo Bend Reservoir through the Toledo Bend Project Joint Operation (TBPJO) with the minimum firm yield of Toledo Bend Reservoir being shared 50-50. Toledo Bend Reservoir was constructed for the purposes of water supply, hydroelectric power generation, and recreation and is licensed by the FERC. The FERC license currently requires a minimum flow release from the spillway at Toledo Bend Reservoir.

The Sabine River Basin has 14 major reservoirs (storage > 5,000 ac-ft), 11 in Texas, two in Louisiana, and one jointly in Texas and Louisiana. All of these projects are non-Federal reservoirs constructed for the purposes of water supply, hydropower, and recreation. There are no flood control reservoirs in the Sabine River Basin.

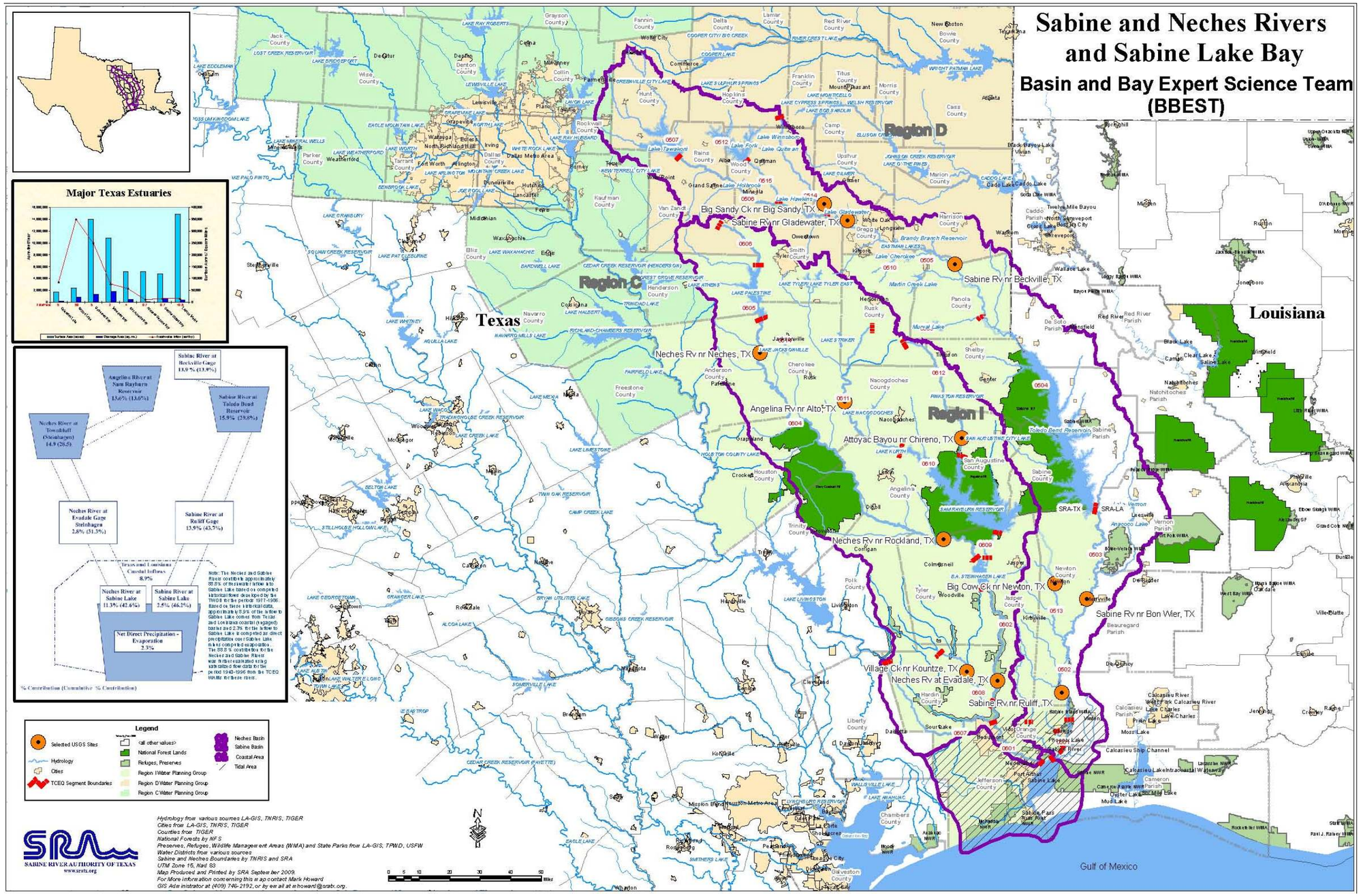
3.2 Neches River Basin

The Neches River Basin is situated in east Texas between the Trinity River Basin to the west, the Sabine River Basin to the north and east, and the Neches-Trinity Coastal Basin to the south. It consists of the main stem Neches River, with headwaters in Van Zandt County, and the Angelina River which joins the Neches River in Jasper County just upstream of B.A. Steinhagen Reservoir. The basin covers approximately 10,000 square miles, is approximately 210 miles long, and ranges in width from just a few miles wide near its mouth to roughly 70 miles wide at its broadest point. Within the basin are 12 water supply lakes (10 of which are major reservoirs), the largest being Sam Rayburn Reservoir which serves as a hydropower reservoir, water supply, and flood control project. Sam Rayburn has nearly 4 million acre feet of total combined storage capacity and is the largest lake completely within the State of Texas. The Neches River empties into the northwest end of Sabine Lake near Port Arthur, Texas. The Angelina-Neches River Authority (ANRA), the Lower Neches Valley Authority (LNVA), and the Upper Neches River Municipal Water

Authority (UNRMWA) have responsibilities relating to the waters of the Neches River Basin in the Sabine-Neches Study Area.

The LNVA manages and operates the Neches River Saltwater Barrier under an agreement with the USACE. In accordance with its permit as issued by TCEQ, there is a minimum pass-through flow requirement of 400 cfs for the saltwater barrier.

FIGURE 5. SABINE AND NECHES RIVERS AND SABINE-NECHES ESTUARY (SABINE LAKE)



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3.3 Sabine-Neches Estuary (Sabine Lake)

3.3.1 Estuary Description

Sabine Lake is a 55,000 to 60,000 acre (volume approximately 300,000 acre-feet), shallow, brackish water lake located on the Texas-Louisiana stateline. Sabine Lake is the smallest major estuary in Texas, but receives the largest volume of freshwater inflow; the combined discharge of the Sabine and Neches Rivers is greater than the freshwater discharge into any other Texas bay system (Sabine River Authority of Texas and Lower Neches Valley Authority 2006). Figure 6 (page 28) shows the relative size and freshwater inflows of Sabine Lake with respect to the other major estuaries in Texas (and the adjacent Calcasieu Lake in Louisiana). Figure 7 (page 29) shows the Coastal Plains of the Calcasieu and Sabine-Neches Drainages. The Sabine-Neches Estuary is further discussed in Section 6.2.3 (page 141).

FIGURE 6. MAJOR TEXAS ESTUARIES

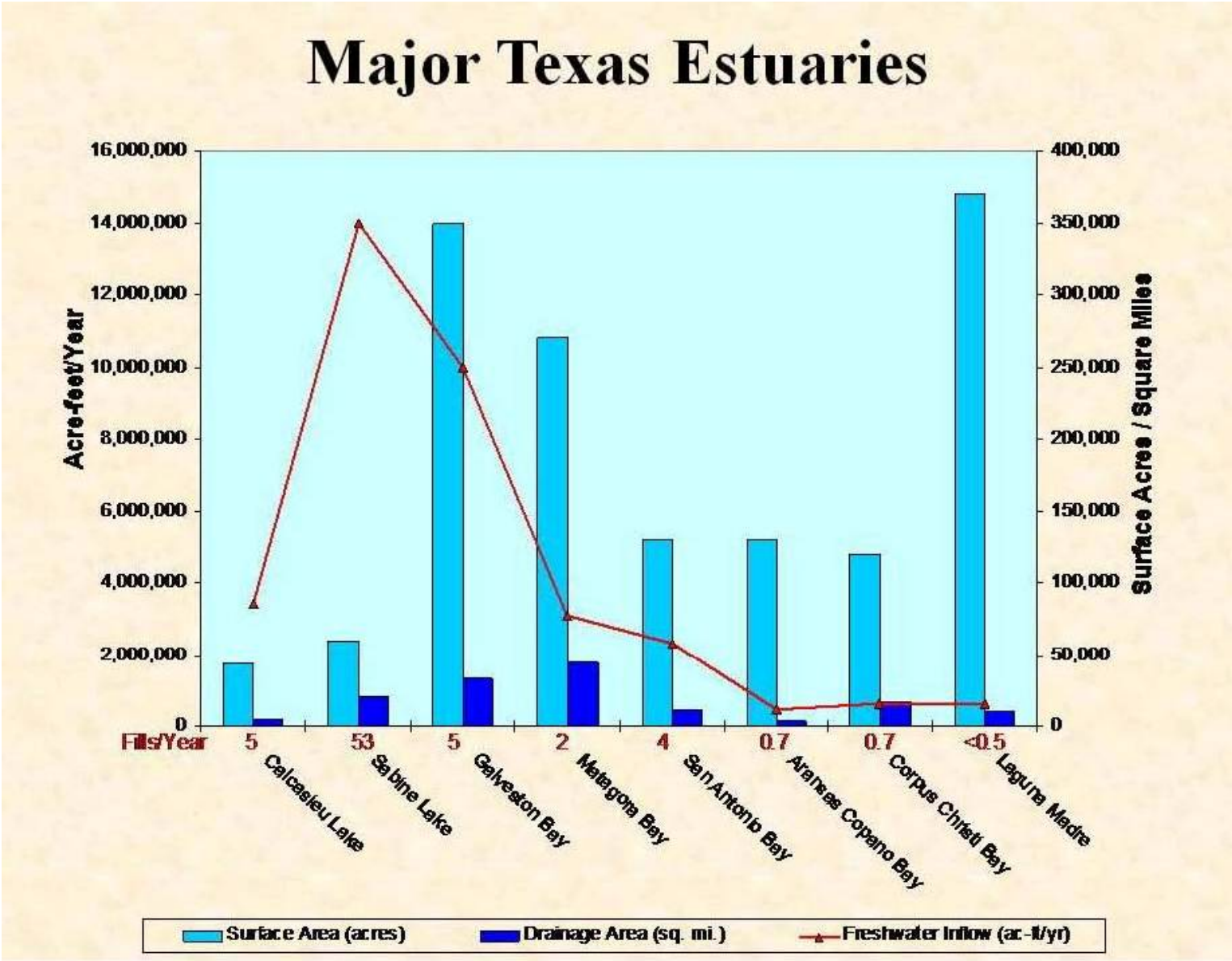
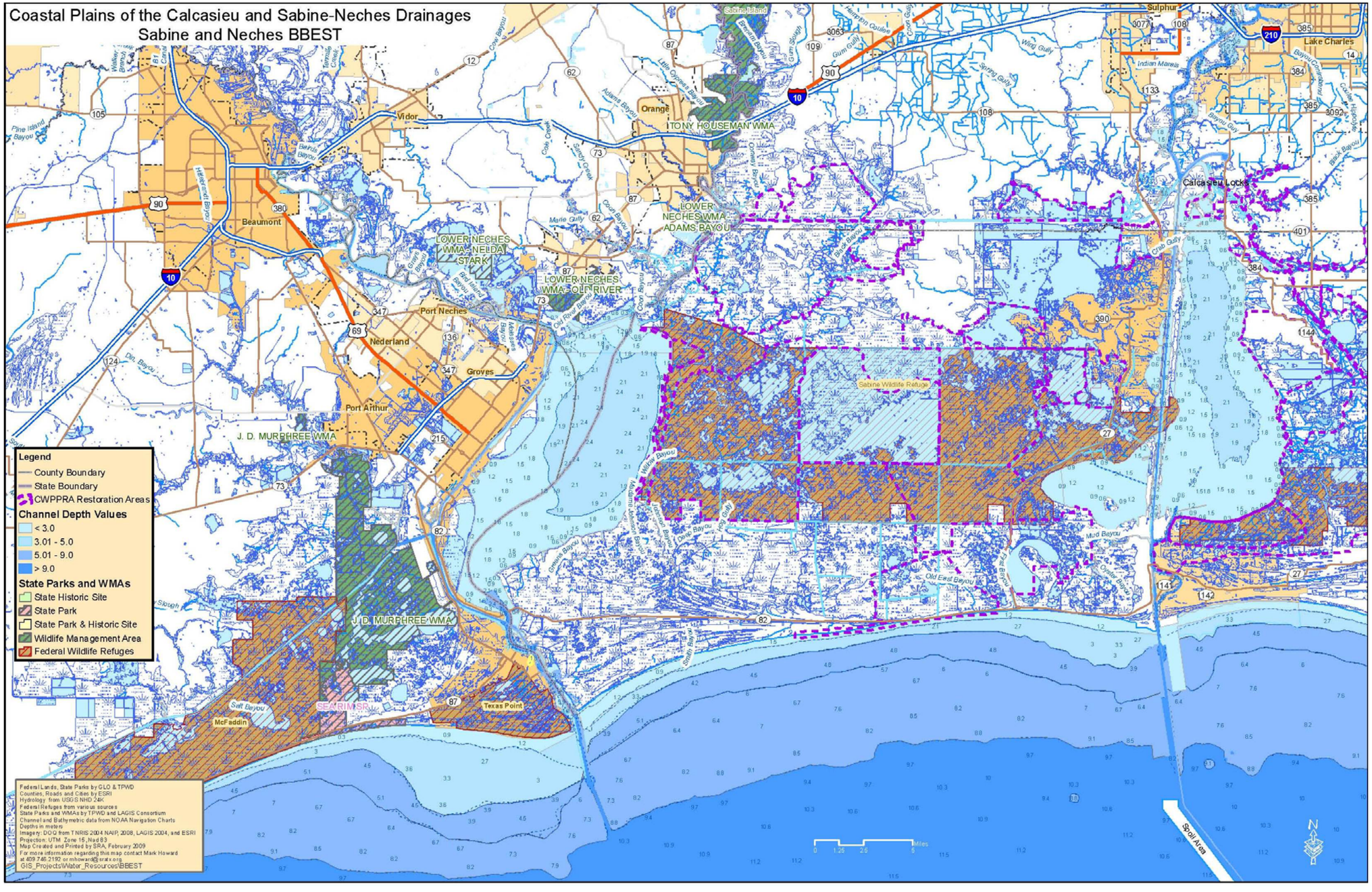


FIGURE 7. COASTAL PLAINS OF THE CALCASIEU AND SABINE-NECHES DRAINAGES



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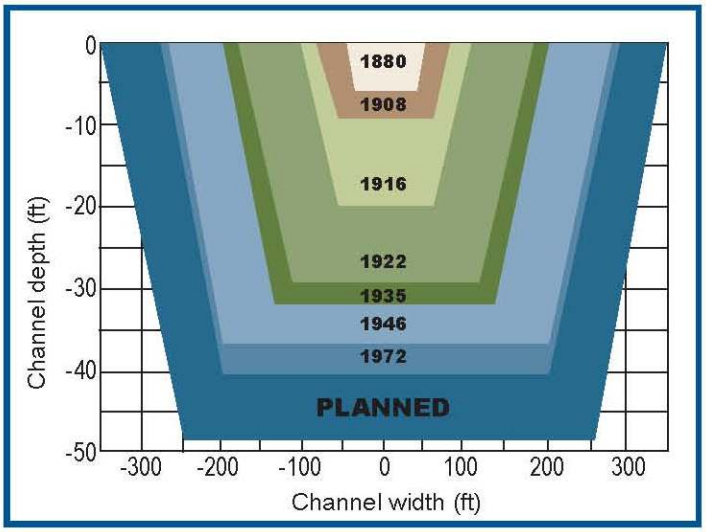
3.3.2 Estuary History

Earliest available records indicate that Sabine Lake was primarily a freshwater lake with extensive sand bar deltas at the mouths of the Sabine and Neches Rivers and the narrow opening to the Gulf of Mexico. In the 1870'S navigation channels began to be maintained in both the Calcasieu Pass (U.S. Army Corps of Engineers 2004) and the Sabine Pass, and navigation channels have been maintained and enlarged ever since. The estuary and its surrounding marshes have been heavily modified. In the past 120 years, a wide range of man-made activities have altered Sabine Lake and its surrounding wetlands and marshes. The current ship channel, the SNWW, completed in 1972 consists of a 40-ft channel to the Port of Beaumont and a 30-ft channel to the Port of Orange (Sutherlin 1996). See Figure 8 (page 32), taken from *Preliminary Investigation Saltwater Barrier* (Sabine River Authority of Texas 2009a). The Calcasieu Ship Channel is maintained at 40-ft depth and 400-ft width. The GIWW completed in 1933 (Sutherlin 1996) and other canals through the marsh have linked Sabine Lake to Calcasieu Lake in multiple locations (Paille 1996).

These navigation channels affect the Sabine-Neches Estuary in at least two ways. First, during times of high tide, they allow saltwater to intrude into the estuary and further upstream into the rivers, lakes, bayous, the GIWW, and marshes. Secondly, during times of flooding, they move fresh water out of the estuary more quickly reducing the amount of marsh land flooding; thereby, giving less retention time for freshwater flows and the accumulation of sediments in the marsh (Boesch, Josselyn et al. 1994, and references therein). Moreover, the USACE is planning additional navigational access improvements in Sabine Lake (Tatum 2009). The USACE plans to complete a draft study of the feasibility and environmental impact of deepening the SNWW from 40-ft to 48-ft and submit the draft for public comments on December 17, 2009. A final report is expected in August 2010. These modifications will undoubtedly exacerbate the impact of the channels.

The dredging of secondary channels for oil and gas drilling in the marshes have allowed saltwater intrusion into the marshes; these canals are a "source of erosive energy on the surrounding marsh" (Boesch, Josselyn et al. 1994, and references therein) with subsequent land subsidence in some areas, resulting in loss of vegetation and erosion of organic soil. Open water lakes have formed in the marshes that have become increasingly unstable and continue to degrade into larger open-water areas under existing conditions (Boesch, Josselyn et al. 1994, and references therein). Today the amount of wetlands lost from coastal Louisiana and Texas is staggering. These canals have been estimated to be responsible for the majority of this loss (Scaife, Turner et al. 1983).

FIGURE 8. HISTORIC WIDENING AND DEEPENING OF THE SABINE-NECHES SHIP CHANNEL[5]



3.4 Regional Water Planning

SB 3 instructs each BBEST to consider all reasonably available science and to base its environmental flow regime recommendations solely on the best science available, without regard to the need for the water for other uses. The Sabine-Neches BBEST has complied with this charge, yet recognizes in a practical sense, that the Sabine-Neches BBASC will consider the science team's recommendations as it works to balance environmental flows with the needs of the people of Texas.

In response to the historic drought of the 1950s (drought-of-record) and in recognition of the need to plan for the future, the Texas Legislature created the TWDB to develop water supplies and prepare plans to meet the state's future water needs. In 1997, with SB 1, the legislature established a new water planning process, based on a "bottom-up," consensus driven approach. Coordinating this water planning process are 16 regional water planning groups (RWPGs), one for each regional water planning area. (Texas Water Development Board. 2007). The Sabine and Neches Basins include Regions I, D, C, and a small portion of Region H.

3.4.1 2007 State Water Plan

The current Texas State Water Plan, "Water for Texas 2007" (Texas Water Development Board. 2007) provides for

[5] The latest USACE draft study report indicates just deepening with selected widening areas; they do not plan to widen the entire channel length.

the orderly development, management, and conservation of water resources and preparation for and response to drought conditions, in order that sufficient water will be available at a reasonable cost to ensure public health, safety, and welfare; further economic development; and protect the agricultural and natural resources of the entire state. Texas Water Code, §16.051.

"Water for Texas 2007" projects water supply needs (demands in excess of existing supplies that would be physically and legally available during a repeat of the drought-of-record) of 3.7 million acre-feet in 2010; 5.9 million acre-feet by 2030; and 8.8 million acre-feet by 2060. The various water management strategies identified to meet these needs include the water supply reservoirs in the Sabine and Neches Basins (mainly Region I, East Texas) which have combined over 2 million acre-feet of annual permitted yield. The regional water plans that will contribute to the 2012 State Water Plan are currently being developed in Regions I, D, C, and H.[6]

3.4.2 Unique Stream Segments

Each RWPG may include in its adopted regional water plan all or parts of stream segments considered as having "unique ecological value." According to TWC Subchapter C. §16.051(e), designation of a unique stream segment "solely means that a state agency or political subdivision of the state may not finance the actual construction of a reservoir in a specific river or stream segment designated by the legislature under this subsection."

To recommend a site, RWPGs prepare a recommendation package to be submitted to the legislature. According to 31 TAC §357.8, recommendation packages should include a description of the site location along with maps, photographs, and documentation with supporting literature and data that characterize a site's unique ecological value. This data must be based upon the following criteria:

- Biological Function: streams displaying significant habitat value including both quantity and quality considering degrees of biodiversity, age, and uniqueness including terrestrial, wetland, aquatic, or estuarine habitats.
- Hydrologic function: stream segments fringed by habitats that perform valuable hydrologic functions relating to water quality, flood attenuation, flow stabilization, or groundwater recharge and discharge
- High water quality/exceptional aquatic life/ high aesthetic value: stream segments and spring resources that are significant due to unique or critical habitats and exceptional aquatic life uses dependent on or associated with high water quality.
- Riparian conservation areas: stream segments fringed by significant areas in public ownership including state and federal refuges, wildlife management areas, preserves, parks, mitigation areas, or other areas held by governmental

[6] http://www.twdb.state.tx.us/wrpi/rwp/rwp.htm, retrieved October 12, 2009

organizations for conservation purposes or stream segments fringed by other areas managed for conservation purposes under a governmentally approved conservation plan.

- Threatened or endangered species/unique communities: sites along streams where water development projects would have significant detrimental effects on state or federally listed threatened and endangered species, and sites along streams significant due to the presence of unique, exemplary, or unusually extensive natural communities.

Recommendations included in regional water plans are incorporated into the State Water Plan and considered by the legislature for designation. If the Texas Legislature designates a stream or river segment as unique, the RWPG must quantitatively assess how recommended water management strategies in a regional plan would affect flows deemed important to the stream or river segment in question.

RWPGs have been concerned with the implications of designation of unique stream segments and the intended effects of designation have been discussed at length among state agencies and RWPGs. The 77th Texas Legislature sought to clarify the regulations in 2002 by adding language indicating that the only intended effect was to prevent development of a reservoir on the designated segment by a political subdivision of the state. However, concerns still remain regarding the implications of designation.

In the 2007 State Water Plan, no unique stream segments were considered by the two predominant water planning regions in the Sabine and Neches Basins.

3.4.2.1 Region I

Region I, which covers a 20-county area including the metropolitan areas of Beaumont-Port Arthur, Lufkin, Nacogdoches, and Tyler, declined to recommend unique stream segments in its 2006 Regional Water Plan due to lack of clarity in regulations. In consideration of its 2011 Regional Water Plan, Region I's RWPG, the East Texas Regional Water Planning Group (ETRWPG), met and considered recommendations of unique stream segments in April and July 2009. The TPWD produced a 121-page document listing ecologically significant river and stream segments in Region I to aid in the identification of potentially unique stream segments (Texas Parks and Wildlife Department 2005). However, the ETRWPG voted in July 2009 to not recommend unique stream segments for its 2011 Regional Water Plan.

3.4.2.2 Region D

TPWD provided a document entitled, "Ecologically Significant River and Stream Segments of Region D, Regional Water Planning Area" (May 2000), which presents information on 14 stream segments within the region meeting one or more of the criteria for designation as ecologically unique. Region D's RWPG, the North East Texas Regional Water Planning Group (NETRWPG), elected to not recommend stream segments for ecologically unique designation. The NETRWPG's 2006 Regional Water Plan (NETRWPG 2006) cites the following reasons for this decision:

1. The RWPG feels that there exists a lack of clarity as to the effects of designation with respect to private property takings issues;
2. The RWPG does not wish to infringe upon the options of individual property owners to utilize stream segments adjacent to their property as they deem appropriate. For example, if reservoirs cannot be built in unique segments, will these become prime candidates for mitigation sites acquired by eminent domain?
3. Despite previous legislative clarification, there remains uncertainty as to the myriad ways in which the designation may ultimately be construed.
4. Where overlap occurs between unique stream candidates and water management strategies, sufficient information to express preference for one use to the exclusion of another is not available at this time.

3.4.3 Unique Reservoir Sites

RWPGs may recommend sites for reservoir construction that have "unique value." The planning groups may prepare a recommendation package including a description of the site, reasons for the unique designation and expected beneficiaries of water supplies developed at a given site. According to 31 TAC §357.7, criteria used to designate unique reservoir sites are as follows:

1. Site specific reservoir development is recommended as a specific water management strategy or alternative long-term scenario in an adopted regional water plan;
2. The location, hydrologic, geologic, topographic, water availability ,water quality, environmental, cultural, and current development characteristics, or other pertinent factors make the site uniquely suited for:
    a. reservoir development to provide water supply for the current planning period; or
    b. where it might reasonably be needed to meet needs beyond the 50-year planning period.

According to TWC Subchapter C §16.051, designation of unique sites for reservoir construction means that "a state agency or political subdivision of the state may not obtain a fee title or an easement that would significantly prevent the construction of a reservoir on a site designated by the legislature under this subsection."

To date, only two sites have been designated as unique reservoir sites in the Neches Basin (and both in Region I) and no sites in the Sabine Basin have been so designated. Following is a brief description of the approach to unique reservoir sites taken by RWPGs in Regions I and D.

3.4.3.1 Region I

Region I has two potential reservoir sites designated as unique sites for reservoir construction. Lake Columbia was designated separately through the legislature[7] and Fastrill Reservoir was recommended by Region C. The two reservoirs are also currently identified as strategies to meet water shortages in the planning period for Regions I (Lake Columbia) and C (Fastrill Reservoir) during the 50-year planning period. The Region I RWPG will review the status of future unique reservoir sites for the 2011 update of its regional water plan in December 2009.

3.4.3.2 Region D

The Region D RWPG recognizes 15 locations where the topography is such that the area could be classified as uniquely suitable as a reservoir site. Six of the 15 potential reservoir sites are located in the Sabine River Basin: Prairie Creek, Big Sandy, Carl Estes (Mineola), Carthage, Kilgore II, and Waters Bluff Reservoirs. However, the NETRWPG recommends that any new reservoir in Region D be pursued only after all other viable alternatives have been exhausted.

3.5 Sabine-Neches Study Area Unique Issues

Issues unique to the Sabine-Neches Study Area include the following.

3.5.1 Texas Louisiana

The Sabine River Basin from the stateline to the mouth of the river as well as the Sabine Neches Estuary is shared with Louisiana—approximately 25 percent of the Sabine River Basin watershed above the river's mouth is in Louisiana. Louisiana does not have a program similar to SB 3.

3.5.2 Texas State Water Quality Flows (7Q2)

Because the Sabine River portion of the study area involves two states, it must be recognized that each state uses a different flow for implementation of water quality standards when calculating effluent limits for water quality permits. In Texas, a 7Q2 (a 7-day low flow with a 2 year recurrence interval) is used as the flow below which water quality standards do not apply. Louisiana uses a 7Q10 (a 7-day low flow with a 10-year recurrence interval) for similar purposes. The applicability of water quality flows to be used in this process is discussed further in Section 5.4. (page 93)

3.5.3 Senate Bill 2: Lower Sabine River Priority Instream Flow Study

The lower Sabine River downstream from Toledo Bend Reservoir to the tidal waters of the Sabine River is included as a priority sub-basin, first tier, for TIFP study under SB 2. The

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[7] Texas Senate Bill 1362 designated the site for Lake Columbia as a site of unique value for the construction of a dam and reservoir in 2003.

upper Sabine River and the upper and lower Neches River areas have not been included in the first tier studies. Although Louisiana agencies (Louisiana Department of Environmental Quality, Louisiana Department of Wildlife and Fisheries, Coastal Protection and Restoration Authority) have participated in SB 2 meetings, Louisiana does not have a similar program and Louisiana stakeholders have expressed the desire to make their own decisions related to how Louisiana's half of the water would be used.

3.5.4 Toledo Bend Project Joint Operations

SRA-TX and SRA-LA collaborated to develop the Toledo Bend Project located on the Sabine River. Construction was completed in October 1966. The Project is jointly operated by SRA-TX and SRA-LA through TBPJO. The Project, which was originally licensed by the FERC's predecessor agency the Federal Power Commission, in 1963, was initially conceived, licensed, and developed primarily as a water supply reservoir, with secondary uses including hydroelectric power generation and recreation. The original license was a 50-year license that is scheduled to expire in September 2013.

Relicensing of the Project is currently underway using the FERC Integrated Licensing Process (ILP)[8] with the anticipated completion of the process in September 2013. The ILP is intended to assess the impact of the Project upon the environment and resources based upon the current conditions and any impacts that may occur in the future as a result of the project operations. The PAD, submitted in September 2008, outlines that there are no major revisions proposed for the operations of the Toledo Bend Project during the next licensing period. The PAD does describe a small hydroelectric generation unit for the spillway to recover energy from the required release from the spillway.

Currently the TBPJO is in the study phase of the ILP. Of relevance to the Sabine-Neches BBEST is a significant amount of aquatic studies that are underway on the lower Sabine River below the Toledo Bend dam. The aquatic studies include fish community sampling and assessment, freshwater mussel distributions, macroinvertebrate sampling, and physical parameters such as water temperature and flows. While the data from this effort is not available at this time, it will provide information that will be used by the TBPJO and FERC to refine future flow conditions and will be available to the Sabine-Neches BBEST for adjustments in the flows that may be needed by the environment.

3.5.5 Sabine River Compact

The Sabine River Compact was signed by representatives of the State of Texas and Louisiana, and the United States on January 26, 1953, and subsequently was ratified by the

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[8] FERC: Hydropower - Integrated Licensing Process (ILP), http://www.ferc.gov/industries/hydropower/gen-info/licensing/ilp.asp, retrieved November 8, 2009

legislatures of the States and approved by the Congress of the United States. The major purposes of the Compact are to:

- provide for the equitable apportionment between the States of Louisiana and Texas of the waters of the Sabine River and its tributaries;
- establish a basis for cooperative planning and action by the States for the construction, operation, and maintenance of projects for water conservation and utilization on the reach of the Sabine River common to both States; and
- provide for the apportionment of the benefits.

As used in the Compact, the word "Stateline" means the point on the Sabine River where its waters in downstream flow first touch the States of both Louisiana and Texas. The essentials of water apportionment provisions of the Compact are as follows:

- Texas retains free and unrestricted use of the water of the Sabine River and its tributaries above the Stateline, subject only to the provisions that the minimum flow of 36 cfs must be maintained at the Stateline.
- Any reservoir constructed in the watershed above the Stateline subsequent to January 1, 1953, will be liable for its prorata share of the guaranteed minimum flow.
- Texas may either use the yield of the reservoirs above the Stateline or allow it to flow downstream in the Stateline reach to a desired point of removal without loss of ownership.
- All free water (free water means all waters other than stored water) in the Stateline reach, without reference to origin will be divided equally between the two States.
- Neither State may construct a dam on the Stateline reach without the consent of the other State.
- Water stored in reservoirs constructed by the States in the Stateline reach shall be shared by each State in proportion to its contribution to the cost of storage.
- Should either State construct a reservoir on a stream tributary to the Stateline reach of the Sabine River, that State is entitled to the yield of the reservoir, but its share of the flow of the Sabine River is reduced by the reduction in flow resulting from the operation of the reservoir.
- Water consumed for domestic and stock water purposed is excluded from the apportionment under the Compact.

3.5.6 Lower Neches River Saltwater Barrier

The LNVA manages and operates the lower Neches River Saltwater Barrier under an agreement with the USACE. There is a minimum flow requirement of 400 cfs for the saltwater barrier.

3.5.7 Cutoff Bayou: Lower Sabine River

The Cutoff Bayou area is an environmental as well as a water supply concern in the lower Sabine River. The stateline river reach in this area has historically flowed with

approximately equal amounts to both the stateline river and to the Old River channel during lower flows. Since Hurricane Rita, the flow split has been determined to be closer to 70 to 80 percent flow to the Old River channel in Louisiana and 20 to 30 percent flow to the Texas stateline reach. Studies are needed to determine measures to stabilize this area before the river reroutes the lower flows entirely to the Old River channel in Louisiana. (AECOM 2009)

3.5.8 USACE Sabine-Neches Waterway Feasibility Study

The USACE is currently completing the Sabine-Neches Waterway Feasibility Study. The recommended plan is to deepen the existing ship channel from 40 to 48 feet. This nine year/15+ million dollar study includes a Hydrodynamic-Salinity Model with a revised period of analysis to include baseline Texas Water Availability Model (WAM) current conditions, completion of the deepening project by 2019 and Texas Water Plan 2007 year 2060 projections for year 2069 conditions. The study also includes analysis of Hydrologic Units in existing marshes/cypress-tupelo swamps in Texas and Louisiana for mitigation and habitat restoration related to the incremental changes of deepening the ship channel. For details of this USACE study, see Section 6.2.3 Sabine-Neches Estuary (Sabine Lake), page 141.

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4 SCIENCE ADVISORY COMMITTEE

4.1 BACKGROUND

The Texas Environmental Flows Science Advisory Committee (SAC) serves as an objective scientific body to advise and make recommendations to the Environmental Flows Advisory Group on issues relating to the science of environmental flow protection and develop recommendations to help provide overall direction, coordination, and consistency. The SAC consists of five to nine members appointed by the advisory group.

The SAC appoints one of its members to serve as a liaison to each basin and BBEST to facilitate coordination and consistency in environmental flow activities throughout the State.

4.2 GUIDANCE

The SAC provides an objective perspective and diverse technical expertise, including expertise in hydrology, hydraulics, water resources, aquatic and terrestrial biology, geomorphology, geology, water quality, computer modeling, and other technical areas pertinent to the evaluation of environmental flows. To date, the SAC has six technical documents available as guidance resources to state BBESTs. Unfortunately, the Sabine-Neches BBEST was unable to take full advantage of the SAC guidance because its timeline predated the availability of the final documents in some cases. However, the SAC liaison assisted the Sabine-Neches BBEST by providing initial drafts of available works in progress, and the group utilized information provided to the extent practical.

The SAC guidance documents to date are as follows.

4.2.1 GEOGRAPHIC SCOPE

Geographic Scope of Instream Flow Recommendations This document presents various factors that could be considered by the BBEST in determining geographic scope for instream flows development. The importance of existing streamflow-gaging stations, primarily operated by the U.S. Geological Survey (USGS), is identified. The report suggests using the USGS Core Network gages as a starting point. It encourages the BBESTs to fully evaluate the adequacy of this network and modify the number of recommended streamflow-gaging stations as deemed appropriate to adequately define the environmental flow regime. (SAC 2009c, Appendix III)

4.2.2 USE OF HYDROLOGIC DATA

Use of Hydrologic Data in the Development of Instream Flow Recommendations for the Environmental Flows Allocation Process and The Hydrology-Based Environmental Flow Regime (HEFR) This document provides an overview of how hydrologic data may be used in the identification of instream flow recommendations pursuant to the requirements of SB 3. As such, it describes one piece of the collaborative process envisioned by SB 3 for the identification of flows to maintain a sound ecological environment in rivers and streams. (SAC 2009f, Appendix VI)

4.2.3 Fluvial Sediment Transport (Geomorphology)

Fluvial Sediment Transport as an Overlay to Instream Flow Recommendations for the Environmental Flows Allocation Process This document reviews various methods for assessing suspended-load and bedload transport, and recommends that the BBESTs consider application of the Sediment Transport Models (SAM) Hydraulic Design Package for estimating effective discharge. (SAC 2009b, Appendix II)

4.2.4 Freshwater Inflow Regime

Methodologies for Establishing a Freshwater Inflow Regime for Texas Estuaries Within the Context of the Senate Bill 3 Environmental Flows Process This document provides background information and discussion of various methods that can be used to develop freshwater inflow recommendations for Texas bays and estuaries. While a few germane references to the literature are made, this document is not intended to be a tutorial on the physics and ecology of estuaries, nor on the range of modeling techniques of potential application. Rather, it attempts to present a succinct summary of methods that are presently sufficiently developed and suitable for application to Texas estuaries, for consideration by the BBESTs. (SAC 2009d, Appendix IV)

4.2.5 Water Quality

Nutrient and Water Quality Overlay on Hydrology-Based Instream Flow Recommendations Water quality is the focus of this overlay document. Numeric and narrative criteria developed by the state address matter carried in suspension and solution, such as dissolved and suspended solids, as well as nutrients, toxics, indicator bacteria, temperature, pH, dissolved oxygen, and other parameters. Under some circumstances all might play a role in the determination of an environmental flow regime. Changes in a flow regime can be expected to produce changes in water quality conditions. The challenge is to ensure that the recommended flow regime protects water quality, particularly during low or subsistence flow conditions, and also considers water quality needs during higher flow conditions. (SAC 2009e, Appendix V)

4.2.6 Biology

Essential Steps for Biological Overlays in Developing Senate Bill 3 Instream Flow Recommendations The Biological Overlay document provides guidance on:

1. Assimilating biological information needed to develop a biological overlay within the context of SB 3;
2. Applying biological information to inform the geographic scope of instream flow recommendations;
3. Addressing decision points required before and during hydrology-based modeling;
4. Applying a biological overlay for the purpose of refining and/or confirming preliminary hydrology-based instream flow recommendations; and
5. Using the biological overlay document in a hydrology-based environmental flow determination. (SAC 2009a, Appendix I)

5 DISCIPLINE REPORTS

The TIFP "Texas Instream Flow Studies: Technical Overview" (Texas Commission on Environmental Quality 2008b) identified four riverine components – biology, hydrology and hydraulics, water quality, and geomorphology – as key disciplines that must be included in any successful instream flow program. SAC guidance reinforced the significance of these disciplines by including them in its guidance (SAC 2009a, Section 5.2). The Sabine-Neches BBEST, under its SB 3 charge to use the "best available science" to develop environmental flow regime recommendations for the Sabine-Neches Study Area (Figure 5 page 25), named subcommittees for each discipline to gather and analyze information related to that riverine component. An overview of the findings of each subcommittee is presented in Section 6 with more extensive information and data found in the appendices of this report.

5.1 HYDROLOGY

The Sabine-Neches BBEST established six subcommittees with two of these, gaging and hydrology, primarily developing recommendations to the Sabine-Neches BBEST on the geographic scope of Instream flow recommendations (using SAC guidance, SAC 2009c, in evaluation of use of USGS gages) and the use of hydrologic data in the development of instream flow recommendations for environmental flows using SAC guidance for utilizing the Hydrology-based Environmental Flow Regime (HEFR) (SAC 2009f).

The Sabine-Neches BBEST selected FNI (Jon Albright) as an outside consultant to prepare three memoranda:

1. "Analysis of BBEST Stream Gages" (Gage Memo) (FNI 2009a)
2. "Hydrology-Based Environmental Flow Regime (HEFR) Analyses for Sabine-Neches Bay and Basin Expert Science Team (BBEST)" (HEFR Memo) (FNI 2009b)
3. "Water Availability Analyses for Sabine-Neches Bay and Basin Expert Science Team" (BBEST) (WAM Memo) (FNI 2009c)

The two subcommittees worked with FNI in the preparation of these memos and have used this baseline work to develop flow regime matrices for work performed by the Biology, Water Quality, and Geomorphology Subcommittees. The Recommendations Report Subcommittee is responsible for bringing the report documentation from each of these disciplines into the final report.

5.1.1 GAGE SELECTION AND GEOGRAPHIC COVERAGE

5.1.1.1 GAGE SELECTION

The Sabine-Neches BBEST selected six USGS stream gages in the Sabine River Basin and six USGS stream gages in the Neches River Basin for hydrologic analyses. These gages serve as the hydrologic basis for flow regime recommendations developed to satisfy the SB 3 environmental flows process. Gage locations are shown in the study area map (Figure 5.

Sabine and Neches Rivers and Sabine-Neches Estuary (Sabine Lake), page 25). Data used in the analysis were obtained from the USGS website.

Two gages in each basin have minimally controlled or altered watersheds. In the Sabine Basin, Big Sandy Creek near Big Sandy has one small recreation reservoir, Lake Winnsboro, in its watershed. Big Cow Creek near Newton has very little modification in its watershed and represents nearly natural conditions. In the Neches Basin, Attoyac Bayou near Chireno is downstream from one small water supply reservoir, Lake Pinkston. Village Creek near Kountze has only a few appropriated water rights upstream.

In addition to the twelve stream gages, the Sabine-Neches BBEST also requested hydrologic analyses of the total inflows into Sabine–Neches Estuary, for a total of thirteen analysis locations.

5.1.1.2 Geographic Coverage of Selected Gages

The SAC has developed guidance for the selection of stream gages for analyses as part of the SB3 process in the report "Geographic Scope of Instream Flow Recommendations" (SAC 2009c, Appendix III). Although this document was not available to the Sabine-Neches BBEST at the time of gage selection, FNI (FNI 2009a, Appendix IX) analyzed several of the criteria in the geographic scope document, including coverage of:

- USGS Core Network of gages;
- TCEQ Water Quality Segments;
- USGS Hydrologic Units;
- TCEQ Ecoregions and TPWD Significant Stream Segments; and
- identified geomorphic process zones.

Based on these criteria, the twelve gages selected by the Sabine-Neches BBEST have sufficient geographic coverage to adequately represent the hydrologic conditions found in the two basins. Three gages, the Sabine River near Ruliff, the Neches River at Evadale and Village Creek near Kountze, measure a significant portion of inflow into Sabine Lake (see Figure 35, page 146). (FNI 2009a)

5.1.2 HEFR Analysis for Sabine-Neches BBEST

FNI conducted hydrologic analyses of the twelve gages in the Sabine-Neches River Basins and inflows into Sabine Lake, including HEFR analyses. This work is discussed in detail in the SAC guidance (SAC 2009f, Appendix VI) and FNI HEFR Memo (FNI 2009b, Appendix X). The Hydrology Subcommittee has used this baseline of hydrology analyses to develop the flow regime matrices presented in this document.

5.1.3 WAM Analysis for Sabine-Neches BBEST

The FNI WAM Memo (FNI 2009c, Appendix XI) describes an analysis of water available for the environmental flows preformed by FNI. These analyses employed the TCEQ WAM) for the Sabine and Neches River Basins, as modified for use by the Region I (East Texas) RWPG. The analyses include assessments of:

- unappropriated and regulated flows;
- frequency of compliance with preliminary hydrology-based environmental flow regime matrices by both naturalized and regulated flows.

The WAM analyses include use of both the current conditions (Run 8) and full authorization (Run 3) scenarios.

5.1.4 Instream Flow Regime Components

Subsistence flows are low flows that occur during times of drought or under very dry conditions (Texas Commission on Environmental Quality 2008b). The primary objective of subsistence flows is to maintain water quality to prevent loss of aquatic organisms due to, for example, lethal high temperatures or low dissolved oxygen levels. Secondary objectives may include providing life cycle cues based on naturally occurring periods of low flow or providing refuge habitat to ensure a population is able to re-colonize the river system once more normal, base flow conditions return.

Base flows represent the range of "average" or "normal" flow conditions in the absence of significant precipitation or runoff events (Texas Commission on Environmental Quality 2008b). Base flows provide instream habitat conditions needed to maintain the diversity of biological communities in streams and rivers. Habitat quality and quantity are important for survival, growth, and reproduction of fish and other aquatic organisms (e.g., mussels and benthic macro invertebrates, other vertebrates, and flora). Base flows can also support the maintenance of water quality conditions and can contribute to the alluvial groundwater that supports riparian habitats, which are important components of river ecosystems.

High flow pulses are short duration, high magnitude (but still within channel) flow events that occur during or immediately following rainfall events (Texas Commission on Environmental Quality 2008b). High flow pulses serve to maintain important physical habitat features and connectivity along a stream channel. Many physical features of a river or stream which provide important habitat during base flow conditions cannot be maintained without appropriate high flow pulses. High flow pulses also provide longitudinal connectivity along the river corridor for many species (e.g., migratory fish), lateral connectivity to near-channel features (e.g., connections to some oxbow lakes), and can support the maintenance of water quality.

Overbank flows are infrequent, high magnitude flow events that produce water levels that exceed channel banks and result in water entering the floodplain (Texas Commission on Environmental Quality 2008b). A primary result of overbank flows is to maintain riparian areas associated with riverine systems. For example, overbank flows transport sediments and nutrients to riparian areas, recharge floodplain aquifers, and provide suitable conditions for seedlings. Overbank flows also provide lateral connectivity between the river channel and the active floodplain, supporting populations of fish or other biota utilizing floodplain habitat during and after flood events. Other objectives for overbank flows include the movement of organic debris to the main channel, providing life cycle cues for various species, and maintaining the balance of species in aquatic and riparian communities.

5.1.5 Hydrologic Data

Hydrologic data have several advantages for characterizing riverine systems over many other forms of environmental data in that they are relatively consistently and continuously measured at numerous locations and are also easily obtainable from the USGS.[9] These characteristics, along with the comparatively simple nature of the data themselves, mean that hydrologic datasets can be evaluated using fairly generic statistical approaches and tools. Thus, hydrologic data typically provide the most convenient, initial understanding of riverine systems.

5.1.6 Advantages and Disadvantages Common to All Hydrologic Methods

Hydrologic methods share certain advantages and disadvantages (relative to biological, geomorphologic, and water quality methods).

Common advantages include:

1. relatively robust and consistent datasets at multiple locations,
2. the understanding that hydrology has been considered the "master variable" with regard to environmental instream flows (Poff, Allan et al. 1997), and
3. ease of use.

Common disadvantages include:

1. a lack of validation against biological, geomorphologic, and water quality data (e.g., the methods are largely designed to mirror some fraction of historical hydrology and are not based on defined flow alteration-ecological response relationships), and
2. unsuitability where hydrologic data are lacking and cannot be synthesized.[10]

Because of these disadvantages, the hydrologic methods are only recommended when sufficient data to define flow alteration – ecological response relationships are unavailable. In Texas, such data are probably currently unavailable on all river segments with the exception of the lower Colorado River (SAC 2009f). As per Dr. Kirk Winemiller, the San Marcos River, lower Sabine River, lower Neches River, and Big Cypress Bayou should be included (Winemiller 2009).

Even though comprehensive datasets to define flow alteration–ecological responses are generally unavailable, some biological, geomorphologic, and water quality data is available

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[9] Real-Time Data for Texas Streamflow, http://waterdata.usgs.gov/tx/nwis/current/?type=flow, retrieved November 3, 2009

[10] Synthesizing hydrologic data involves a wealth of complexities that are beyond the scope of SAC guidance.

in each major river basin. Thus, following the application of any of these hydrologic methods, the SAC recommended that the available data be used to corroborate or refine selected hydrology-based flow recommendations, as appropriate.

5.1.7 Available Methods

The Instream Flow Council has described and summarized a number of methods for assessing instream flow requirements (Annear, Chisholm et al. 2004). Over 30 techniques are grouped into three broad categories: Standard Setting, Incremental, and Monitoring/Diagnostic. Standard Setting methods (e.g., the Lyons Method) set limits to define threshold flow regimes and can be done relatively quickly using hydrologic data but are not considered as rigorous as methods that also use biologic data. Incremental methods (e.g., the SB 2 TIFP method) analyze one or more variables to enable assessment of different flow management alternatives. Incremental methods are often considered more scientifically accepted but also require more resources to execute since site-specific data must be collected. Monitoring/Diagnostic methods are those methods that can be used to assess conditions and how they change over time. An example of this type of method is the Nature Conservancy's Indicators of Hydrologic Alteration method (IHA).

Based on recommendations from the SAC created by the Study Commission on Water for Environmental Flows (Senate Bill 1639 from 2003), TCEQ created a Technical Review Group (TRG) to review available instream flow assessment tools and to develop one or more desktop methodologies specifically applicable to Texas river and stream conditions. The term "desktop" refers to methods that can be applied using readily available information and do not require site-specific field studies.

The TRG focused its initial review on desktop methodologies that have been applied to Texas streams (Technical Review Group 2008). These included the Lyons Method, the Consensus Criteria for Environmental Flow Needs, the Texas Method, and IHA. After further deliberation the TRG chose to focus its final review on the Lyons Method and IHA.

In addition to the above methods, the HEFR method is a new, relatively flexible computational approach for developing a flow regime matrix that is consistent with the TIFP. HEFR was initiated by TPWD with input from other agencies and organizations as an alternative to the Lyons Method for use in water rights permitting. Although the method as a whole has not been peer reviewed, the Environmental Flow Components (EFC) algorithm and IHA software used by HEFR for hydrographic separation have been used extensively. In addition, HEFR forms the framework for the environmental flow recommendations in the Brazos River Authority's Systems Operation draft water right permit pending at the TCEQ.

Following a HEFR technical workshop (February 24, 2009), a number of enhancements and modifications were suggested and implemented. This work has been completed at the direction of the SAC. Alternative methods of hydrographic separation and methods of identifying and characterizing high flow pulses and overbank events have been evaluated and implemented. The current version of HEFR includes both the original TPWD methods and the new alternative methods.

The method is based on simple summary statistics of individual flow regime components. Either the EFC algorithm (in the IHA software) or the Modified BFI with Threshold (MBFIT) method (implemented in a Microsoft Excel™ spreadsheet) is used as a convenient tool to parse a hydrograph into individual flow regime components. Excel is then used to efficiently develop summary statistics of these flow regime components. Other software tools could be used for either or both of these steps.

In the context of SB 3, the HEFR methodology has several advantages, including:

1. it is computationally efficient, allowing for repeated tests and exploratory analyses;
2. there is significant flexibility in setting parameters to parse the hydrograph as well as summary statistics of the flow regime components,
3. the results have the same format as expected results from the TIFP studies, and
4. it provides an initial set of recommendations that reflect key aspects of the natural flow regime including multiple flow components and hydrologic conditions (Poff, Allan et al. 1997).

Disadvantages of this method are:

1. there is no track record of application;
2. there are few precedents for some of the decisions that must be made by the analyst;
3. there is a lack of theoretical basis (linkage of particular statistical element to environmental health);
4. HEFR is specific while most matrix methods give a range for each criteria;
5. HEFR is sensitive to flow separation and period of record which can give different answers for gages with little or no upstream impacts;
6. reference to other environmental factors (biology, water quality, and geomorphology for example) is needed to increase confidence that the tables produced by the HEFR method have any meaning.

5.1.8 HEFR Basics

HEFR was developed to efficiently use hydrologic data to populate a flow regime matrix. As a hydrologic method, it suffers from many of the same weaknesses as other hydrologic methods described above. However, unlike other hydrologic methods, HEFR can generate values for an entire flow regime in which the different flow regime components, hydrologic conditions, and component characteristics are internally consistent. The results are internally consistent in the sense that:

1. hydrologic conditions (e.g., dry, average, and wet) are tied to percentiles of a distribution, and thus the recommendation under average conditions is guaranteed to equal or exceed the recommendation under dry conditions (and similar for wet versus average);

2. the hydrographic separation that generates the flow regime component values is performed using a single software tool (different tools are provided, but any given simulation will use only one); and
3. high flow pulse and overbank flow characteristics of duration, magnitude, and volume are generated using a consistent set of quantified flow regime components, as opposed to different statistical measures of the entire hydrograph (e.g., as in the Texas Hydrologic Assessment Tool ,TX-HAT).

HEFR begins with the selection of a flow gage and a period of record. A hydrographic separation algorithm is then used to parse the daily hydrograph into the four or more flow regime components, based on user-specified parameters. This parsing classifies each day of the hydrograph as one of the four flow regime components (subsistence, base, high-flow pulse, or overbank; see Table 2. Instream Flow Regime Components Definitions, page 11). Excel is used to post-process the hydrographic separation and to generate summary statistics. These summary statistics are also specified by the user.

Thus, the core foundation of HEFR is flow separation and statistical summaries of each flow regime component. The specific decisions and tools used in the current version of HEFR were identified through discussions and negotiations; however, they are not incontrovertible. Decisions and tools may change because of location, professional judgment, context, objectives, and/or convenience.

5.1.9 Approach

The Sabine-Neches BBEST used hydrologic data to develop initial values for a flow regime and then modified the selected values in cases where additional information (e.g., water quality, biology, and geomorphology) was available, a reasonable and scientifically defensible approach in the context of SB 3.

5.1.10 Sabine-Neches BBEST Hydrology

The Sabine-Neches BBEST selected HEFR as the desktop method to use for developing the required flow matrices for the Sabine and Neches River Basins and the Sabine-Neches Estuary.

Following selection of HEFR as the desktop hydrologic method for use, the Sabine-Neches BBEST Gages Subcommittee evaluated information on the USGS gages in the Neches and Sabine basins. Of the gages in these basins, the Gages Subcommittee recommended 6 for use in each basin. Table 3 (page 51) presents the gages recommended for use (denoted by checkmark) and the information considered in selecting each.

Table 4 (page 52) lists the selected gages and Figure 5 (page 25) shows the locations of each within the Sabine-Neches Study Area. In addition to the twelve stream gages, the BBEST also requested hydrologic analyses of the total inflows into the Sabine-Neches Estuary, for a total of thirteen analysis locations.

Figure 10 and Figure 11 (page 54) show the period of record for each gage and the year major reservoirs were built upstream from the gage for the Sabine Basin and Neches Basin, respectively. Data used in the analysis were obtained from the USGS website.[11]

The Sabine-Neches BBEST considered a number of issues for which decisions must be made to run HEFR. The first considerations were the period of record for use in the HEFR runs, how the seasons would be defined, and whether to use IHA or MBFIT as the hydrographic separation algorithm.

[11] United States Geological Survey, Surface Water Daily Data for Texas, available on-line at http://waterdata.usgs.gov/tx/nwis/dv/?referred_module=sw, retrieved October 8, 2009

TABLE 3. PRELIMINARY SELECTION OF STREAM FLOW GAGES FOR EVALUATION

Select	River Basin	USGS Stream Gage Name	Map#	USGS#	First Full Year	Full Years of Record	USGS Rating	Gage Status	Drainage Area (sqmi)	WAM Primary Control Area	Region I & State Water Plan	Reservoir Site	Unique Reservoir Site	TWDB Ecologically Significant Segment	USFWS Bottomland Hardwood Preservation Site
✓	Sabine	Big Sandy Creek n. Big Sandy	109	8019500	1940	69	Good	Active	231	Yes	No	Yes	No	No	Priority 2
✓	Sabine	Sabine River n. Gladewater	110	8020000	1933	76	Good	Active	2791	Yes	No	Yes	No	No	No
	Sabine	Sabine River n. Tatum	116	8022000	1939	39	Fair	Replaced by Beckville in 1978	3493		No				
✓	Sabine	Sabine River n. Beckville	116	8022040	1979	30	Good	Active	3589	Yes	Yes	Yes	No	Yes	Priority 1
	Sabine	Tenaha Creek n. Shelbyville	123	8023200	1952	29	Good	Out in 1981	97.8	Yes	No	Yes	No	No	Priority 2
	Sabine	Sabine River n. Burkeville	129	8026000	1956	53	Fair	Active	7482	Yes	Yes	Yes	No	Yes	No
✓	Sabine	Sabine River n. Bon Wier	130	8028500	1924	85	Fair	Active	8229	Yes	Yes	Yes	No	Yes	No
✓	Sabine	Big Cow Creek n. Newton	131	8029500	1953	56	Fair	Active	128	No	Yes	Yes	No	No	No
	Sabine	Cypress Creek n. Buna	132	8030000	1953	30	Good	Out in 1983	69.2	?	No	No	No	Yes	No
✓	Sabine	Sabine River n. Ruliff	133	8030500	1925	84	Fair	Active	9329	Yes	Yes	No	No	Yes	Priority 2
	Sabine	Cow Bayou n. Mauriceville	134	8031000	1953	39	Fair	Out in 1986. Active since 2002	83.3	Yes	No	No	No	No	No
✓	Neches	Neches River n. Neches	139	8032000	1940	69	Good	Active	1145	Yes	Yes	Yes	Yes	Yes	Priority 1
	Neches	Neches River n. Alto	140	8032500	1944	34	Good	Out in 1978	1945	Yes	No	Yes	Yes	Yes	Priority 1
	Neches	Neches River n. Diboll	141	8033000	1940	46	Good	Out in 1985	2724	Yes	No	Yes	No	Yes	Priority 1
✓	Neches	Neches River n. Rockland	143	8033500	1904	105	Fair	Active	3636	Yes	Yes	Yes	No	Yes	No
	Neches	Mud Creek n. Jacksonville	147	8034500	1940	46	Good	Out in 1979. Active since 2001	376	Yes	No	Yes	Yes	Yes	No
✓	Neches	Angelina River n. Alto	149	8036500	1960	49	Good	Active	1276	Yes	Yes	Yes	No	No	No
	Neches	Angelina River n. Lufkin	150	8037000	1940	39	Good	Out in 1979. Active since 2001	1600	Yes	No	No	No	Yes	Priority 1
✓	Neches	Attoyac Bayou n. Chireno	153	8038000	1940	45	Good	Out in 1985	503	Yes	No	No	No	Yes	Priority 4
✓	Neches	Neches River @ Evadale	161	8041000	1922	87	Fair	Active	7951	Yes	Yes	Yes	No	Yes	No
✓	Neches	Village Creek n. Kountze	162	8041500	1940	69	Good	Active	860	Yes	Yes	No	No	Yes	No
	Neches	Pine Island Bayou n. Sour Lake	163	8041700	1968	41	Fair	Active	336	Yes	No	No	No	Yes	Priority 2

TABLE 4. SELECTED STREAMFLOW GAGES FOR EVALUATION

USGS Gage Name	USGS Gage Number	HUC	County	Datum NGVD 29 (Feet)	Start Date	End Date	# of Full Years of Record	Drainage Area (Sq Mi)	Un-controlled Drainage Area [b] (Sq Mi)	Percent Un-controlled [b]
SABINE BASIN										
Big Sandy Creek nr Big Sandy[a]	8019500	12010002	Upshur	278.38	10/1/1939	9/30/2008	68	231	204	88%
Sabine River nr Gladewater	8020000	12010002	Gregg	243.85	10/1/1932	current	76	2,791	1,404	50%
Sabine River nr Beckville	8022040	12010002	Panola	190.00	10/1/1938	current	70	3,589	2,044	57%
Sabine River nr Bon Wier	8028500	12010005	Newton	33.42	10/1/1923	current	85	8,229	842	10%
Big Cow Creek nr Newton	8029500	12010005	Newton	134.69	5/1/1952	current	56	128	128	100%
Sabine River nr Ruliff	8030500	12010005	Newton	-5.92	10/1/1924	current	84	9,329	1,942	21%
NECHES BASIN										
Village Creek nr Kountze	8041500	12020006	Hardin	25.12	5/1/1939	current	69	860	860	100%
Neches River at Evadale	8041000	12020003	Jasper	8.25	4/1/1921	current	87	7,951	378	5%
Attoyac Bayou nr Chireno	8038000	12020005	San Augustine	169.58	8/1/1939	10/31/1954	14	503	489	97%
					10/1/1955	9/30/1985	29			
Angelina River nr Alto	8036500	12020004	Cherokee	204.30	3/1/1959	current	49	1,276	987	77%
Neches River nr Rockland	8033500	12020003	Tyler	88.41	12/1/1912 [c]	current	96	3,636	2,763	76%
Neches River nr Neches	8032000	12020001	Cherokee	264.06	3/1/1939	current	69	1,145	306	27%

a Gage is currently out of service because of bridge construction at the gaging site.

b Uncontrolled drainage area is the portion of the gage's watershed located downstream from reservoirs.

c Start of continuous record. Rockland has incomplete data back to 7/1/1903.

FIGURE 9. SELECTED GAGES LOCATION MAP

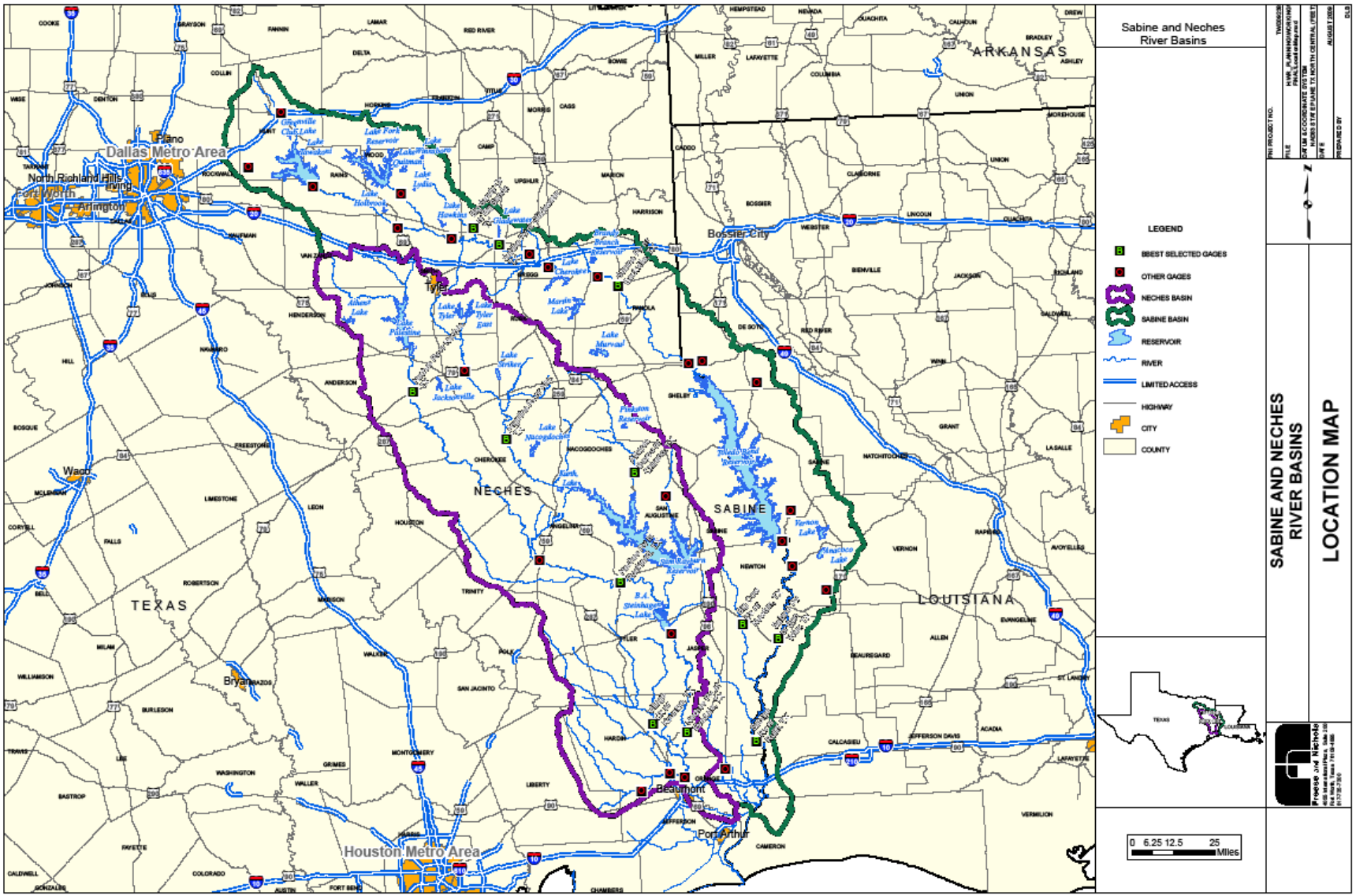
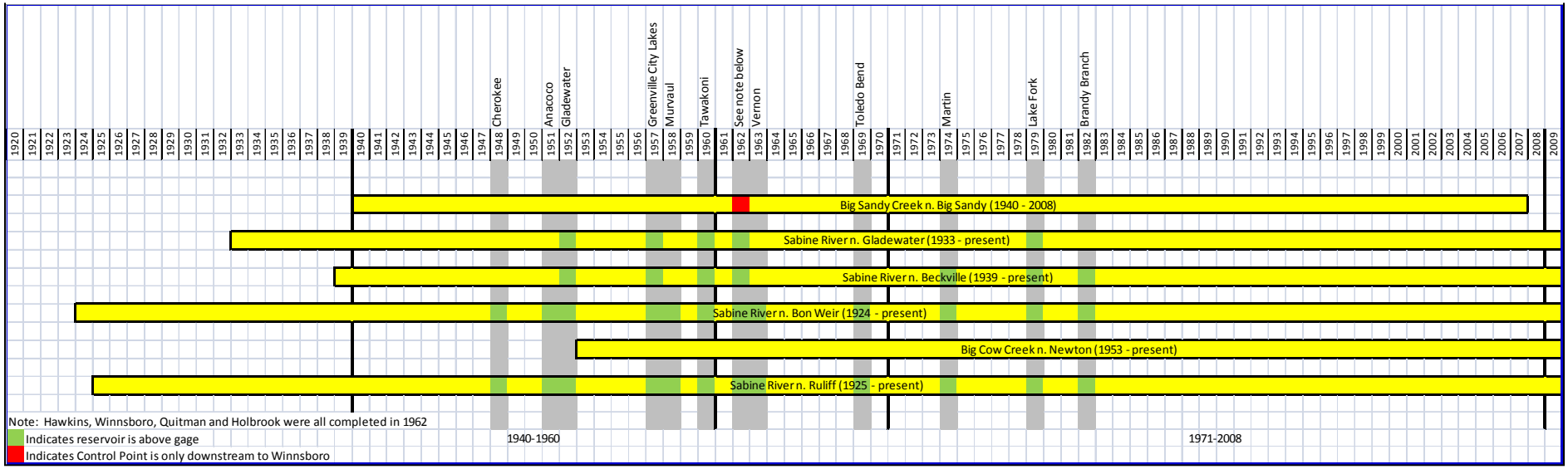
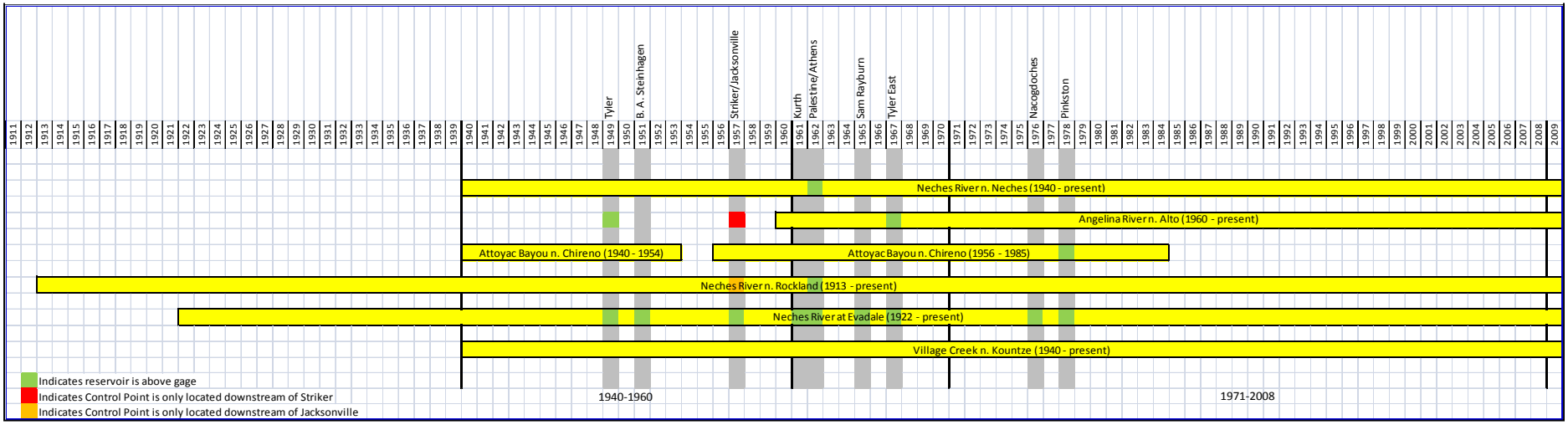


FIGURE 10. SABINE BASIN PERIOD-OF-RECORD FOR BBEST SELECTED GAGES



Note: Hawkins, Winnsboro, Quitman, and Holbrook are known collectively as the "Wood County Lakes."

FIGURE 11. NECHES BASIN PERIOD-OF-RECORD FOR SELECTED GAGES



In examining the periods of record available for the selected gages, it was obvious the overall period of record was split into a period prior to construction of the two large reservoirs, Sam Rayburn and Toledo Bend, and one after. There are a total of 24 major reservoirs (14-Sabine [2 in Louisiana]; 10-Neches) with eight constructed in the 1940-1960 "pre-dam" period. The Sabine-Neches BBEST decided to run HEFR for three periods:

1. the full period of record available at each gage;
2. the period from 1940 to 1960; and
3. the period from 1970 to present.

As expected, the only gages showing differences between the pre and post reservoir runs were those downstream of the hydropower reservoirs: Bon Wier and Ruliff on the Sabine and Evadale on the Neches. Ultimately, the Sabine-Neches BBEST decided to use the runs for the full period of record for all 12 gages.

As can be seen on the graphs of median flow per square mile of drainage area for each gage in Appendix 1, Figures 16 thru 19 on pages 24 - 27 of the Gage Memo (FNI 2009a), there is a very consistent seasonal pattern for flow in each basin. There is a wet winter, transitional periods in spring and fall, and a dry summer. The periods do not match the traditional calendar seasons exactly, but are not offset a full month either. The Sabine-Neches BBEST elected to use winter as January through March, spring as April through June, summer as July through September, and fall as October through December.

Comparison of the two hydrographic separation methods may be found in Appendix 2 of the Gage Memo on pages 8 - 16. Based on the results of this comparison, the Sabine-Neches BBEST selected the MBFIT method as best for the Sabine-Neches Study Area.

The Sabine-Neches BBEST next decision point was subsistence flows. Using the definition adopted for subsistence flow (Table 2) and the work done on water quality for the gage locations, the Sabine-Neches BBEST decided to not specify 7Q2 as the default subsistence flow at each gage location. The Sabine-Neches BBEST had HEFR determine the median value of the 10th percentile of base flows at each gage as subsistence flow at that location.

A maximum of six HEFR runs were made for each gage location. Those runs were for the three periods discussed earlier with output for each period in the original percentile based format and in the frequency distribution output. A discussion of the differences between the two outputs can be found in Appendix 2 pages 27, 28, and 45. Printed copies of the matrices for each run are also in Appendix 2.

5.1.11 Use of 7Q2 and Other Alternate Low Flow Statistics

During early trial runs using the HEFR flow analysis tool, the problem of minimum flow criteria arose. FNI provided the following excerpted from the full document (FNI 2009b), Appendix X:

> *HEFR provides the option to specify a minimum "water quality protection flow". If this parameter is specified, base or subsistence flow statistics produced by HEFR may never fall below this value. HEFR guidance suggest using a 7Q2 (a historical*

7-day average low flow with a 2-year recurrence interval) as this limit. In Texas, a 7Q2 is used as the flow below which water quality standards do not apply. It is also considered when determining stream loading for wastewater discharges. Other states, including Louisiana, use a 7Q10 (a 7-day low flow with a 10-year recurrence interval) for similar purposes. The 7Q2 is also used as a minimum flow limit in other desktop environmental flow methods such as the Lyons or Consensus methods described in the SAC hydrologic methods (SAC 2009f). Table 11 lists the 7Q2 values for the BBEST gages published in the Texas Surface Water Quality Standards (this table is reproduced in this report as Table 5, below).

One of the issues with using a 7Q2 for a minimum discharge is the influence of hydropower at the Ruliff, Bon Wier and Evadale gages. Table 5 (reproduced in this report as Table 6, below) compares 7Q2 and 7Q10 values at these three gages calculated using the Environmental Protection Agency's DFLOW model. (7Q10 values are used in the State of Louisiana and are included for comparison purposes.) The periods in this table include the period prior to the construction of Sam Rayburn Reservoir for the Evadale gage and Toledo Bend Reservoir for the Ruliff and Bon Wier gages. Note that the pre-dam 7Q2 values are significantly lower than the published 7Q2 values. The reason for the discrepancy between the published 7Q2 and the DFLOW output for the Ruliff gage is unknown.

TABLE 5. PUBLISHED 7Q2 VALUES

USGS Stream Gage Name	USGS#	7Q2 (cfs)
Big Sandy Creek n. Big Sandy	8019500	12.4
Sabine River n. Gladewater	8020000	46.4
Sabine River n. Beckville	8022040	75.9
Sabine River n. Bon Wier	8028500	703.1
Big Cow Creek n. Newton	8029500	30
Sabine River n. Ruliff	8030500	1,121.3
Neches River n. Neches	8032000	70.7
Neches River n. Rockland	8033500	111.7
Angelina River n. Alto	8036500	37.7
Attoyac Bayou n. Chireno	8038000	25.6
Neches River @ Evadale	8041000	1,838.6
Village Creek n. Kountze	8041500	78.9

TABLE 6. COMPARISON OF PUBLISHED 7Q2 TO DFLOW 7Q2 AND 7Q10 FOR HYDROPOWER INFLUENCED GAGES

Gage	Period	DFLOW Output[a]									
		Pre-Dam			TCEQ Published Period			Full Period			
		7Q2	7Q10	Period	7Q2	7Q10	Period	7Q2	7Q10	HEFR	Period
Evadale	'66-'96	308	138	'22-'64	1,839	361	'66-'96	497	167	228	'22-'08
Ruliff	'68-'96	683	349	'25-'65	1,109	584	'68-'96	895	417	396	'25-'08
Bon Wier	'68-'96	399	218	'24-'65	703	371	'68-'96	545	250	241	'24-'08

a. Values in cfs

> *Using a 7Q2 as a minimum flow recommendation primarily affects subsistence criteria. Subsistence flows are infrequently occurring low flows during extremely dry periods. However, with a 2-year recurrence interval, a 7Q2 is not a particularly rare occurrence. When considering recommendations for subsistence criteria, the BBEST [needed to] balance the function of subsistence flows (the minimum flow to sustain life) and the presence of waste loading in the stream with the natural occurrence of extremely low flows. In the case of hydropower influenced gages, the BBEST [had to] consider how hydropower operations affect biology, as well as the potential for hydropower operations to cease or be reduced in the future. [For example-future use of Toledo Bend for direct diversion water supply use with hydropower generation occurring only during spills, releases would return downstream flow to naturalized summer patterns.]*
>
> *The BBEST elected not to use a 7Q2 as a limit in the HEFR runs because it can easily be added as a limit later in the process if needed.*

After review of biology and water quality overlays the Sabine-Neches BBEST determined there was not sufficient evidence to modify HEFR-derived subsistence flows with other flow statistics. After review of EPA's DFLOW biologically-derived low flow statistics (xBy) documentation and sources on hydrologically derived low flow statistics (xQy), the Sabine-Neches BBEST concluded that none of these methods determine what the ecological subsistence flow should be for a specific stream.

Both xQy and xBy are strictly focused on determining the flow below which stream standards do not apply (this is sometimes called the "low-flow exclusion" in water quality standards). The hydrologic method uses historical flows and the biological method uses

response of organisms to a toxicant in an effluent. But both are aimed at establishing water quality limitations in NPDES[12] permits. Therefore, one method is not better than the other when it comes to determining subsistence flow because neither is actually looking at the ecological health of the stream. As a result, the Sabine-Neches BBEST does not recommend the use of either method as a check-point for its subsistence flow recommendations.

Other flow selection methods were considered, and the BBEST concluded that each has certain strengths and weaknesses. The biology subcommittee had earlier recommended the 95th percentile of flows as the subsistence threshold, for which the account and rationale are given in the biological overlay document (Appendix XIII), but this was later rejected in favor of the HEFR subsistence estimates, by consensus. There is no evidence that the subsistence flows the BBEST selected are inappropriate, and there is evidence that dissolved oxygen in the stream is sufficient at the selected subsistence flows. Flows at and, in many cases, below the HEFR subsistence flow have occurred before; and the Sabine-Neches BBEST agrees the ecological health of the Sabine and Neches basins is currently good. Based on these demonstrations of the health of the streams, the preponderance of current knowledge is that subsistence flow recommendations for the gages are based on the soundest of science that is currently available. Future consideration is dependent on studies to fill data gaps and subsequent confirmation of specifically identified subsistence flow alterations through the adaptive management process.

5.1.12 Sabine-Neches Estuary Flow Matrix

In addition to the HEFR analyses for the 12 stream gages, a HEFR analysis was performed on inflows into Sabine Lake. A discussion of how the Sabine-Neches Estuary inflow was developed is in Appendix 2 pages 49-51.

Table 7 (page 60) compares the annual volume from the HEFR runs using the percentile-based approach for Sabine Lake to the annual volume for MinQ[13], MaxC[14] and MaxQ[15] (Kuhn and Chen 2005) from the State Methodology for bay and estuary inflows. HEFR matrix volumes for each flow condition (25th percentile, median or 75th percentile) are shown for base flows only, base plus pulse flows and with the entire HEFR overbank event added to each condition. (Overbank flows may not occur in any given year.) Subsistence

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[12] EPA National Pollutant Discharge Elimination System, http://cfpub.epa.gov/npdes/, retrieved November 4, 2009

[13] MinQ: the minimum inflow that meets the salinity and biological constraints of the State Methodology model

[14] MaxC: the State Methodology model solution with the maximum total (annual) catch and satisfies applicable constraints; this inflow lies between MinQ and MaxQ

[15] MaxQ: the maximum inflow which satisfies all the salinity and biological constraints of the State Methodology model

flows have not historically occurred during the winter and spring months. In these months the fall HEFR result was used to calculate volumes.

Comparing HEFR to the State Methodology shows that the HEFR 25th percentile (dry) conditions are less than the MinQ unless an overbank event occurs during the year. Base plus pulse flows for median (average) conditions are less than MinQ for the Full Period and Pre-Dam time periods, but are more than MinQ for the Post-Dam period. MaxC values are exceeded for the median (average) condition if an overbank event occurs during the year. The 75th percentile (wet) condition is relatively close to the MaxQ even without the occurrence of an overbank flow.

Also note that for the HEFR results in Table 7, most of the volume entering the estuary is included in the base flow component. The base flow by itself is about 70% of the Base + Pulse volume in the 25th percentile (dry) conditions and over 90% for 75th percentile (wet) condition. Also, note that the Post-Dam HEFR results have higher volumes than the Full Period or Pre-Dam results.

Figure 12 (page 61) compares the seasonal distribution of the HEFR volumes to the seasonal distribution using the State Methodology. (The monthly State Methodology values were summed by the same seasons used in the HEFR analysis.) Note that the distribution for the HEFR volumes without overbank flows is similar to the State Methodology, with the highest flows occurring during the winter months and the lowest during the summer months. The occurrence of an overbank flow can alter the distribution. The HEFR volumes are for the Full Period of record. The Pre-Dam and Post-Dam periods have similar results. The Sabine-Neches BBEST chose not to use results from the State Methodology, referencing *Methodologies for Establishing a Freshwater Inflow Regime for Texas Estuaries Within the Context of the Senate Bill 3 Environmental Flows Process* (SAC 2009d, Appendix IV):

> *… for this as well as technical issues in the development of these flow patterns, these flow recommendations are not endorsed as satisfactory for the objective of Senate Bill 3 of maintaining a sound ecological environment.*

TABLE 7. COMPARISON OF HEFR ANNUAL VOLUMES TO STATE METHODOLOGY FOR THE SABINE-NECHES ESTUARY

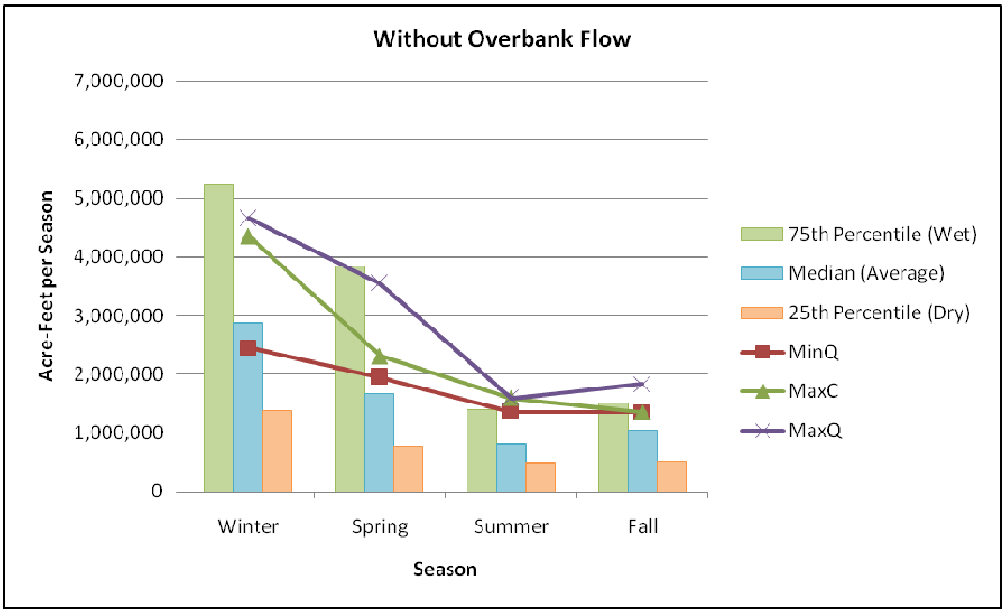
HEFR Annual Volumes (Values in Acre-Feet per Year)

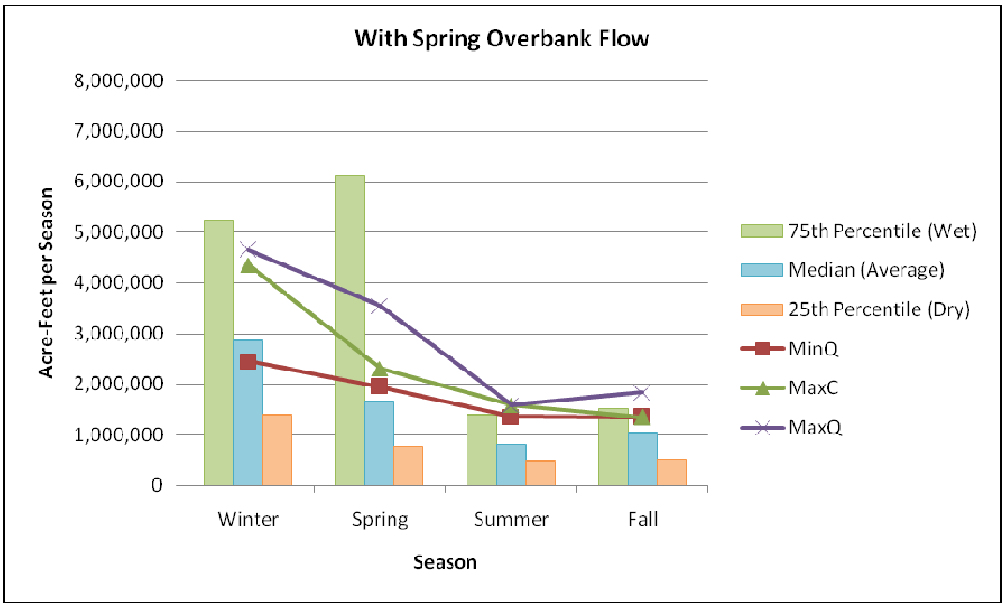
	Full Period (41-05)	Pre-Dam (41-60)	Post-Dam (71-05)
Subsistence	549,757	535,467	680,223
25th Percentile (Dry) Condition			
Base Only	2,243,997	2,316,804	3,306,215
Base + Pulse	3,150,508	3,643,588	4,114,963
Base + Pulse + Overbank	6,451,892	8,646,629	7,316,168
Median (Average) Condition			
Base Only	5,018,915	5,013,258	7,240,502
Base + Pulse	6,380,477	6,325,716	8,234,125
Base + Pulse + Overbank	9,467,182	10,719,867	11,271,050
75th Percentile (Wet) Condition			
Base Only	11,076,875	10,520,563	13,694,250
Base + Pulse	11,986,199	11,300,553	14,298,506
Base + Pulse + Overbank	14,266,063	14,416,682	16,359,393

State Methodology

MinQ	7,114,000
MaxC	9,596,600
MaxQ	11,619,300

FIGURE 12. COMPARISON OF SEASONAL FLOW VOLUMES FOR FULL PERIOD HEFR AND STATE METHODOLOGY FOR SABINE LAKE, WITH AND WITHOUT OVERBANK FLOW





5.2 Biology (Ecological Review)

The Sabine-Neches BBEST established a subcommittee of its members with expertise in stream and riparian ecology to lead the evaluation of the statistically-derived HEFR matrix in terms of biological response mechanisms. This Biology Overlay Subcommittee assisted in selection of focal species thought to best represent the flora and fauna most responsive to flow characteristics of the two river basins and the Sabine-Neches Estuary. A large body of knowledge is represented in the cumulative educational and applied experience of the biological subcommittee members, BIO-WEST's research team who performed the biological literature review, the body of knowledge amassed in available literature, TPWD, and the NWF. The Biological Overlay Subcommittee's report appears in its entirety in Appendix XIII and is summarized here in terms of decisions and processes that were directly related to the recommendations and recognitions the Sabine-Neches BBEST is providing.

5.2.1 Fluvial Ecosystem Realm

The Sabine-Neches BBEST's Biological Overlay Subcommittee adopted the basic approach for determining environmental flow recommendations for the fluvial realm of the Sabine and Neches river basins recommended by the SAC (SAC 2009a, Appendix I) which involves defining and estimating subsistence flow, base flow, high flow pulses, and overbanking flow pulses. Hydrological output was then compared with biological data and modified as needed to comply with the needs of floral and faunal focal species selected by the Sabine-Neches BBEST.

5.2.2 SAC Recommended Procedure for Biological Overlays

STEP 1. Establish clear, operational objectives for support of a sound ecological environment and maintenance of the productivity, extent, and persistence of key aquatic habitats in and along the affected water bodies.

The Sabine-Neches BBEST adopted the definition proposed by the SAC (Section 1.2.4, page 9).

STEP 2. Compile and evaluate readily available biological information and identify a list of focal species.

The Sabine-Neches BBEST extensively reviewed available information for ecosystems and important species in the basins of interest. Early in this process, a list of focal species was identified, and these species were the main focus of the biological overlays. It also relied on ecological studies from other major Texas river systems (i.e., Brazos, Colorado), as well as inferences based on life history information compiled from the literature, and reliance on general habitat suitability criteria developed for species from multiple regions. BIO-WEST was contracted to provide synopses of our focal species for both fluvial and estuarine systems (BIO-WEST 2009b; BIO-WEST 2009a)[16]; these are available in Appendix VIII and VII, respectively.

[16] Citations refer to bibliography items in the Recommendations Report, not the Biology Overlay Discipline Report; they may vary (e.g. "a" vs. "b" and citation style).

STEP 3. Obtain and evaluate geographically-oriented biological data in support of a flow regime analysis.

Following initial reviews and deliberations and in consultation with our hydrological analysis contractor (FNI 2009a) 12 gages were selected with sufficient historical flow records to provide broad geographic coverage within the two basins. Reports were obtained for studies of historical records of fishes in the Sabine Basin (Bonner and Runyan 2007; Bart 2008) and historical records of freshwater mussel collections in the Sabine and Neches basins were reported by (Howells, Neck et al. 1996). An analysis of wetland and riparian vegetation communities was performed by the NWF and Greater Edwards Aquifer Alliance (GEAA) (Appendix XVII), and the Sabine-Neches BBEST's analysis of this information appears below in the section addressing flow pulses.

STEP 4. Parameterize the flow regime hydrological analysis using ecological and biological data.

Due to severe time constraints and the limited nature of the biological information available, little biological information was used to set or modify default parameters for both the hydrographic separation method (MBFIT) and the HEFR analysis.

STEP 5. Evaluate and refine the initial flow matrix.

The flow regime matrix produced by the HEFR hydrological analysis was evaluated to ensure that the ecological needs of the major components of the biological system, their water quality requirements, and geomorphic processes that create and maintain their habitats are maintained. According to the SAC Biological Overlay Guidance document, this final step is perhaps the most critical one in the environmental flow evaluation process. Three multidisciplinary integration workshops were convened to evaluate and refine the flow regime matrix.

5.2.2.1 Subsistence Flows

Current Conditions and Responses of Focal Species to Subsistence Flows

Subsistence flows represent the minimum flow requirement to maintain populations during periods of severe and prolonged drought. Subsistence flows thus should be viewed as the emergency ration of water required to prevent local extirpation of aquatic and riparian species (Richter 2003; Acreman and Dunbar 2004; Richter, A.T. Warner et al. 2006), and references therein. Subsistence flows provide minimal yet sufficient habitat of sufficient quality such that populations can rebound upon reestablishment of base flow conditions. Thus, subsistence flow conditions are infrequent.

Few site-specific studies have been performed in the Sabine and Neches River Basins to inform the Sabine-Neches BBEST's recommendations for subsistence flows. Werner (1982a; Werner 1982b) performed an analysis of hydraulic habitat in the lower Sabine River and lower Neches River reaches. Werner's maintenance flows are defined in a manner that blends elements of what are now defined as subsistence flows and base flows. Thus, it is difficult to make a direct comparison of his flow recommendations with those derived by the Sabine-Neches BBEST from HEFR analysis of hydrological data. In addition, Werner provided recommended flows during periods of drought, and these would be equivalent to what we now refer to as subsistence flows. In general, Werner's recommendations for drought/maintenance flows are significantly higher than the values obtained by the HEFR hydrological analysis.

Although no other specific instream flow studies have been completed in the Sabine-Neches Study Area, the Biological Overlay Subcommittee's evaluation of biological/ecological responses to flow variation was greatly aided by data collected over broader spatial and temporal scales (Evans and Noble 1979; Moriarty and Winemiller 1997; Bonner and Runyan 2007; Bart 2008) and other studies summarized in BIO-WEST (2009b). No species of fishes, mussels, or wetland/floodplain plants appear to have been extirpated from the basins as a result of subsistence flow conditions. A trend in the lower reaches of the mainstems of both the Sabine and Neches Rivers is toward higher flow during exceptionally dry summers, as compared to historical flows under the same conditions. This is due to summertime hydropower releases (summer is the period when energy demand is high). Major changes in minnow communities in the lower Sabine River documented by both Bart (2009) and Bonner and Runyan (2007) appear to be due to altered hydrology and a reduction in delivery of fine sediments and reduced turbidity that favored species associated with clear-water conditions (e.g. *Cyprinella venusta*) and simultaneously resulted in reductions of minnows preferring turbid waters and fine bottom sediments (e.g. *Cyprinella lutrensis*, *Notropis buchanani*). Long-term trends in subsistence flows in the unregulated upper reaches of tributaries are not apparent, and available evidence suggests that no native faunal or floral elements have been extirpated from the basins. In streams such as Village Creek, the fish fauna and riparian vegetation community seem to be in good condition. Ecologically Significant River & Stream Segments of Region I (East Texas) Regional Water Planning Area (Texas Parks and Wildlife Department 2005) provides a good overview of the current state of many of these tributaries.

Subsistence Flow Recommendations

For lack of specific studies to address the subsistence flow component, the Subcommittee's ecological analysis began with the HEFR subsistence estimates from each gage. As explained in Section 5.1 of this report, HEFR outputs were used to estimate subsistence flows based on historical streamflow data and manipulation of the MBFIT option. For the ecological analysis, the HEFR subsistence estimates for each season from each gage were compared with: 1) the recorded minimum flows, 2) percentiles of seasonal flows, 3) the 5th percentile of all flows, 4) 7Q2 and 7Q10 values which are a standard used by the state and federal agencies for water quality risk assessment under severe low-flow conditions (Table 4 and 5, FNI , HEFR Memo, Sept. 17, 2009), and Werner's (1982a; Werner 1982b) drought flow recommendations based on PHABSIM[17]/IFIM[18] analysis (the latter only available for the lower Neches and Sabine River segments).

Initially, the Sabine-Neches BBEST considered use of the lowest seasonal subsistence flow from MBFIT/HEFR analysis for the subsistence flow recommendation. The reasoning here was that if no fish populations are known to have been lost from the rivers and streams over the past 50 years of hydrological records and biological surveys, then this is evidence that the local biodiversity (populations of plants and animals) are able to recover and persist when faced with these severe reductions in flow. Next, the Sabine-Neches BBEST discussed problems with this reasoning. First, it is important to consider the frequency of occurrence and

[17] Physical Habitat Simulation (Software), http://www.fort.usgs.gov/Products/Software/PHABSIM/, retrieved November 19, 2009

[18] Instream Flow Incremental Methodology, http://www.fort.usgs.gov/Products/Software/IFIM/, retrieved November 19, 2009

duration of these low flow events. By definition, subsistence flows are intended to be severe but infrequent events of low flow. The risk of setting subsistence flows too low is that aquatic and riparian populations of plants and animals might experience stressful environmental conditions, including crowding that leads to increased predation mortality, for unusually long periods with excessive frequency. Initial adoption of the summer seasonal subsistence flow from HEFR for the entire year resulted in seasonal flows well below levels ever recorded for the segment in the winter. Winter is the season when flows tend to be higher naturally. Second, adoption of the summer seasonal subsistence flow level for all seasons resulted in many seasonal values that were significantly below 7Q2, and values recommended by Werner for the two lower river segments, though such subsistence flow levels are comparable to available 7Q10 values (Table 6) for the full period of record. Third, it seemed possible that although responses of water quality factors during Winter may not appear to be as potentially impactful as during Summer and early Fall, unforeseen ecological factors (e.g., those related to metabolism of ectothermic organisms at low winter temperatures) may result in negative influences on aquatic and riparian systems if Winter flows were permitted to fall to levels never before observed in the ecosystems.

Some members of the Biological Overlay Subcommittee supported use of the 5th percentile of all recorded flows as the subsistence flow criterion, because there appears to be growing support for its adoption within the environmental flows literature, especially in the absence of site-specific findings from research on habitat availability, habitat connectivity, and water quality. Through a consensus workshop approach, Acerman, Dunbar et al. (2006) established the Q95 (5th percentile) as the hands-off (emergency low flow) criterion for regulatory standards to ensure ecological protection for rivers and lakes in the United Kingdom. Acerman, Dunbar et al. (2006) concluded that the "Q95 marks a significant point where below which conditions in the river change rapidly and hence the river is more sensitive to flow change." Citing this and other work, Hardy, Addley et al. (2006) used the monthly Q95 in the Klamath River in California as the ecological base flow (= subsistence flow) recommendation. In Texas, BIO-WEST (2008a) used the 5th percentile flow as a starting point for evaluating subsistence flow recommendations in the lower Colorado River. BIO-WEST evaluated this flow level and found only a few instances where individual habitat categories went to 0 or below 5% of the available habitat in a given reach (BIO-WEST 2008a). Although extreme, these conditions when considered with monthly variation were deemed appropriate for an initial subsistence flow recommendation. Subsistence levels for the lower Colorado River were then modified (in some cases up and in some down) based on specific results from water quality modeling and reach-specific species requirements (BIO-WEST 2008a). Preliminary subsistence flow guidelines for the lower San Antonio River identified by BIO-WEST (2008b) were also compared to 5th percentile flows. Although field investigations were performed, the preliminary subsistence flow values proposed were conservatively higher than the historical 5th percentile (through 1971). It is noted, however, that treated effluent comprises a significant component of the subsistence and base flows of the San Antonio River.

Next, the Sabine-Neches BBEST re-examined the issue of setting a single subsistence threshold versus separate seasonal thresholds. There is extensive support within the instream flow literature for adoption of monthly or seasonal subsistence flow recommendations. As a result, Sabine-Neches BBEST ultimately decided to make subsistence flow recommendations on a seasonal basis.

As a result of deliberations by the BBEST Biological Overlay Subcommittee and the full membership of the Sabine-Neches BBEST, a series of adjustments were made to the subsistence flow estimates from the MBFIT/HEFR hydrological analysis.

The Sabine-Neches BBEST recommends adoption of the seasonal subsistence flows from MBFIT/HEFR, unless 1) the seasonal value is less than the summer value in which case the summer value is adopted by default, and 2) MBFIT/HEFR failed to calculate a value (this occurred usually for winter) in which case the lowest recorded flow value for that season at that gage was adopted by default. The Sabine River near Beckville subsistence flow was modified to be consistent with the Sabine River Compact minimum flow requirement.

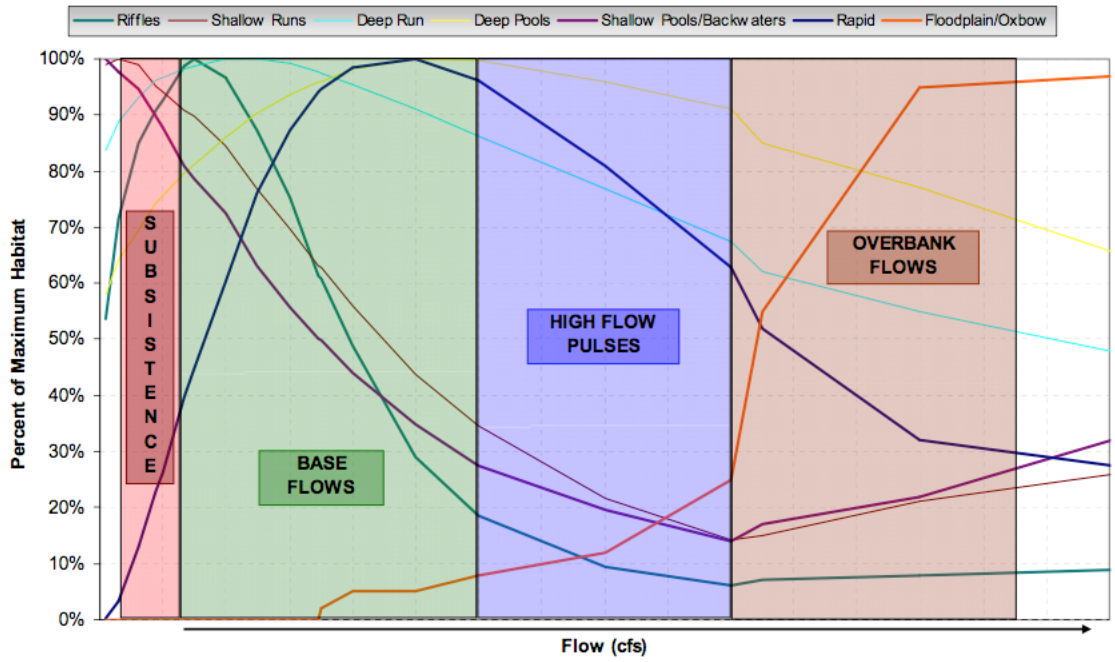
5.2.2.2 BASE FLOWS

Current Conditions and Responses of Focal Species to Base Flows –

Ecological roles of base flows include providing suitable habitat, maintaining habitat diversity, and supporting the survival, growth, and reproduction of aquatic organisms. Base flows are also important for riparian areas (see Table 1. Some ecological functions performed by Instream flow regime components in the SAC guidance *Essential Steps for Biological Overlays in Developing Senate Bill 3 Instream Flow Recommendations* (SAC 2009a, Appendix I)). Information on focal species (i.e., species that indicate the needs for a group of species with similar ecological requirements) can be used to confirm and refine base flow estimates. Flow-ecology relationships discovered in literature reviews were used to guide our interpretations of likely species responses to flow variation in the east Texas basins. Qualitative life history information and conceptual models of focal species' life cycles, such as data on fish spawning seasons, were used to evaluate hydrologically derived base-flow estimates during different seasons and across dry, average, and wet years.

To guide inferences about required base flows during dry, average, and wet years, the Subcommittee examined the findings from the extensive research conducted by BIO-WEST (2008a; BIO-WEST 2008b). The Subcommittee acknowledges that some degree of inter-annual variation in base flows is natural, and very necessary to maintain a balance of aquatic species belonging to different habitat guilds. This is because some fish guilds will have more habitat available to them during dry-year conditions and others will have less (Figure 13). The relative availability of habitat types generally undergoes a shift with a transition to average and wet year conditions (BIO-WEST 2008a; BIO-WEST 2008b). This shifting in the amount of instream habitat during years with different amounts of rainfall is important for maintaining secure populations of all the species characteristic of the region's rivers and streams.

FIGURE 13. HABITAT AVAILABILITY CURVES FOR SEVEN FISH HABITAT GUILDS IN THE LOWER COLORADO RIVER, TEXAS



This figure was derived from recent instream flows research by BIO-WEST (BIO-WEST 2008a)

Periods of prolonged and stable base flow, especially during the summer-fall, can be beneficial for many species in terms of feeding interactions. Predatory fishes can exploit prey populations that are at higher per-unit-area densities during periods of low flow. For sight-oriented predators, water generally is more transparent during these periods when prey populations are more concentrated. Mussels can filter feed on higher densities of water-column food resources (phytoplankton and derived fine particulate organic detritus) during periods of extended base flow (Rypel, Haag et al. 2009). Also, sediments become more stable, which is beneficial for many mussel species (Vaughn and Taylor 1999; Strayer 2008). Certain minnow species spawn and may have better recruitment during prolonged periods of stable base flow during summer (e.g., ironcolor shiner). Base flow conditions also are important for survival of riparian plants that obtain groundwater from the hyporheic zone during periods of low rainfall (Rypel, Haag et al. 2009).

Base Flow Recommendations

For the ecological analysis, the HEFR base flows for dry-year, average-year, and wet-year estimates from each gage were compared with information on the ecology of focal species (BIO-WEST 2009a, Appendix VIII) and, when appropriate, findings from the BIO-WEST instream flow study of fishes in the lower Colorado River (BIO-WEST 2008a). Adoption of base flow benchmarks for dry years (low precipitation years when reservoir pools are low), average years, and wet years (high precipitation years when reservoir pools are high) was deemed critical for protecting populations of aquatic organisms within the various diverse habitat guilds.

Base flow estimates from the HEFR analysis were deemed ecologically suitable.

5.2.2.3 High Flow Pulses and Overbank Flows

High flow pulses shape physical habitat of the river channel, contribute to sediment transport and flushing of silt and fine particulate matter and provide other geomorphic and water quality functions. Biological roles include providing spawning cues and habitat for some species of fish and facilitating connectivity to oxbows and other wetlands. The timing of high flow pulses may be critical for triggering spawning migrations or actual spawning events. The role of high flow pulses for supporting aquatic and riparian/floodplain plants and animals was summarized in the SAC Biological Overlays Guidance Document (SAC 2009a, Appendix I).

The evaluation of the benefits to the biota of high pulses must focus on two components: time (or more accurately—the timing and duration of the pulse in relation to the requirements for spawning cues, feeding opportunities of juveniles, etc.) and space (or more accurately—how the rise in water level interacts with local landscape topography/geomorphology to produce connections with and enhancement of marginal and off-channel aquatic habitats). In evaluating the spatial aspects of high flow pulses, various kinds of maps are extremely useful (topographic, digital elevation, wetlands, vegetation categories, etc.). The Subcommittee relied on NWS estimates of overbank flooding[19] and a specific analysis by the NWF and the GEAA (Appendix XVII).

Responses of Aquatic Focal Species to High Flow Pulses

Tributaries: Although lateral connectivity to off-channel floodplain habitats is relatively less important in smaller headwaters and tributaries (e.g. Angelina River, Village Creek) than larger mainstem reaches located downstream, it is still critical, from an ecological standpoint, to have periodic high flow pulses to permit organisms to occupy marginal habitats for feeding and/or reproduction (connected backwaters, sloughs, etc.).

Mainstem river/floodplains: A great deal of ecological literature demonstrates that paddlefish, alligator gar, flathead catfish, blue sucker, and other species characteristic of large mainstem rivers have major requirements for high flow pulses. High flows transport eggs/larvae of broadcast spawners and the availability of submerged bank feeding habitats increases during high flows. Some degree of stability in flow pulses is beneficial for substrate nesting/guarding centrarchids. High flow pulses during spring are most beneficial for spotted bass and other sunfishes when they have 3 weeks time to construct a nest, spawn, and guard the eggs and larvae until they are large enough to swim effectively. White crappie prosper greatly within the lentic and highly productive environment of oxbows which are maintained by pulse flows (Zeug, Winemiller et al. 2005).

[19] National Weather Service River Forecast Center, West Gulf RFC, http://www.srh.noaa.gov/wgrfc/, retrieved November 6, 2009

TABLE 8. SABINE/NECHES FISH SPECIES WITH SPAWNING SYNCHRONIZED TO FLOW PULSES DURING LATE WINTER-SPRING (FEBRUARY-JUNE) WITHIN-CHANNEL, WATER-COLUMN SPAWNERS (N= 26)

Sabine-Neches BBEST FOCAL SPECIES: Paddlefish, blue sucker, white bass, shoal chub, emerald shiner, sabine shiner

OTHER Sabine/Neches SPECIES: gizzard shad, threadfin shad, cypress minnow, Mississippi silvery minnow, pallid shiner, ribbon shiner, redfin shiner, silver chub, golden shiner, blackspot shiner, ghost shiner, silverband shiner, weed shiner, mimic shiner, river carpsucker, smallmouth buffalo, spotted sucker, blacktail redhorse, yellow bass, freshwater drum

Spawning in submerged river margins* (eggs scattered on vegetation, rocks or other submerged structure, or nest constructed) (N=18)

Sabine-Neches BBEST FOCAL SPECIES: Alligator gar, black crappie, white crappie, spotted bass, harlequin darter

OTHER Sabine/Neches SPECIES: Longnose gar, spotted gar, red shiner, blacktail shiner, fathead minnow, bullhead minnow, creek chub, creek chubsucker, lake chubsucker, yellow bullhead, blue catfish, channel catfish, redfin pickerel

* This list only includes fish species that are strongly responsive to high flow pulses, usually moving into newly submerged littoral habitats or littoral habitats that become deeper with more suitable hydraulics (e.g., slow back eddies) to spawn or nest. This list does not include other species that spawn or nest in littoral habitats even without springtime cues provided by high flow pulses (e.g., the various sunfish species, darters, and topminnows). (Winemiller 2009)

Responses of Focal Species to Overbanking Flows

As discussed in the SAC Biological Overlays Guidance Document, overbanking flows are important for moving coarse woody debris and sediments, scouring deep pools and depositing sediments to form sandbanks, and allowing aquatic organisms to colonize ephemeral aquatic floodplain habitats. The inundation of floodplains allows seeds of bottomland hardwood tree species to disperse or germinate following flood subsidence. The overbanking flow components of a flow matrix (as derived from the HEFR analysis) thus have important functions for the ecological system. It is essential to recognize that overbanking flows are a part of the natural flow regime that maintains the native biodiversity of the two basins. Two terrestrial focal species, overcup oak and water tupelo, have aspects of their lifecycle dependent on periodic high flood pulses. These bottomland hardwood tree species require periodic flooding (including occasional growing season overbank flows) for successful germination, seedling recruitment, and elimination of upland plant species that are competitively superior on well-drained soils (Sharitz and Mitsch 1993).

Among alligator gars and other gar species, adults and juveniles (particularly juveniles) commonly move into flooded plains to feed opportunistically on insects, amphibians, and other fish species that also exploit temporarily abundant food resources (Robertson 2008). Many small fishes also use temporarily flooded riparian habitats to feed on terrestrial and soil invertebrates (Kwak 1988).

Pulse Flow and Overbanking Flow Recommendations

HEFR pulse flows were evaluated in the context of ecological information compiled for the Sabine-Neches BBEST's focal species (BIO-WEST 2009b, and sources cited therein). For the issue of lateral connectivity of aquatic habitats, we also relied on ecological inferences derived from research findings on the ecological dynamics of the lower Brazos River by Winemiller and colleagues (Winemiller, Tarim et al. 2000; Zeug, Winemiller et al. 2005; Zeug and Winemiller 2007; Robertson 2008; Zeug and Winemiller 2008; Zeug, Peretti et al. 2009). Protection of high flow pulses during late winter and early spring is essential for providing spawning cues and environmental conditions required for successful spawning and early life stage survival for a great many fish species in the streams and rivers of the region. High flow pulses during other times of the year are important for inducing varying degrees of lateral aquatic habitat connectivity which provides for movement between the main channel and backwater/off-channel habitats.

To quantify the extent of lateral connectivity of aquatic habitats during high flow pulses and overbanking events, we also examined the percent flooding of wetland and bottomland hardwood vegetation zones in several of our reaches (this information was provided by the NWF and the GEAA; Appendix XVII). High flow pulse and overbank flow values generated from the HEFR outputs were evaluated for the total area of Pineywoods Riparian Ecotones identified in the NWF/GEAA inundation flows analysis. Determining the amount of riparian area inundated by the recommended high flow pulses and overbank flows is not only important in evaluating if riparian needs are being met, but will also help evaluate other important aspects of high flow pulses such as channel maintenance, lateral floodplain connectivity, and migratory and spawning cues. Data from the NWF/GEAA analysis was used to develop a relationship between flow and the percent total area of Pineywoods Riparian Ecotones inundated. The analysis was set up as such:

- Data were obtained from the NWF Overbank Analysis Excel spreadsheet.
- Only gauges with more than two observations were used (valid observations were those that were indicated as being used in the "BH Inflows Analysis").
- A best fit trend line was applied to the data (linear or logarithmic).
- The percentage of the total wetland/riparian vegetation community zone inundated was determined for each high flow pulse category.

Results of the regression models developed between flow and percent area of inundation are shown in Figure 2[20] of the Sabine-Neches BBEST Biological Overlay Approach Discipline Report (Appendix XIII). Only four gages had sufficient data to develop models (Big Sandy, Ruliff, Neches, Evadale) and correlation (i.e., R^2) for all four models was high. The model equations developed for each of the four gages were then applied to the HEFR high flow pulses, including the 1-per-year overbanking flow, to predict the percent total area of the

[20] Relationship between observed flow and percent total area of Pineywoods Riparian Ecotones (wetlands and bottomland hardwood vegetation communities) inundated using NWF/GEAA overbanking flows analysis for the maintenance of bottomland hardwoods

pineywoods wetland/riparian zones inundated (Table 1[21], Appendix XIII). Results of this analysis are shown in each of the gages HEFR version 2 outputs (Figures 3 – 6, Appendix XIII). HEFR-derived high flow pulses of 2-per-season and 1-per-season plus overbanking pulses of 1-per-2 years in the upper basin gages (Neches and Big Sandy) provide good levels of riparian zone inundation. For the lower basin gages (Evadale and Ruliff), overbanking (1-per-2 year) flow outputs provide sufficient riparian inundation (100% inundation for both gages), but the smaller 2-per-season and 1-per-season high flow pulses do not appear to be sufficient for providing a degree of lateral connectivity and flooding of the pineywoods wetland/riparian zones on an annual basis (0% inundation for all high flow pulses at the Evadale gage, and only up to 25% inundation for the 1-per-season flows and 0% inundation for all 2-per-season flows).

Flow versus percent-area-of-inundation relationships were only possible for 4 gages, nonetheless a trend is observed geographically. It appears that the HEFR high flow pulse and the 1-per-2 year overbanking flows may be sufficient to maintain riparian habitats and lateral connectivity for both of the upper basin gauges in the Neches and Sabine Rivers. The two seasonal categories of HEFR high flow pulses (2-per-season, 1-per-season) for the three lower-reach gauges are not sufficient to inundate riparian areas on an annual basis in both the lower Sabine River and lower Neches River. Given this trend, the Biology Overlay Subcommittee recommends a 1-per-year high flow pulse for all three of lower basin gages (all located below reservoirs) to ensure that sufficient riparian inundation, lateral connectivity, and channel maintenance flows are attained. These flows also would facilitate migration and spawning of river fishes if provided during the months of February-May.

Based on the analysis of these multiple sources of information, it was concluded that the following categories of flood pulses in the HEFR output matrix require protection: 2-per-season, 1-per-season, and 1-per-year (the latter for the three lower river segments only: Neches River at Evadale, Sabine River at Bon Wier, Sabine River at Ruliff) or 1-per-2 years (for the other 9 segments). Clearly, other high pulse categories would be beneficial for the ecosystems, both aquatic and riparian/wetland, but in the Subcommittee's judgment and based on currently available information, these three are most essential for a sound ecological environment. It also is important to emphasize that the larger pulses (1-per-year; 1-per-2 years) are essential for the long-term maintenance of the biota and ecosystems, because these are, in addition to providing critical ecological functions, the flow levels that cause significant movement of bed materials, a process that creates both instream and floodplain aquatic habitat structure. This latter category also causes more extensive flooding in the lower reaches of the two rivers, which is critical for maintaining plant communities of wetlands and bottomland forests. The magnitudes of these 1-per-year and 1-per-2 years flows would inundate the lowest areas within floodplains – the areas associated with wetland and riparian vegetation communities. Nonetheless there also could be variable degrees of risk to certain economic activities in the floodplains, property, and public safety.

Seasonal high flow pulses have recognized ecological benefits and are recommended for protection with certain reservations associated with environmental and operational liability

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[21] Predicted percent area of inundation for overbanking flows and high flow pulses derived from our HEFR frequency-based analysis using the full period of record

risks. The Sabine-Neches BBEST also recognizes the ecological functions and benefits of overbank flows, but does not recommend actions be taken to produce such flows. Climatic conditions and flood events are expected to produce these levels of flow even with full use of existing water rights and realistic projections of water supply development.

5.2.3 Estuarine Ecosystem Realm

According to the SAC Guidance Document for Estuarine Ecosystems (SAC 2009d, Appendix IV), "the estuarine ecosystem is complex, comprised of many variables and their interactions." "Much of the complexity of estuaries derives from their nature as a transitional watercourse between freshwater and marine water. This is reflected in the multiple external forces controlling the estuary." "The exchange between estuary and sea is mainly affected by tides, gravity currents and meteorology (especially wind stress). Exchange between estuary and sea also manifests itself in the organisms, …. Many of the important estuarine animals, notably major fish and shellfish species, migrate between the sea and the estuary at various life-history stages. Most immigrate into the estuary from the sea as young, and mature in the estuary, taking advantage of sheltered, food-rich environments, then return to the sea as adults." "A direct measure of the physical exchange with the sea is the salinity distribution within the estuary. Salinity is the quintessential estuary parameter." "Most freshwater organisms cannot survive if salinity is too high, and most seawater organisms cannot survive if salinity is too low. An estuary is therefore an inhospitable environment for these "stenohaline" organisms. There are, however, "euryhaline" organisms that have a physiological capability to function—even thrive—in the intermediate and variable salinities of an estuary. The range and distribution of salinities can therefore be important demarcators of suitable habitat for estuarine species. The spatial estuarine gradient is fundamental for regulating differences in the functions, habitats, and integrity along the salinity gradient. Much is known about salinity gradients in estuaries and the average salinity over long time periods is an indicator of organisms' habitat." (SAC 2009d, Appendix IV)

Estuarine ecosystems are spatially heterogeneous, physically and biologically dynamic, and highly complex owing to interactions among numerous environmental variables and diverse species spanning a range of salinity tolerances and ecological niches. Given these realities and complexities, the initial position examined by the Sabine-Neches BBEST was that the Sabine Lake estuary would receive the freshwater inflows that result from the HEFR-hydrological analysis and recommendations of flow components for the Sabine-Ruliff, Neches Evadale, and Village Creek gages. Once these volumes were calculated, we addressed the question: what are the likely responses of estuarine components? This was examined following two approaches. First, the Sabine-Neches BBEST contracted BIO-WEST to provide a literature review and summary of focal species for the Sabine Lake ecosystem (BIO-WEST 2009a, Appendix VII). Several plant, invertebrate, and fish species were selected to cover a range of population responses to salinity levels in Upper Gulf Coast estuaries. Second, the Sabine-Neches BBEST enlisted the help of the NWF to analyze the potential responses of estuarine focal species to the salinity regimes resulting from the HEFR-derived freshwater inflows to the ecosystem. The NWF approach estimated habitat suitability within three zones of the estuary as a function of salinity regimes. Third, the Sabine-Neches BBEST examined (analysis performed under contract by Freese and Nichols) the relationship between the HEFR-derived freshwater inflows to Sabine Lake with inflow requirements estimated from Freshwater Inflow Recommendation for the Sabine Lake Estuary of Texas and Louisiana (Kuhn and Chen 2005). The Subcommittee considered these two different approaches to be the best available science available for evaluating the suitability of freshwater inflows derived from the fluvial analysis for meeting the ecological needs of the estuarine ecosystem. Clearly, more research is needed and refinements to these analyses are warranted to reduce uncertainty. Nonetheless, these approaches, at

present, provided the most feasible and robust means for independent assessment of environmental flows for the estuary. Both analyses supported the view that the fluvial-derived environmental flow recommendations fall within the range of values that should provide freshwater inflows sufficient to maintain a sound ecological environment within Sabine Lake under its current geomorphological configuration.

5.2.3.1 National Wildlife Federation (NWF) Analysis of Habitat Suitability for Key Estuarine Species under Alternative Flow Regimes

The recent SB 3 SAC report on methods for establishing an estuarine inflow regime (SAC 2009d, Appendix IV) recognizes a variety of potential approaches. The goal of these approaches is to link freshwater inflows, and its various attributes such as timing and volume, to the biologic response of the estuary. One of the principal methods for characterizing the biota of the estuary is the "Key Species" method. For the purposes of establishing an estuarine inflow regime, key species should exhibit sensitivity to inflow-controlled parameters, such as salinity or nutrient concentrations.

An analysis performed by NWF to assist the Sabine-Neches BBEST (Appendix XVI) focused on key species with specified salinity tolerance ranges (salinity suitability relationships) and used a variety of methods for coupling species' biologic responses to the inflow-salinity patterns. The NWF analysis focused on a suite of four species and two marshland communities, all with well-established and published salinity tolerance (a.k.a. salinity suitability) information. These key species and communities are: *Rangia cuneata* larvae, blue crab juveniles, oysters, Olney bulrush (adults and seedlings), Intermediate Marsh, and Brackish Marsh. The bivalve mollusk *R. cuneata*, blue crabs, oysters, and the Olney bulrush were recommended "focal species" in a previous report to the BBEST (BIO-WEST 2009a). As per Dr. Richard Harrel, the larval stage of *R. cuneata* is not suitable as a focus or key species: it is present for only a short time period after spawning; it is very steno-tolerant to everything; after a few days it is benthic; and after a few months it is eury-tolerant (Harrel 2009). The spatial extent and abundance of oyster and blue crabs are well known in Sabine Lake based on the TPWD's long-term sampling program. The Olney bulrush was recommended by BIO-WEST (2009a, Appendix VII) due to its likely occurrence in the marsh types surrounding Sabine Lake.

The spatial extent and abundance of *R. cuneata* was not well established for Sabine Lake and thus an important preliminary undertaking was a field investigation with sonar imaging and field sampling. In summary, *R. cuneata* are widespread in the majority of Sabine Lake, approximately the upper three-fourths of the estuary. Thus *R. cuneata* is a very good key species for this estuary evaluation not only because of the well-defined salinity tolerance limits of the larvae (more below), but also due to the fact that they comprise a substantial benthic biomass in much of the estuary. The two marshland communities are widespread around the margins of Sabine Lake as indicated by Kuhn and Chen (2005).

The NWF analysis focused on two of the four flow components because of their likely importance in the overall flow regimes and potential role in influencing the ecology of Sabine Lake. Time limitations prevented a more complete evaluation of the full spectrum of flow components. First, they focused on the "base average" condition flows because they may be in effect for a substantial portion of the time as these environmental flow regimes are implemented. However, because no attainment frequency for this component has been explicitly specified as of the time of their analysis, the precise percentage of time those conditions might be expected to pertain is unclear. Their second primary area of focus was "subsistence" flows. Flows of this low magnitude should be rare events, occurring only during very dry, near drought-of-

record, periods (Texas Commission on Environmental Quality 2008b). They focused on subsistence flows in order to assess their implications for Sabine Lake.

To assess the implications of adopting and implementing the proposed HEFR-derived flows, they used a procedure similar to that employed by the TWDB and TPWD in earlier salinity modeling of Sabine Lake (Kuhn and Chen 2005). The HEFR-derived flow values were substituted for the actual historic values at the three BBEST sites Sabine River at Ruliff, Neches River at Evadale, and Village Creek near Kountze. Other historic inflow contributions as reflected in TWDB records, including from other gaged watersheds (Pine Island Bayou and Cow Bayou) as well as ungaged areas below these gauges and other wholly ungaged drainages, remained unchanged.

Figures 7[22] and 8[23] of Appendix XIII illustrate the salinity response at the mid-estuary site for representative "average" and "very dry" years 1999 and 1996, respectively (Figure 7 of Appendix XIII is reproduced below as Figure 14). For 1999 the salinities shown are those predicted with the salinity-inflow regression for both the historic inflows and the synthetic inflow record constructed with the HEFR-derived values at the "base average and high-tier seasonal pulse" levels at the Ruliff, Evadale, and Village Creek sites. Similarly, for the 1996 depictions, the regression-predicted salinity responses are shown for both the historic values and the synthetic inflow record, but here HEFR subsistence flows at the three sites are substituted in for the March-June period.

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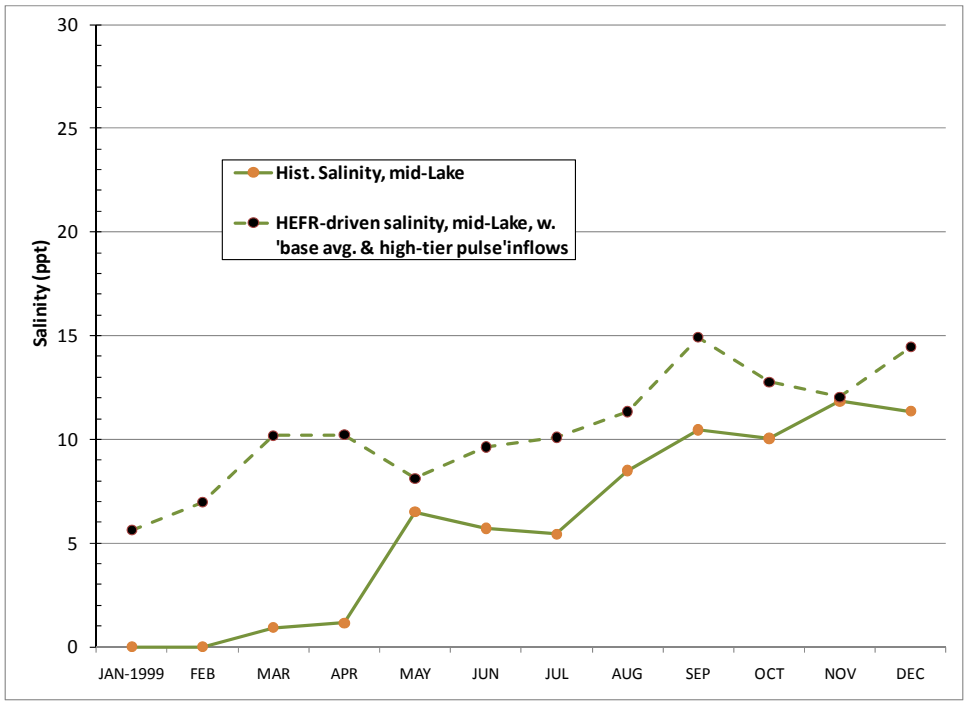
[22] Predicted salinity in Sabine Lake under the original historic inflows for 1999 and with the synthetic inflow record of HEFR-derived values corresponding to "base average and high-tier seasonal pulse" for the sites at Ruliff, Evadale, and Village Creek

[23] Illustration of the predicted salinity in Sabine Lake under the original historic inflows for 1996 and with the synthetic inflow record of HEFR-derived values corresponding to "subsistence" levels for the March – June period at the sites at Ruliff, Evadale, and Village Creek

FIGURE 14. PREDICTED SALINITY IN SABINE LAKE UNDER THE HISTORIC INFLOWS FOR 1999



This graphic is for the synthetic inflow record of HEFR-derived values corresponding to "base average and high-tier seasonal pulse" for the sites at Ruliff, Evadale, and Village Creek.

Salinity Suitability of Key Species and Communities

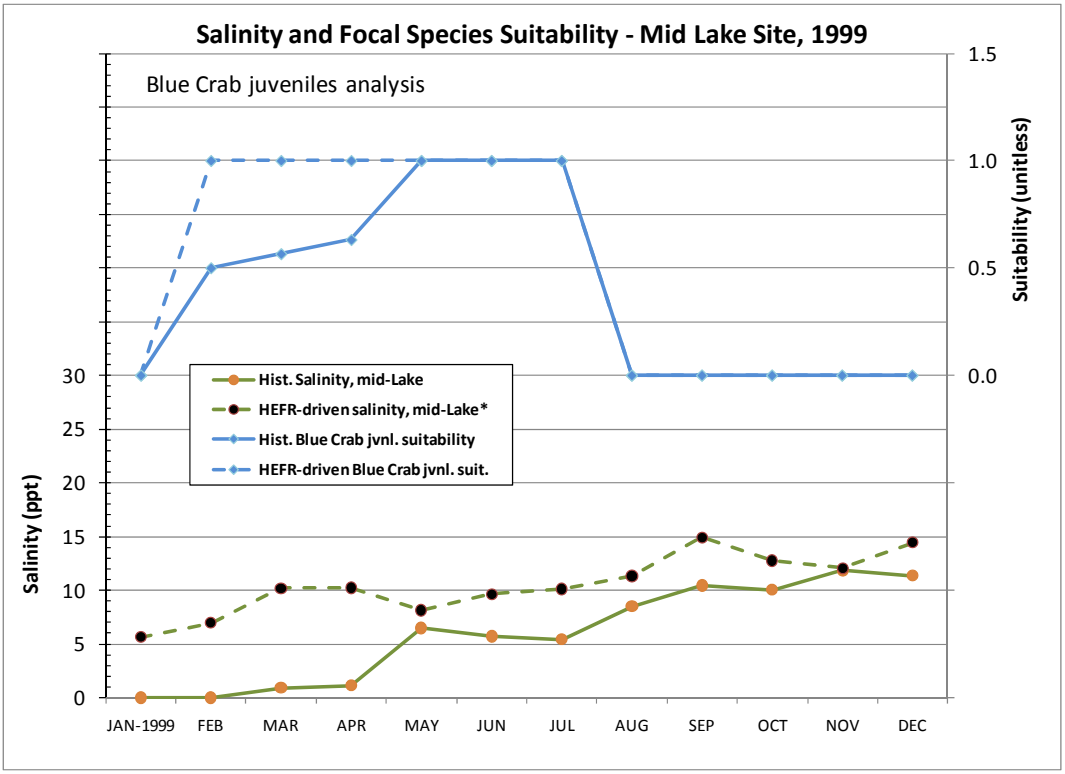
Another essential element of the NWF analysis is the published salinity suitability information for the four key species (*R. cuneata*, oysters, blue crab, and Olney bulrush) and two key marshland community types (intermediate and brackish). This information provides the critical link between freshwater inflows, the associated salinity patterns, and the ecological health of the biota in the estuary. With a salinity suitability relationship, as shown in Figure 9[24] of Appendix XIII for blue crabs, they were able to ascribe a relative level of significance for any given salinity for that species or community. With a suite of such relationships, a broad perspective was sought regarding the potential effects of salinity changes tied to freshwater inflow alterations.

They also examined important seasonal considerations for each focal species. These are essentially the portions of the year in which the relationship of salinity to biologic health is thought to be most important. Figure 15, below, illustrates how the predicted salinities, salinity suitability curve, and the seasonal constraints (blue crabs as an example) were used in the analysis. On the bottom half of the figures are the

[24] The salinity suitability relationship for blue crabs (based on the synthesis of literature from LCRA-SAWS (2007))

salinity responses for historic inflows and the HEFR-derived "base average and high-tier seasonal pulse" inflows at the Ruliff, Evadale, and Village Creek sites. Appearing in the top half of the graph are the computed salinity suitability for both of the salinity traces. In the upper panel, only salinities for the period Feb.-July are used; for the remainder of the months, a default value of 0.0 is shown.

FIGURE 15. ILLUSTRATION OF SALINITY SUITABILITY RELATIONSHIP FOR BLUE CRABS



Findings: Salinity Suitability Analysis of HEFR-derived Inflows

Inflows at the "base average and high-tier seasonal pulse" level – the Sabine River at Ruliff, Neches River at Evadale, and Village Creek near Kountze segments were assigned flows at the "base average and high-tier seasonal pulse" level for the whole year. 1980 was used as an example year since historic total inflows were at the 50th percentile of the historic record for 1941-2005. All other inflow contributions to Sabine Lake were maintained at their historic level during the year. Findings of habitat suitability analysis for several focal species are shown in Figure 11 a-f of Appendix XIII (Figure 11a, 11b, and 11f are reproduced below as Figure 16, Figure 17, and Figure 18, respectively).

FIGURE 16. SALINITY AND FOCAL SPECIES SUITABILITY FOR RANGIA LARVAE - MID SABINE LAKE SITE, 1980

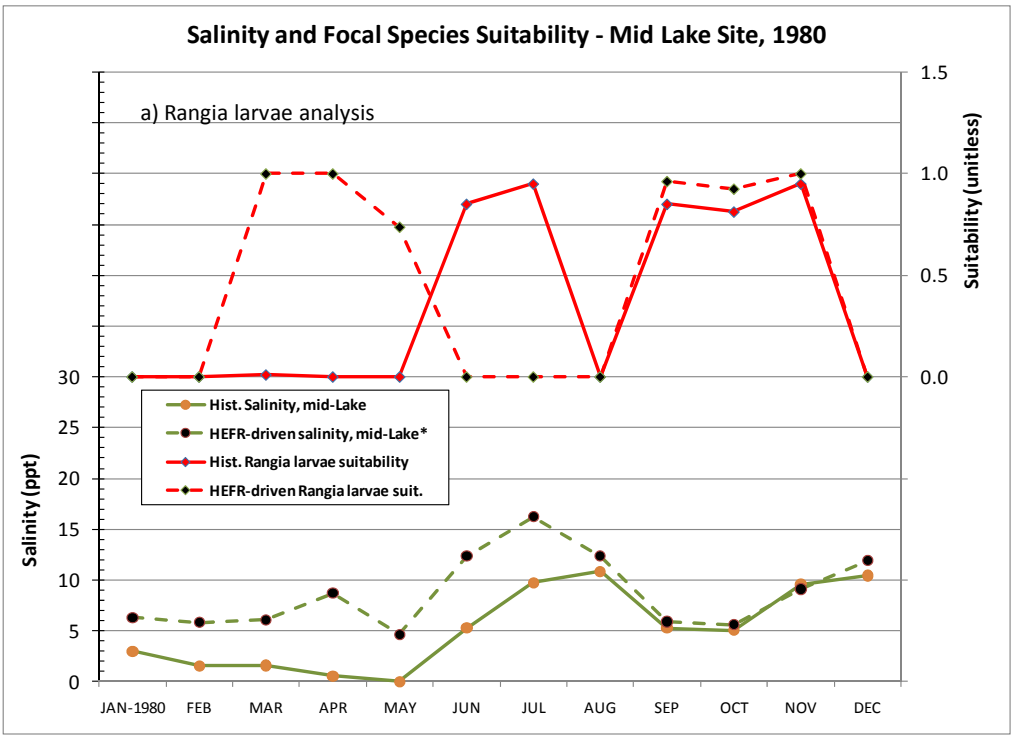


FIGURE 17. SALINITY AND FOCAL SPECIES SUITABILITY FOR BLUE CRAB JUVENILES- MID SABINE LAKE SITE, 1980

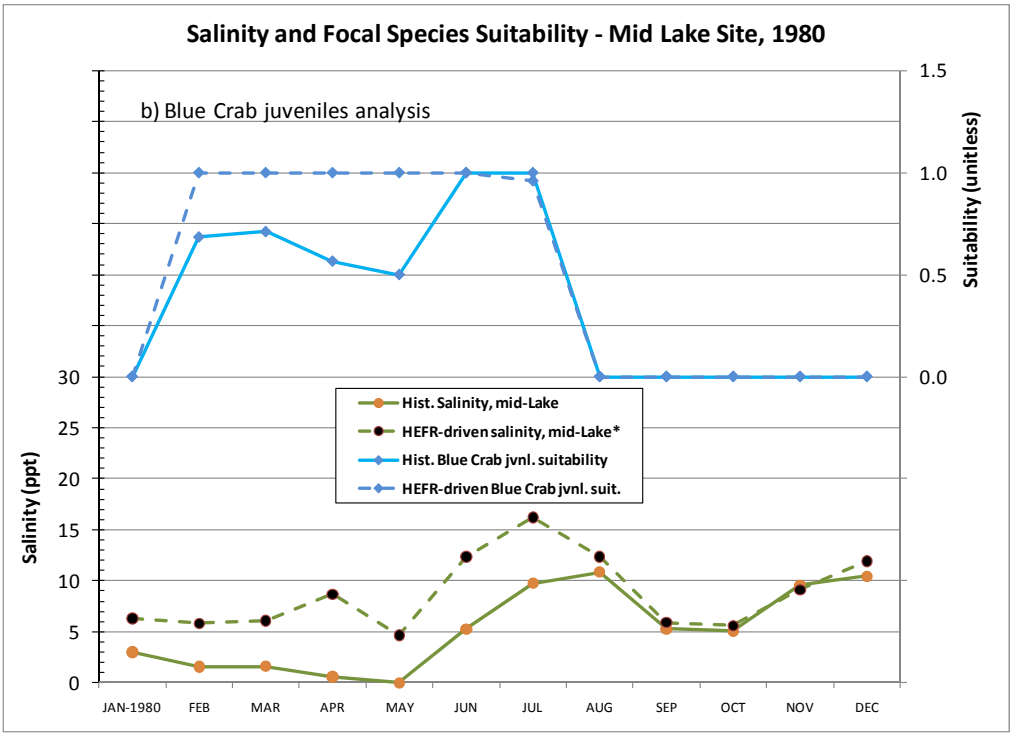
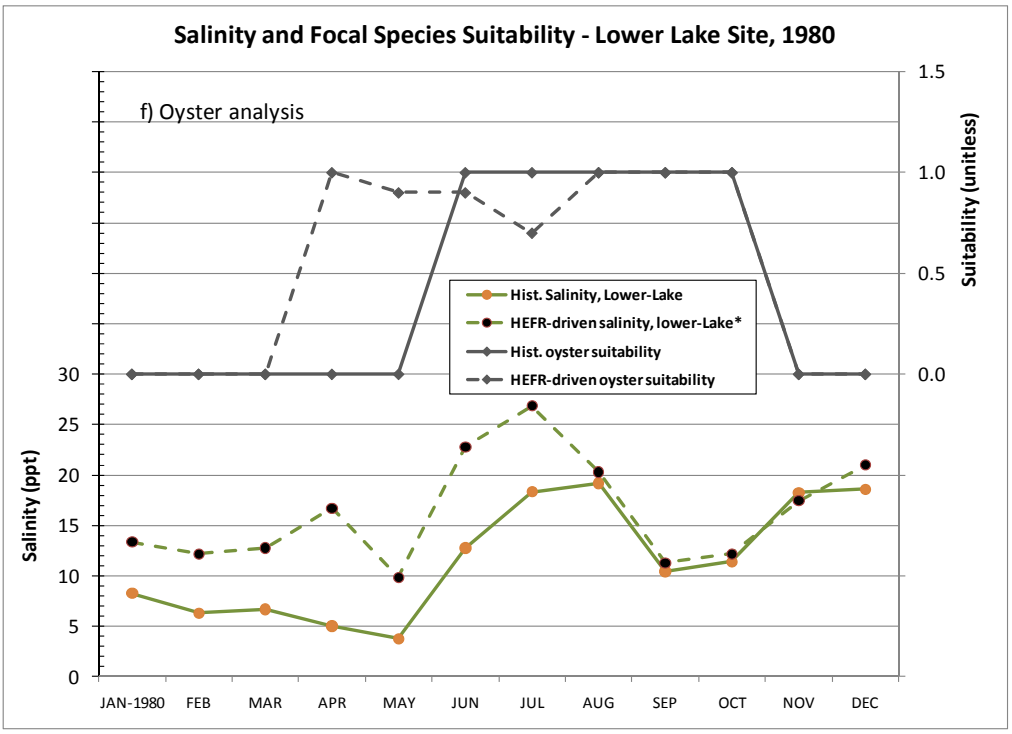


FIGURE 18. SALINITY AND FOCAL SPECIES SUITABILITY FOR OYSTERS - LOWER SABINE LAKE SITE, 1980



Discussion of Estuarine Inflow - Focal Species Findings

Generally, the base average conditions, represented here by the "base average and high-tier seasonal pulse" analyses, appear to be reasonable in terms of the average salinity suitability for *R. cuneata*, blue crabs, oysters, and brackish marsh. The average salinity suitability for these four key species and communities vary among years, but the overall average for the thirteen years are not greatly different when comparing the historical conditions to the HEFR-based conditions. In fact, conditions for blue crabs and oysters, both tolerant euryhaline species, might improve based on these analyses.

The most significant area of concern for the base average conditions was with the marshland species and community that are less salinity tolerant: the Olney bulrush and intermediate marsh. Both the upper- and mid-Sabine Lake areas showed significant reductions in salinity suitability on average for this species and the intermediate marsh community.

With subsistence flows for a four-month period, they concluded that there would be more potential for widespread deleterious impacts, although presumably on a less frequent basis. Assumed subsistence flows did not include periodic dry base flows. Since one assumes these very low inflows would occur in what is already a very dry year (e.g. one similar to 1967), essentially the HEFR-derived inflows amplify an already bad situation for most of the key species and communities. For instance *R. cuneata* suitability moved from an already poor value of about 0.2 to just 0.06 on average at the upper lake site for the 4 very dry years. Even for these four driest years of the historic record, there was some portion of the year in which *R. cuneata* reproduction (larval survival) was possible at the upper lake site. However, under the "subsistence" inflow scenario, three of the four years would lose even this limited suitability. A somewhat lesser, but still substantial, decline in *R. cuneata* suitability was evident at the mid-Sabine Lake site.

Unlike the analysis at "base average" conditions, "subsistence" inflows would be expected to result in a significant deleterious impact on the brackish marsh communities according to their analysis. Conditions for the less salinity tolerant Olney bulrush and intermediate marsh are already so poor, even under historic conditions in these very dry years, that the incremental effects of the "subsistence" inflows are small. Finally, under the "subsistence" inflow conditions, there were significant declines in salinity suitability conditions even for blue crabs and oysters.

5.2.3.2 The State Methodology for Estimating Freshwater Inflow Needs of Bays and Estuaries

General Procedure

The TWDB and the TPWD are responsible for determining the total inflow to each bay necessary "...for the maintenance of productivity of economically important and ecologically characteristic sport or commercial fish and shellfish species and estuarine life upon which such fish and shellfish are dependent," referred to as "beneficial inflows" [TWC §11.147]. The State Methodology is documented in an extensive report (Longley 1994), consisting of many components of study, data compilations and analyses, and modeling. The methodology arrives at a solution for a given estuary that is a sequence of monthly flows that will achieve a specified "goal". Central to the inflow determination are two sets of relationships:

1. salinity at selected locations in the estuary as a function of inflow, and
2. abundances of several key species as a function of inflow. Both of these are determined by a statistical fit to data.

For the salinity-inflow relationship, a multivariate linear regression is used on two independent inflow variables, the monthly mean flows corresponding to, and preceding, the date of salinity measurement. More important is the relation between inflow and the abundance of key species. For further discussion of the State Methodology, see the Sabine-Neches BBEST Biological Overlay Discipline Report (Appendix XIII).

5.2.3.3 Comparison of HEFR-Generated Freshwater Inflows to Sabine Lake with Freshwater Inflow Requirements Based on the State Methodology

A HEFR hydrological analysis was performed on inflows into Sabine Lake was performed under contract with the Sabine-Neches BBEST by FNI (FNI 2009b). The flow data consisted of historical daily flows from the selected study gages Village Creek near Kountze, Neches River at Evadale and Sabine River near Ruliff, plus the USGS gages Pine Island Bayou near Sour Lake (08041700) and Cow Bayou near Mauriceville (08031000). The historical daily gage flows were added to estimated ungaged inflows obtained from the TWDB. The ungaged flows consist of monthly data for the period from 1941 to 2005. These flows were distributed to daily using historical flow patterns from the Kountze gage. TWDB also has monthly estimates of diversions and return flows for the ungaged data. These data were distributed evenly throughout each month and the diversions were subtracted and the return flows added to the daily flows. TWDB also has historical monthly precipitation and evaporation estimates for Sabine Lake. These data were not included in the inflows. The median net precipitation on Sabine Lake (precipitation – evaporation) for the 1941 to 2005 period averages about 49,000 acre-feet per year, which is less than 1 percent of the average annual flow into the Sabine Lake.

Table 7 (page 60) compares the annual volume from the HEFR runs using the percentile-based approach for Sabine Lake to the annual volume for MinQ, MaxC and MaxQ from the State Methodology for bay and estuary inflows. HEFR matrix volumes for each flow condition (25th percentile, median or 75th percentile) are

shown for base flows only, base plus pulse flows and with the entire HEFR overbank event added to each condition. Subsistence flows have not historically occurred during the winter and spring months. In these months the fall HEFR result was used to calculated volumes.

Comparing HEFR-generated flow components to the State Methodology shows that the HEFR 25th percentile (dry) conditions are less than the MinQ unless an overbank event occurs during the year. Base + pulse flows for median (average) conditions are less than MinQ for the Full Period and Pre-dam time periods, but are more than MinQ for the Post-dam period. MaxC values are only exceeded for the median (average) condition if an overbank event occurs during the year. The 75th percentile (wet) condition is relatively close to the MaxQ even without the occurrence of an overbank flow.

Most of the volume entering Sabine Lake is included in the base flow component. The base flow by itself is about 70% of the Base + Pulse volume in the 25th percentile (dry) conditions and over 90% for 75th percentile (wet) condition. Post-dam HEFR results have higher volumes than the Full Period or Pre-dam results.

Figure 12 (page 61) compares the seasonal distribution of the HEFR volumes to the seasonal distribution using the State Methodology. The monthly State Methodology values were summed by the same seasons used in the HEFR analysis. The distribution for the HEFR volumes without overbank flows is similar to the State Methodology, with the highest flows occurring during the winter months and the lowest during the summer months. The occurrence of an overbank flow can significantly alter the distribution, however. The HEFR volumes are for the Full Period of record. The Pre-Dam and Post-Dam periods have similar results.

5.2.3.4 Impacts of Oil and Gas Exploration and Ship Channel Dredging on Salinity and Ecological Dynamics in Sabine Lake and Fringing Wetlands

Changes to the Sabine-Neches Estuary (Sabine Lake) began in the 1870's with navigation channels being cut through the offshore bar at the mouth of both Sabine Pass and Calcasieu Pass (Morton 1996; U.S. Army Corps of Engineers 2004). These navigation channels have been maintained and enlarged ever since. The current SNWW completed in 1972 consists of a 40-ft channel to the Port of Beaumont and a 30-ft channel to the Port of Orange. The Calcasieu Ship Channel is maintained at 40-ft depth and 400-ft width. The GIWW completed in 1933 (Sutherlin 1996) and other canals through the marsh have linked Sabine Lake to Calcasieu Lake in multiple locations (Paille 1996). Some of these connections have been plugged (rock weir control structures) by restoration efforts but the two systems are still linked.

Today the Sabine-Neches Estuary and the Calcasieu Estuary cannot be viewed separately. The system is a marsh at its center cut by an impressive network of canals and secondary channels with many open water areas therein, bracketed by deep water channels to the east and west, with a shallower channel cut through the north end (GIWW) and a chenier ridge to the south protecting it from the Gulf of Mexico. The Sabine National Wildlife Refuge occupies some 125,000 acres in the middle stretching from the east shore of Sabine Lake to the west shore of Calcasieu Lake, with three man-made impoundments totaling 33,000 acres (largest being 30,000 acres). The proximity of the channel to the east (Calcasieu Ship Channel) seems to have a greater effect on the marsh than the channel to the west (SNWW) which is protected somewhat by a spoil bank and Sabine Lake. This is evidenced by salinity data showing higher numbers on the east side of the marsh than the west (Paille 1996). These navigation channels affect the Sabine-Neches Estuary in at least two ways. First during times of high tide they allow saltwater to intrude into the estuary and further upstream into the rivers, lakes, bayous, the GIWW and marshes. Secondly, during times of flooding they move fresh water out of the estuary more quickly reducing the amount of marsh land flooding; thereby, giving less

retention time for fresh water flows and the accumulation of sediments in the marsh (Boesch, Josselyn et al. 1994, and references therein). The GIWW allows water to infiltrate the marsh through unprotected locations. At times of low flow and high tide, which in this area means a strong southerly wind, saline waters move up the deep channels of the SNWW and the Calcasieu Ship Channel and into the GIWW. Saline waters also flow into Sabine Lake through connections with the SNWW at the north and south end of the Lake as well as the lower Sabine and Neches Rivers. This sometimes leaves the center of the lake fresher than either end. These saline waters then move into the marshes though canals and secondary channels from the GIWW, the Calcasieu Ship Channel and Sabine Lake. These canals, dredged for the petroleum operations, have had a devastating effect on the marsh by allowing saltwater intrusion into the marshes; and are a "source of erosive energy on the surrounding marsh" (Boesch, Josselyn et al. 1994, and references therein) with subsequent land subsidence in some areas resulting in loss of vegetation and erosion of organic soil. Open water lakes have formed in the marshes that have become increasingly unstable and continue to degrade into larger open-water areas under existing conditions (Boesch, Josselyn et al. 1994, and references therein; Tatum 2009). Today the amount of wetlands lost from coastal Louisiana and Texas is staggering. These canals have been estimated to be responsible for the majority of this loss (Scaife, Turner et al. 1983).

During periods of normal and high flows, fresh water as expected freshens the rivers and lakes but is expedited to the Gulf through the enlarged openings of both navigation channels. It is uncertain how much freshwater inflows affect the marshes other than freshening the canals. However, precipitation seems to contribute most of the fresh water to the marsh as shown by salinity data (Paille 1996).

5.2.4 Adaptive Management

SB 3 envisions an adaptive management process for revisiting the environmental flow standards and environmental flow set-asides derived through the TCEQ rulemaking procedure. The SB 3 adaptive management process envisions that additional data, information, and studies will be necessary in order to make informed decisions regarding future changes to environmental flow recommendations. The on-going TIFP studies will provide useful information, but more research will likely be needed. In particular, dependence upon hydrology-based environmental flow recommendations, which may be largely required to meet the aggressive time frames specified in SB 3, highlights the need for future adaptation of the adopted flow standards. While application of the pre- and post-biological overlay process can substantively improve the hydrology-based recommendations, future refinements and validation will accrue only from the use of new and better science developed through the adaptive management process.

The Biology Overlay Subcommittee has identified several priority areas for research that would greatly assist in filling critical information gaps.

1. More data and improved knowledge of the ecological conditions and responses to flow variation are needed for the zone between the subsistence flow and dry base flow thresholds for each season. Field studies are needed in multiple stream and river segments of the basins to reveal relationships between key environmental parameters and biotic components during periods of low flow.
2. Additionally, more thought and deliberation are needed regarding alternative implementation guidelines (policies) for water diversions as flows change within the zone lying between the thresholds for subsistence and dry base flows. The concern here is that diversions under dry-year base flow conditions could drive flows to the subsistence flow threshold for long periods of time.

The subsistence flow defines a very rare occurrence, on the order of the lowest 1-2 percentile of all recorded flows.

3. More research is needed to establish, with greater precision and accuracy, the relationships between discharge and inundation of riparian bottomland hardwood and wetland zones of the floodplain. The Subcommittee was only able to obtain data for a limited number of stream and river segments, but more aerial images may be available for analysis, and additional high quality images should be obtained in the future.
4. Research is needed to quantify relationships between flow pulses (timing, duration, frequency) and reproduction and recruitment of important fish populations, within mainstem and tributary segments of the basins. Research is needed for species that complete their life cycle within the main channel as well as those that use both channels and backwaters (aquatic floodplain habitats).
5. More research is needed to establish relationships between the freshwater inflows established under the fluvial environmental flow recommendations and biological components of Sabine Lake. Given the heterogeneity and diversity of the estuarine ecosystem, focal species should receive greatest attention.
6. Relationships between freshwater inflows and salinity in fringing marshes, especially in the northern regions of Sabine Lake are needed. The influence of wind, tides, and depth of human-constructed channels on salinity dynamics in these regions should be examined.

5.2.5 BIO-WEST Ecological Review

BIO-WEST, Inc., was awarded contracts to assist in identification of focal species for fluvial and estuarine habitats that have characteristics representative of the majority of the flow-sensitive biota in the Sabine and Neches Basins and the Sabine-Neches Estuary. Focal species were selected by BIO-WEST, in collaboration and coordination with the Biological Subcommittee of the Sabine-Neches BBEST and state agency personnel involved in the TIFP. An attempt was made to select species which are known to be flow-dependent, use a variety of habitats, and exhibit multiple feeding and reproductive strategies. Special consideration was given to species of conservation concern, and economically important sport fish.

5.2.5.1 Fluvial

The purpose of the Bio-West Fluvial Focal Species Summary Report (BIO-WEST 2009b, Appendix VII) was to summarize information for select focal species regarding:

- Basic life history and ecological information including environmental requirements for reproduction and recruitment into adult populations and habitats used by various life stages;
- Spatial and temporal trends in population abundance or biodiversity within the basins (where available); and
- Key relationships between flow variation and the ecology of the species at the individual or population level.

Focal Species Selection

Eighteen riverine focal species were chosen to support environmental flow recommendations of the Sabine-Neches BBEST. The list of focal species was collectively identified by BIO-WEST in collaboration and coordination with the Biological Subcommittee of the Sabine-Neches BBEST, and state agency personnel involved in the Texas Instream Flow Program (TIFP). Expert opinion on freshwater mussels was also gathered

from researchers at local universities (Dr. Neil Ford, UT-Tyler; and Charles Randklev, University of North Texas). Focal species included 14 fish taxa, two mussel species, and two floodplain vegetation species (Table 9).

TABLE 9. FOCAL RIVERINE/FLOODPLAIN SPECIES IDENTIFIED TO SUPPORT INSTREAM FLOW RECOMMENDATIONS OF THE SABINE-NECHES BBEST

Common Name	Scientific Name	River/Trib/Floodplain	Unique Distribution in Texas	Species of concern	Sportfish
paddlefish	*Polyodon spathula*	River	Limited	Yes	--
white bass	*Morone chrysops*	River	--	--	Yes
flathead catfish	*Pylodictis olivaris*	River	--	--	Yes
shoal chub	*Macrhybopsis hyostoma*	River	--	--	--
emerald shiner	*Notropis atherinoides*	River	--	--	--
blue sucker	*Cycleptus elongatus*	River	Limited	Yes	--
spotted bass	*Micropterus punctulatus*	River/Tributary	--	--	Yes
dusky darter	*Percina sciera*	River/Tributary	--	--	--
sabine shiner	*Notropis sabinae*	River/Tributary	East TX	--	--
harlequin darter	*Etheostoma histrio*	Tributary	East TX	--	--
freckled madtom	*Noturus nocturnus*	Tributary	East TX	--	--
ironcolor shiner	*Notropis chalybaeus*	Tributary	East TX	Yes	--
alligator gar	*Atractosteus spatula*	River/Floodplain	--	Yes	--
black/ white crappie	*Pomoxis spp.*	River/Floodplain	--	--	Yes
Texas pigtoe	*Fusconaia askewi*	River/Tributary	East TX	Yes	--
pistolgrip	*Tritogonia verrucosa*	River/Tributary	--	--	--
overcup oak	*Quercus lyrata*	Floodplain	East TX	--	--
water tupelo	*Nyssa aquatica*	Floodplain	East TX	--	--

5.2.5.2 ESTUARINE

The Estuarine Focal Species Summary Report's (BIO-WEST 2009a, Appendix VII) goal was to:

- Summarize the dependencies of focal species with regard to habitat conditions, especially as affected by freshwater inflow variation, salinity patterns and seasonality;
- Provide graphical or tabular summaries of population abundance or biodiversity trends within the estuary; and
- Describe key relationships between inflow and salinity variation and the ecology of focal species at the individual or population level

Sabine-Neches Estuary Focal Species

Ten estuarine focal species were chosen to support environmental flow recommendations to the Sabine-Neches BBEST. The list of focal species was collectively identified by BIO-WEST in collaboration and coordination with the Biological Subcommittee of the Sabine-Neches BBEST, state agencies involved in the Texas Bays and Estuary Study Program, Louisiana Department of Wildlife and Fisheries (LDWF), and local universities.

Table 10, below, lists the selected species and a summary of the inflow-related traits for each species this table is from the BIO-WEST, Inc., Estuarine Focal Species Report (Appendix VII).

TABLE 10. ESTUARINE-DEPENDENT FOCAL SPECIES INTENDIFIED TO SUPPORT ENVIRONMENTAL FLOW RECOMMENDATIONS OF THE SABINE-NECHES BBEST

Wetland Plants	Bivalve Mollusks
Olney bulrush (*Schoenoplectus americanus*)	Atlantic rangia (*Rangia cuneata*)
Saltmeadow cordgrass (*Spartina patens*)	American oyster (*Crassostrea virginica*)
Crustaceans	**Fish**
White shrimp (*Litopenaeus setiferus*)	Atlantic croaker (*Micropogonias undulatus*)
Brown shrimp (*Farfantepenaeus aztecus*)	Spot (*Leiostomus xanthurus*)
Blue crab (*Callinectes sapidus*)	Gulf menhaden (*Brevoortia patronus*)

5.2.6 NATIONAL WILDLIFE FEDERATION

Voluntary work performed by the National Wildlife Federation and their consulting firms was provided to the Biology Subcommittee of the Sabine-Neches BBEST.

5.2.6.1 NATIONAL WILDLIFE FEDERATION *RANGIA* STUDY

Salinity Suitability Analyses of *Rangia cuneata* and Other Characteristic Species and Communities of the Sabine-Neches Estuary in Order to Develop a Freshwater Inflow Regime. The NWF provided this report in support of the efforts of the Sabine-Neches BBEST to develop an estuarine inflow regime for the Sabine-Neches Estuary. Much of

the information is summarized in the Biology Subcommittee's report (Appendix XIII) and the full NWF report is provided in Appendix XVI.

5.2.6.2 National Wildlife Federation Bottomland Hardwood Forests Study

"Analyses of Satellite Imagery in the Sabine and Neches River Basins in Support of Developing Overbank Instream Flow Recommendations for the Maintenance of Bottomland Hardwood Forests."

Bottomland plant species often have characteristics allowing them to tolerate conditions such as flooding that are not as well tolerated by upland or invasive species. Periodic flooding thus benefits certain species adapted to these habitats. A second NWF report done for the Sabine-Neches BBEST provided satellite imagery analyses on overbank events for their beneficial bottomland forest inundation characteristics at several sites. This report is also referenced by the Biological Subcommittee report in Appendix XIII and the full NWF report is provided in Appendix XVII.

5.3 Geomorphology (Sediment Transport)

Fluvial sediment transport has been widely recognized as an important process to maintaining a sound ecological environment within both alluvial and estuarine environments. The TWDB has conducted studies of sediment transport and geomorphological characterization within Texas river systems starting in the late 1990's and has continued those studies into this decade, especially as it relates to the SB 2 program. As a part of this SB 3 process, the Sabine Neches BBEST has reviewed these historical studies by the TWDB and the conclusions of those studies have been summarized in this section of the report. The Sabine Neches BBEST has also reviewed the guidance documents developed by the SAC that address fluvial sediment transport. These guidance documents recommend certain analyses that are considered useful to the environmental flows allocation process as it relates to sediment transport. Appendix XIV contains the complete Geomorphic Overlay discipline report for the Sabine-Neches BBEST.

5.3.1 Recent Senate Bill 2 Studies

5.3.1.1 Geomorphic Processes, Controls, and Transition Zones in the Lower Sabine River, Final Report, June 2007

The TWDB retained Jonathan D. Phillips PhD and Michael C. Slattery, PhD to conduct a study of geomorphic processes, controls, and transition zones in the lower Sabine River as a part of the SB2 work program (Phillips and Slattery 2007). The specific objectives of the study were to:

- Develop a baseline characterization of the condition and behavior of the lower Sabine River (downstream of Toledo Bend reservoir);
- Examine longitudinal (downstream) changes in flow processes and energetics, channel and valley morphology, and patterns of recent geomorphic change;
- Classify the lower Sabine (based on items 1, 2) into geomorphic process zones;
- Identify the primary controls—both contemporary and historic—of the geomorphic process zones; and
- Identify the current location, primary controls over, and potential future changes in critical transition zones.

The primary findings of this study are outlined here.

Sediment Discharge

Measurements of sediment concentration and transport are rare for the lower Sabine River. The USGS collected depth-integrated suspended sediment samples at the Sabine River nr Ruliff (Ruliff) station for the 1974-1995 period. A summary of these measurements is given in Table 3 in (Phillips and Slattery 2007). Using reservoir survey data from the upper Sabine basin to estimate delivery of eroded sediment to streams, Phillips (2003) found that if all sediment delivered to channels were transported by the river it would imply sediment yields of more than 400 t km^{-2} yr^{-1}. This is at least an order of magnitude higher than is typical of the region, and is larger than the 159 t km^{-21} recorded in the Trinity River over the 1936-1946 period, which represents the highest suspended sediment yield for the lower reaches of a major river in Texas over a period of years (Solis, Longley et al. 1994). The low sediment yield at Ruliff (8.9 t km^{-2} yr^{-1}) is not unusual for streams in the southeast Texas coastal plain (see Table 4. Measurements and estimates of fluvial sediment yields in southeast Texas in (Phillips and Slattery 2007)).

Estuary Sediment Delivery

Ravichandran, Baskaran et al. (1995) determined sedimentation rates in Sabine Lake using 239,240Pu profiles, which were 4 to 5 mm yr^{-1} in both the upper and lower estuary. If this is extrapolated over the entire 53,349 ha (131,828 acres) surface area of the estuary, assuming a density of 0.7 t m^{-2}, it implies a sediment yield of nearly 37 t km^{-2} yr^{-1} for the entire upstream drainage area of Sabine Lake, which includes the Neches as well as the Sabine River—if all the sediment comes from those two rivers. A significant portion of the sedimentation, however, likely comes from autochthonous organic matter, shoreline erosion, marine and coastal sources, reworking of bed sediments, and local fluvial inputs from coastal watersheds (Phillips and Slattery 2006).

According to TCB|AECOM (2006, p. 6-6), the Sabine and Neches Rivers discharge "large quantities of fine muddy sediment" into Sabine Lake, with "very little bedload sand … transported along the lower Neches and Sabine Rivers." Mud-rich freshwater, especially during floods, spreads extensively across the upper lake area and reduces salinity. During floods, suspended sediment may reach the Gulf, but most is deposited within Sabine Lake. Within the lake, sandy bedload sediment is generally restricted to small areas near river mouths (TCB|AECOM 2006, p. 6-6). However, the extent to which suspended sediment in the lake is derived from river inputs is unknown.

Stream Power

The relative sediment transport capacity of streams is directly related to stream power, which for a cross-section is given by

EQUATION 1. RELATIVE SEDIMENT TRANSPORT CAPACITY OF STREAMS

$$\Omega = \gamma Q S$$

where γ is specific gravity of water, Q is discharge, and S is energy grade slope.

For the gaging stations at Burkeville, Bon Wier, and Ruliff, stream power for the bankfull, flood stage discharges were calculated, using channel bed slopes calculated from the Digital Elevation Model (DEM) in the immediate vicinity of the gaging stations (from three to four meander wavelengths upstream to a similar distance downstream of the site). As discussed earlier, bankfull or flood stage flows occur at different frequencies at each site. However, beyond being a convenient reference, bankfull flow may represent the maximum net downstream sediment transport.

Results (Table 11, below) (Phillips and Slattery 2007, Table 5) show a significant decrease in stream power between Burkeville and Bon Wier, with an increase at Ruliff, due to channel slopes about double those at the upstream sites. At the Ruliff station, however, channel slope from the DEM likely overestimates the energy grade slope due to the thalweg being cut to below sea level, and the tidal backwater effects. Similar calculations for 50, 10, and 1 percent probability flows show comparable stream power at Burkeville and Bon Wier, with apparently higher power at Ruliff.

To overcome the limitations of using channel slopes calculated from digital elevation data, stream power was calculated for several specific times during the October 2006 flood event. For any specific time, gage heights at the Bon Wier and Ruliff stations, the gage datums, and the distance between stations allows calculation of the mean water surface slope. These calculations were made for the point at which flow at Ruliff went overbank (Q = 516 m^3 sec^{-1}), the peak flow at the site (Q = 1640), and the beginning of the falling limb (Q = 492). Results, below, show stream powers at near bankfull flow (Qbf = 510 m^3 sec^{-1}) considerably lower than bankfull stream power at the upstream stations. Such a reduction in sediment transport capacity downstream is common in the lower coastal plain reaches of other rivers in Texas and elsewhere (Phillips and Slattery 2007; Phillips and Slattery 2006).

TABLE 11. CROSS-SECTIONAL STREAM POWER (Ω) FOR BANKFULL FLOWS, BASED ON CHANNEL SLOPES

	Burkeville	Bon Wier	Ruliff
Slope	0.0004	0.00034	0.00079
Q (m^3 sec^{-1})	1880	793	510
Ω (W m^{-1})	7.3696	2.6423	3.9484

TABLE 12. CROSS-SECTIONAL STREAM POWER AT SABINE RIVER NR RULIFF DURING OCTOBER 2006 FLOOD EVENT, BASED ON WATER SURFACE SLOPES

	Slope	Q (m3 sec-1)	Ω (W m-1)
Beginning of overbank flow	0.00015	516	0.7452
Peak flow	0.00013	1640	2.0374
Receding limb	0.00010	492	0.5068

Summary and Conclusions

Flows in the lower Sabine River are affected by the climate and hydrologic response of the drainage basin, releases from Toledo Bend Reservoir, water withdrawals, and tidal and coastal backwater effects. Releases from Toledo Bend create a highly pulsed discharge regime, but the effects exhibit both spatial and temporal decay. The influence of dam releases on flow is reduced downstream—dam releases dominate flow at the Burkeville gaging station, but are superimposed on patterns determined by watershed runoff at Ruliff. Dam releases are most influential during dry, low-flow periods, and hydrographs reflect runoff responses during wet, high-flow periods. The effects of the dam are most evident on an hour and daily time scale, and do not substantially influence monthly or annual mean flows, or peak flows.

Water diversions have significant impacts on flows, but such effects have been less in recent decades (see fig. 4), and either do not have discernible effects on freshwater inflows to Sabine Lake, or any effects have been offset by

climatic trends. Coastal backwater effects are strongest at Sabine Lake, declining in importance upstream. These effects are evident, however, as far upstream as Ruliff and beyond.

Overbank flow—and the associated alluvial sedimentation—is increasingly common further downstream of Toledo Bend. The most important feature of the lowermost, deltaic portion of the river is the complex and changing patterns and routing of flow. A majority of flow between Cutoff Bayou and the Sabine/Old River confluence is carried by the Old River channel. The potential geomorphic causes and implications of this are addressed in the next section.

Sediment transport data are scarce, but records from the Ruliff station indicate low sediment yields that are considerably less than delivery of sediment to the fluvial system. This in turn suggests significant alluvial sediment storage, which is consistent with the extensive and active alluvial floodplains in the lower Sabine, and increasing overbank flow occurrence and decreasing stream power further downstream.

5.3.1.2 Geomorphic Equilibrium in Southeast Texas Rivers, Final Report, November, 2007

The TWDB retained Jonathan D. Phillips, PhD to address the geomorphic equilibrium of the coastal plain portions of the Brazos/Navasota, Trinity, and Sabine Rivers, Texas (Phillips 2007). Equilibrium concepts are of major theoretical importance in fluvial geomorphology, but also have critical applied implications. River management, assessment, engineering, and classification are often based on concepts of geomorphic equilibrium, and implicit or explicit assumptions that fluvial systems are in, or develop towards, some form of equilibrium.

However, the assumption of equilibrium (or tendencies toward it) is not always valid and is increasingly criticized as a reasonable assumption for models and assessments. Further, equilibrium is variously and sometimes poorly defined. The purpose of this study was to critically review the concept of equilibrium in fluvial systems in general, and in the specific context of southeast Texas. Rigorous definitions of geomorphic equilibrium were developed and applied to the study rivers, with particular reference to fluvial response to environmental change, and to implications for the TIFP.

Conclusions

The conclusions of this study were notable in regards to this SB 3 effort and are repeated here.

> *Relaxation time equilibrium may be present in the rivers of southeast Texas, and the presence (or absence) of RTE is useful in assessing river conditions and in the application of analytical techniques and models. Characteristic form and steady-state equilibrium are far less common, and clearly cannot be assumed. In general, no inherent tendency toward any stronger form of equilibrium – characteristic forms, steady-states, grade, etc. – can be assumed, at least not in the form of any single characteristic or stable equilibrium state.*
>
> *Equilibria are arguably useful as a reference condition, but should not be assumed to necessarily be any more common, important, or "natural" than disequilibrium or nonequilibrium states. Managers cannot assume that there is any single normal, natural, or otherwise normative condition for the alluvial rivers of the study area, and should recognize the possibility – indeed, the likelihood – of multiple modes of adjustment and potential responses to disturbance.*

5.3.2 Science Advisory Committee Recommendations

The SAC provided guidance for the inclusion of fluvial sediment transport as a possible overlay to the HEFR approach for determination of an environmental flow regime required by Texas SB 3. Although numerous sources

associate the majority of fluvial sediment transport with high-pulse flows, the discussion and guidance provided by the SAC are not contingent on an exclusive association of sediment transport with HEFR-based high-pulse flows. In many cases, a healthy sediment regime can be associated either with overbank, high-pulse, or even base flows. The SAC provided a rationale and context to justify inclusion of a sediment transport overlay to the environmental flows allocation process, discussed various methods of assessment (including use of historical data), and recommended the effective discharge approach to assess sediment transport at gaging stations as further discussed below.

An analysis of effective discharge of suspended-sediment load (SSL), bedload, bed-material load, and/or total load at streamflow gaging stations is recommended by the SAC to potentially be used to modify HEFR-based flow prescriptions for establishing environmental flows. Specifically, a SAM (Hydraulic Design Package) analysis of effective discharge of bed-material load is suggested for assessments of instream habitat conditions and dynamics. For the majority of locations, the high-pulse flow or overbank-flow categories are expected to be associated with the cumulative majority of sediment transport over time. Sediment transport, although relatively straightforward in its association with discharge, does not encompass the breadth of fluvial geomorphic processes. Furthermore, concepts of steady-state equilibrium challenge assumptions that a constant discharge value is responsible for the cumulative majority of sediment transport over time. Finally, practitioners utilizing effective discharge for rivers in Texas are warned to be cognizant of the contemporary sediment-transport regime and historical channel adjustments at each location considered. Assignment of an effective discharge to altered or regulated rivers is recognized as being problematic and implementation efforts could be harmful if a holistic perspective (e.g., sediment trapped behind reservoirs, non-representative cross section to estimate bedload transport, etc.) is not considered.

The SAM Hydraulic Design Package is proposed as a very useful desktop tool to assist practitioners in modeling sediment transport and determining effective discharge at streamflow-gaging stations. It conveniently facilitates the choice of a sediment-transport model equation based on user input, and can be used to compare annual sediment loads for existing and HEFR-based hydrologic conditions. Although SAM is a useful tool to compare observed sediment-transport loads and effective discharge with HEFR-based conditions, little can be done using readily available desktop methods to prescribe a “sediment-load regime” that would adequately maintain instream ecology. The chief reason for this is the paucity of historically-observed geomorphic and sediment-transport data for rivers in Texas, contrasting with the availability of streamflow data for HEFR-based flow-regime analyses. Further, various fluvial processes (e.g., channel bar deposition and modification, channel migration, floodplain sedimentation) initiate and/or occur over a range of flows and, therefore, are dependent on sufficient rates of sediment transport during those flows. The unavailability of data for Texas rivers obfuscates the determination of optimized sediment concentrations or loads for these physically- and ecologically-relevant flows. At minimum, the practitioners responsible for environmental-flow prescriptions at a given site should be cautious if bed-material load is shown to be considerably reduced as a result of an implementable schedule of flows.

5.3.3 SAM Application

Under the SB 3 process for the Sabine-Neches BBEST, the TWDB performed an SAM analysis of effective discharge of sediment transport at several USGS gaging stations with in the Neches and Sabine basins (Sabine-Neches BBEST Geomorphology Overlay Discipline Report, Appendix XIV). At each gaging station, the effective discharge was computed using the methodology described in Biedenharn, Copeland et al. (2000) for three different flow scenarios:

1. The unadjusted historical period of record (HPOR);

2. HPOR modified by assuming present day operation of diversions and storage in the basin (also called TCEQ WAM Run 8); and
3. HPOR modified by assuming future operations of full permitted diversions and reservoir storage without any regulation or adjustment for proposed environmental flow regime permit controls (also called TCEQ WAM Run 3).

The results of these analyses are summarized in the table below and are outlined in more detail in Appendix XIV. It should be recognized that an analysis of effective discharge does not encompass nor entirely explain the breadth of fluvial geomorphic processes. Sediment transport, however, is a fairly straightforward process to relate with streamflow, and collection of sediment-transport data commonly occurs simultaneously with streamflow at a gaging station. Furthermore, computation of effective discharge based on bed-material load is the widely accepted method for evaluating changes in channel morphology. Effective discharge of suspended load offers comparatively less insight toward assessments of instream habitat conditions and dynamics.

TABLE 13. EFFECTIVE DISCHARGE AND HIGH FLOW PULSES

	WAM Run 8 Effective Discharge in cfs	Number of Days Flow is in Effective Discharge Bin	Highest Seasonal High flow Pulse	Duration of Highest Seasonal High Flow Pulse	HEFR Overbank Flow	HEFR Overbank Flow Frequency	Annual Duration of HEFR Overbank Flow Frequency
Sabine River Basin							
Ruliff	21760	19	9880	22	29000	1 per year	60
Bon Wier	19997	9	20600	17	28700	1 per year	28
Beckville	5960	15	7200	24	16100	1 per 2 years	45
Gladewater	5650	8	5,570	24	18,100	1 per 2 years	22
Neches River Basin							
Evadale	17622	5	8700	22	19500	1 per year	38
Rockland	5500	12	6910	22	18500	1 per 2 years	41
Chireno	1264	12	1200	12	7520	1 per 2 years	27

TABLE 14. EFFECTIVE DISCHARGE FOR RUN 8 AND RUN 3

Location	Run 8 Effective Discharge	WAM Run 8 Annual Water yield AC-FT	WAM Run 8 Annual Sediment Yield Tons	Run 3 Effective Discharge	WAM Run 3 Annual Water yield AC-FT	WAM Run 3 Annual Sediment Yield Tons	Sediment Function used
Sabine River Basin							
Ruliff	21760	6,146,000	284,688	21,065	4,222,000	144,000	ENGELUND-HANSEN
Bon Wier	19997	4,919,000	81,674	13,812	3,066,000	43,643	YANG,D50
Beckville	5960	1,731,000	111,579	5,961	1,393,000	81,675	ENGELUND-HANSEN
Gladewater	5650	1,213,000	300,433	5,437	969,000	206,775	ENGELUND-HANSEN
Neches River Basin							
Evadale	17622	4,718,000	279,335	16,202	4,237,000	221,440	YANG,D50
Rockland	5500	1,706, 000	154,333	5,406	1,469,000	130,108	YANG,D50
Chireno	1264	314,000	12,510	*	*		YANG,D50

5.3.4 CONCLUSIONS

In spite of the presence of major reservoirs within the Neches and Sabine River systems, recent geomorphological studies by the TWDB under the SB 2 program indicate that these systems are likely functioning normally for Gulf Coast riverine systems with regard to sediment transport. Except for relatively short reaches immediately below the reservoirs, the measurement of sediment concentration and transport are at levels that would be expected and desired for these systems, indicating a present level of health and a sound ecological environment as it relates to fluvial geomorphology. No adjustments to the HEFR regime for fluvial geomorphology were considered to be appropriate by the Sabine-Neches BBEST based on the detailed study for these systems provided by the TWDB under SB2 and on the limited analysis using the SAM application. Based on comparisons of the Effective Discharge for WAM Run 8 to the HEFR proposed by Sabine-Neches BBEST, evidence indicates that high-pulse flows and overbank flows will provide sufficient flow to maintain the existing dynamic equilibrium within these two riverine basins.

As expected, comparisons of WAM Run 8 to WAM Run 3 at each of the gaging stations analyzed for this study show a decrease in volume of water and sediment flow passing each gage. At Ruliff, the most downstream gage used in this study on the Sabine River, Run 3 average water volume is about 66% of the Run 8 volume and the sediment load for Run 3 is about 50% less on average than the Run 8 sediment load. The effective discharge at Ruliff remains about 21,000 cfs for both Run 3 and Run 8. This implies the channel geometry may change over time

within this reach of the river because of the lesser amounts of flow and sediment transport in the channel; however, this change does not suggest inadequate sediment transport. Depending on the how the flow and sediment diversions occur upstream of Ruliff, the channel could remain relative stable or could change gradually. The effective discharge for Run 3 at Bon Wier is reduced by about 30% and the channel in this area could be impacted similar to Ruliff. The difference between the Effective Discharge and annual water and sediment yield for Beckville and Gladewater gages on the Sabine River, for the Evadale and Rockland gages on the Neches River, and for the Attoyac Bayou at Chireno gage do not indicate significant changes in channel bathymetry will likely occur as a result of the future upstream diversions. Further analysis at Ruliff and Bon Wier is advisable to better address the potential changes associated with such a large change in overall average flow. However, this is a worse than worst case scenario at Bon Wier and Ruliff since future conditions include like amounts of diversions directly from the reservoir for Louisiana which is a highly unlikely condition.

5.4 Application of Water Quality in Environmental Flows

Although water quality is an important aspect of environmental flow recommendations development, its application as an overlay to flow regimes identified by hydrologic analyses is not necessarily straightforward. Section 5.4 addresses the application of water quality to environmental flow recommendations for the Sabine and Neches River basins. Included are discussions of water quality regulations as applicable to environmental flows, the availability of water quality data in the basins, and the relationship of water quality to flow.

5.4.1 Regulatory Perspectives in Water Quality

The Clean Water Act (CWA) of 1972,[25] with a stated goal to "restore and maintain the physical, chemical, and biological integrity of the nation's waters", set in motion a regulatory framework that would enable a substantial change in the character of the nation's surface waters. The intervening years since the passage of the CWA have seen dramatic improvements in surface water quality throughout the country, primarily through reductions in pollutant discharges from point sources of pollution, such as industrial and municipal wastewater treatment facilities.

Certain water quantity data, such as flow or discharge, are available at each of the 12 USGS gages selected[26] for the Sabine and Neches River basins on, essentially, a daily basis. However, the development of environmental flows recommendations for these watersheds suffers from a lack of sufficient data to describe water quality conditions at subsistence flows. TCEQ's TCRP[27] addresses the need for water quality data with water samples being collected at a number of stations throughout the Sabine-Neches Study Area monthly or quarterly.

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[25] Clean Water Act (CWA) | Agriculture | US EPA, http://www.epa.gov/oecaagct/lcwa.html, retrieved November 7, 2009

[26] The 12 gages selected for study are all in freshwater and largely non-industrial areas upstream from the tidal portions of the Lower Sabine and Neches River Basins.

[27] TCEQ, Texas Clean Rivers Program: An Introduction, http://www.tceq.state.tx.us/compliance/monitoring/crp/. Both the LNVA and SRA-TX are TCRP Partners (see http://www.lnva.dst.tx.us/ and http://www.sratx.org/srwmp/tcrp/, respectively). Retrieved November 7, 2009

Linking water quality and environmental flows also requires consideration of the Texas Surface Water Quality Standards (TSWQS)[28] as currently applied. In streams and rivers, TSWQS for the protection of aquatic life are based on flows at or above a minimum flow level known as the 7Q2 flow – defined as the minimum daily flow for a 7-day period with a return period of two years. Although TSWQS do not apply at flows below the 7Q2, this does not imply that water quality cannot be maintained at flows lower than 7Q2.

The application of the TSWQS should not be confused with the development of environmental flow recommendations, particularly at subsistence flows or in base flow ranges. Subsistence flows and some base flows in the Sabine-Neches Study Area are well below the published 7Q2 flow. Available data demonstrates that water quality is generally good at flow levels at least as low as subsistence flows. It is neither necessary nor appropriate to use the 7Q2 flow, as published in the TSWQS, as a default subsistence flow in the environmental flow regime; as such, 7Q2 will not be so used in the SB 3 environmental flow recommendations for the Sabine and Neches River basins.

Appendix XII-1 summarizes Sabine and Neches Basin water quality impairments appearing on the 2008 Texas 303(d) List. None of the 12 gages selected for SB 3 consideration are listed as impaired for any water quality parameter that would be expected to be affected in any great extent by the level of environmental flow in the stream at the gage, or by future diversions of water from the stream at these locations.

5.4.2 Available Water Quality Data

Water quality data for the Sabine and Neches Rivers are made available primarily through the TCRP – administered by the governing river authorities for each basin – SRA-TX for the Sabine River Basin and LNVA and the ANRA for the Neches River Basin.

At the selected gages or nearby TCRP sampling locations, a variety of water quality parameters are routinely monitored under the TCRP, including dissolved oxygen (DO), water temperature, pH, alkalinity, total phosphorus, chlorophyll-a, conductivity, total dissolved solids, turbidity, and fecal coliform. The data reflect grab samples collected at the sites generally on a quarterly or monthly basis, although some parameters are monitored more frequently. This report has focused primarily on water quality data available at the selected gage sites in order to evaluate the relationship between flow and water quality. In the case of nutrient data, however, TCRP sampling stations near the selected gage locations were included.

In the case of DO, the lack of diurnal data that would show the true distribution of DO over the course of the day could present a problem for evaluating the potential impact of low DO on aquatic life in the streams. Fish, for example, can exist in water with DO concentrations of around 3 mg/L for short periods of time. However, prolonged exposure to low DO concentrations will adversely impact aquatic life. Studies designed to collect diurnal DO data[29] are underway as of this writing in the lower Sabine River Basin.

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[28] TCEQ, Texas Surface Water Quality Standards, http://www.tceq.state.tx.us/nav/eq/eq_swqs.html, retrieved November 7, 2009

[29] As part of the Federal Energy Regulatory Commission Relicensing process for hydropower production at the Toledo Bend Dam, the Toledo Bend Project Joint Operation has deployed data sondes at several locations below Toledo Bend reservoir in the river to study water quality on a continuous basis.

5.4.3 Flow and Water Quality Relationships

The USGS gages monitor flow on a continuous basis (i.e., 15 minute intervals); thus, flow-quality relationship can be established if there is a sufficient number of water quality data points collected when the flow gage is operational -- water quality data were, thereby, linked to river flow assessed as daily average discharge in cfs. The period of record for flow at each gage is generally significantly longer than that for water quality; and the water quality data periods of record are not equal for all gages, but range from as early as 1960 to 2009. There is no water quality data at any of these gages prior to 1960. Table 15 (page 96) summarizes the number of water quality data points available for each of the 12 selected gages in the Sabine-Neches Study Area.

Data collected at the 12 USGS gage locations were generally used for this analysis; however, data from both the USGS gages and nearby TCRP sampling stations were sometimes utilized to develop a sufficient number of flow-quality points for total phosphorus and chlorophyll-a. The TCRP stations selected were a short distance upstream or downstream from a gage and were not influenced by tributaries. Data agglomeration was performed in order to capture a sufficient number of total phosphorus and chlorophyll-a data for a more complete evaluation. Nutrient values from 1972 to 2008 were used in this analysis.

Using these data, the relationship of water quality to flow was evaluated. A graph of flow (on the abscissa) and quality (on the ordinate) was constructed for each parameter in Table 15. These graphs are contained in Appendix XII-1. For each gage, the subsistence flow, dry summer base flow, and wet winter base flow are shown, as well. The purpose of showing the subsistence flow and range of base flows is to highlight where water quality data collection has occurred with respect to these selected flows at each gage. Appendix XII-1 also provides a discussion of the observed relationship between the various water quality parameters and flow at the various gages.

TABLE 15. SUMMARY OF WATER QUALITY DATA AVAILABLE AT SELECTED GAGES IN THE SABINE AND NECHES RIVER BASINS

Gage Identification	Number of Available Water Quality Data Points for Each Water Quality Parameter [1]										
	Dissolved Oxygen	Water Temperature	pH	Alkalinity	Total Phosphorus	Chlorophyll-a	Field Conductivity	Laboratory Conductivity	Total Dissolved Solids	Turbidity	Fecal Coliform
Sabine Basin											
Big Sandy Creek near Big Sandy	93	215	NA	NA	26	11	117	190	11	11	1
Sabine near Gladewater	441	446	88	NA	12	NA	309	193	NA	NA	NA
Sabine near Beckville	294	317	123	NA	13	NA	292	236	NA	48	NA
Sabine near Bon Wier	377	1,965	281	121	20	55	1,266	2,293	73	NA	NA
Big Cow Creek near Newton	27	31	NA	NA	13	NA	30	16	NA	NA	NA
Sabine near Ruliff	920	1,172	1,025	643	25	45	793	684	264	90	164
Neches Basin											
Neches near Neches	194	320	197	115	47	38	184	441	43	NA	NA
Neches near Rockland	328	380	356	95	20	20	190	517	37	48	NA
Angelina near Alto	39	41	58	36	44	36	41	23	55	NA	NA

Gage Identification	Number of Available Water Quality Data Points for Each Water Quality Parameter [1]										
	Dissolved Oxygen	Water Temperature	pH	Alkalinity	Total Phosphorus	Chlorophyll-a	Field Conductivity	Laboratory Conductivity	Total Dissolved Solids	Turbidity	Fecal Coliform
Attoyac Bayou near Chireno	79	78	81	55	NA	NA	68	71	12	NA	NA
Neches at Evadale	494	528	806	307	94	40	355	742	292	107	132
Village Creek near Kountze	48	163	193	79	42	NA	89	233	8	NA	NA

(1) The data used for each gage are data collected at the specific gage, except for total phosphorus and chlorophyll-*a*. Data for these parameters came from the gages plus other nearby TCRP sampling stations.

5.4.4 Selection of Water Quality Parameters for Environmental Flow Recommendations

Although not all available water quality data provide information useful to the development of environmental flows, a few stand out as viable candidates because of their close relationship to maintenance of aquatic life. The SAC document "Essential Steps for Biological Overlays in Developing SB 3 Instream Flow Recommendations" (SAC 2009a) identifies water temperature, DO, pH, conductivity, and turbidity as parameters that are important to survival, growth, and reproduction of aquatic organisms. This document goes on, however, to focus on water temperature and DO as the primary parameters supporting survival and reproduction of aquatic life. The other parameters may constrain or limit the distribution and abundance of aquatic organisms.

Both DO and water temperature are easily and accurately measured with field equipment and as a result there are a significant number of data points available for each at the 12 gages. Furthermore, in comparison to most available water quality data, DO and water temperature have, by far, the greatest number of data points at the widest range of flows.

Some consideration was given to the selection of nutrient or nutrient-related data (i.e., total phosphorus and chlorophyll-a) as parameters for consideration in developing environmental flow recommendations. However, at this time, there is an insufficient body of data available for these parameters, particularly at base and subsistence flows, to effectively use them.

Therefore, based on these factors, DO and water temperature were considered by the Sabine-Neches BBEST as the primary water quality parameters in development of environmental flow recommendations. Appendix XII-2 summarizes DO and water temperature data for each gage. Using these parameters, environmental flow regime recommendations were evaluated for consistency with water quality.

5.4.5 Integrating Water Quality into Environmental Flow Recommendations

An environmental flow regime may cover a wide range of flows from subsistence and base flows on the lower end to high-flow pulses and overbank flows on the upper end. Water quality problems may exist at any or all of the flows. The question is, however; is there a critical range to consider with respect to DO and water temperature? If so, can water quality considerations be limited to this critical range? The graphs seen in Appendix XII-2 indicate that the relationship between flow and water quality is generally weak. Water quality in both the Sabine and Neches River basins typically meets Stream Standards within the range of flows for which data have been collected. This is true of DO and water temperature as well. Based on the data, DO concentrations throughout the range of flows are generally well above TSWQS criteria. Water temperature is more related to season than to flow, and is within an acceptable range for supporting aquatic life.

However, almost all of the available water quality data have been collected in the streams at flows at or above what has been identified as subsistence flow. As flows increase, the availability of data increases, but even the lower end of base flows generally have some data limitations. The available data suggest that water quality will generally be adequate to support an appropriate aquatic ecosystem even at subsistence flow. Therefore, while it can be presumed that water quality at flow levels expected in the stream most of the time will be good, extending that presumption to flows below subsistence levels could be problematic.

Subsistence flows lower or higher than those recommended for the basins could be justified, if sufficient data were available for evaluation. It is important, therefore, to prioritize additional sampling trips to

better characterize water quality conditions during extreme low flow periods; and, as such, additional water quality study at low and subsistence flow is recommended.

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6 Development of Environmental Flows Recommendations/ Recognitions/ Unresolved Issues

SB 3 charged each BBEST with recommending an environmental flow regime adequate to support a sound ecological environment for each group's river basin and bay system. Over the allotted timeframe of 12 months, following available SAC guidance and SB 3 criteria, the Sabine-Neches BBEST, its flow discipline subcommittees, and the group's consultants used the best available science for the Sabine-Neches Basin Study Area to devise its flow regime recommendations.

During the course of the past year, it has become clear that the Sabine-Neches BBEST recommendation charge requires further clarity. Taking its charge from the "theoretical" to the "practical", the Sabine-Neches BBEST was able to make some specific environmental flow recommendations, while in other cases (for example overbank flows) the group agreed to recognize the ecological value of such flows but not recommend them. As indicated below, this process also involves unresolved issues, the need for future studies, and ultimately, adaptive management to address the unresolved issues. Section 6 contains the summation of the work of the Sabine-Neches BBEST with these observations.

- **Recommendations** – The Sabine-Neches BBEST has reached consensus and can agree by defining recommendations as a course of action that is recommended as advisable. For example, some elements of the flow regime such as subsistence flows may be recommended with an advisable course of action.
- **Recognition** – For some issues, the Sabine-Neches BBEST may be able to move forward with recognition of the value of a particular element of the flow regime where for example overbank flows provide a defined value to the ecological environment, but it has recognized that it cannot recommend them since they have the potential to cause extensive damage to private property and endanger the public.
- **Unresolved Issues** –The Sabine-Neches BBEST has been given a charge that contains an immense scope of work with limited resources and presents a huge challenge to accomplish in a very limited time frame; the group agrees that there are unresolved issues for which it will recommend future studies. For example, the group agrees that it has set a certain bar for subsistence flows and at the same time agree that these flows are placeholders pending future studies and work which would provide the information to fill data gaps.
- **Future Studies** – Agreement that available science in some areas is insufficient to draw the necessary conclusions at this time, and there is a need for future studies designed to address these unanswered questions.
- **Adaptive Management** – Adaptive management is a tool that provides for future corrections as they are defined and agreed to through specific studies.

6.1 Instream Flow Regime Application

6.1.1 Introduction

This section of the Recommendations Report summarizes key elements and considerations in the development and application of environmental flow regimes for the Sabine and Neches River Basins in accordance with the provisions of SB 3 of the 80th Texas Legislature. The Sabine-Neches BBEST expects that the TCEQ will consider direct translation of seasonal subsistence and base flow values within recommended flow regimes into environmental flow standards and, ultimately, consider such values as potential permit conditions applicable to new surface water appropriations. Permit conditions may be defined as a set of rules specifying when impoundment or diversion of streamflows is authorized under a specific water rights permit. The following subsections focus on key elements of a flow regime and relevant observations of the Sabine-Neches BBEST, example application of a flow regime, and consideration of attainment frequencies in flow regime application.

6.1.2 Elements of a Recommended Flow Regime

6.1.2.1 Subsistence Flows

Subsistence flows were initially calculated as the median of the lowest 10 percent of historical base flows by season using HEFR. Resulting subsistence flow values, and particularly those derived for the summer season, were compared to geographically proximate water quality sampling data maintained by TCEQ. Frequent violations of stream standards for dissolved oxygen and temperature have not occurred and would not be expected to occur at the statistically-derived subsistence flow values. Nevertheless, in order to maintain essential environmental features of fluvial ecosystems (e.g., minimal instream habitat to avoid extirpations of aquatic populations, moisture content of hyporheic zones for riparian vegetation) during periods of stress due to drought, the Sabine-Neches BBEST recommends that all seasonal subsistence flows be greater than or equal to the statistically-derived subsistence flow for the summer season at each reference gage location. Twenty-two cfs is used as the summer and fall seasonal subsistence flow at Beckville for compliance with Sabine River Compact minimum flow requirements at the state line (the statistically-derived values for the summer and fall seasons were 20 cfs and 19 cfs, respectively). As HEFR application generally did not produce a winter subsistence flow, the Sabine-Neches BBEST recommends, in the absence of data to indicate otherwise, use of the minimum daily flow value recorded during the winter season so long as it is greater than or equal to the subsistence flow for the summer season at each reference gage location.

Analysis of available hydrologic, biologic, geomorphic, and water quality data; and the exercise of best professional judgment, suggest that recommended subsistence flows will provide aquatic habitat, longitudinal connectivity, dissolved oxygen, and temperature sufficient to ensure survival of endemic species for transient periods. Active data collection and monitoring under subsistence flow conditions is recommended to more quantitatively assess the potential effects of extended periods of subsistence flows on native species.

It is the consensus of the Sabine-Neches BBEST that translation of seasonal subsistence flows into environmental flow standards and permit conditions should not result in more frequent occurrence of flows less than the recommended seasonal subsistence values as a result of the issuance of new surface water appropriations or amendments.

6.1.2.2 Base Flows

Seasonal base flow values for dry, average, and wet conditions were calculated using default HEFR application assumptions as the respective 25th percentile, median, and 75th percentile base flow values for each season. Resulting base flow values were compared to geographically proximate water quality sampling data maintained by TCEQ. Frequent violations of TSWQS criteria for dissolved oxygen and temperature have not occurred and would not be expected to occur at the statistically-derived base flow values.

Analysis of available hydrologic, biologic, geomorphic, and water quality data; and the exercise of best professional judgment, suggest that recommended base flows will provide variable flow conditions, suitable and diverse aquatic habitat, longitudinal connectivity, soil moisture, and water quality sufficient to sustain native species for extended periods.

The Sabine-Neches BBEST recognizes under implementation of these initial environmental flow thresholds for seasonal base flows, there would be water available for human uses (see analysis below). Our recommended base-flow thresholds allow for diversion and storage of water at all flow levels exceeding the base flow threshold as determined for a given condition (dry, average, wet). Thus, there may be extensive periods when flows are less than the historical levels associated with base-flow types of conditions. Also, because variation in rainfall and surface runoff results in natural flow variability in rivers of the Northern Gulf of Mexico Coastal Plains, periods of low flow during drought will cause flows to fall below the base flow threshold for the dry condition (discussed above under Section 6.1.2.1 Subsistence Flows). However, the implication of an environmental base-flow recommendation is that flows lower than these thresholds should not be the *direct* result of issuance of new surface water appropriations or amendments except under dry hydrologic conditions. ***The Sabine-Neches BBEST has proposed base-flow thresholds for environmental protection based on current scientific understanding of fluvial and estuarine ecosystems and the best data, studies, and interpretations available at this time. It is anticipated that as new studies and monitoring information become available, these base flow thresholds may be revised.***

6.1.2.3 Pulse Flows

Peak flow rates for high flow pulses with frequencies of two (2) per season and one (1) per season were calculated using the frequency-based method in HEFR. All recommended peak flow rates are limited to the Overbank Threshold identified in FNI HEFR Memo Table 2 (FNI 2009b) unless NWS data from FNI HEFR memo Table 3 (FNI 2009b) indicates bankfull or flooding conditions at a lower flow. Pulse durations were derived by the default (ln-ln) regression method in HEFR. Pulse volumes were derived by the default (quadratic) regression method in HEFR for reference gage locations where reasonable values were

obtained for all seasons. Pulse volumes for all seasons at Ruliff and Evadale, however, were derived by the alternative (ln-ln) regression method. Similarly, the volume for the summer pulse with a frequency of 2 per season at Rockland was derived by the alternative (ln-ln) regression method.

Analysis of available hydrologic, biologic, geomorphic, and water quality data; and the exercise of best professional judgment, suggest that recommended pulses will provide high in-channel flows of short duration, recruitment events for organisms, lateral connectivity, channel and substrate maintenance, limitation of upland vegetation encroachment into riparian zones, and in-channel water quality restoration after prolonged low flow periods as necessary for long-term support of a sound ecological environment.

The Sabine-Neches BBEST understands that translation of seasonal pulse flows of specified frequencies into environmental flow standards and permit conditions may result in less frequent occurrence of high flow pulses as a result of the issuance of new surface water appropriations or amendments. Hence, the Sabine-Neches BBEST has derived recommended high flow pulses on the basis of historical seasonal frequencies and analysis of ecological processes associated with high flow pulses, but recognizes and accepts that the ultimate attainment frequency associated with each seasonal pulse event within the flow regime will often be less than that based on the historical frequency of occurrence derived by HEFR7.1 and shown in Figure 23 through Figure 34. Natural climatic variation will determine that the environmental flow targets for high flow pulses frequently will not be met. Several examples are provided below (Section 6.1.4). ***The Sabine-Neches BBEST recognizes such reductions in high flow pulses will be a consequence of the interaction between water use and natural variation in precipitation. The Sabine-Neches BBEST views these reductions as an acceptable environmental risk at this time and accepts that they are subject to review as new studies and information become available.***

6.1.2.4 Overbank Flows

Peak flow rates for overbank flow events with a frequency of one (1) per two (2) years were calculated using the frequency-based method in HEFR for all reference gage locations as shown in Figure 23 through Figure 34. Overbank event durations were derived by the default (ln-ln) regression method in HEFR. Overbank event volumes were derived by the default (quadratic) regression method in HEFR. On the basis of research conducted by NWF (Appendix XVII), overbank events with a frequency of one (1) per two (2) years were replaced with events having a frequency of one (1) per year at the Bon Wier, Ruliff, and Evadale reference gage locations as these more frequent events are of sufficient magnitude to exceed the bankfull condition and provide for substantial inundation of riparian bottomland hardwood areas.

Analysis of available hydrologic, biologic, geomorphic, and water quality data; and the exercise of best professional judgment, suggest that overbank flows will provide high flows exceeding channel capacity, life phase cues for organisms, riparian vegetation diversity maintenance, conditions conducive to seedling development, floodplain connectivity,

lateral channel movement, floodplain maintenance, recharge of floodplain water table, flushing of organic material into the channel, nutrient deposition in the floodplain, and restoration of water quality in isolated floodplain water bodies as necessary for long-term support of a sound ecological environment. ***Overbank flows may, however, cause extensive damage to private property and endanger the public. Therefore, the Sabine-Neches BBEST recognizes the ecological benefits of these events, but cannot recommend that such events be produced. Hence, the Sabine-Neches BBEST does not recommend that overbank flows be included as part of an environmental flow standard or as future permit conditions due to concerns associated with flooding and liability.***

6.1.3 Definition of Hydrologic Condition (Wet/Average/Dry)

The Sabine-Neches BBEST considered instantaneous or cumulative flow, Palmer Drought Severity Indices, and reservoir storage as potential means of defining hydrologic conditions. Additional information regarding each method is available in Attachment B to FNI's September 17, 2009 memorandum regarding Water Availability Analyses (Appendix XI). Ultimately, the Sabine-Neches BBEST selected reservoir storage as the recommended means of defining hydrologic conditions as it provides recognition of drought persistence in the contexts both natural variability and water supply operations.

Hydrologic condition at any specific location is defined on the basis of cumulative water supply storage in major reservoirs located upstream and the frequency of occurrence of such storage subject to full use of authorized water rights (TCEQ Run3). Wet conditions are associated with cumulative upstream storage that would be exceeded less than 25 percent of the time during a season. Similarly, dry conditions are associated with cumulative upstream storage that would be exceeded more than 75 percent of the time during a season. Average conditions would apply at times when neither wet nor dry conditions are applicable. For the purposes of defining hydrologic conditions, only major reservoirs from which a significant component of the firm yield is being used should be considered. Reservoirs supporting steam-electric power generation should not be considered for definition of hydrologic conditions. ***The Sabine-Neches BBEST recommends that the applicable hydrologic condition for the entire season be defined on the basis of an assessment of hydrologic condition at the beginning of the first day of the season thereby recognizing both drought persistence and practical operations.***

6.1.4 Example Application of a Flow Regime

An important consideration in providing recommendations of environmental flow regimes is the understanding of how such regimes might be applied to new surface water appropriations. Hence, the Sabine-Neches BBEST's understanding… of potential flow regime application is summarized in the following series of examples for Big Sandy Creek near Big Sandy, Texas in the Sabine River Basin (Figure 23). Successive examples focus on dry, average, and wet hydrologic conditions and move from low to high flow situations subject to each hydrologic condition. Examples are referenced by "Line #" in Table 16, below.

TABLE 16. INSTREAM FLOW REGIME APPLICATION: BIG SANDY CREEK EXAMPLE

Instream Flow Regime Application
Big Sandy Creek Example

Line #	Season	Hydrologic Condition	Seasonal Pulse	Inflow (cfs)	Pass (cfs)	Impound or Divert (cfs)	Line Notes
1	Winter	Dry	n/a	15	15	0	Pass all inflow.
2	Winter	Dry	n/a	25	20	5	Pass seasonal Subsistence flow.
3	Winter	Dry	n/a	75	66	9	Pass Dry Base flow.
4a	Winter	Dry	n/a	400	66	334	Pass Dry Base flow. Seasonal pulse does not apply September through February.
4b	Spring	Dry	0	400	313	87	2 per Season Pulse applies. Pass inflow up to 313 cfs for 13 days or 5062 acft.
4c	Spring	Dry	1	400	30	370	Seasonal pulse met. Pass Dry Base flow.
4d	Summer	Dry	0	75	50	25	2 per Season Pulse applies. Pass inflow up to 50 cfs for 6 days or 671 acft.
4e	Summer	Dry	1	75	14	61	Seasonal pulse met. Pass Dry Base flow.
4f	Fall	Dry	n/a	150	20	130	Pass Dry Base flow. Seasonal pulse does not apply September through February.
5	Winter	Average	n/a	75	75	0	Pass all inflow.
6	Winter	Average	n/a	150	106	44	Pass Average Base flow.
7	Winter	Average	0 or 1	400	358	42	2 per Season Pulse applies. Pass inflow up to 358 cfs for 10 days or 5932 acft.
8	Winter	Average	0 or 1	1000	358	642	Pulse day 2. Pass inflow up to 358 cfs for 9 days or 5932 acft.
9	Winter	Average	2	1000	106	894	Seasonal pulses met. Pass Average Base flow.
10	Winter	Wet	n/a	100	100	0	Pass all inflow.
11	Winter	Wet	0	200	163	37	Pass Wet Base flow.
12	Winter	Wet	0	1000	942	58	1 per Season Pulse applies. Pass inflow up to 942 cfs for 16 days or 14,544 acft.
13	Winter	Wet	0	900	900	0	Pulse day 2. Pass inflow up to 942 cfs for 15 days or 14,544 acft.
14	Winter	Wet	1	1000	163	837	Seasonal pulse met. Pass Wet Base flow.

General Notes

1) Flows passed for senior water rights count towards satisfaction of specified subsistence, base, and pulse flow rates and volumes.
2) The applicable hydrologic condition for the entire season is defined on the basis of assessment of hydrologic condition at the beginning of the first day of the season thereby recognizing both drought persistence and practical operations.
3) Each season is independent of the preceding and subsequent seasons with respect to high flow pulse frequency.
4) Overbank flows may cause extensive damage to private property and endanger the public. Therefore, the S&NBBEST recognizes the ecological benefits of these events, but cannot recommend such events be produced.
5) With regard to recommended high flow pulses in the Spring and Summer seasons under Dry hydrologic conditions, it is noted that the Spring season should be shifted to March through May and the summer season should be shifted to June through August. See Recommendation 8 in Section 2.1.8.

6.1.4.1 Dry Hydrologic Conditions

1. If inflow is less than the seasonal subsistence value, then all inflow must be passed and none impounded or diverted (Line #1).
2. If inflow is less than the seasonal base value and greater than the seasonal subsistence value, then the seasonal subsistence value must be passed and the balance may be impounded or diverted to the extent available subject to senior water rights (Line #2.
3. If inflow is less than the seasonal high flow pulse peak value with a frequency of two (2) per season and greater than the seasonal base value, then the seasonal base value must be passed and the balance may be impounded or diverted to the extent available subject to senior water rights (Line #3).
4. Under dry conditions (extended dry period as defined by the reservoir storage threshold), there is no requirement to pass high flow pulses for the environment during the months of September through February (Lines #4a and #4f, General Note #5). This assumes such occurrences to be naturally rare events based on the historical record.
5. During the months of March through May, if inflow is greater than the Spring seasonal high flow pulse peak value with a frequency of two (2) per season and less than one (1) high flow pulse has occurred within the three month period, then all inflow up to the high flow pulse peak value must be passed until either the recommended duration or volume for the Spring season has been achieved. The balance of inflow may be impounded or diverted to the extent available subject to senior water rights (Line #4b). Each season is independent of the preceding and subsequent seasons with respect to high flow pulse frequency.
6. During the months of March through May, if inflow is greater than the Spring seasonal high flow pulse peak value with a frequency of two (2) per season and one (1) qualifying high flow pulse has occurred within the three month period, then the Spring seasonal base flow value must be passed and the balance may be impounded or diverted to the extent available subject to senior water rights (Line #4c).
7. During the months of June through August, if inflow is greater than the Summer seasonal high flow pulse peak value with a frequency of two (2) per season and less than one (1) high flow pulse event has occurred within the three month period, then all inflow up to the peak value must be passed until either the recommended duration or volume for the Summer season has been achieved. The balance of inflow may be impounded or diverted to the extent available subject to senior water rights (Line #4d). Each season is independent of the preceding and subsequent seasons with respect to high flow pulse frequency.
8. During the months of June through August, if inflow is greater than the Summer seasonal high flow pulse peak value with a frequency of two (2) per season and one (1) qualifying high flow pulse event has occurred within the three month period, then the Summer seasonal base value must be passed and the balance may be impounded or diverted to the extent available subject to senior water rights (Line #4e).

6.1.4.2 Average Hydrologic Conditions

1. If inflow is less than the seasonal base value, then all inflow must be passed and none impounded or diverted (Line #5).
2. If inflow is less than the seasonal peak value with a frequency of two (2) per season and greater than the seasonal base value, then the seasonal base value must be passed and the balance may be impounded or diverted to the extent available subject to senior water rights (Line #6).
3. If inflow is greater than the seasonal high flow pulse peak value with a frequency of two (2) per season and less than two (2) high flow pulses have occurred within the season, then all inflow up to the peak value must be passed until either the recommended duration or volume has been achieved. The balance of inflow may be impounded or diverted to the extent available subject to senior water rights (Lines #7 and #8). Each season is independent of the preceding and subsequent seasons with respect to high flow pulse frequency. If two qualifying high flow pulses do not occur or more than two qualifying high flow pulses do occur within a season, then the recommended high flow pulse frequency for the following season remains two (2) per season.
4. If inflow is greater than the seasonal high flow pulse peak value with a frequency of two (2) per season and two (2) qualifying high flow pulses have occurred within the season, then the seasonal base value must be passed and the balance may be impounded or diverted to the extent available subject to senior water rights (Line #9).

6.1.4.3 Wet Hydrologic Conditions

1. If inflow is less than the seasonal base value, then all inflow must be passed and none impounded or diverted (Line #10).
2. If inflow is less than the seasonal peak value with a frequency of one (1) per season and greater than the seasonal base value, then the seasonal base value must be passed and the balance may be impounded or diverted to the extent available subject to senior water rights (Line #11).
3. If inflow is greater than the seasonal high flow pulse peak value with a frequency of one (1) per season and less than one (1) high flow pulse has occurred within the season, then all inflow up to the peak value must be passed until either the recommended duration or volume has been achieved. The balance of inflow may be impounded or diverted to the extent available subject to senior water rights (Lines #12 and #13). Each season is independent of the preceding and subsequent seasons with respect to high flow pulse frequency. If one qualifying high flow pulse does not occur or more than one qualifying high flow pulse does occur within a season, then the recommended high flow pulse frequency for the following season remains one (1) per season.
4. If inflow is greater than the seasonal high flow pulse peak value with a frequency of one (1) per season and one (1) qualifying high flow pulse has occurred within the season, then the seasonal base value must be passed and the balance may be

impounded or diverted to the extent available subject to senior water rights (Line #14).

6.1.4.4 General Considerations

Under all hydrologic conditions, the Sabine-Neches BBEST recommends that flows passed for senior water rights count towards satisfaction of any specified subsistence, base, and pulse flow rates and volumes. It is anticipated that the level of flow regime complexity incorporated into permit conditions will be consistent with the size of the potential impoundment or diversion project. For example, permit conditions applicable to a major reservoir on the mainstem of a river might be fairly comprehensive, while permit conditions associated with a small run-of-river diversion might include only selected components of the flow regime.

6.1.5 Attainment Frequencies in Flow Regime Application

To the extent that the Sabine and Neches River Basins and the Sabine Lake Estuary presently represents a sound ecological environment, the Sabine-Neches BBEST agrees with the observation in SAC guidance documentation that recommendations based solely on the preservation of the full range of historical flow components (and their historical frequencies of occurrence) logically might be considered to represent the maximum flow quantities supporting a sound ecological environment. Based on review and analysis of currently available information (hydrology, sediment dynamics, water quality, biology), the Sabine-Neches BBEST recognizes that some lesser quantities of flow and/or lesser frequencies of occurrence may be adequate for environmental protection. For example, fluvial sediment transport overlay analyses by TWDB staff acting at the request of the Sabine-Neches BBEST have demonstrated that flows based on full use of all authorized water rights (as compared to historical uses and uses representative of current conditions) are adequate to avoid undesirable channel degradation.

Attainment frequency guidelines may be defined as the recommended frequencies of occurrence of various flow components expressed as a percentage of time that specified flow magnitudes are expected to be equaled or exceeded during specified seasonal or annual time periods with existing and proposed water use activities fully operational. In the context of an environmental flow regime or standard, attainment frequency guidelines can be applicable to base, pulse, and/or overbank flows; however, the need to achieve minimum subsistence flows generally applies all of the time to the extent upstream flows are available.

Some have suggested that it is appropriate to consider the effects of flow regime application under an “infinite infrastructure” scenario. This infinite infrastructure scenario assumes that, once a particular set of environmental flow requirements has been implemented, the only flow remaining in a stream or passing into an estuarine system is the environmental flow prescription itself. In other words, all other streamflow would be fully consumed by existing or proposed water development projects. The occurrence of such flow conditions has been demonstrated to be highly impracticable and essentially impossible, either with full use of existing water rights or with new project development.

Hence, the Sabine-Neches BBEST has focused on the consideration of finite infrastructure examples such as full use of existing water rights or construction and operation of a project similar to the once proposed Big Sandy Reservoir on Big Sandy Creek.

It is important to recognize that both realistic operations of water supply systems and the prior appropriation water rights system play very important roles in the maintenance and reliable occurrence of flows under dry hydrologic conditions to the extent such flows are naturally available. Clearly, the bed and banks delivery of reliable water supplies from large reservoir projects to downstream points of diversion contributes to the maintenance of flow in the intervening stream segment. Under dry hydrologic conditions, such water deliveries may exceed seasonal subsistence and approach seasonal base flows within a recommended flow regime. Similarly, hydropower releases from major reservoirs may contribute at higher levels within a recommended flow regime. The prior appropriation system also functions to ensure the occurrence of instream flows upstream of a major reservoir or run-of-river water right, particularly the critical maintenance of such flows in the range between subsistence and base under dry hydrologic conditions. As major reservoirs are not full and run-of-river rights may not be fully satisfied under dry hydrologic conditions, junior water rights and future applicants for surface water appropriation located upstream would be required to pass inflows for downstream water rights. The Sabine-Neches BBEST believes that it is imperative that TCEQ recognize the contributions of downstream runoff, water deliveries, hydropower releases, and inflow passage to honor downstream water rights towards maintenance of recommended flow regimes supportive of a sound ecological environment.

As a quantitative example to illustrate the translation of a flow regime into permit conditions and demonstrate the potential effects on instream flows and their frequency of occurrence, the Sabine-Neches BBEST has considered construction and long-term operations of the once proposed Big Sandy Creek Reservoir***. It is noted that this reservoir project is not recommended to meet projected needs for additional water supply in the current State Water Plan and that its construction would occur, if ever, well beyond the 50-year state water planning horizon.*** For the purposes of this illustrative example, however, it is assumed that this reservoir would be located at the reference gage location on Big Sandy Creek, have a storage capacity of 76,179 acre-feet at the top of the conservation pool, and be operated with direct diversions of the firm yield subject to application of the recommended flow regime (Figure 23 HEFR Matrix for Big Sandy Creek Near Big Sandy, Texas, page 118) in the form of permit conditions described herein. The assumed simulation period is 1940 through 1996 and seasonal hydrologic conditions are defined by reservoir storage in accordance with Table 4 of FNI's September 17, 2009 memorandum regarding Water Availability Analyses (FNI 2009c).

Figure 19, Figure 20, and Figure 21 illustrate daily regulated flows passing the Big Sandy reference gage location with and without Big Sandy Creek Reservoir operations subject to potential application of the recommended flow regime for selected years representative of

wet (1946), average (1959), and dry (1956) hydrologic conditions, respectively. These figures each include streamflow sequences based on three scenarios:

1. USGS historical gaged streamflow as used to derive the recommended flow regime;
2. Regulated streamflow with Big Sandy Creek Reservoir in operation subject to recommended flow regime application; and
3. Regulated streamflow with Big Sandy Creek Reservoir in operation subject to recommended flow regime application and senior water rights associated with Toledo Bend Reservoir pursuant to a pending application for amendment.

It is assumed, and fundamentally supported by recommended definition, that Toledo Bend Reservoir would not be full under dry hydrologic conditions. Hence, if the pending application for amendment is ultimately approved, all inflows to Big Sandy Creek Reservoir could be passed to honor senior water rights in Toledo Bend Reservoir under dry hydrologic conditions. Finally, Figure 22 shows historical and regulated frequencies of streamflow passing the Big Sandy reference gage location. For perspective, Figure 22 also shows regulated streamflow frequencies assuming “infinite infrastructure” with only flows specified in the flow regime remaining unconsumed.

FIGURE 19. APPLICATION EXAMPLE - PROPOSED BIG SANDY RESERVOIR - WET CONDITIONS

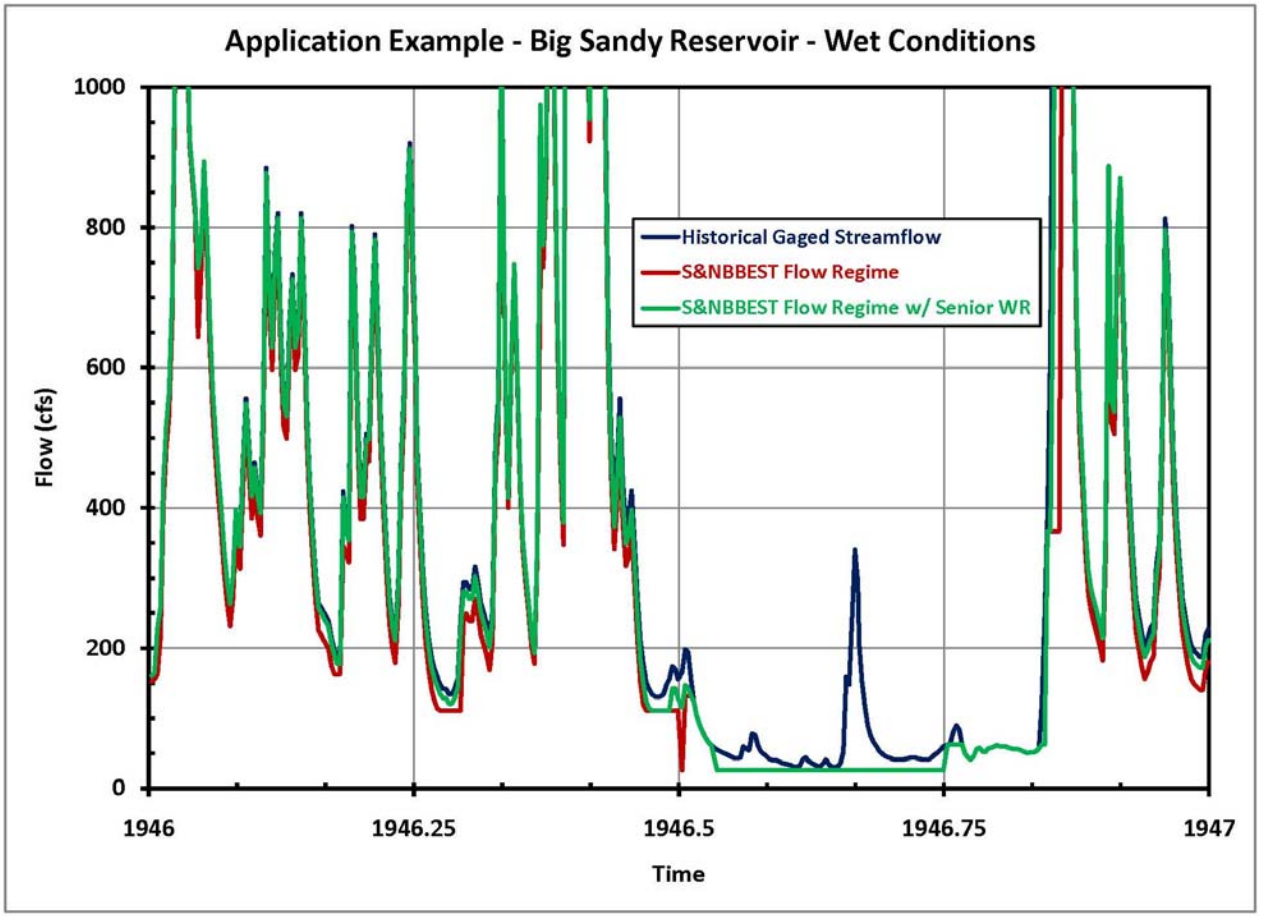


FIGURE 20. APPLICATION EXAMPLE - PROPOSED BIG SANDY RESERVOIR - AVERAGE CONDITIONS

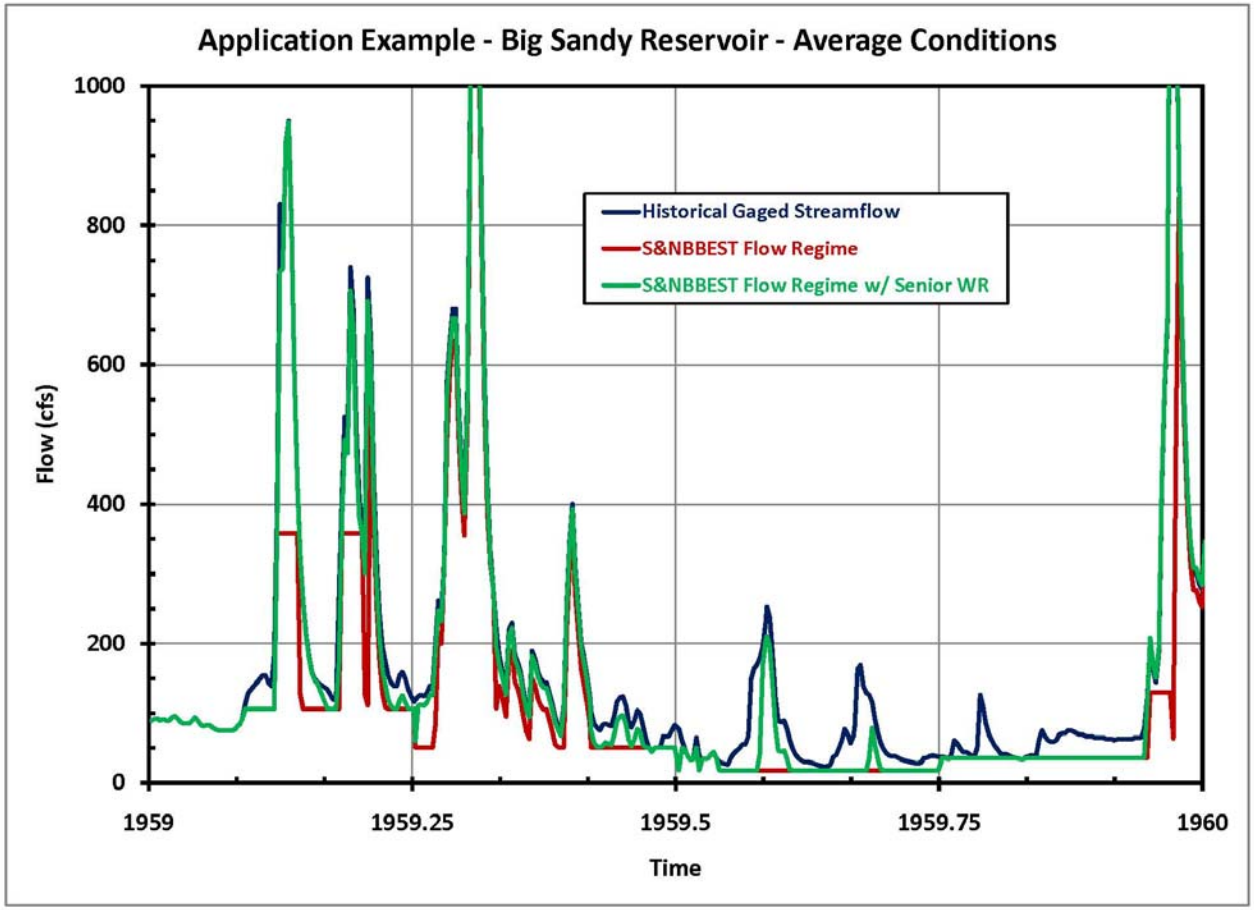


FIGURE 21. APPLICATION EXAMPLE - PROPOSED BIG SANDY RESERVOIR - DRY CONDITIONS

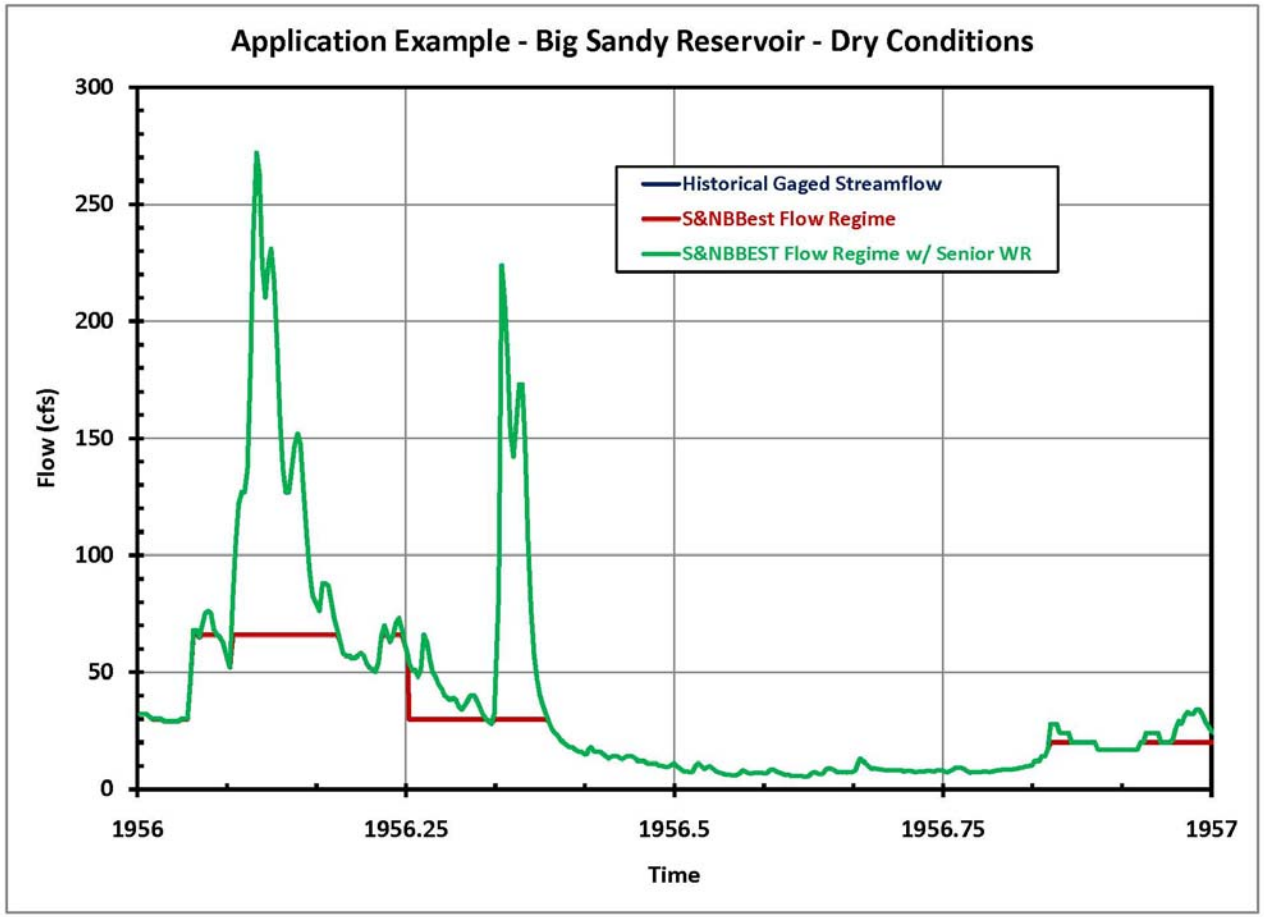
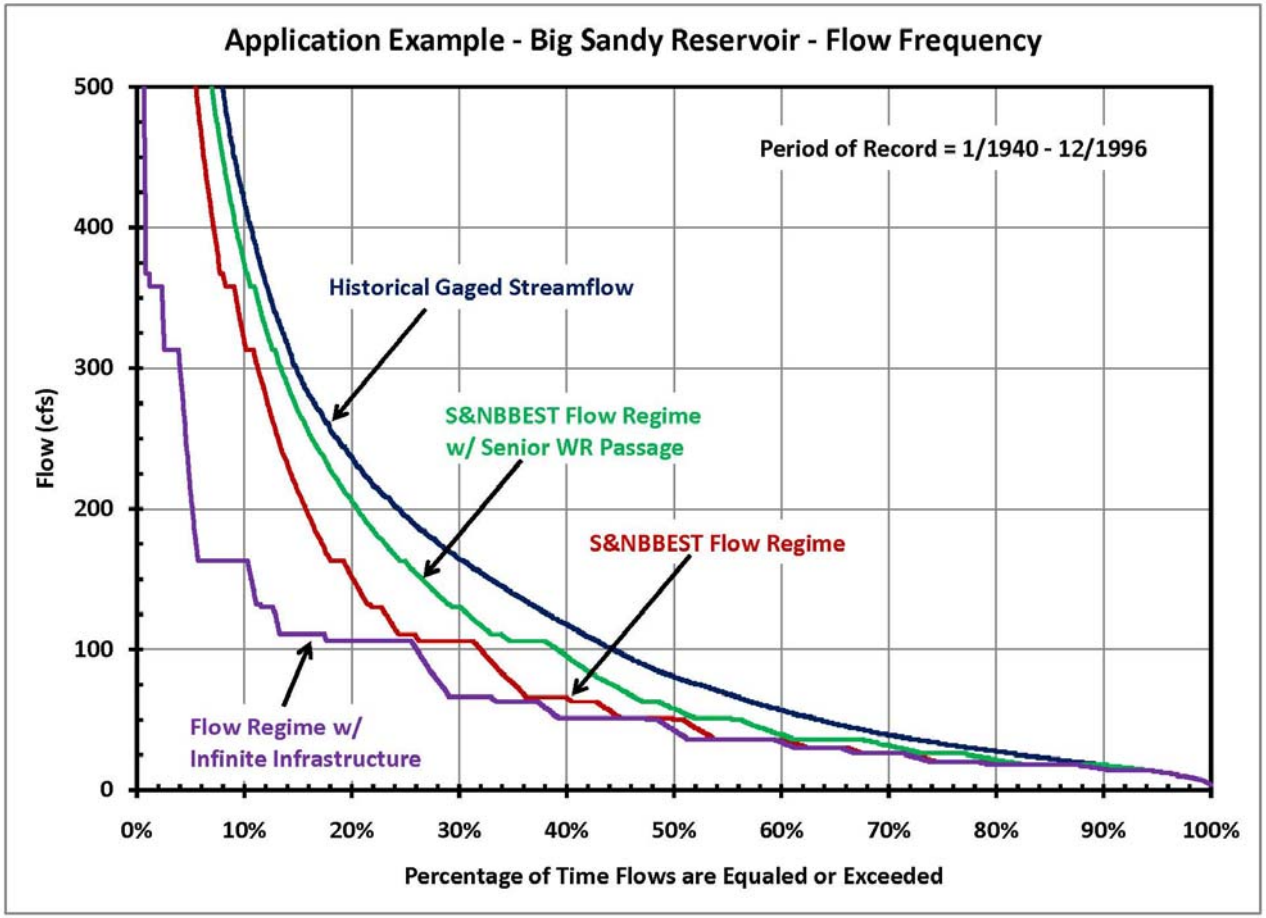


FIGURE 22. APPLICATION - PROPOSED BIG SANDY RESERVOIR - FLOW FREQUENCY



Key observations upon review of Figure 19, Figure 20, Figure 21, and Figure 22 include the following:

1. Leveling of the regulated streamflow frequency curves is apparent at specified flow values (potential permit conditions) within the recommended flow regime.
2. Flows at the seasonal subsistence level occur no more frequently than they did historically in the spring, summer, and fall seasons.
3. Flows at the winter subsistence level occur no more frequently than they did historically if inflow passage for senior water rights is accounted for in accordance with the pending application to amend the water right for Toledo Bend Reservoir.
4. With regard to higher flows expected to be equaled or exceeded about half the time, the assumption of infinite infrastructure represents a condition that is quite different from that with implementation of a major reservoir project on Big Sandy Creek, even though such implementation is far beyond the planning horizon.

The Sabine-Neches BBEST understands that consideration of one example of potential flow regime application does not address all potential ecological concerns at all locations throughout the Sabine and Neches River Basins. This example suggests that flow regime application in accordance with recommendations presented herein will likely support a sound ecological environment at many locations. However, since frequencies of attainment for various flows will be less than observed historically, additional study will be required to ascertain potential environmental effects of these recommendations.

6.1.6 Geographic Interpolation

The Sabine-Neches BBEST has provided flow regime recommendations at streamflow gaging stations located throughout the Sabine and Neches River Basins. These reference locations are, among other things, representative of major streams above and below existing reservoirs as well as tributary streams in the upper and lower portions of each river basin. The Sabine-Neches BBEST recommends that the TCEQ develop appropriate methods for interpolation of flow conditions applicable to future inter-adjacent permits and amendments from reference locations for which flow regimes supporting a sound ecological environment are established. Such methods should include, at a minimum, drainage area adjustments, but may also include consideration of springflow contributions, channel losses, aquifer recharge zones, soil cover complex, and other factors as necessary and appropriate. The Sabine-Neches BBEST understands that the TCEQ has initiated a research project focused on development of methods for geographic interpolation of flow regimes.

6.2 HEFR Output Matrices for Selected Stream Flow Gaging Stations in the Sabine and Neches River Basins

6.2.1 Sabine Basin

6.2.1.1 Big Sandy Creek near Big Sandy, TX

Sub-Basin Description This gage has a minimally controlled watershed with one small recreation reservoir, Lake Winnsboro. The drainage area above the gage is 231 sq-mi, of which 204 sq-mi (88%) is uncontrolled (FNI 2009a). Big Sandy Creek enters the Sabine River at river mile 412.42 (U.S. Army Corps of Engineers 1969)[30]. It is in TCEQ Stream Segment 0514, Big Sandy Creek: from the confluence with the Sabine River in Upshur County to a point 2.6 kilometers (1.6 miles) upstream of SH 11 in Hopkins County. This segment is characterized by low rolling hills with extensive forests and is in the South Central Plains Ecoregion. This area is largely rural with no cities over 5,000 (Sabine River Basin 2008 Summary Report, Sabine River Authority of Texas 2009b).

[30] The official U.S. Geological Survey river miles originate at the mouth of the Sabine River at Sabine Lake (RM 0.0) and terminate at the source (divide) at RM 579.40.

FIGURE 23. HEFR MATRIX FOR BIG SANDY CREEK NEAR BIG SANDY, TEXAS

USGS 08019500 Big Sandy Ck nr Big Sandy, TX

Full Period

Overbank Flows	Qp: 2,930 cfs with Frequency 1 per 2 years Volume is 35,703 Duration is 30			
	Overbank flows may cause extensive damage to private property and endanger the public. Therefore, the Sabine-Neches BBEST recognizes the ecological benefits of these events, but cannot recommend such events be produced.			
High Flow Pulses	Qp: 942 cfs with Frequency 1 per season Volume is 14,544 Duration is 16	Qp: 950 cfs with Frequency 1 per season Volume is 12,852 Duration is 19	Qp: 132 cfs with Frequency 1 per season Volume is 2,054 Duration is 11	Qp: 367 cfs with Frequency 1 per season Volume is 6,055 Duration is 14
	Qp: 358 cfs with Frequency 2 per season Volume is 5,932 Duration is 10	Qp: 313 cfs with Frequency 2 per season Volume is 5,062 Duration is 13	Qp: 50 cfs with Frequency 2 per season Volume is 671 Duration is 6	Qp: 130 cfs with Frequency 2 per season Volume is 2,189 Duration is 9
	Translation of seasonal pulse flows of specified frequencies into environmental flow standards and permit conditions may result in less frequent occurrence of high flow pulses as a result of the issuance of new surface water appropriations or amendments. This reduced frequency of occurrence is deemed an acceptable environmental risk at this time, subject to review as new studies and information become available.			
Base Flows (cfs)	163	111	26	63
	106	51	18	36
	66	30	14	20
	Seasonal base flows represent thresholds for environmental protection based on current scientific understanding of fluvial and estuarine ecosystems. As new studies and monitoring information become available, these base flow thresholds may be revised.			
Subsistence Flows (cfs)	20	9	8	8
	Translation of seasonal subsistence flows into environmental flow standards and permit conditions should not result in more frequent occurrence of flows less than the recommended seasonal subsistence values as a result of the issuance of new surface water appropriations or amendments.			
	Jan, Feb, Mar	Apr, May, Jun	Jul, Aug, Sep	Oct, Nov, Dec
	Winter	Spring	Summer	Fall

6.2.1.2 Sabine River near Gladewater, TX

Sub-Basin Description The drainage for this gage is 2,791 sq-mi, of which 1,404 sq-mi (50%) is uncontrolled (FNI 2009a). This gage is at river mile 397.48 (U.S. Army Corps of Engineers 1969). It is in TCEQ Segment 0506, Sabine River Below Lake Tawakoni: from a point 100 meters (110 yards) downstream of US 271 in Gregg County to Iron Bridge Dam in Rains County.

FIGURE 24. HEFR MATRIX FOR SABINE RIVER NEAR GLADEWATER, TEXAS

USGS 08020000 Sabine Rv nr Gladewater, TX

Full Period

Overbank Flows	Qp: 18,100 cfs with Frequency 1 per 2 years Volume is 483,275 Duration is 44			
	Overbank flows may cause extensive damage to private property and endanger the public. Therefore, the Sabine-Neches BBEST recognizes the ecological benefits of these events, but cannot recommend such events be produced.			
High Flow Pulses	Qp: 5,570 cfs with Frequency 1 per season Volume is 194,743 Duration is 24	Qp: 5,070 cfs with Frequency 1 per season Volume is 140,612 Duration is 25	Qp: 730 cfs with Frequency 1 per season Volume is 13,480 Duration is 17	Qp: 2,240 cfs with Frequency 1 per season Volume is 66,875 Duration is 21
	Qp: 1,880 cfs with Frequency 2 per season Volume is 48,599 Duration is 15	Qp: 1,580 cfs with Frequency 2 per season Volume is 51,150 Duration is 16	Qp: 168 cfs with Frequency 2 per season Volume is 2,752 Duration is 7	Qp: 380 cfs with Frequency 2 per season Volume is 1,098 Duration is 11
	Translation of seasonal pulse flows of specified frequencies into environmental flow standards and permit conditions may result in less frequent occurrence of high flow pulses as a result of the issuance of new surface water appropriations or amendments. This reduced frequency of occurrence is deemed an acceptable environmental risk at this time, subject to review as new studies and information become available.			
Base Flows (cfs)	836	664	78	232
	472	283	46	105
	277	119	34	49
	Seasonal base flows represent thresholds for environmental protection based on current scientific understanding of fluvial and estuarine ecosystems. As new studies and monitoring information become available, these base flow thresholds may be revised.			
Subsistence Flows (cfs)	45	22	14	17
	Translation of seasonal subsistence flows into environmental flow standards and permit conditions should not result in more frequent occurrence of flows less than the recommended seasonal subsistence values as a result of the issuance of new surface water appropriations or amendments.			
	Jan, Feb, Mar	Apr, May, Jun	Jul, Aug, Sep	Oct, Nov, Dec
	Winter	Spring	Summer	Fall

6.2.1.3 Sabine River near Beckville, TX

Sub-Basin Description The drainage area for this gage is 3,589 sq-mi, of which 2,044 sq-mi (57%) is uncontrolled (FNI 2009a). This gage is at river mile 327.00 (U.S. Army Corps of Engineers 1969). It is in TCEQ Segment 0505, Sabine River Above Toledo Bend Reservoir: from a point immediately upstream of the confluence of Murvaul Creek in Panola County to a point 100 meters (110 yards) downstream of US 271 in Gregg County. Segment 0505 is located in the South Central Plains Ecoregion and is characterized by extensive forests and somewhat level terrain. Land use is 57.6% forests, 32.6% agriculture and 13.5% wetlands. There are numerous industries, oilfields and six cities with populations greater than 5,000. There are more than 100 permitted discharges and it contains the highest concentration of population in the Sabine Basin. (Sabine River Authority of Texas 2009b).

FIGURE 25. HEFR MATRIX FOR SABINE RIVER NEAR BECKVILLE, TEXAS

USGS 08022040 Sabine Rv nr Beckville, TX

Full Period

Overbank Flows	Qp: 16,100 cfs with Frequency 1 per 2 years Volume is 541,644 Duration is 45			
	Overbank flows may cause extensive damage to private property and endanger the public. Therefore, the Sabine-Neches BBEST recognizes the ecological benefits of these events, but cannot recommend such events be produced.			
High Flow Pulses	Qp: 7,200 cfs with Frequency 1 per season Volume is 302,174 Duration is 24	Qp: 7,030 cfs with Frequency 1 per season Volume is 220,513 Duration is 27	Qp: 1,120 cfs with Frequency 1 per season Volume is 19,863 Duration is 16	Qp: 3,250 cfs with Frequency 1 per season Volume is 100,717 Duration is 21
	Qp: 2,900 cfs with Frequency 2 per season Volume is 84,998 Duration is 15	Qp: 2,160 cfs with Frequency 2 per season Volume is 72,092 Duration is 15	Qp: 285 cfs with Frequency 2 per season Volume is 5,436 Duration is 6	Qp: 628 cfs with Frequency 2 per season Volume is 7,245 Duration is 9
	Translation of seasonal pulse flows of specified frequencies into environmental flow standards and permit conditions may result in less frequent occurrence of high flow pulses as a result of the issuance of new surface water appropriations or amendments. This reduced frequency of occurrence is deemed an acceptable environmental risk at this time, subject to review as new studies and information become available.			
Base Flows (cfs)	1580	1260	122	356
	807	526	74	141
	438	232	51	75
	Seasonal base flows represent thresholds for environmental protection based on current scientific understanding of fluvial and estuarine ecosystems. As new studies and monitoring information become available, these base flow thresholds may be revised.			
Subsistence Flows (cfs)	66	28	22	22
	Translation of seasonal subsistence flows into environmental flow standards and permit conditions should not result in more frequent occurrence of flows less than the recommended seasonal subsistence values as a result of the issuance of new surface water appropriations or amendments.			
	Jan, Feb, Mar	Apr, May, Jun	Jul, Aug, Sep	Oct, Nov, Dec
	Winter	Spring	Summer	Fall

6.2.1.4 Sabine near Bon Wier, TX

Sub-Basin Description The drainage area for this gage is 8,229 sq-mi, of which 842 sq-mi (10%) is uncontrolled (FNI 2009a). This gage is downstream of Toledo Bend Reservoir (river mile 156.45) at river mile 97.71 (U.S. Army Corps of Engineers 1969). It is in TCEQ Segment 0503, the Sabine River above Caney Creek: from a point immediately upstream of the confluence with Caney Creek in Newton County up to Toledo Bend Dam in Newton County. Segment 0503 is located in the South Central Plains Ecoregion. This region is locally termed the "piney woods." This region of mostly irregular plains represents the western edge of the southern coniferous forest belt. Timber is the main industry in Segment 0503, which is largely rural and only one city has a population greater than 5,000. (Sabine River Authority of Texas 2009b)

In the HEFR analyses for Sabine-Neches BBEST, below, the gage with the most discrepancies was the Bon Wier gage relative to the downstream (59 river miles) Ruliff gage (see Section 6.2.1.6, page 127). In most cases, it is expected that the downstream gage would have higher values than the upstream gage. However, the HEFR values for Bon Wier are almost always significantly higher than Ruliff. The reason for this discrepancy may stem from NWS bankfull and flood stage discharges, but it is unclear based on available information if threshold parameters should be changed and how this would translate into environment needs. The current FERC relicense studies may shed more light on this issue at the Bon Wier gage.

FIGURE 26. HEFR MATRIX FOR SABINE RIVER NEAR BON WIER, TEXAS

USGS 08028500 Sabine Rv nr Bon Wier, TX

Full Period

Overbank Flows	Qp: 28,700 cfs with Frequency 1 per year Volume is 931,140 Duration is 28			
	Overbank flows may cause extensive damage to private property and endanger the public. Therefore, the Sabine-Neches BBEST recognizes the ecological benefits of these events, but cannot recommend such events be produced.			
High Flow Pulses	Qp: 20,600 cfs with Frequency 1 per season Volume is 690,800 Duration is 17	Qp: 16,500 cfs with Frequency 1 per season Volume is 483,992 Duration is 21	Qp: 7,360 cfs with Frequency 1 per season Volume is 175,009 Duration is 14	Qp: 8,960 cfs with Frequency 1 per season Volume is 249,617 Duration is 17
	Qp: 13,800 cfs with Frequency 2 per season Volume is 421,966 Duration is 14	Qp: 6,700 cfs with Frequency 2 per season Volume is 151,163 Duration is 12	Qp: 5,880 cfs with Frequency 2 per season Volume is 132,571 Duration is 13	Qp: 2,590 cfs with Frequency 2 per season Volume is 40,957 Duration is 7
	Translation of seasonal pulse flows of specified frequencies into environmental flow standards and permit conditions may result in less frequent occurrence of high flow pulses as a result of the issuance of new surface water appropriations or amendments. This reduced frequency of occurrence is deemed an acceptable environmental risk at this time, subject to review as new studies and information become available.			
Base Flows (cfs)	15400	6680	1120	1110
	5870	1590	656	615
	1460	857	478	478
	Seasonal base flows represent thresholds for environmental protection based on current scientific understanding of fluvial and estuarine ecosystems. As new studies and monitoring information become available, these base flow thresholds may be revised.			
Subsistence Flows (cfs)	479	279	241	241
	Translation of seasonal subsistence flows into environmental flow standards and permit conditions should not result in more frequent occurrence of flows less than the recommended seasonal subsistence values as a result of the issuance of new surface water appropriations or amendments.			

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Winter			Spring			Summer			Fall		

6.2.1.5 Big Cow Creek near Newton, TX

Sub-Basin Description Big Cow Creek near Newton has very little modification in its watershed and represents nearly natural conditions. The drainage area for this gage is 128 sq-mi, of which 128 sq-mi (100%) is uncontrolled (FNI 2009a). Big Cow Creek enters the Sabine River at river mile 76.00 (U.S. Army Corps of Engineers 1969). This gage is in TCEQ Segment 0513, Big Cow Creek: from the confluence with the Sabine River in Newton County to a point 4.6 Kilometers (2.9 miles) upstream of R 255 in Newton County. Segment 0513 is located in the Western Gulf Coast Plain Ecoregion. This region is characterized by small rolling hills to the north becoming relatively flat to the south. Segment 0513 is largely rural with no major industries or cities and will probably remain largely rural for the near future. (Sabine River Authority of Texas 2009b)

FIGURE 27. BIG COW CREEK NEAR NEWTON, TEXAS

USGS 08029500 Big Cow Crk nr Newton, TX

Full Period

Overbank Flows	Qp: 3,180 cfs with Frequency 1 per 2 years Volume is 18,325 Duration is 17			
	Overbank flows may cause extensive damage to private property and endanger the public. Therefore, the Sabine-Neches BBEST recognizes the ecological benefits of these events, but cannot recommend such events be produced.			
High Flow Pulses	Qp: 1,080 cfs with Frequency 1 per season Volume is 7,387 Duration is 10	Qp: 862 cfs with Frequency 1 per season Volume is 6,075 Duration is 10	Qp: 191 cfs with Frequency 1 per season Volume is 1,447 Duration is 7	Qp: 790 cfs with Frequency 1 per season Volume is 5,038 Duration is 9
	Qp: 693 cfs with Frequency 2 per season Volume is 4,911 Duration is 8	Qp: 350 cfs with Frequency 2 per season Volume is 2,545 Duration is 7	Qp: 109 cfs with Frequency 2 per season Volume is 873 Duration is 5	Qp: 322 cfs with Frequency 2 per season Volume is 2,232 Duration is 7
	Translation of seasonal pulse flows of specified frequencies into environmental flow standards and permit conditions may result in less frequent occurrence of high flow pulses as a result of the issuance of new surface water appropriations or amendments. This reduced frequency of occurrence is deemed an acceptable environmental risk at this time, subject to review as new studies and information become available.			
Base Flows (cfs)	106	74	48	64
	78	52	36	46
	56	38	28	36
	Seasonal base flows represent thresholds for environmental protection based on current scientific understanding of fluvial and estuarine ecosystems. As new studies and monitoring information become available, these base flow thresholds may be revised.			
Subsistence Flows (cfs)	28	20	20	20
	Translation of seasonal subsistence flows into environmental flow standards and permit conditions should not result in more frequent occurrence of flows less than the recommended seasonal subsistence values as a result of the issuance of new surface water appropriations or amendments.			
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

6.2.1.6 SABINE NEAR RULIFF, TX

Sub-Basin Description The drainage area for this gage is 9,329 sq-mi, of which 1,942 sq-mi (21%) is uncontrolled. This gage is downstream of Toledo Bend Reservoir (river mile 156.45) at river mile 40.20 (U.S. Army Corps of Engineers 1969). It is in TCEQ Segment 0502, Sabine River Above Tidal: from West Bluff in Orange County to the confluence with Caney Creek in Newton County. It measures a significant portion of the inflow into Sabine Lake (FNI 2009a). Segment 0502 is located in the Western Gulf Coast Plain Ecoregion. This region is characterized by small rolling hills to the north and becoming relatively flat to the south. Segment 0502 is largely rural with no major industries or cities and will probably remain largely rural for the near future (Sabine River Authority of Texas 2009b).

FIGURE 28. HEFR MATRIX FOR SABINE RIVER NEAR RULIFF, TEXAS

USGS 08030500 Sabine Rv nr Ruliff, TX

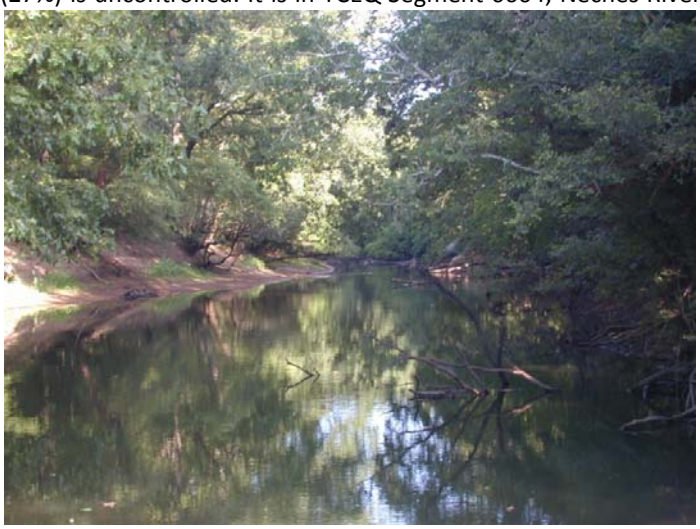
Full Period

Overbank Flows	Qp: 29,000 cfs with Frequency 1 per year Volume is 1,760,073 Duration is 60			
	Overbank flows may cause extensive damage to private property and endanger the public. Therefore, the Sabine-Neches BBEST recognizes the ecological benefits of these events, but cannot recommend such events be produced.			
High Flow Pulses	Qp: 9,880 cfs with Frequency 1 per season Volume is 261,464 Duration is 22	Qp: 9,880 cfs with Frequency 1 per season Volume is 253,851 Duration is 21	Qp: 6,600 cfs with Frequency 1 per season Volume is 157,936 Duration is 19	Qp: 6,030 cfs with Frequency 1 per season Volume is 110,471 Duration is 15
	Qp: 1,600 cfs with Frequency 2 per season Volume is 10,202 Duration is 3	Qp: 3,250 cfs with Frequency 2 per season Volume is 42,883 Duration is 8	Qp: 3,380 cfs with Frequency 2 per season Volume is 54,321 Duration is 11	Qp: 2,020 cfs with Frequency 2 per season Volume is 17,662 Duration is 5
	Translation of seasonal pulse flows of specified frequencies into environmental flow standards and permit conditions may result in less frequent occurrence of high flow pulses as a result of the issuance of new surface water appropriations or amendments. This reduced frequency of occurrence is deemed an acceptable environmental risk at this time, subject to review as new studies and information become available.			
Base Flows (cfs)	5063	3035	1430	1400
	2565	1795	870	970
	1520	1208	670	735
	Seasonal base flows represent thresholds for environmental protection based on current scientific understanding of fluvial and estuarine ecosystems. As new studies and monitoring information become available, these base flow thresholds may be revised.			
Subsistence Flows (cfs)	949	436	396	396
	Translation of seasonal subsistence flows into environmental flow standards and permit conditions should not result in more frequent occurrence of flows less than the recommended seasonal subsistence values as a result of the issuance of new surface water appropriations or amendments.			
	Jan, Feb, Mar	Apr, May, Jun	Jul, Aug, Sep	Oct, Nov, Dec
	Winter	Spring	Summer	Fall

6.2.2 Neches Basin

6.2.2.1 Neches River near Neches, TX

Sub-Basin Description The drainage area for this gage is 1,145 sq-mi, of which 306 sq-mi (27%) is uncontrolled. It is in TCEQ Segment 0604, Neches River Below Lake Palestine. (FNI 2009a) Segment 0604 begins at Blackburn Crossing Dam at Lake Palestine in Anderson/Cherokee County and extends to a point immediately upstream of the confluence of Hopson Mill Creek in Jasper/Tyler County. The uppermost portion of the segment (where this station is located) is characterized by dissected irregular plains with some low, rolling hills consisting of low to moderate gradient streams with sandy and silty substrates. It is part of the Tertiary Uplands of the South Central Plains Ecoregion.[31]



[31] Most of the segment description information for the Neches Basin stations is from the TCEQ, ANRA, and LNVA basin reports.

FIGURE 29. HEFR MATRIX FOR NECHES RIVER AT NECHES, TEXAS

USGS 08032000 Neches Rv at Neches, TX

Full Period

Overbank Flows	Qp: 7,280 cfs with Frequency 1 per 2 years Volume is 172,590 Duration is 38			
	Overbank flows may cause extensive damage to private property and endanger the public. Therefore, the Sabine-Neches BBEST recognizes the ecological benefits of these events, but cannot recommend such events be produced.			
High Flow Pulses	Qp: 1,370 cfs with Frequency 1 per season Volume is 39,549 Duration is 13	Qp: 1,370 cfs with Frequency 1 per season Volume is 31,846 Duration is 15	Qp: 248 cfs with Frequency 1 per season Volume is 4,029 Duration is 7	Qp: 782 cfs with Frequency 1 per season Volume is 19,996 Duration is 12
	Qp: 833 cfs with Frequency 2 per season Volume is 19,104 Duration is 10	Qp: 820 cfs with Frequency 2 per season Volume is 20,405 Duration is 12	Qp: 113 cfs with Frequency 2 per season Volume is 1,339 Duration is 4	Qp: 345 cfs with Frequency 2 per season Volume is 5,391 Duration is 8
	Translation of seasonal pulse flows of specified frequencies into environmental flow standards and permit conditions may result in less frequent occurrence of high flow pulses as a result of the issuance of new surface water appropriations or amendments. This reduced frequency of occurrence is deemed an acceptable environmental risk at this time, subject to review as new studies and information become available.			
Base Flows (cfs)	814	524	108	172
	408	194	73	104
	178	87	42	73
	Seasonal base flows represent thresholds for environmental protection based on current scientific understanding of fluvial and estuarine ecosystems. As new studies and monitoring information become available, these base flow thresholds may be revised.			
Subsistence Flows (cfs)	51	21	12	13
	Translation of seasonal subsistence flows into environmental flow standards and permit conditions should not result in more frequent occurrence of flows less than the recommended seasonal subsistence values as a result of the issuance of new surface water appropriations or amendments.			
	Jan, Feb, Mar	Apr, May, Jun	Jul, Aug, Sep	Oct, Nov, Dec
	Winter	Spring	Summer	Fall

6.2.2.2 Neches River near Rockland, TX

Sub-Basin Description The drainage area for this gage is 3,636 sq-miles, of which 2,763 sq-mi (76%) is uncontrolled (FNI 2009a). It is in TCEQ Segment 0604, Neches River Below Lake Palestine. (FNI 2009a) This station is located in the lower portion of Segment 0604 in the Southern Tertiary Uplands of the South Central Plains Ecoregion. Mixed pine-hardwood forest and longleaf pine forests dominate the region. This area includes public land consisting of numerous State Parks, Recreation Areas, and National Forests.

FIGURE 30. HEFR MATRIX FOR NECHES RIVER AT ROCKLAND, TEXAS

USGS 08033500 Neches Rv at Rockland, TX

Full Period

Overbank Flows	Qp: 18,500 cfs with Frequency 1 per 2 years Volume is 661,717 Duration is 41			
	Overbank flows may cause extensive damage to private property and endanger the public. Therefore, the Sabine-Neches BBEST recognizes the ecological benefits of these events, but cannot recommend such events be produced.			
High Flow Pulses	Qp: 6,910 cfs with Frequency 1 per season Volume is 256,523 Duration is 22	Qp: 5,600 cfs with Frequency 1 per season Volume is 167,866 Duration is 23	Qp: 615 cfs with Frequency 1 per season Volume is 13,365 Duration is 11	Qp: 2,240 cfs with Frequency 1 per season Volume is 72,600 Duration is 17
	Qp: 3,080 cfs with Frequency 2 per season Volume is 82,195 Duration is 14	Qp: 1,720 cfs with Frequency 2 per season Volume is 39,935 Duration is 12	Qp: 195 cfs with Frequency 2 per season Volume is 1,548 Duration is 5	Qp: 515 cfs with Frequency 2 per season Volume is 649 Duration is 8
	Translation of seasonal pulse flows of specified frequencies into environmental flow standards and permit conditions may result in less frequent occurrence of high flow pulses as a result of the issuance of new surface water appropriations or amendments. This reduced frequency of occurrence is deemed an acceptable environmental risk at this time, subject to review as new studies and information become available.			
Base Flows (cfs)	2500	2160	151	381
	1390	1020	88	168
	548	382	61	82
	Seasonal base flows represent thresholds for environmental protection based on current scientific understanding of fluvial and estuarine ecosystems. As new studies and monitoring information become available, these base flow thresholds may be revised.			
Subsistence Flows (cfs)	67	29	21	21
	Translation of seasonal subsistence flows into environmental flow standards and permit conditions should not result in more frequent occurrence of flows less than the recommended seasonal subsistence values as a result of the issuance of new surface water appropriations or amendments.			
	Jan, Feb, Mar	Apr, May, Jun	Jul, Aug, Sep	Oct, Nov, Dec
	Winter	Spring	Summer	Fall

6.2.2.3 Angelina River near Alto, TX

Sub-Basin Description The drainage area for this gage is 1,276 sq-mi, of which 987 sq-mi (77%) is uncontrolled. It is in TCEQ Segment 0611, Angelina River Above Sam Rayburn Reservoir. Segment 0611 of the Angelina River extends from the aqueduct crossing 1.0 kilometer (0.6 mile) upstream of the confluence of Paper Mill Creek in Angelina/Nacogdoches County to the confluence of Barnhardt Creek and Mill Creek at FM 225 in Rusk County. The upper segment is part of the Tertiary Uplands located in the South Central Plains Ecoregion. The landscape is dissected by numerous small streams and primarily consists of rolling hills, gently to moderately sloping.

FIGURE 31. HEFR MATRIX FOR ANGELINA RIVER NEAR ALTO, TEXAS

USGS 08036500 Angelina Rv nr Alto, TX

Full Period

Overbank Flows	Qp: 9,690 cfs with Frequency 1 per 2 years Volume is 204,931 Duration is 29			
	Overbank flows may cause extensive damage to private property and endanger the public. Therefore, the Sabine-Neches BBEST recognizes the ecological benefits of these events, but cannot recommend such events be produced.			
High Flow Pulses	Qp: 3,530 cfs with Frequency 1 per season Volume is 89,332 Duration is 18	Qp: 2,760 cfs with Frequency 1 per season Volume is 59,278 Duration is 20	Qp: 397 cfs with Frequency 1 per season Volume is 7,129 Duration is 13	Qp: 1,500 cfs with Frequency 1 per season Volume is 34,291 Duration is 16
	Qp: 1,620 cfs with Frequency 2 per season Volume is 37,114 Duration is 13	Qp: 1,100 cfs with Frequency 2 per season Volume is 24,117 Duration is 14	Qp: 146 cfs with Frequency 2 per season Volume is 2,632 Duration is 8	Qp: 588 cfs with Frequency 2 per season Volume is 12,038 Duration is 12
	Translation of seasonal pulse flows of specified frequencies into environmental flow standards and permit conditions may result in less frequent occurrence of high flow pulses as a result of the issuance of new surface water appropriations or amendments. This reduced frequency of occurrence is deemed an acceptable environmental risk at this time, subject to review as new studies and information become available.			
Base Flows (cfs)	971	518	69	176
	581	206	48	92
	252	82	36	47
	Seasonal base flows represent thresholds for environmental protection based on current scientific understanding of fluvial and estuarine ecosystems. As new studies and monitoring information become available, these base flow thresholds may be revised.			
Subsistence Flows (cfs)	55	18	11	16
	Translation of seasonal subsistence flows into environmental flow standards and permit conditions should not result in more frequent occurrence of flows less than the recommended seasonal subsistence values as a result of the issuance of new surface water appropriations or amendments.			
	Jan, Feb, Mar	Apr, May, Jun	Jul, Aug, Sep	Oct, Nov, Dec
	Winter	Spring	Summer	Fall

6.2.2.4 Attoyac Bayou near Chireno, TX

Sub-Basin Description The drainage area for this gage is 503 sq-mi, of which 489 sq-mi (97%) is uncontrolled. This gage has measured basically natural flow for most of this period of record and represents a major tributary in the Neches Basin with minimal control. It is in TCEQ Segment 0612, Attoyac Bayou. (FNI 2009a) Segment 0612 is from a point 3.9 kilometers (2.4 miles) downstream of Curry Creek in Nacogdoches/San Augustine County to FM 95 in Rusk County. This station is located in the middle of the segment which is in the Tertiary Uplands portion of the South Central Plains Ecoregion. Land cover is mixed forest, pasture, and pine plantations with timber production, livestock and poultry production as the most common land uses in the region.

FIGURE 32. HEFR MATRIX FOR ATTOYAC BAYOU NEAR CHIRENO, TEXAS

USGS 08038000 Attoyac Bayou nr Chireno, TX

1956-1984 Period

Overbank Flows	Qp: 7,520 cfs with Frequency 1 per 2 years Volume is 91,536 Duration is 27			
	Overbank flows may cause extensive damage to private property and endanger the public. Therefore, the Sabine-Neches BBEST recognizes the ecological benefits of these events, but cannot recommend such events be produced.			
High Flow Pulses	Qp: 1,200 cfs with Frequency 1 per season Volume is 19,704 Duration is 12	Qp: 1,200 cfs with Frequency 1 per season Volume is 18,062 Duration is 15	Qp: 390 cfs with Frequency 1 per season Volume is 5,384 Duration is 12	Qp: 898 cfs with Frequency 1 per season Volume is 16,133 Duration is 12
	Qp: 837 cfs with Frequency 2 per season Volume is 13,871 Duration is 10	Qp: 690 cfs with Frequency 2 per season Volume is 10,618 Duration is 13	Qp: 146 cfs with Frequency 2 per season Volume is 1,888 Duration is 7	Qp: 405 cfs with Frequency 2 per season Volume is 6,353 Duration is 9
	Translation of seasonal pulse flows of specified frequencies into environmental flow standards and permit conditions may result in less frequent occurrence of high flow pulses as a result of the issuance of new surface water appropriations or amendments. This reduced frequency of occurrence is deemed an acceptable environmental risk at this time, subject to review as new studies and information become available.			
Base Flows (cfs)	339	178	48	122
	188	96	28	65
	107	49	20	34
	Seasonal base flows represent thresholds for environmental protection based on current scientific understanding of fluvial and estuarine ecosystems. As new studies and monitoring information become available, these base flow thresholds may be revised.			
Subsistence Flows (cfs)	29	10	10	10
	Translation of seasonal subsistence flows into environmental flow standards and permit conditions should not result in more frequent occurrence of flows less than the recommended seasonal subsistence values as a result of the issuance of new surface water appropriations or amendments.			
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

6.2.2.5 Neches River at Evadale, TX

Sub-Basin Description The drainage area for this gage is 7,951 sq-mi, of which 378 sq-mi (5%) is uncontrolled. The Evadale gage is downstream of the Sam Rayburn/B.A. Steinhagen reservoir system and measures a significant portion of the inflow into Sabine Lake. It is in TCEQ Segment 0602, Neches River Below BA Steinhagen Lk (FNI 2009a). Segment 0602 is from the Neches River Saltwater Barrier in Jefferson/Orange County to the Town Bluff Dam in Jasper/Tyler County. The segment is primarily located in the Flatwoods portion of the South Central Plains Ecoregion. The segment is characterized by flat plains and low gradient streams with sandy and silty substrates. Five units of the Big Thicket National Preserve are located within the segment. Land uses include timber production, oil and gas production, and some pasture and cattle production.

FIGURE 33. HEFR MATRIX FOR NECHES RIVER AT EVADALE, TEXAS

USGS 08041000 Neches Rv at Evadale, TX

Full Period

Overbank Flows	Qp: 19,900 cfs with Frequency 1 per year Volume is 812,910 Duration is 37			
	Overbank flows may cause extensive damage to private property and endanger the public. Therefore, the Sabine-Neches BBEST recognizes the ecological benefits of these events, but cannot recommend such events be produced.			
High Flow Pulses	Qp: 8,700 cfs with Frequency 1 per season Volume is 246,099 Duration is 22	Qp: 8,700 cfs with Frequency 1 per season Volume is 246,099 Duration is 22	Qp: 3,680 cfs with Frequency 1 per season Volume is 69,561 Duration is 13	Qp: 4,160 cfs with Frequency 1 per season Volume is 71,531 Duration is 13
	Qp: 2,020 cfs with Frequency 2 per season Volume is 20,920 Duration is 6	Qp: 3,830 cfs with Frequency 2 per season Volume is 68,784 Duration is 12	Qp: 1,540 cfs with Frequency 2 per season Volume is 21,605 Duration is 9	Qp: 1,570 cfs with Frequency 2 per season Volume is 17,815 Duration is 7
	Translation of seasonal pulse flows of specified frequencies into environmental flow standards and permit conditions may result in less frequent occurrence of high flow pulses as a result of the issuance of new surface water appropriations or amendments. This reduced frequency of occurrence is deemed an acceptable environmental risk at this time, subject to review as new studies and information become available.			
Base Flows (cfs)	4988	3960	3230	2730
	2635	3210	2250	1570
	1750	1640	527	465
	Seasonal base flows represent thresholds for environmental protection based on current scientific understanding of fluvial and estuarine ecosystems. As new studies and monitoring information become available, these base flow thresholds may be revised.			
Subsistence Flows (cfs)	228	266	228	228
	Translation of seasonal subsistence flows into environmental flow standards and permit conditions should not result in more frequent occurrence of flows less than the recommended seasonal subsistence values as a result of the issuance of new surface water appropriations or amendments.			
	Jan, Feb, Mar	Apr, May, Jun	Jul, Aug, Sep	Oct, Nov, Dec
	Winter	Spring	Summer	Fall

6.2.2.6 VILLAGE CREEK NEAR KOUNTZE, TX

Sub-Basin Description The drainage area for this gage is 860 sq-mi, of which 860 sq-mi (100%) is uncontrolled. This gage is unaffected by hydropower and measures a significant portion of the inflow into Sabine Lake. It is in TCEQ Segment 0608, Village Creek (FNI 2009a). Segment 0608 is from the confluence with the Neches River in Hardin County to the confluence of Big Sandy Creek and Kimball Creek in Hardin County. The segment is located in the Flatwoods and Southern Tertiary Uplands of the South Central Plains Ecoregion. Land uses include timber production, oil and gas production, pasture and cattle production, recreation, and wildlife habitat.

FIGURE 34. HEFR MATRIX FOR VILLAGE CREEK NEAR KOUNTZE, TEXAS

USGS 08041500 Village Crk nr Kountze, TX

Full Period

Overbank Flows	Qp: 12,400 cfs with Frequency 1 per 2 years Volume is 170,313 Duration is 29			
	Overbank flows may cause extensive damage to private property and endanger the public. Therefore, the Sabine-Neches BBEST recognizes the ecological benefits of these events, but cannot recommend such events be produced.			
High Flow Pulses	Qp: 2,070 cfs with Frequency 1 per season Volume is 38,134 Duration is 13	Qp: 2,070 cfs with Frequency 1 per season Volume is 31,650 Duration is 15	Qp: 814 cfs with Frequency 1 per season Volume is 11,418 Duration is 13	Qp: 2,070 cfs with Frequency 1 per season Volume is 31,143 Duration is 13
	Qp: 2,010 cfs with Frequency 2 per season Volume is 36,927 Duration is 13	Qp: 1,380 cfs with Frequency 2 per season Volume is 23,093 Duration is 13	Qp: 341 cfs with Frequency 2 per season Volume is 6,159 Duration is 8	Qp: 712 cfs with Frequency 2 per season Volume is 11,426 Duration is 9
	Translation of seasonal pulse flows of specified frequencies into environmental flow standards and permit conditions may result in less frequent occurrence of high flow pulses as a result of the issuance of new surface water appropriations or amendments. This reduced frequency of occurrence is deemed an acceptable environmental risk at this time, subject to review as new studies and information become available.			
Base Flows (cfs)	672	335	135	236
	424	189	91	138
	240	106	70	89
	Seasonal base flows represent thresholds for environmental protection based on current scientific understanding of fluvial and estuarine ecosystems. As new studies and monitoring information become available, these base flow thresholds may be revised.			
Subsistence Flows (cfs)	83	49	41	41
	Translation of seasonal subsistence flows into environmental flow standards and permit conditions should not result in more frequent occurrence of flows less than the recommended seasonal subsistence values as a result of the issuance of new surface water appropriations or amendments.			
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

6.2.3 Sabine-Neches Estuary (Sabine Lake)

6.2.3.1 Estuary Description

Numerous man-made alterations have influenced the current ecological condition in the Sabine-Neches Estuary and the lower tidal reaches of the Sabine and Neches Rivers. These systems are generally sound, exhibiting good overall water quality and diverse fish and wildlife communities (Tatum 2009). The Sabine-Neches Estuary receives more fresh water than all other estuaries on the Texas Gulf Coast (see Table 17, page 143) and provides enough fresh water to Sabine Lake for the focal species studied there (NWF 2009). Sediment transport and concentration are within a range that is indicative of a sound ecological environment (Section 5.3, page 86). However, navigation channels and marsh canals are limiting the effectiveness of these fresh water inflows and sediment loads (Boesch, Josselyn et al. 1994, and references therein). See also Section 0 ***This page intentionally blank***

Estuary History (page 30), Section 5.2.1 Fluvial Ecosystem Realm (page 62), and Figure 5 Sabine and Neches Rivers and Sabine-Neches Estuary (Sabine Lake) (page 25).

The Sabine-Neches BBEST considered information presented indicating the Sabine-Neches Estuary has an uncommonly large volume of freshwater inflows applied to its relatively small size (Table 17, below). The SAC "Report on Water for Environmental Flows" (Science Advisory Committee 2004) provided the following summary statement and data table for the Sabine-Neches Estuary (Section 4.3.1, page 4-5):

> *Sabine Lake, a lagoonal embayment, which encompasses the estuaries of the Neches and Sabine Rivers, is located on the state line with Louisiana, receives the highest inflow per unit volume of the Texas bays, and has abundant freshwater marshes around its periphery. Salinities generally remain low and in many areas promote the growth of plants that thrive in freshwater. The Salt Bayou marsh complex, where ducks, juvenile shrimp, and fish thrive, contains over 60,000 acres of valuable habitat. Many of these intermediate marshes in the Sabine Lake system have been damaged or lost due to saltwater intrusion resulting from ship channels, brine disposal from historic oilfield exploration and production, and relative sea level rise. Extensive marsh restoration efforts are ongoing around Sabine Lake. The pending deepening and widening of the Sabine-Neches Waterway and continuing relative sea level rise will result in more saltwater entering the bay from the Gulf with unknown consequences to the health of the bay and its freshwater marshes.*

TABLE 17. SUMMARY INFORMATION FOR MAJOR TEXAS ESTUARIES

Bay	Surface Area (acres)	Drainage Area as % of Texas	Drainage Area (sq. miles)	Average Annual Freshwater Inflow (acre-feet)	Average Salinity ppt (a)	Number Of Fish Species (b)
Sabine Lake	60,000	7	18,000	14,000,000	5	115
Galveston Bay	350,000	12	33,000	10,000,000	15	163
Matagorda Bay	270,000	16	44,000	3,100,000	20	181
San Antonio Bay	130,000	4	11,000	2,300,000	15	180
Aransas-Copano Bay	130,000	1	2,700	440,000	15	174
Corpus Christi Bay	120,000	6	17,000	600,000	30	187
Laguna Madre	370,000	4	10,000	610,000	35	192

(a) Orlando, et al, 1993—Average salinities have been rounded to the nearest 5 ppt.
(b) Texas Parks and Wildlife Department Coastal Fisheries monitoring data from 1977 to 1997.

6.2.3.2 SAC Guidance on Modeling Inflow Recommendations to the Sabine-Neches Estuary

The SAC provides guidance on some methods that were reviewed for possible application in recommending inflows to meet needs of an estuarine environment, specifically, in the Sabine-Neches Study Area case, for the Sabine-Neches Estuary. Three such methods include the State Methodology (which was used by the State to develop recommendations for inflows and is discussed in more detail in Section 5.2 Biology (Ecological Review), page 62 and Appendix XIII), the Salinity zone approach (discussed below), and the HEFR analyses (discussed below). According to "Methodologies for Establishing a Freshwater Inflow Regime for Texas Estuaries" (SAC 2009d):

> *The salinity-zone approach assesses the suitability of the distribution of salinity within an estuary for a specific organism. … It therefore is a combination of salinity-preference/tolerance limits and salinity mapping, and requires data depicting both classes of information. … Its novelty is in the geographical display of the salinity information within the estuary in a form that is relevant to the organism of concern, … An alternative is to employ the predictions of salinity from a hydrodynamic/ salinity-transport model at a specified inflow regime.*

Strengths of the salinity zone approach

- Provides quantitative measure of the extent of the desirable salinity range within the estuary;
- Is not as sensitive to minor variations in inflow and associated isohaline locations;

- Allows capability to combine salinity zone with other geographical features of the estuary, e.g. shallow-water zones, marshes, etc.; and
- Affords graphic display capability to easily communicate results.

Weaknesses of the salinity zone approach

- Is dependent upon the accuracy with which isohaline patterns may be delineated.
- In the case of the TPWD verification analysis, is based upon TxBLEND-generated isohalines, which is not yet a well-validated model. (Note that the calibration results support the use of TxBLEND for this purpose, validation of the model is in progress, and that other models could equally well be used.)

The salinity zone approach is the basis for much of the work done in the NWF study of *R. cuneata* and other species Study (Appendix XVI). The bottom line from the NWF study was that some species such as blue crab, oysters, and *R. cuneata*, could have increased suitability indices under average conditions but some concerns were expressed for marsh species (recognizing open water modeled salinities were used for marsh species habitat) and for some of the species under subsistence flow conditions. It is also of note that subsistence flows at the time of the NWF analysis were later adjusted from a single, year-round value, to seasonal values, which are expected to improve subsistence flow conditions that were modeled in the NWF study. Furthermore, the NWF study did not include passage of seasonal base flows under dry hydrologic conditions.

The SAC recognized the use of HEFR as an estuary inflows recommendation tool and provided some insight into its utility and some situations where it might not be fully effective (SAC 2009d):

Strengths of HEFR include

- Hydrologic data are relatively robust and consistent at multiple locations, compared to other potential datasets. HEFR shares this strength with other hydrologic methods;
- Hydrology has been considered the master variable in regards to environmental instream flows and may also be considered a very important variable with regards to estuarine inflows. HEFR shares this strength with other hydrologic methods.
- HEFR is computationally efficient, allowing for repeated tests and exploratory analyses;
- There is significant flexibility in setting parameters to parse the hydrograph as well as summary statistics of the flow regime components;
- HEFR outputs have the same format as expected results from the TIFP studies;
- HEFR provides an initial set of recommendations that reflect key aspects of the natural flow regime including multiple flow components and hydrologic conditions (Poff, Allan et al. 1997).

Weaknesses of HEFR include

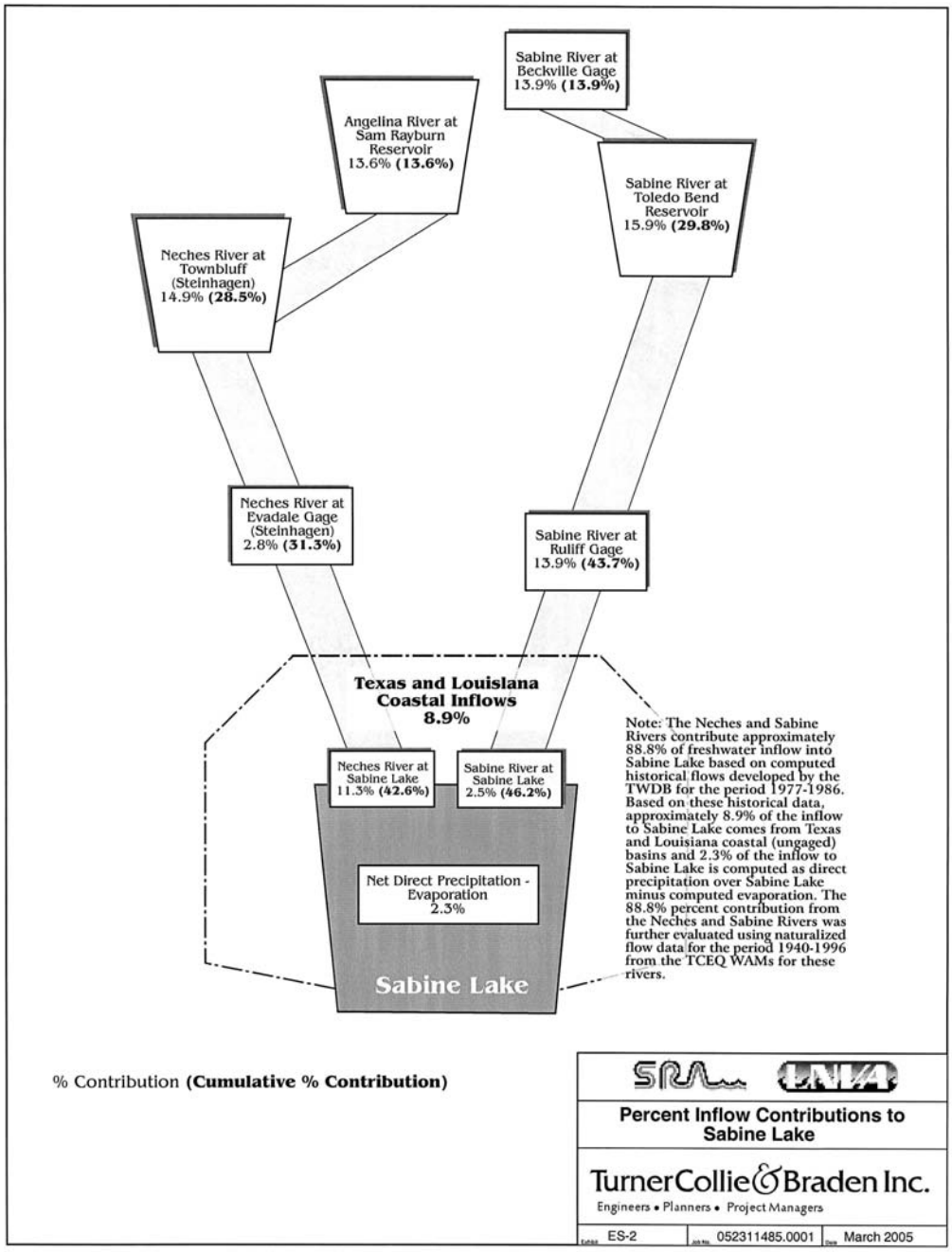
- HEFR is largely designed to mirror some fraction of historical hydrology and is not based on a defined flow alteration - ecological response relationship. In a similar vein, HEFR has not been validated against biological, geomorphological, and water quality data. HEFR shares this weakness with other hydrologic methods.
- HEFR is not suitable where hydrologic data are lacking and cannot be synthesized. HEFR shares this weakness with other hydrologic methods.

- There is no track record of application of HEFR, especially in an estuary setting, and there are few precedents for some of the decisions that must be made.
- HEFR would not provide useful results in minor bays or lagoons with little inflow.

The HEFR analysis methodology was used by the Sabine-Neches BBEST in its inflows recommendations. The Sabine-Neches BBEST recognized ongoing work in Sabine Lake and the surrounding marshes towards a goal to minimize the impacts of manmade saltwater intrusion routes into the marshes (discussed more fully in Section 0 ***This page intentionally blank***

Estuary History, page 30) and chose to recommend HEFR inflows from the most downstream gages as inflows sufficient to meet estuary needs if there was no compelling evidence to indicate otherwise (Figure 35, below).

FIGURE 35. PERCENT INFLOW CONTRIBUTIONS TO SABINE LAKE



6.2.3.3 U.S. Army Corps of Engineers Sabine-Neches Estuary Project

The Sabine-Neches BBEST further recognized ongoing efforts by the USACE in modeling salinity in the estuary as a part of their ongoing considerations for further deepening the Sabine-Neches Ship Canal. The USACE has spent approximately $15 million since 2000 on modeling and feasibility studies for a project that proposes to deepen the channel from forty feet to forty-eight feet plus advanced dredging from the Gulf of Mexico, through Sabine Lake and up to the Port of Beaumont. Much of the USACE work is still in draft documents undergoing edit and review and was not available for reference by the Sabine-Neches BBEST. However, some main points can still be made regarding this substantial work and its application to the Sabine-Neches BBEST's process. Extensive three-dimensional hydro-dynamic salinity modeling with salinity and flow data collected for the project was used to predict salinity changes from the project. In addition, the USACE included increased upstream water demands, return flows, and reservoir storage capacities based on 2007 Texas State Water Plan (Texas Water Development Board. 2007) data and WAM Run 8 in its salinity and inflow model to predict future conditions to year 2060. In addition to freshwater inflow modeling, the USACE modeled predicted future sea level rise and its impacts on salinity. The Sabine-Neches BBEST understands some additional analyses were requested since that meeting and modeling results may change. The USACE is proposing to utilize dredge material to assist in the mitigation and restoration of habitat loss due to incremental salinity increases from the project. Other habitat protection measures being undertaken, for example, in Louisiana, include rock weir control structures to reduce saltwater intrusion into fresh and intermediate marshes through manmade navigation channels. The USACE project is the culmination of nine years of work and is far beyond the scope of analysis the Sabine-Neches BBEST had time or resources to perform. The Sabine-Neches BBEST suggests information from USACE work will soon be available to supplement its knowledge of the estuary and will assist in determination of future assessment needs and evaluation of estuarine habitat mitigation/restoration programs as they relate to adaptive management (a draft report is scheduled to be released for public review on December 17, 2009, and a final report is expected in August 2010).

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7 GLOSSARY OF TERMS AND ACRONYMS

7Q10 - The lowest average stream flow for seven consecutive days with a recurrence interval of 10 years

7Q2 - The lowest average stream flow for seven consecutive days with a recurrence interval of two years, as statistically determined from historical data. In Texas, the minimum flow at which the Surface Water Quality Standards generally apply.

ANRA - Angelina Neches River Authority

Base flows - the component of an instream flow regime that represents normal flow conditions (including variability) between precipitation events. Base flows provide a range of suitable habitat conditions that support the natural biological community of a specific river sub-basin.

BBASC - Bay and Basin Area Stakeholder Committee

BBEST - Bay and Basin Expert Science Team

cfs - cubic feet per second - U.S. customary unit volumetric flow rate, which is equivalent to a volume of 1 cubic foot flowing every second.

CWA - Clean Water Act

Environmental flow analysis - for Senate Bill 3 - application of a scientifically derived process for predicting the response of an ecosystem to changes in instream flows or freshwater inflows.

Environmental flow regimes - for Senate Bill 3 - schedules of flow quantities that reflect seasonal and yearly fluctuations for specific areas of watersheds, and that are shown to be adequate to support a sound ecological environment and to maintain the productivity, extent, and persistence of key aquatic habitats.

Estuary condition - the suite of physical and chemical variables potentially important, either directly or indirectly, to the functioning of an estuary ecosystem.

DEM – Digital Elevation Model

DO - the amount of oxygen gas dissolved in a given quantity of water at a given temperature and atmospheric pressure. Dissolved oxygen is a requirement for the metabolism of aerobic organisms and also influences inorganic chemical reactions. Oxygen dissolves into water by diffusion from the surrounding air, is introduced through rapid movement (aeration), or is produced as a byproduct of photosynthesis.

EFAG - Environmental Flows Advisory Group

EFC - Environmental Flow Components

EPA - Environmental Protection Agency

ETRWPG - East Texas Regional Water Planning Group

FERC - Federal Energy Regulatory Commission

FNI - Freese and Nichols, Inc

GEAA - Greater Edwards Aquifer Alliance

GIWW - Gulf Intracoastal Waterway

Habitat preference - some aspect of the habitat that a species will use out of proportion to its availability.

Habitat requirement - some aspect of the habitat without which a species cannot survive over the long term.

Habitat specialists - species that require specific substrates, current velocities, or depths.

HEFR - Hydrology-Based Environmental Flow Regime - A methodology that provides a relatively flexible computational approach for developing a flow regime matrix that is consistent with the TIFP multi-tiered framework for describing essential flow requirements.

High flow pulses - the component of an instream flow regime that represents short-duration, in-channel, high flow events following storm events. These flows maintain riparian areas and provide lateral connectivity between the river channel and active floodplain. They may also provide life-cycle cues for various species.

HPOR – Historical Period of Record

HUC - Hydrologic Unit Code - The United States is divided and sub-divided into successively smaller hydrologic units which are classified into four levels: regions, sub- regions, accounting units, and cataloging units. The hydrologic units are arranged within each other, from the smallest (cataloging units) to the largest (regions). Each hydrologic unit is identified by a unique code (a HUC) consisting of two to eight digits based on the four levels of classification in the hydrologic unit system.

IFIM - Instream Flow Incremental Methodology

IHA - Indicators of Hydrologic Alteration - a software program that provides useful information for those trying to understand the hydrologic impacts of human activities or trying to develop environmental flow recommendations for water managers. This program was developed by scientists at the Nature Conservancy to facilitate hydrologic analysis in an ecologically- meaningful manner.

ILP - Integrated License Process

Instream flow recommendations - instream flow conditions (i.e., the magnitude and timing of flow events) necessary to maintain an ecologically sound environment in rivers and streams as developed by applying the best available methods. Recommendations are in the form of an instream flow regime that includes subsistence flows, base flows, high flow pulses, and overbank flows.

LDWF - Louisiana Department of Wildlife and Fisheries

ln – Natural Logarithm

LNVA - Lower Neches Valley Authority

Lyons Method - Desk-top method for establishing environmental flows. Specifies 40 percent of the monthly median flow from October to February and 60 percent of the monthly median flow from March to September as minimum flows, with the 60 percent level chosen to be more protective of the riverine ecosystem during the spring and summer periods, considered most critical to the warmwater fishes found in Texas. Default TCEQ method for permitting new, relatively small water rights or for amending certain existing water rights.

MaxC – the State Methodology model solution with the maximum total (annual) catch and satisfies applicable constraints; this inflow lies between MinQ and MaxQ

MaxQ – the maximum inflow which satisfies all the salinity and biological constraints of the State Methodology model

MBFIT - Modified Base Flow Index with Threshold method - hydrographic separation algorithm

MinQ – the minimum inflow that meets the salinity and biological constraints of the State Methodology model

NPDES - National Pollutant Discharge Elimination System

NRC - National Research Council

NWF – National Wildlife Federation

NWS – National Weather Service

Obligate riverine species - requires flowing water habitat for all or part of their life cycle.

Overbank flows - the component of an instream flow regime that represents infrequent, high flow events that exceed the normal channel. These flows maintain riparian areas and provide lateral connectivity between the river channel and active floodplain. They may also provide life-cycle cues for various species.

PAD – Pre-Application Document

PHABSIM - Physical Habitat Simulation (Software)

RWPG - Regional Water Planning Group

SAC - Science Advisory Group

SAM – Sediment Transport Model

SB1 – Senate Bill 1

SB2 - Senate Bill 2

SB3 - Senate Bill 3

Sabine-Neches BBEST - Sabine and Neches Rivers and Sabine Lake Bay and Basin Expert Science Team

SNWW - Sabine Neches Waterway

SRA-LA - Sabine River Authority of Louisiana

SRA-TX - Sabine River Authority of Texas

SRCA - Sabine River Compact Administration

SRC - Sabine River Compact

SSL - Suspended-Sediment Load

Subsistence flows - the component of an instream flow regime that represents infrequent, naturally occurring low flow events that occur for a seasonal period of time. They maintain sufficient water quality and provide sufficient habitat to ensure organism populations capable of recolonizing the river system once normal, base flows return.

TBPJO - Toledo Bend Project Joint Operation

Thalweg - (sometimes called the "valley line") is a line drawn to join the lowest points along the entire length of a streambed or valley in its downward slope, defining its deepest channel. It thus marks the natural direction (the profile) of a watercourse. The thalweg is almost always the line of fastest flow in any river. The term is also sometimes used to refer to a subterranean stream that percolates under the surface and in the same general direction as the surface stream.

TIFP - Texas Instream Flows Program

TCEQ - Texas Commission on Environmental Quality

TCRP – Texas Clean Rivers Program

TPWD - Texas Parks and Wildlife Department

TSWQS - Texas Surface Water Quality Standards

TWC – Texas Water Code

TWDB - Texas Water Development Board

TX-HAT - Texas Hydrologic Assessment Tool

UNRMWA - Upper Neches River Municipal Water Authority

USACE - United States Army Corp of Engineers

USFWS - U.S. Fish and Wildlife Service

USGS - U.S. Geological Survey

WAM - Water Availability Model

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8 ANNOTATED BIBLIOGRAPHY

Acreman, M. and M. J. Dunbar (2004). "Defining environmental river flow requirements- a review." Hydrology and Earth System Sciences **8**: 861-876.

Acreman, M. C., M. J. Dunbar, et al. (2006). Development of Environmental Standards (Water Resources) Stage 3: Environmental Standards. Project WFD48. Scotland & Northern Ireland Forum for Environmental Research. Edinburgh, Scotland**:** 143 pp.

AECOM (2009). Cutoff Bayou Investigation.

The hydrologic flow conditions in the lower Sabine River Basin are complexly interrelated. That is evidenced by the historic and present flow distribution between the Texas and Louisiana channels occurring near Cutoff Bayou. Recent observations indicate that during low flow conditions, distribution appears to favor Louisiana with greater quantities of water. If recently observed trends were to continue, there is potential for flow during normal flow, and especially during low flow, conditions to be essentially eliminated in the Sabine River within Texas below Cutoff Bayou. These conditions may establish the Old River in Louisiana as the sole conveyance channel to the Gulf of Mexico through that reach. The purpose of this preliminary investigation is to determine what engineered measures might be taken to change this trend and to re-establish the historical flow distribution observed at the Cutoff Bayou area.

Annear, T., I. Chisholm, et al. (2004). Instream Flows for Riverine Resource Stewardship, revised edition. Cheyenne, Wyoming. Retrieved November 6, 2009, from http://www.atlasbooks.com/marktplc/00710.htm.

This book provides a detailed description of riverine ecosystem management concepts and strategies for aquatic resource managers and others involved in the determination of instream flow needs and water management. This revised edition is fully illustrated and cites over 600 references to provide a comprehensive treatment of riverine ecology, the role of the public, and legal aspects of river management. The book contains 46 policy statements related to program development and study design and includes descriptions and critical opinions of 34 instream flow methods.

Bart, H. L. (2008). Extraction, analysis, and summary of fish community data from the Sabine River System (Louisiana, Texas). Final Report to Sabine River Authority of Texas. Retrieved November 5, 2009, from ftp://ftp.sratx.org/pub/BBEST/Library/BBEST_027.pdf.

Data from periodic fish surveys of the Sabine River covering a 60 year time period were extracted from the fish collection database of the Tulane University Museum of Natural History.

Biedenharn, D. S., R. R. Copeland, et al. (2000). Effective discharge calculation: A practical guide. U. S. Army and C. o. Engineers. Washington, D.C.

BIO-WEST (2008a). Lower Colorado River, Texas. Instream Flow Guidelines. Colorado River Flow Relationships to Aquatic Habitat and State Threatened Species: Blue Sucker. Technical report prepared for the Lower Colorado River Authority and San Antonio Water System. Round Rock, Texas. Retrieved October 1, 2009, from http://www.lcra.org/library/media/public/docs/lswp/findings/BIO_LSWP_IFguidelines_FINAL.pdf.

This study was developed to assess potential impacts or benefits resulting from the LCRA-SAWS Water Project (LSWP) and address the environmental principles applied to the project.

BIO-WEST (2008b). Preliminary instream flow assessment for the Lower San Antonio River (Interim subsistence and Base-Dry instream flow guidelines development), Report to the San Antonio River Authority.

BIO-WEST (2009a). Estuarine Focal Species Summary Report. Retrieved November 8, 2009, from http://www.sratx.org/BBEST/RecommendationsReport/LinkedDocuments/FINAL_Estuarine_Report_Sabine_BBEST_31Aug09.pdf.

This document provides a summary of ecological information on focal plant and animal species within the Sabine-Neches Estuary (Sabine Lake) to support environmental flow recommendations by the Sabine/Neches Basin and Bay Expert Science Team (BBEST).

BIO-WEST (2009b). Fluvial Focal Species Summary Report. Retrieved November 8, 2009, from http://www.sratx.org/BBEST/RecommendationsReport/LinkedDocuments/FINAL_Fluvial_Report_Sabine_BBEST_31Aug09.pdf.

This document provides a summary of ecological information on focal aquatic and riparian species within the Sabine River and Neches River watersheds to support instream flow recommendations by the Sabine/Neches Basin and Bay Expert Science Team (BBEST).

Boesch, D. F., M. N. Josselyn, et al. (1994). "Scientific assessment of coastal wetland loss, restoration and management in Louisiana." Journal of Coastal Research(Special Issue No. 20).

Bonner, T. and D. T. Runyan (2007). Fish assemblage changes in three Western Gulf Slope drainages. Final Report to the Texas Water Development Board (2205-483-033). Final Report to Sabine River Authority of Texas. Retrieved November 5, 2009, from ftp://ftp.sratx.org/pub/BBEST/Library/BBEST_006.pdf.

Analyzed existing biological data for the Lower Sabine River sub-basin (as well as two other sub-basins in the state) and constructed an annotated species list. Also evaluated changes in the fish assemblage over time.

Dilts, E., P. Leonard, et al. (2005). Development of an Integrated Flow Regime Recommendation for the Cheoah River, N.C. Proceedings of the 2005 Georgia Water Resources Conference, University of Georgia. Retrieved November 3, 2009, from http://www.uga.edu/water/publication/uploads/DiltsE-GWRCpaper.pdf.

Hydrologic pattern and variability are key determinants of aquatic community structure and stability, but instream flow recommendations commonly fail to reflect these critical components of a natural flow regime, focusing instead on provision of static, minimum flows. Restoration of a true, natural flow regime is often not possible given the existing constraints on stream systems and the competing interests of multiple water users. However, sustained biological diversity and ecosystem function are dependent on the maintenance of intra- and interannual flow regimes and natural functions. Providing an integrated flow regime that is patterned on a natural flow regime should therefore be more

ecologically beneficial than other flow regime alternatives that ignore natural hydrologic pattern and variability. The principles of a natural flow regime were applied to the development of an integrated flow regime recommendation for the Cheoah River, North Carolina. The integrated flow regime recommendation consisted of a seasonally variable, aquatic base flow component and a natural-like high flow component, which was characterized by seasonally variable frequency, magnitude, and duration high flow events. The integrated flow regime recommendation was designed to balance the water demands of hydropower generation and reservoir-based recreation, while still achieving resource agency aquatic habitat restoration objectives and providing opportunities for whitewater boating.

Dyson, M., G. Bergkamp, et al., Eds. (2003). The essentials of environmental flows, International Union for Conservation of Nature and Natural Resources. Retrieved November 2, 2009, from http://cmsdata.iucn.org/downloads/flow.pdf.

Environmental Flows Advisory Committee (2006). Final Report. Austin, Texas. Retrieved September 15, 2009, from http://www.twdb.state.tx.us/EnvironmentalFlows/pdfs/REPORT/EFAC_FINAL_REPORT.pdf.

Evans, J. W. and R. L. Noble (1979). "The longitudinal distribution of fishes in an east Texas stream." American Midland Naturalist **101**: 333-343.

FNI (2009a). Analysis of BBEST Stream Gages. Fort Worth, Texas, Freese Nichols, Inc. Retrieved November 8, 2009, from http://www.sratx.org/BBEST/RecommendationsReport/index.html#Topic19.

The Sabine and Neches Rivers and Sabine Lake Bay Basin and Bay Expert Science Team (BBEST) selected six United States Geological Survey (USGS) stream gages in the Sabine River Basin and six USGS stream gages in the Neches River Basin for hydrologic analyses. These gages will serve as the hydrologic basis for flow regime recommendations developed to satisfy the Senate Bill 3 (SB3) environmental flows process. This memorandum describes pertinent data regarding the stream gages, discusses the adequacy of these gages to evaluate flow trends in the Sabine and Neches River Basins and into Sabine Lake, and offers some analyses of flow trends observed at these gages.

FNI (2009b). Hydrology-Based Environmental Flow Regime (HEFR) Analyses for Sabine-Neches Bay and Basin Expert Science Team (BBEST). Fort Worth, Texas, Freese Nichols, Inc. Retrieved November 8, 2009, from http://www.sratx.org/BBEST/RecommendationsReport/index.html#Topic21.

The Senate Bill 3 Science Advisory Committee for Environmental Flows (SAC) developed a draft guidance document Use of Hydrologic Data in the Development of Instream Flow Recommendations for the Environmental Flows Allocation Process and the Hydrology-Based Environmental Flow Regime (HEFR) Methodology to guide the basin advisory groups in developing flow recommendations. One of the options in this document is employing the Hydrology-Based Environmental Flow Regime (HEFR) methodology to determine an environmental flow regime based on historical hydrology. The Sabine Neches Bay and Basin Expert Science Team (BBEST) hired Freese and Nichols, Inc. (FNI) to conduct hydrologic analyses at twelve gages in the Sabine and Neches River Basins and inflows into Sabine Lake, including HEFR analyses.

FNI (2009c). Water Availability Analyses for Sabine-Neches Bay and Basin Expert Science Team (BBEST). Fort Worth, Texas, Freese Nichols, Inc. Retrieved November 8, 2009, from http://www.sratx.org/BBEST/RecommendationsReport/index.html#Topic24.

This memorandum describes an analysis of water available for environmental flows performed by Freese and Nichols, Inc., (FNI) for the Sabine & Neches Rivers and Sabine Lake Bay and Basin Expert Science Team (BBEST). These analyses employed the Texas Commission on Environmental Quality (TCEQ) Water Availability Models (WAM) for the Sabine and Neches River Basins, as modified for use by the Region I Water Planning Group.

Hardy, T. B., C. Addley, et al. (2006). Evaluation of Interim Instream Flow Needs in the lower Klamath River, Phase II, Final Report. Washington D.C., Prepared for: U.S. Department of the Interior**:** 229 pp.

Harrel, R. (2009). Comment on Draft Sabine-Neches BBEST Environmental Flows Recommendations Report. J. W. Tatum.

Howells, R. G., R. W. Neck, et al. (1996). Freshwater Mussels of Texas. Austin, Texas, Texas Parks and Wildlife Press.

This publication provides an introduction to the unionid mussels of Texas with descriptions of each and a general overview of the family, as well as a brief description of other bivalves which may occur in fresh waters of the state.

Kuhn, N. L. and G. Chen (2005). Freshwater Inflow Recommendation for the Sabine Lake Estuary of Texas and Louisiana. Austin, Texas. Retrieved November 6, 2009, from http://midgewater.twdb.state.tx.us/bays_estuaries/Publications/Freshwater%20Inflow%20Recommendation%20for%20the%20Sabine%20Esturary%20of%20Texas%20and%20Louisiana%20-%202005.pdf.

Freshwater inflows are integral to the proper functioning of Texas bays and estuaries. These inflows provide a key source of nutrients and sediments, and also create the salinity gradient within the bay system, which is the defming characteristic of an estuary. Texas Parks and Wildlife Department (TPWD) and the Texas Water Development Board (TWDB) have been charged by the Texas Legislature with determining the freshwater inflows that provide suitable salinity, nutrient and sediment loading regimes (i.e., support a sound estuarine environment) for Texas bays. This report presents the results of the freshwater inflow analysis for the Sabine Lake system.

Kwak, T. J. (1988). "Lateral movement and use of flood plain habitat by fishes of the Kankakee River, Illinois." American Midland Naturalist **120**: 241-249.

Longley, W. L., Ed. (1994). Freshwater Inflows to Texas Bays and Estuaries: Ecological Relationships and Methods for Determination of Needs, Texas Water Development Board. Retrieved September 17, 2009, from http://midgewater.twdb.state.tx.us/bays_estuaries/Publications/FreshwaterInflows-%20Ecological%20Relationships%20and%20Methods%20for%20Determination%20of%20Needs%20-%201994.pdf.

This report integrates the results of recent studies with earlier information to provide a comprehensive overview of the importance of freshwater inflows to Texas estuaries. The report emphasizes the relationship of inflows with the

chemical composition and physical nature of estuarine ecosystems, bay habitat distribution, physiological processes, biological productivity, and abundance of fish and shellfish populations. In addition, the report presents a methodology for determining the amount and timing of beneficial inflows needed to maintain the productivity of economically important fisheries species, and the estuarine life on which they depend. This procedure deals effectively with competing inflow requirements among organisms and includes provisions for achieving management goals for specific estuarine habitats and species.

Maidment, D., P. Montagna, et al. (2005). Scientific Principles for Definition of Environmental Flows. Environmental Flows Conference. Texas State University, San Marcos, Texas. Retrieved September 15, 2009, from http://www.ce.utexas.edu/prof/maidment/nrc/TexasInstream/EnvironmentalFlowsConference/EnvFlowPrinciples.pdf.

The purpose of this memorandum is to describe some scientific principles for the establishment of environmental flow requirements in Texas streams, rivers, bays and estuaries.

Moriarty, L. J. and K. O. Winemiller (1997). "Spatial and temporal variation in fish assemblage structure in Village Creek, Hardin County, Texas." Texas Journal of Science **49**(3): Supplement 85-110.

Morton, R. A. (1996). Geological and Historical Development of Sabine Lake-An Overview. Sabine Lake Conference: Where Texas and Louisiana Come Together. Beaumont, Texas. . Retrieved November 7, 2009, from ftp://ftp.sratx.org/pub/BBEST/Library/SabineLakeConferenceSept1996/.

National Research Council Committee (2005). The Science of Instream Flows: A Review of the Texas Instream Flow Program. Washington, D.C., The National Academies Press. from http://books.nap.edu/catalog.php?record_id=11197.

Three state agencies the Texas Water Development Board (TWDB), the Texas Parks and Wildlife Department (TPWD), and the Texas Commission on Environmental Quality (TCEQ) asked a committee of the National Research Council (NRC) to review the Programmatic Work Plan (PWP) and Technical Overview Document (TOD) that outline the state s instream flow initiative. The committee suggested several changes to the proposed plan, such as establishing clearer goals, modifying the flow chart that outlines the necessary steps for conducting an instream flow study, and provide better linkages between individual studies of biology, hydrology and hydraulics, physical processes, and water quality.

NETRWPG (2006). Regional Water Plan
Region D - North East Texas Regional Water Planning Group. Retrieved September 28, 2009, from http://www.twdb.state.tx.us/RWPG/main-docs/2006RWPindex.asp.

This report gives the results of the Second Round planning process for Region D, one of the regions created to implement Senate Bill One. This region is made up of all or part of 19 counties in northeast Texas, including Bowie, Camp, Cass, Delta, Franklin, Gregg, Harrison, Hopkins, Hunt, Lamar, Marion, Morris, Rains, Red River, Smith, Titus, Upshur, Van Zandt and Wood.

NWF (2009). Salinity Suitability Analyses of Rangia cuneata and Other Characteristic Species and Communities of the Sabine-Neches Estuary in Order to Develop a Freshwater Inflow

Regime. Austin, Texas, National Wildlife Federation. Retrieved November 8, 2009, from http://www.sratx.org/BBEST/RecommendationsReport/LinkedDocuments/NWF-SabNechEstuaryFocalSpeciesAnalyses-103109-fnl.pdf.

The analyses presented herein were designed to support the efforts of the Sabine-Neches BBEST to develop an estuarine inflow regime for the Sabine-Neches Estuary (Sabine Lake). Focus was on a suite of four specific species and two marshland communities, all with well-established and published salinity tolerance (a.k.a. salinity suitability) information.

Opdyke, D. (2009). "HEFR: An Overview, with Emphasis on the Most Important Decision Points, April 28, 2009." Presentation to SB3 Sabine-Neches BBEST. Retrieved November 19, 2009, 2009, from http://www.tceq.state.tx.us/assets/public/permitting/watersupply/water_rights/eflows/20090428_hefrppt.pdf.

Paille, R. (1996). Water Exchange Patterns and Salinity of Marshes Between Calcasieu and Sabine Lakes. Sabine Lake Conference: Where Texas and Louisiana Come Together. Beaumont, Texas. Retrieved November 6, 2009, from ftp://ftp.sratx.org/pub/BBEST/Library/SabineLakeConferenceSept1996/.

The Sabine National Wildlife Refuge is located between Calcasieu and Sabine Lake, midway between the GulfIntracoastal Waterway (GIWW) to the north and the Gulf of Mexico to the south. Salinity of refuge and adjacent marshes has been monitored routinely by refuge personnel since 1966. Water flow patterns were monitored via routine visual observations during 1991 and 1992.

Phillips, J. D. (2003). "Toledo Bend reservoir and geomorphic response in the lower Sabine River." River Research and Applications **19** (2): 137 - 159. Retrieved November 8, 2009, from http://www3.interscience.wiley.com/journal/102523968/abstract?CRETRY=1&SRETRY=0.

Downstream geomorphic responses of stream channels to dams are complex, variable, and difficult to predict, apparently because the effects of local geological, hydrological, and operational details confound and complicate efforts to apply models and generalizations to individual streams. This sort of complex geomorphic response characterizes the Sabine River, along the Texas and Louisiana border, downstream of the Toledo Bend dam and reservoir. Toledo Bend controls the flow of water and essentially prevents the flux of sediment from three-quarters of the drainage basin to the lower Sabine River. Although the channel is scoured immediately downstream of the dam, further downstream there is little evidence of major changes in sediment transport or deposition, sand supply, or channel morphology attributable to the impoundment. Channels are actively shifting, banks are eroding, and sandbars are migrating, but not in any discernibly different way than before the dam was constructed. The Sabine River continues to transport sand downstream, and alluvial floodplains continue to accrete. The relatively small geomorphic response can be attributed to several factors. While dam releases are unnaturally flashy and abrupt on a day-to-day basis, the long-term pattern of releases combined with some downstream smoothing creates a flow regime in the lower basin which mimics the pre-dam regime, at least at monthly and annual time scales. Sediment production within the lower Sabine basin is sufficient to satisfy the river's sediment transport capacity and maintain pre-dam alluvial sedimentation regimes. Toledo Bend reservoir has a capacity: annual inflow ratio of 1.2 and impounds 74% of the Sabine drainage basin, yet there has been minimal geomorphic response in the lower river, which may seem counterintuitive.

However, the complex linked geomorphic processes of discharge, sediment transport and loads, tributary inputs, and channel erosion include interactions which might increase as well as decrease sediment loads. Furthermore, if a stream is transport-limited before impoundment, the reduced sediment supply after damming may have limited impact. Copyright © 2003 John Wiley & Sons, Ltd.

Phillips, J. D. (2007). Geomorphic Equilibrium in Southeast Texas Rivers. Project Report for the Texas Water Development Board and Texas Instream Flow Program, TWDB contract number 0605830636. Lexington, KY. Retrieved November 4, 2009, from http://www.twdb.state.tx.us/RWPG/rpgm_rpts/0605830636_geomorphicEquilibrium.pdf.

This report is based on a study of the geomorphic equilibrium of the coastal plain portions of the Brazos, Trinity, and Sabine Rivers, and of river systems of southeast Texas more generally. River and stream management, assessment, engineering, and classification is often based on concepts of geomorphic equilibrium, and implicit or explicit assumptions that fluvial systems are in, or develop towards, some form of equilibrium. The purpose of this study is to determine the extent to which that is indeed the case in the study area.

Phillips, J. D. and M. C. Slattery (2007). Geomorphic Processes, Controls, and Transition Zones in the Lower Sabine River. Project Report for the Texas Water Development Board and Texas Instream Flow Program, TWDB contract number 0600010595. Retrieved November 4, 2009, from http://www.twdb.state.tx.us/RWPG/rpgm_rpts/0600010595_Sabine.pdf.

This report is based on a cooperative research study of the geomorphology of the Lower Sabine River, Texas (and Louisiana). The study focussed on delineating major geomorphic process zones, identification of major geomorphic controls, and determination the location and primary controls over key “hinge points” or transition zones.

Phillips, J. D. and M. C. Slattery (2006). "Sediment storage, sea level, and sediment delivery to the ocean by coastal plain rivers." Progress in Physical Geography **30**: 513-530.

Poff, N. L., J. D. Allan, et al. (1997). "The Natural Flow Regime: A Paradigm for River Conservation and Restoration." BioScience **47**(11): 769-784. Retrieved November 3, 2009, from http://www.nature.org/initiatives/freshwater/files/natflow.pdf.

The ecological integrity of river ecosystems depends on their natural dynamic character.

Poff, N. L. and J. V. Ward (1989). "Implications of streamflow variability and predictability for lotic community structure: a regional analysis of streamflow patterns." Canadian Journal of Fisheries and Aquatic Sciences **46**(10): 1805-1818. Retrieved November 3, 2009, from http://rydberg.biology.colostate.edu/~poff/Public/poffpubs/Poff1989(CJFAS_flow_var).pdf.

Long-term discharge records (17-81 yr) of 78 streams from across the continental United States were analyzed to develop a general quantitative characterization of streamflow variability and predictability. Based on (1) overall flow variability, (2) flood regime patterns, and (3) extent of intermittency, 11 summary statistics were derived from the entire record for each stream. Using a non hierarchical clustering technique, nine stream types were identified: harsh intermittent, intermittent flashy, intermittent runoff, perennial flashy, perennial runoff, snowmelt, snow + rain, winter rain, and mesic groundwater. Stream groups separated primarily on combined measures of intermittency, flood frequency, flood predictability, and

overall flow predictability, and they showed reasonable geographic affiliation. A conceptual model that incorporates the nine stream clusters in a hierarchical structure is presented. Also, the positions of the 78 streams in a continuous three-dimensional flow space illustrate the wide range of ecologically important hydrologic variability that can constrain ecological and evolutionary processes in streams. Long-term daily streamflow records are a rich source of information with which to evaluate temporal and spatial patterns of lotic environments across many physiographic and ecographic regions. Relative positions of streams in flow space provide a conceptual framework for evaluating a priori the relative importance of abiotic and biotic factors in regulating population and community processes and patterns.

Ravichandran, M., M. Baskaran, et al. (1995). "Geochronology of sediments in the Sabine-Neches estuary, Texas, U.S.A." Chemical Geology **125**: 291-306.

Richter, B. D., J. L. M. A.T. Warner, et al. (2006). "A collaborative and adaptive process for developing environmental flow recommendations." River Research and Applications **22**: 297-318.

Richter, B. D., J. V. Baumgartner, et al. (1996). "A Method for Assessing Hydrologic Alteration Within Ecosystems." Conservation Biology **10**(4): 1163-1174. Retrieved November 3, 2009, from http://www.tufts.edu/water/pdf/iha_meth.pdf.

Hydrologic regimes play a major role in determining the biotic composition, structure, and function of aquatic, wetland, and riparian ecosystems. But human lan and water uses are substantially altering hydrologic regimes around the world. Improved quantitative evaluations of human-induced hydrologic changes are needed to advance research on the biotic implications of hydrologic alteration and to support ecosystem management and restoration plans. We propose a method for assessing the degree of hydrologic alteration attributable to human influence within an ecosystem. This method, referred to as the "Indicators of Hydrologic Alteration," is based upon an analysis of hydrologic data available either from existing measurement points within an ecosystem (such as at stream gauges or wells) or model-generated data. ... This method is intended for use with other ecosystem metrics in inventories of ecosystem integrity, in planning ecosystem management activities, and in setting and measuring progress toward conservation or restoration goals.

Richter, B. D., et al (2003). "Ecologically sustainable water management: managing river flows for ecological integrity." Ecological Applications **13**: 206-224.

Robertson, C. R., S.C. Zeug, and K.O. Winemiller (2008). "Associations between hydrological connectivity and resource partitioning among sympatric gar species (Lepisosteidae) in a Texas river and associated oxbows." Ecology of Freshwater Fish **17**: 119-129.

Robinson, A. T., R. W. Clarkson, et al. (1998). "Dispersal of Larval Fishes in a Regulated River Tributary." Transactions of the American Fisheries Society **127**: 772-786. Retrieved November 3, 2009, from http://afsjournals.org/doi/abs/10.1577/1548-8659(1998)127%3C0772:DOLFIA%3E2.0.CO%3B2.

We investigated longitudinal distributions, nearshore movements, and drift of larval native fishes (humpback chub Gila cypha, speckled dace Rhinichthys osculus, bluehead sucker Catostomus discobolus, and flannelmouth sucker Catostomus

latipinnis) in the Little Colorado River, a tributary to the regulated Colorado River in Grand Canyon, Arizona, to determine spawning sites, larval dispersal patterns, and amount of drift into the mainstem Colorado River. Larval distributions and drift indicated native fishes spawned throughout the terminal 14.2 km of the Little Colorado River. In addition, distribution, drift, and trap data suggest an active component to dispersal for all four native species. Drift of larval native fish was greater near shore than midchannel, and except for speckled dace larvae, which were prone to drift at night, larval native fish did not exhibit diel periodicity in drift. During a 46-d period in 1993, we estimated that over 370,000 native fish larvae drifted out of the Little Colorado River into the Colorado River. Regulated discharge from Glen Canyon Dam has all but eliminated spring–summer ponding of tributary mouths that occurred when ascending flows in the Colorado River coincided with descending and base flows in tributaries; thus, drifting larvae are allowed to pass directly into the Colorado River. Survival of larvae now transported into the Colorado River is probably poor because of perennially cold water temperatures and instability of nearshore habitats.

Rypel, A. L., W. R. Haag, et al. (2009). "Pervasive hydrologic effects on freshwater mussels and riparian trees in southeastern floodplain ecosystems." Wetlands **29**: 487-504.

Sabine River Authority of Texas (1999). Comprehensive Sabine Watershed Management Plan. Orange, Texas. Retrieved September 8, 2009, from http://www.sratx.org/srwmp/comprehensive_plan/.

Sabine River Authority of Texas (2009a). Preliminary Investigation Saltwater Barrier. Retrieved October 6, 2009, from ftp://ftp.sratx.org/pub/BBEST/Library/BBEST_020.pdf.

The lower Sabine River forms the boundary between Louisiana and Texas before emptying into Sabine Lake, an important tidal estuary of the Gulf of Mexico. Saltwater intrusion has altered the tidal landscape of the lower Sabine River Basin and will continue to make an impact if a solution is not implemented. The U. S. Army Corps of Engineers' Sabine-Neches Waterway deepening and widening project will accelerate saltwater intrusion and associated impacts.

Sabine River Authority of Texas (2009b). Sabine River Basin 2008 Summary Report. Retrieved October 7, 2009, from http://www.sratx.org/srwmp/tcrp/state_of_the_basin/summary_reports/default.asp.

This is the five year Texas Clean Rivers Program assessment report for the Sabine River Basin. The purpose of the assessment as defined by the Texas Clean Rivers Act (TCRA) is not to mandate exhaustive and detailed water quality studies, but to identify significant issues affecting water quality in each watershed (river basin) of the state and to provide sufficient information for the TCEQ, river authorities, and other governmental entities to take appropriate corrective action to maintain and improve water quality in each basin. The TCRA also required the TCEQ to establish by rule the level of detail required for each watershed and river basin assessment. The ongoing assessment program is known as the Clean Rivers Program (CRP).

Sabine River Authority of Texas and Lower Neches Valley Authority (2006). Sabine Lake: Ecological Condition of the Sabine-Neches Estuary. **Executive Summary**. Retrieved October 6, 2009, from ftp://ftp.sratx.org/pub/EcoConditionsReport/.

Sabine River Compact Administration (2008). Fifty-Fourth Annual Report. Retrieved October 12, 2009, from ftp://ftp.sratx.org/pub/BBEST/Library/BBEST_086.pdf.

This Annual Report has the following content: Members of the Administration; Officers of the Administration; Standing Committees; Meetings; Fiscal; General Activities;Hydrologic Conditions;Hydrologic Stations; Official Gaging Stations; Appendix A. Audit Report; Appendix B. Gaging Station Records; Appendix C. The Sabine River Compact; Appendix D. By-Laws; Appendix E. Rules and Regulations; and Appendix F. Toledo Bend Reservoir ALERT System.

SAC (2009a). Essential Steps for Biological Overlays in Developing Senate Bill 3 Instream Flow Recommendations. Retrieved November 8, 2009, from http://www.sratx.org/BBEST/RecommendationsReport/LinkedDocuments/biologyoverlay.pdf.

The Biological Overlay document provides guidance on: 1) Assimilating biological information needed to develop a biological overlay within the context of SB 3; 2) Applying biological information to inform the geographic scope of instream flow recommendations; 3) Addressing decision points required before and during hydrology-based modeling; 4) Applying a biological overlay for the purpose of refining and/or confirming preliminary hydrology-based instream flow recommendations; and 5) Using the biological overlay document in a hydrology-based environmental flow determination.

SAC (2009b). Fluvial Sediment Transport as an Overlay to Instream Flow Recommendations for the Environmental Flows Allocation Process. Retrieved November 8, 2009, from http://www.sratx.org/BBEST/RecommendationsReport/LinkedDocuments/sac_2009_04_sedtransport(2).pdf.

This document reviews various methods for assessing suspended-load and bedload transport, and recommends that the BBESTs consider application of the SAM Hydraulic Design Package for estimating effective discharge. A detailed example is presented, cautioning that it presents a worst-case scenario in which annual flow volumes are strictly limited to the HEFR-prescribed results in all respects.

SAC (2009c). Geographic Scope of Instream Flow Recommendations**:** 23. Retrieved November 8, 2009, from http://www.sratx.org/BBEST/RecommendationsReport/LinkedDocuments/GeoScope-20090403.pdf.

The purpose of this paper is to address the geographic scope of environmental flow regime recommendations for the Senate Bill 3 (SB 3) process. The question of geographic scope for the SB 3 process is a matter of recommending the number and spatial distribution of locations where flow regime recommendations will be developed. This document does not address implementation of flow recommendations.

SAC (2009d). Methodologies for Establishing a Freshwater Inflow Regime for Texas Estuaries Within the Context of the Senate Bill 3 Environmental Flows Process. Retrieved November 8, 2009, from http://www.sratx.org/BBEST/RecommendationsReport/LinkedDocuments/eirmethods_rev_13_060209(2).pdf.

This document provides background information and discussion of various methods that can be used to develop freshwater inflow recommendations for Texas bays and estuaries. While a few germane references to the literature are

made, this document is not intended to be a tutorial on the physics and ecology of estuaries, nor on the range of modeling techniques of potential application. Rather, it attempts to present a succinct summary of methods that are presently sufficiently developed and suitable for application to Texas estuaries, for consideration by the Basin and Bay Expert Science Teams (BBESTs).

SAC (2009e). Nutrient and Water Quality Overlay on Hydrology-Based Instream Flow Recommendations. Retrieved November 8, 2009, from http://www.sratx.org/BBEST/RecommendationsReport/LinkedDocuments/WQ%20Overlay_11-3-2009.pdf.

Water quality is the focus of this overlay document. Numeric and narrative criteria developed by the state address matter carried in suspension and solution, such as dissolved and suspended solids, as well as nutrients, toxics, indicator bacteria, temperature, pH, dissolved oxygen, and other parameters. Under some circumstances all might play a role in the determination of an environmental flow regime. Changes in a flow regime can be expected to produce changes in water quality conditions. The challenge is to ensure that the recommended flow regime protects water quality, particularly during low or subsistence flow conditions, and also considers water quality needs during higher flow conditions.

SAC (2009f). Use of Hydrologic Data in the Development of Instream Flow Recommendations for the Environmental Flows Allocation Process and the Hydrology-Based Environmental Flow Regime (HEFR) Methodology (DRAFT). Retrieved November 8, 2009, from http://www.sratx.org/BBEST/RecommendationsReport/LinkedDocuments/hydrologicmethods04202009.pdf.

This document provides an overview of how hydrologic data may be used in the identification of instream flow recommendations pursuant to the requirements of SB 3. As such, it describes one piece of the collaborative process envisioned by SB 3 for the identification of flows to maintain a sound ecological environment in rivers and streams.

Scaife, W. W., R. E. Turner, et al. (1983). "Coastal Louisiana Recent Land Loss and Canal Impacts." Environmental Management **7**(5): 433-442. Retrieved November 3, 2009, from http://www.springerlink.com/content/q1442h01164n7rr7/fulltext.pdf?page=1.

Annual coastal land loss in the sedimentary deltaic plain of southern Louisiana is 102 km 2, which is correlated with manmade canal surface area. The relationships between land loss and canals are both direct and indirect and are modified by the deltaic substrate, distance to the coast, and availability of new sediments. Loss rates are highest in the youngest of the former deltas nearest the coast; they are lowest in the more consolidated sediments far from the coast. The average estimate for land loss at zero canal density in the six regression equations developed was 0.09% _+ 0.13% annually, the present land loss rates approach 0 8% annually Although additional analyses are needed, we conclude that canals are causally related to a significant portion of the total coastal land loss rates The relation probably involves an interruption of local and regional hydrologic regimes. Reduction of the present acceleration in land loss rates is possible by managing present canals more effectively, by not permitting new ones, and by changing the design of new canals to allow more natural water flow.

Science Advisory Committee (2004). Report on Water for Environmental Flows. Austin, Texas: 158. Retrieved September 15, 2009, from http://www.twdb.state.tx.us/EnvironmentalFlows/pdfs/SAC%20FINAL%20REPORT_102704.pdf.

Sharitz, R. R. and W. J. Mitsch, Eds. (1993). Southern floodplain forests. Biodiversity of the Southeastern United States Lowland Terrestrial Communities. New York, Wiley.

Solis, R. S., W. L. Longley, et al. (1994). Influence of inflow on sediment deposition in delta and bay systems. Freshwater Inflows to Texas Bays and Estuaries. W. L. Longley. Austin, Texas, Texas Water Development Board: 56 - 70.

Strayer, D. L. (2008). Freshwater Mussel Ecology: A Multifactor Approach to Distribution and Abundance. , University of California Press, Berkeley.

Sutherlin, J. (1996). Historical Development of the Marsh System on the West Side of Sabine Lake. Sabine Lake Conference: Where Texas and Louisiana Come Together. Beaumont, Texas. Retrieved November 6, 2009, from ftp://ftp.sratx.org/pub/BBEST/Library/SabineLakeConferenceSept1996/.

Restoring hydrology, which in effect should restore function and productivity in coastal marshes, is a priority mission of the Upper Coast Wetland Ecosystem Project within the Texas Parks and Wildlife Department. Interior coastal wetlands and marshes associated with Sabine Lake are of special concern to TPWD. For wetland hydrology to be restored, a thorough understanding of historical changes within the natural drainage systems must exist. Taylor's Bayou and the Neches and Sabine Rivers are the 3 major drainages associated with Sabine Lake in Jefferson and Orange Counties. Taylor's Bayou and its tributaries drain the vast majority of Jefferson County. The Neches and Sabine Rivers drain vast areas of east Texas and west Louisiana, and both empty into Sabine Lake.

Tatum, J. W. (2009). Sabine-Neches Estuary and Lower Tidal Sabine River: A System in Transition. Sabine and Neches Rivers and Sabine Lake Bay and Bay Expert Science Team Meeting. Lake Palestine, Texas. Retrieved October 6, 2009, from http://www.tceq.state.tx.us/assets/public/permitting/watersupply/water_rights/eflows/02202009snslb_tatumwhitepaper.pdf.

Topics of this white paper include: description of Sabine-Neches Estuary (Sabine Lake); History / Timeline of Sabine Lake; Need for Habitat Restoration / Protection; Hydrology of Sabine Lake; and Tidal River Hydrology / Habitat.

TCB|AECOM (2006). Sabine Lake: Ecological Condition of the Sabine-Neches Estuary. Retrieved October 6, 2009, from ftp://ftp.sratx.org/pub/EcoConditionsReport/.

In 2002, the Sabine River Authority of Texas and the Lower Neches Valley Authority Boards of Directors, recognizing the critical need to balance water use and to protect the environment, authorized the development of initial baseline studies to help characterize the long-term, environmental flow needs of the Sabine and Neches River Basins and to evaluate how to meet these needs. The Ecological Condition of the Sabine-Neches Estuary report documents the baseline studies conducted and serves as the definitive compendium or reference source for the estuary including the identification and compilation of research studies, investigations, modeling efforts, future projects, and historical conditions of Sabine Lake and the Sabine-Neches Estuary.

Technical Review Group (2008). Review of Desk-top Methods for Establishing Environmental Flows in Texas Rivers and Streams. Kirk Winemiller, TRG Chair. Austin, Texas. Retrieved November 6, 209, from http://www.tceq.state.tx.us/assets/public/permitting/watersupply/water_rights/txefsacdesktop.pdf.

This Technical Review Group convened in August of 2007 to review and assess existing information and documents regarding instream environmental flow requirements and desk-top and other methodologies with the goal of making recommendations to the State as to how its current desk-top procedures could be improved to provide more appropriate estimates of environmental flow needs for rivers and streams.

Texas Commission on Environmental Quality (2008a). "Sabine and Neches Rivers and Sabine Lake Bay Basin and Bay Area Stakeholder Committee and Basin and Bay Expert Science Team ". Retrieved October 6, 2009, from http://www.tceq.state.tx.us/permitting/water_supply/water_rights/eflows/sabinenechessabinelakebay.html.

This Web site lists Sabine and Neches Rivers and Sabine Lake Bay Basin and Bay Area Stakeholder Committee and Basin and Bay Expert Science Team members as well as meeting materials.

Texas Commission on Environmental Quality (2008b). Texas Instream Flow Studies: Technical Overview. Austin, Texas. Retrieved September 15, 2009, from http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/R369_InstreamFlows.pdf.

Texas Legislature (2007). Senate Bill 3. Retrieved September 17, 2009, from http://www.legis.state.tx.us/BillLookup/History.aspx?LegSess=80R&Bill=SB3.

Relating to the development, management, and preservation of the water resources of the state; providing penalties.

Texas Parks and Wildlife Department (2005). Ecologically Significant River & Stream Segments of Region I (East Texas) Regional Water Planning Area. Austin, Texas.

The purpose of this report is to identify and document those river and stream segments that meet the outlined criteria established by 31 TAC 357.8(b) as having significant ecological value. The report is intended to provide the Region I RWPG with the technical information necessary to prepare a recommendation package of ecologically unique river and stream segments under 31 TAC 357.8(a), which may be included in the regional water plan.

Texas Parks and Wildlife Department (2008). Decision Points Relevant to using Hydrology Data to Quantify Environmental Flow Recommendations. Retrieved November 2, 2009, from http://www.tceq.state.tx.us/assets/public/permitting/watersupply/water_rights/eflows/decisionpointsdocument.pdf.

Texas Water Development Board. (2007). Water for Texas, 2007. Austin, Tex., Texas Water Development Board. from http://www.twdb.state.tx.us/publications/reports/State%5FWater%5FPlan/2007/2007StateWaterPlan/2007StateWaterPlan.htm.

Tyus, H. M., C. W. Brown, et al. (2000). "Movements of Young Colorado Pikeminnow and Razorback Sucker in Response to Water Flow and Light Level." Journal of Freshwater Ecology **15**(4): 525-535.

U.S. Army Corps of Engineers (1969). Sabine River Basin, Texas, River Milages. Fort Worth, Texas.

Sabine mileages were taken from late 1930 Tobin aerial mosaics and were reexamined in 1946 using AAA photographs and aerial photos of the flood of April 1945. New mileages have been inserted using most recent USGS quadrangle maps. These are the official U.S. Geological Survey river miles for the Sabine River Basin, Texas.

U.S. Army Corps of Engineers (2004). Louisiana Coastal Area (LCA), Louisiana: Ecosystem Restoration Study. Retrieved November 3, 2009, from http://www.lca.gov/final_report.aspx.

The goal of the LCA Plan is to reverse the current trend of degradation of the coastal ecosystem. The plan maximizes the use of restoration strategies that reintroduce historic flows of river water, nutrients, and sediment to coastal wetlands, and that maintain the structural integrity of the coastal ecosystem. Execution of the LCA Plan would make significant progress towards achieving and sustaining a coastal ecosystem that can support and protect the environment, economy, and culture of southern Louisiana and thus, contribute to the economy and well-being of the Nation. Benefits to and effects on existing infrastructure, including navigation, hurricane protection, flood control, land transportation works, agricultural lands, and oil and gas production and distribution facilities were considered in the formulation of coastal restoration plans.

Vaughn, C. C. and C. M. Taylor (1999). "Impoundments and the decline of freshwater mussels: a case study of an extinction gradient." Conservation Biology **13**: 912-920.

Werner, F. T. (1982a). Instream Needs for the Neches River below B. A. Steinhagen Lake. U.S. Fish and Wildlife Service Report. Houston, Texas**:** 34 p. Retrieved November 5, 2009, from ftp://ftp.sratx.org/pub/BBEST/Library/BBEST_063.pdf.

This report represents the Fish and Wildlife Service's (FWS) examination of the freshwater flows required to meet habitat needs of the resident fish and recreational demands that occur in the Neches River below B.A. Steinhagen Lake.

Werner, F. T. (1982b). Instream Needs for the Sabine River below Toledo Bend. U.S. Fish and Wildlife Service Report. Houston, Texas**:** 34 p. Retrieved November 5, 2009, from ftp://ftp.sratx.org/pub/BBEST/Library/BBEST_064.pdf.

The lower Sabine River is drained by an undammed stretch of the Sabine River (156.5 miles) which separates Texas and Louisiana between Toledo Bend and Sabine Lake

Winemiller, K. (2009). Comment on Draft Sabine-Neches BBEST Environmental Flows Recommendations Report. J. W. Tatum.

Winemiller, K. O., S. Tarim, et al. (2000). "Spatial variation in fish assemblages of Brazos River oxbow lakes." Transactions of the American Fisheries Society **129**: 451-468.

Zeug, S. C., D. Peretti, et al. (2009). "Movement into floodplain habitats by gizzard shad (Dorosoma cepedianum) revealed by dietary and stable isotope analyses." Environmental Biology of Fishes **84**: 307-314.

Zeug, S. C. and K. O. Winemiller (2007). "Ecological correlates of fish reproductive activity in floodplain rivers: a life history-based approach." Canadian Journal of Fisheries and Aquatic Sciences **64**: 1291-1301.

Zeug, S. C. and K. O. Winemiller (2008). "Evidence supporting the importance of terrestrial carbon in a large-river food web." Ecology **89**: 1733-1743.

Zeug, S. C., K. O. Winemiller, et al. (2005). "Response of Brazos River oxbow fish assemblages to patterns of hydrologic connectivity and environmental variability." Transactions of the American Fisheries Society **134**: 1389-1399.

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9 APPENDICES

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August 31, 2009

Transmittal to Basin and Bay Expert Science Teams (BBESTs)

Report # SAC-2009-05

Title: Essential Steps for Biological Overlays in Developing Senate Bill 3 Instream Flow Recommendations.

The Instream Biology Workgroup, formed by the Science Advisory Committee (SAC) has completed the attached draft document which constitutes another deliverable from the Senate Bill 3 SAC to assist the BBESTs in carrying out their responsibilities to develop instream environmental flow regime recommendations. This document deals with the important issue of using available biological information and data. It presents information for the BBESTs to consider to both inform a HEFR-based analysis and to overlay biological data and information to refine a hydrology-based flow matrix.

The document presents guidance on available sources of biological information and methods for assimilating the data for application in the SB 3 process. It also presents methods for mapping the data to address the geographic scope of flow recommendations. Finally, it presents how decision points in setting up hydrology-based models can be influenced by available biological information, and a process by which the results can be refined and/or confirmed by applying current biological knowledge.

While the SAC does not believe that sufficient biological data exist to directly prescribe an environmental flow regime, we strongly suggest that available data can be used to inform flow regime decision-making in the short term. The adaptive management provisions of SB 3 will no doubt be the vehicle for obtaining and employing new information and "science" in the future.

Participation by members from both current BBESTs was extremely helpful in completing this document, and many of their ideas are offered herein. Because of regular coordination and information exchange, the SAC feels that the existing BBESTs have already benefited from the concepts developed in this report in their work. The SAC is hopeful that these and future BBESTs will find this information useful in their deliberations, and we invite feedback as we all move forward with our respective responsibilities under SB3.

Robert J. Huston, Chairman, SB3 Science Advisory Committee

Essential Steps for Biological Overlays in Developing Senate Bill 3 Instream Flow Recommendations

Senate Bill 3 Science Advisory Committee for Environmental Flows

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Document Version Date: August 31, 2009

Report # SAC-2009-05

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SECTION 1. INTRODUCTION AND BACKGROUND

Senate Bill 3 (SB 3), passed by the Texas Legislature in 2007, directed the development of environmental flow recommendations through a new regulatory approach, using a local stakeholder process and the best available science, and culminating in Texas Commission on Environmental Quality (TCEQ) rulemaking. SB 3 directed the use of an environmental flow regime in developing flow standards from the environmental flow recommendations and defined a regime as a schedule of flow quantities that reflects seasonal and yearly fluctuations that typically would vary geographically and that are shown to be adequate to support a sound ecological environment and to maintain the productivity, extent, and persistence of key aquatic habitats. Initial flow recommendations by the local basin and bay expert science teams (BBEST) are to be made without regard to the need for the water for other uses. Although water availability may be an important consideration, at this stage it is not the primary driver of the analysis. Additionally, SB 3 clearly recognizes that in areas with little or no unappropriated water available to meet environmental flow needs, the Environmental Flows Advisory Group (EFAG), along with the Basin and Bay Area Stakeholder Committees and their respective BBEST, are to try to find innovative ways to provide water for environmental needs.

The Science Advisory Committee (SAC) published guidance on using hydrologic data as a method to develop initial instream flow recommendations as part of SB 3 efforts (SAC 2009a). One of the approaches outlined is the Hydrology-Based Environmental Flow Regime (HEFR) methodology which uses hydrologic data to populate an initial flow regime matrix consisting of monthly/seasonal schedules for subsistence flows, base flows, high flow pulses, and overbank flows. The hydrology-based approach constitutes one piece of the multidisciplinary process envisioned by SB 3 for the identification of flows needed to maintain a sound ecological environment in Texas rivers and streams. Completion of the process requires input from other scientific disciplines including biology, geomorphology, and water quality to ensure that environmental flow recommendations are broad-based, use the best available scientific information, and are adequate to support all processes and functions that maintain a sound ecological environment. To facilitate the use of other disciplines to inform, confirm, or modify the hydrology-based initial flow regime matrix, the SAC set out to develop guidance documents related to the overlay of biologic, geomorphologic, and water quality information. SAC 2009b presents information regarding geomorphological, specifically sediment transport, considerations. An additional guidance document addressing water quality overlay issues is in preparation.

This Biological Overlay document provides guidance on:

1) Assimilating biological information needed to develop a biological overlay within the context of SB 3 (Section 2),

2) Applying biological information to inform the geographic scope of instream flow recommendations (Section 3),
3) Addressing decision points required before and during hydrology-based modeling, (Section 4),
4) Applying a biological overlay for the purpose of refining and/or confirming preliminary hydrology-based instream flow recommendations (Section 5), and
5) Using the biological overlay document in a hydrology-based environmental flow determination (Section 6).

Input from BBEST members through the Instream Biology Workgroup helped to inform the development of this document as a tool that the BBESTs can use to apply biological information in their deliberations. The document offers some background information, but more importantly is meant to be utilitarian and provide the essential steps the BBESTs can use to develop instream flow recommendations in the short time prescribed by SB 3.

1.1 Intersection of Senate Bills 2 and 3

In 2001, Senate Bill 2 (SB 2) created the Texas Instream Flow Program (TIFP), which mandated that Texas Parks and Wildlife Department (TPWD), Texas Water Development Board (TWDB), and TCEQ conduct studies to determine flow conditions in the State's rivers and streams necessary to support a sound ecological environment. Priority studies of the lower Sabine, middle Trinity, middle and lower Brazos, lower Guadalupe, and lower San Antonio rivers are to be completed by December 31, 2016. The TIFP is intended to be transparent and to strive for compatibility with existing programs. *Texas Instream Flow Studies: Technical Overview* (TCEQ et al. 2008) provides a general framework for studies but recognizes that individual methods and procedures for technical studies must be tailored to address specific basin conditions.

Senate Bill 3, passed in 2007, established an aggressive schedule for determining environmental flow standards adequate to support a sound ecological environment in the State's river basins and bay systems. These standards must consist of a schedule of flow quantities, reflecting seasonal and yearly fluctuations that may vary by location. The SB 3 schedule does not allow for the development of multi-year site-specific instream flow studies such as those mandated by SB 2. Instead, SB 3 requires that environmental flow standards be predicated upon the best science and data currently available; it is intended that adaptive management be employed to refine the flow standards in the future. In order to effectively utilize the results from the TIFP studies through the adaptive management process, it is considered desirable for the initial SB 3 flow standards to be consistent with the flow regime framework that is to be applied in the TIFP studies for structuring instream flow recommendations.

Because of the inability to conduct extensive field studies and analyses during the SB 3 process, the consideration of biological factors in the development of instream flow recommendations very likely will have to be more generalized and time efficient. That is the intent of the procedures and information presented in this document, with the idea

that as more site-specific and detailed results emerge from the SB 2 and other studies, the instream flow regime recommendations and standards can be refined as appropriate through the adaptive management process (see Section 5.6).

1.2 Overview of Texas Rivers and Streams

Texas has approximately 307,385 km (191,000 miles) of low- to medium-gradient, warm water rivers and streams. Most Texas rivers originate within the boundaries of the state and flow into the bays and estuaries bordering the Gulf of Mexico after traversing several different physiographic regions and biotic provinces. Rainfall varies from more than 127 cm (50 inches) per year in the east to less than 25 cm (10 inches) per year in the west. Stream flows are directly related to episodic rainfall-runoff events, although the base flows of some Texas rivers and streams are groundwater dependent, while other stream segments are dominated by wastewater return flows from municipal areas.

Collectively, Texas' rivers and streams are biologically diverse, to some degree resulting from the wide range of topography, plant communities and geology found within the state's borders. A recent publication on biodiversity in the U.S. indicates that Texas ranks second in diversity, third in endemism, and fourth in extinctions of flora and fauna (Stein 2002). Streams and rivers in the state provide habitat for more than 268 species of fish, of which more than 170 are native fishes that spend most or all of their life in freshwater (Hubbs et al. 2008). Nearly 40% of these fish species are of conservation concern. Native fish communities consist entirely of warm water species, and their diversity reflects transitions from a Mississippi Valley fauna to the north and east to a Rio Grande fauna to the south and west (Conner and Suttkus 1986). East Texas rivers have diverse fish communities, and rivers in west Texas are more depauperate (Edwards et al. 1989, Linam et al. 2002). While benthic aquatic invertebrates in Texas streams are likewise diverse, this fauna remains poorly documented. It is possible that the number of species of aquatic invertebrates occurring throughout the state numbers in the thousands. In addition, the biogeographic origins of the invertebrate faunal elements found in Texas streams are equally diverse with representatives being known from the Gulf Coastal Plain, Chihuahuan Desert, Great Plains, and the Neotropics. Similar to the fishes, invertebrate diversity and densities are higher in eastern Texas when compared to those of the western portion of the state. More than 50 species of unionid mussels inhabit Texas rivers, streams, canals, reservoirs, lakes, and ponds (Howells et al. 1996). Mussel populations in Texas are commercially valuable (shell harvesting) and good environmental indicators yet little studied. Anadromous organisms such as American eel and river shrimp (or "prawn") may travel far upstream into rivers, streams, and spring systems to complete their life cycle (Bowles et al. 2000). Texas is also not without its share of non-native species that inhabit aquatic environments. The most problematic of these include riparian, submerged, and floating plants, aquatic snails, mussels and clams, fish, and mammals. These non-native species introductions have altered the composition of lotic assemblages and in some instances have negatively influenced native species within a drainage or sub-drainage.

The physical, chemical, and biological characteristics of Texas river basins reflect many geologic, hydrologic, and anthropogenic influences, especially those associated with municipal, industrial, and agricultural development over the last century. No major river in Texas remains completely free-flowing or free from non-point or point source discharges. Instream and riparian habitats have been altered by land-use practices, channel modifications, and changes to hydrologic regimes from construction of dams and their operation, diversion of surface water, and pumping of groundwater. Indeed, all of the major rivers in Texas are regulated to some extent by the water supply operations of the 211 major reservoirs designed to meet the needs of a growing population; some of these reservoirs also provide flood control and generate hydroelectric power.

1.3 Instream Flow Science

Recent publications have summarized the state of instream flow science in North America (Annear et al. 2004) and in Texas (NRC 2005). The Texas Instream Flow Program (TCEQ et al. 2008) used the basic principles outlined in these reports to develop its technical framework for how comprehensive instream flow assessments will be performed to develop flow conditions needed to maintain a sound ecological environment in rivers and streams. Generally, multidisciplinary assessments (biology, hydrology, geomorphology, and water quality) will be used to identify a regime of instream flow components including subsistence flows, base flows, high flow pulses and overbank flows (TCEQ et al. 2008).

The immediate task for developing the flow standards required under SB 3 is to identify in a short time frame, and without the benefit of completed TIFP or other studies, an instream flow regime at a particular location on a stream that will support a sound ecological environment and maintain the productivity, extent, and persistence of key aquatic habitats. The degree to which such a flow regime conforms to the basic structure of that being proposed for application in the TIFP studies is an important consideration. It is recognized however that consistency between SB 3-developed environmental flow standards and results from the TIFP studies, while desirable, will not always be feasible due to conflicting timelines and other considerations. In such cases the results from TIFP studies should be incorporated into environmental flow requirements through the adaptive management provisions of SB 3.

1.3.1 Biology

The biological component of instream flow studies includes developing an understanding of relationships (i.e., flow-ecology relationships) between aquatic communities, life histories, habitat (e.g., instream, riparian) and the physical processes that create and maintain system habitat, water quality, and hydrology (Bovee et al. 1998, Annear et al., 2004). Riverine communities include freshwater and estuarine fishes and other vertebrates (e.g., turtles), invertebrates (e.g., caddisflies, stoneflies, mayflies, and dragonflies), mollusks (e.g., mussels and snails), crustaceans (e.g., crayfish and river shrimp), aquatic macrophytes and algae, and riparian flora and fauna. Some are obligate riverine species requiring flowing water habitat for all or part of their life cycle. Others

are habitat specialists that require specific substrates, current velocities, or depths. These organisms offer important target species for instream flow evaluations.

The life history and ecology of lotic organisms must be considered in the evaluation of instream flows regardless of the approach. Using fish as an example, the fundamental aspects of interest are growth, survival, and reproductive success (spawning and recruitment). Information on foraging behavior, habitat use, the timing of those activities (e.g., seasonal changes), and temperature regime is essential to understanding growth. Data on habitat use of prey items may also provide valuable information. Ensuring reproductive success involves many habitat considerations for spawning adults, eggs, fry, and juveniles; spawning behavior or reproductive mode (Johnston 1999); and water quality issues (e.g., temperature cues). Flow regimes largely determine the quality and quantity of physical habitat available to aquatic organisms in rivers and streams (Bunn and Arthington 2002). Habitat conditions are generally characterized in terms of current velocity, depth, substrate composition, and instream cover such as large woody debris, undercut banks, boulders, macrophytes, and other cover types (Bovee et al. 1998). Habitat complexity (heterogeneity) is a primary factor affecting diversity of fish assemblages (Gorman and Karr 1978, Angermeier 1987, Bunn and Arthington 2002, Arrington et al. 2005) and heterogeneous habitats offer more possibilities for resource (niche) partitioning (Wootton 1990, Willis et al. 2005). Flow regimes also influence physical (geomorphology) and chemical (water quality) conditions in rivers and streams, which in turn influence biological processes.

Temporal considerations (i.e., spawning season, timing with peak flows, photoperiod, etc.) must also be considered when evaluating the ecological requirements of species representing diverse life history strategies (Hubbs 1996; Stalnaker et al. 1996). With respect to inter-annual (between year) variation in flows, short-lived fishes may require certain flows every year while populations of long-lived fishes may be sustained by meeting flow needs less frequently. Intra-annual (within a year) variation in flows is important to organisms that respond to the seasonal peaks and valleys of natural flow regimes for spawning or migratory behaviors. Scientists making recommendations on flow regimes must be cognizant of temporal considerations to incorporate inter-annual flow variability on an appropriate scale. For example, the life history of a long-lived (decades) species such as paddlefish is different from that of certain minnows, which may live, reproduce, and die in two or less years. These considerations clearly dictate that temporal aspects of instream flow management differ between groups of organisms. Furthermore, habitat requirements of species may shift seasonally and diurnally, and they may also differ by sex or life-stage.

1.3.2 Hydrology

Hydrology refers to the flow of water and has four dimensions: lateral (channel-floodplain interactions), longitudinal (headwater to mouth), vertical (channel-groundwater interactions), and temporal, including inter- and intra-annual variation. The characteristics of hydrology, which define the flow regime, include the magnitude, duration, timing, frequency and rate of change (Poff and Ward 1989, Richter et al. 1996). Hydrology plays a key role in determining the composition, distribution, and diversity of

aquatic communities since many riverine biota have evolved life history strategies that correspond to natural flow regimes.

1.3.3 Geomorphology

Geomorphology includes those physical processes that form and maintain stream channels and habitat, flush fine sediments, and transport sediment loads. Geomorphic processes occur over a range of flows but stream power, the energy available for sediment transport processes, increases with discharge. As a result, individual, large-magnitude flow events have a greater effect on the physical features of a river system than individual, small-magnitude events. Large flow events occur less frequently than small flow events and their overall effect is often less than the cumulative effect of more moderate flow events that occur with greater frequency. In combination with the characteristics of the available sediment supply, the balance of flow magnitude and frequency acts to form the physical characteristics of a river or stream.

1.3.4 Water Quality

Water quality parameters including temperature, dissolved oxygen concentrations, pH, conductivity, turbidity (fine sediment), and other parameters, are important to growth, survival, and reproduction of aquatic organisms. Water quality characteristics reflect watershed geology, land use, climate, and sources of organic matter and nutrients. Water temperature has a significant influence on growth (metabolic rate), survival (e.g., lethal temperatures), and reproduction (e.g., spawning cues and egg incubation) of stream fishes and macroinvertebrates because these organisms are cold-blooded (Armour 1991). Temperature ranges tolerated by organisms vary by taxa and life-stage. Factors that influence temperature include streamflow, channel width, thermal inputs, riparian shading, and current velocity. Dissolved oxygen (DO) influences survival and distribution of lotic biota since many organisms have specific dissolved oxygen requirements. Streamflow, water temperature, turbulence, organic matter decomposition, algal and macrophyte photosynthesis and respiration, and animal respiration all influence dissolved oxygen concentrations in lotic systems. Turbidity, conductivity, pH, and other factors may constrain or limit the distribution and abundance of aquatic biota.

1.4 Instream Flow Regime Components

Variations in the magnitude, frequency, duration, timing, and rate of change of stream flows are all critical components of a natural flow regime (Poff et al. 1997). Variability in stream flow is manifested to stream biota as a change in habitat availability. Consequently, the life histories of stream fishes and other aquatic organisms are adapted to the seasonal and inter-annual variability of low, base, and high flow components. Hydrologic pattern and variability are therefore key determinants of aquatic community structure and stability (Poff and Ward 1989, Poff et al. 1997, Richter et al. 1996, Dilts et al. 2005).

Alterations to a natural flow regime may result in decreased diversity and abundance of aquatic species inhabiting lotic systems. While the elimination of high flows can result in reduced species densities and community diversity (Robinson et al., 1998), stable flow

regimes that lack seasonal and interannual variability may favor generalist and non-native species (Tyus et al. 2000). In addition, seasonal and interannual flow variability may benefit native species that have developed life history strategies in response to natural flows. Thus, providing a flow regime based on the natural flow paradigm should provide ecological benefits in stream systems (Dilts et al. 2005).

Following guidance from the National Research Council (NRC) review of the Texas Instream Flow Program (NRC 2005), the TIFP uses multidisciplinary assessments to identify a regime of instream flow components including subsistence flows, base flows, high flow pulses and overbank flows. The SAC (2009a) adopted this same framework in order to maximize consistency in the framework of environmental flow recommendations in Texas.

Subsistence flows are infrequent low flows that occur during times of drought or under very dry conditions (TCEQ et al. 2008). The primary objectives of subsistence flows are to maintain water quality criteria and prevent loss of aquatic organisms due to, for example, lethal high temperatures or low dissolved oxygen levels. Secondary objectives may include providing life cycle cues based on naturally occurring periods of low flow or providing refuge habitat to ensure a population is able to re-colonize the river system once more normal, base flow conditions return. Assuming that native fauna are adapted to survive brief periods of subsistence flows; these low flow levels can help to purge invasive species from a stream system. Subsistence flows can also sustain a minimum level of connectivity between pools during dry times.

Base flows represent the range of “average” or “normal” flow conditions in the absence of significant precipitation or runoff events (TCEQ et al. 2008). Base flows provide instream habitat conditions needed to maintain the diversity of biological communities in streams and rivers. Habitat quality and quantity are important for survival, growth, and reproduction of fish and other aquatic organisms such as mussels and benthic macroinvertebrates, other vertebrates, and flora. Base flows can also support the maintenance of water quality conditions and can contribute to the alluvial groundwater that supports riparian habitats, which are important components of river ecosystems. Base flows also enable fish to move longitudinally within the stream to feeding and spawning areas, and can keep fish and amphibian eggs wet and suspended.

High flow pulses are short duration, high magnitude, in-channel flow events that occur during or immediately following rainfall events (TCEQ et al. 2008). High flow pulses serve to maintain important physical habitat features and connectivity along a stream channel. Many physical features of a river or stream, which provide important habitat during base flow conditions, cannot be maintained without appropriate high flow pulses. High flow pulses also provide longitudinal connectivity along the river corridor for many species (e.g., migratory fish), lateral connectivity to near-channel features (e.g., connections to some oxbow lakes), and can support the maintenance of water quality. Water quality functions include the resetting of water quality conditions after periods of prolonged drought, movement of fine sediments and silts to expose cobbles and rocky substrates, and the scouring of macrophytes from the channel.

Overbank flows are infrequent, high magnitude flow events that produce water levels that exceed channel banks and result in water entering the floodplain (TCEQ et al. 2008). Overbank flows serve to maintain riparian areas associated with riverine systems. For example, overbank flow transports sediments and nutrients to riparian areas, recharge floodplain aquifers, and provide suitable conditions for seedlings. Overbank flows also provide lateral connectivity between the river channel and the active floodplain, supporting populations of fish or other biota utilizing floodplain habitat during and after flood events. Other functions of overbank flows include moving organic debris to the main channel, providing life cycle cues for various species, maintaining the balance of species in aquatic and riparian communities, driving lateral movement of the river channel, and delivering sediments and nutrients to floodplains, bays, and estuaries.

Some ecological functions of each of these flow components are summarized in Table 1 (adapted from Richter et al. 2006 and TCEQ et al. 2008), which also offers a list of evaluation approaches and levels of effort that can be used to address each of these roles. In addition to identifying individual flow regime components such as the four discussed above, it is important to adequately characterize the components themselves. Important aspects of these flow regime components may include flow magnitude (rate and/or volume), duration, timing, frequency, and rate of change. Each of these characteristics may have important ecological implications and thus may need to be quantified (Poff et al. 1997, TCEQ et al. 2008). For example, rise rates that are too rapid may wash aquatic organisms downstream before they can find shelter along the river margins. Conversely, fall rates that are too rapid may lead to stranding or isolation of aquatic organisms in shallow areas.

Table 1. Some ecological functions performed by instream flow regime components (adapted from Richter et al. 2006 and TCEQ et al. 2008) and example evaluation approaches and level of effort associated with each approach.

Subsistence Flows - Ecological Role	Evaluation Approaches (level of effort)
Maintain water quality standards, i.e. suitable water temperatures, dissolved oxygen levels, and other parameters of water chemistry	7Q2 or other flow that protects water quality (low); existing water quality model (moderate); new water quality model (high)
Maintain critical aquatic habitats (e.g., riffles) and longitudinal connectivity	visual observation (low); cross-section ratings and other hydraulic methods (moderate); habitat-based model (high)
Concentrates biota into limited space leading to increased predation, mortality, and other stressors	literature review of life histories (low); biological sampling (moderate); bioenergetics and/or habitat models (high)
May shift community structure including changes in non-natives, lotic-adapted, and intolerant biota	assemblage data analysis (low); biological sampling (moderate); population dynamics model (high)

Base Flows - Ecological Role	Evaluation Approaches (level of effort
Provide suitable habitat for aquatic organisms	standard-setting e.g., Lyons Method (low); cross-section ratings and other hydraulic methods (moderate); habitat-based model (high)
Maintain diversity of habitats	habitat mapping (moderate); habitat-based modeling (high)
Support growth, survival, and reproduction of aquatic organisms	review available life history information (low); assemblage sampling and/or tracking studies (moderate); population dynamics modeling (high)
Maintain water table levels in floodplain and soil moisture for plants	Soil Survey Geographic Database (low); groundwater depth sampling (moderate); gradient of inundation model (high)
Provide connectivity along channel corridor	visual observation (low); hydrologic model (high)

High Flow Pulses - Ecological Role	Evaluation Approaches (level of effort)
Shape physical habitat of river channel including pools, runs and riffles	visual observation (low); longitudinal features measurements (moderate)
Flush out silt and fine particulate materials	sediment budget (moderate)
Redistribute some substrates (sand, gravel, cobble)	bed material analysis (low); sediment budget (moderate)
Prevent riparian vegetation from encroaching into channel	review available life history information (low); gradient of inundation modeling (high)
Restore normal water quality conditions after prolonged subsistence or low base flows	7Q2 or other flow that protects water quality (low); existing water quality model (moderate); new water quality model (high)
Provide spawning cues for some species	review available life history information (low); sampling or tracking studies (moderate to high); population dynamics modeling (high)
Provide connectivity to oxbows/wetlands	review available life history information (low); assemblage sampling or tracking studies (moderate to high); hydraulic modeling (moderate to high)

Overbank Flows - Ecological Role	Evaluation Approaches (level of effort)
Provide migration and spawning cues for some species	review available life history information (low); biological sampling (moderate); population dynamics modeling (high)
Provides allochthonous food subsidies for fish and other biota	review available life history information (low); biological sampling (moderate); food web dynamics modeling (high)
Provide spawning and nursery areas for fish and other biota	review available life history information (low); biological sampling (moderate); otolith microchemistry (high)
Facilitate exchange of nutrients, sediments, organics and woody debris	targeted assessments (high)
Recharge floodplain water table	Soil Survey Geographic Database (low); groundwater depth sampling (moderate); gradient of inundation model (high)
Maintain balance and diversity in floodplain forests	remote sensing (moderate); vegetative sampling (moderate); inundation modeling (high)
Drive lateral movement of river channel forming new habitats (secondary channels, oxbow lakes)	visual observation (low); River Styles Framework (high)
Shape physical habitats of channel and floodplain	visual observation (low); River Styles Framework (high)
Redistribute coarse substrates (gravel, cobble, boulder) in channel	bed material analysis (low); sediment budget (moderate)
Scour rooted aquatic vegetation from the channel	visual observation (low); hydraulic modeling (high)
Purge invasive species from aquatic and riparian communities	Review available life history information (low), biological sampling (moderate); population dynamics modeling

SECTION 2. DEVELOPMENT OF INFORMATION FOR BIOLOGICAL OVERLAY

The primary objective for developing a biological overlay is to obtain biological and corresponding water quality, flow, velocity and habitat data that can be used to develop predictive relationships between flow regimes and important natural resources and ecological functions of instream and riparian resources (i.e. flow-ecology relationships). A thorough account of an approach for assembling data and knowledge for a biological overlay is presented for the Savannah River (Richter et al. 2006) and an application in Texas for Caddo Lake and the Cypress Basin is found in Winemiller et al. (2005). Appendix B in Camp Dresser & McKee et al. (2009) presents a series of flow-ecology relationships in support of a watershed flow evaluation tool developed for the Roaring Fork watershed in Colorado.

The first step in developing the information for the biological overlay is the preparation of the literature review and resulting associated documentation for important resources and focal species. Early in this process, focal species should be identified, and these species will be the focus of the biological overlays. Care must be taken to identify a suitable set of species that, when their ecological requirements are met, will provide broad protection for most of the biological components of the ecosystem including instream and riparian resources. Species that have key habitat requirements (such as a shallow water habitat for spawning or rearing), critical time periods (for example, limited spawning season), or other flow dependencies are important to consider. For example, many darter species in Texas solely use riffle habitats, which, as flows decline, become exposed or unsuitable (e.g., insufficient depth or current velocity) for occupation. Further, darter species have specific critical time periods for spawning (Hubbs 1996), which generally occur during the spring months when streamflow conditions are higher. The TIFP (TCEQ et al. 2008) defines key species (i.e., indicator or focal species) as "species that are targeted for instream flow assessment or more generally taxa of interest; may include lotic-adapted species, imperiled species, sport fishes, or other species related to study objectives." This definition can be used as a starting point for identifying a list of focal species.

Although the list of focal species and the associated documentation may be tasked to an individual or to a research team it is important to solicit input from experts familiar with the river basin and its associated ecology. This can be done through an initial meeting of individual BBEST group members, agency staff and/or a research team. The BBEST can either conduct the study directly or nominate an organization or academic institute to conduct the literature review and prepare documentation describing existing data and knowledge of the river system, native species, and their flow dependencies. The primary purpose of the literature review is to identify key aspects of flow regimes that are important in sustaining the health of the instream and riparian biological communities and to identify the resources (e.g., studies, models, other tools) available to evaluate and refine instream flow estimates.

2.1 River Basin, Regional and Ecoregion Data Resources

The data obtained from the literature review will depend upon the degree to which the river ecosystem has been studied, the nature and volume of data collected, and the amount of relevant information that can be useful from similar river systems (See River Types in Section 3.2.1). Whenever possible, data on endemic species from the target river system should be utilized. Examples of potential sources of information are listed in Table 2 and discussed below. Currently studies are being conducted in various watersheds funded primarily by SB 2 and other state project funds (e.g. Bonner and Runyan 2007). These studies along with basin-specific published literature will be key future information sources for biological overlays.

Many past studies have focused on instream resources only. It is important that, whenever possible, data on riparian habitat and associated biological resources be included in the evaluation as the ecological processes of these areas are flow regime dependent. The riparian zone is a transitional semi-terrestrial area regularly influenced by freshwater, normally extending from the edges of the river to the edges of upland communities (Naiman et al. 2005). Important biologically related functions of the riparian zone may include crucial habitat for long-range migrations of terrestrial animals such as neotropical birds and serving as nutrient filters through interception of pollution-laden runoff (Fischer 2000, NRC 2002, Naiman et al. 2005). Many aquatic species, including some that are common in the main channel, use off-channel aquatic habitats during at least some portion of their life cycle. Thus, access to these habitats, established by high flow pulses that result in lateral connectivity, is required with certain degrees of frequency, and during certain periods of the year. Certain fish species have enhanced recruitment and population abundance when lateral connections between the channel and oxbow lakes occur during the appropriate time of year (Zeug et al. 2005, Zeug and Winemiller 2007, 2008).

Information on the distribution and status of state and federally listed threatened and endangered species should be evaluated within the study watershed. Concern for the preservation and recovery of these species may be the primary factor guiding instream flow recommendations. The impact on adjacent jurisdictional riparian wetland communities may also be an important factor. Sources of information include online listings and databases maintained by the State of Texas and USFWS and recent compilations of life history data by TPWD (Campbell 2003, TPWD 2009a, USDA 2009).

Unfortunately, geographically-specific biological data and knowledge may be sparse or entirely lacking. In some cases, long-term monitoring in large rivers may be lacking and consisting only of sampling at decadal or greater time steps, or associated with before and after reservoir construction (Rinne et al. 2005). Within the state of Texas, routine agency monitoring of fish and aquatic wildlife populations are largely limited to reservoirs and coastal estuaries. An alternative approach is to use biological data from adjacent river systems exhibiting similar hydrology, geomorphology, and ecoregion characteristics and biological assemblages (Connor and Suttkus 1986, Edwards et al. 1989, Rosgen 1994, Rosgen 1996, Abell et al. 2000, Brierly and Fryirs 2000 and 2005, Griffith et al. 2007,

Thorp et al. 2008). A concurrent comparison of each river's geomorphology, flow regime, and species assemblage composition would help determine if the two river systems have similar biota and environmental conditions and whether utilization of these data would be appropriate. Further discussion of river types and classification is found in Section 3.

If biological data on key species are essentially lacking and there are no data available for an adjacent river, then the next option is to try to obtain pertinent life history data for target species from the literature collected under similar flow regimes, habitats and thermal regimes. This can include use of habitat suitability criteria developed for key species. For example, the USFWS has developed habitat suitability criteria for various species of fish and wildlife (Hubert et al. 1984, USFWS 2000). However, caution should be exercised when transferring habitat and flow suitability criteria generated in one basin for a species or guild, to another basin. For example, fish habitat utilization models developed in one river and applied to another river, even within the same region of a state, can exhibit poor correlation between observed and predicted occurrences of species (Leftwich et al. 1997), although there are tests that can be performed to evaluate transferability (see Freeman et al. 1997). In these data-poor situations, the BBEST may recommend that, in the future, site-specific habitat and biological field data that can be related to flow regimes should be collected as part of the SB 3 adaptive management Work Plan.

Regardless of whether information was assembled on biota within the basin or from studies in other basins, it is important to clearly identify key habitat requirements and preferences of target biological species and assemblages. A habitat requirement is any aspect of the habitat without which a species cannot survive over the long term (Morrow and Fischenich 2000). If any of these requirements is not met, the population will decline and be locally extirpated. A habitat preference involves use of some aspect of the habitat by an organism that is in greater proportion than its availability in the organism's environment. For example, fish may seek out areas of optimal water temperatures (thermal refugia) during the critical summer and winter periods, or seek high current velocities in riffles and avoid stagnant pools.

2.2 Information Sources Habitat Requirements

Sources of information on specific habitat needs of organisms will vary considerably depending on how well an organism, species or guild of species has been studied. For example, more life history information is usually available for commercial and game species than for non-game species. Some useful sources of information for fish include regional (Texas and adjacent areas) fish survey books (Douglas 1974, Robison and Buchanan 1989, Sublette et al. 1990, Miller and Robison 2004, Miller et al. 2006, Thomas et al. 2007, Hubbs et al. 2008) and websites on freshwater fishes (e.g. Texas Freshwater Fishes located at http://www.bio.txstate.edu/~tbonner/txfishes/). Fish survey books are a good starting point for locating information about habitat requirements and life histories for many fish species. They usually provide specific descriptions of appearance and physical characteristics of the different fish species and may also give a

variety of life history and habitat data. It also is informative to consult guides from adjacent states since many species distributions extend into Texas. Similar state and regional guides for aquatic invertebrates, crayfish, mussels, wildlife, and wetland/riparian plants exist (McCafferty 1983, Ehrlich et al. 1988, USFWS 1988 and 1993, Howells et al. 1996, Eastman and Hansen 1999, Stutzenbaker 1999, Dixon 2000, Smith 2001, Thorp and Covich 2001, Voshell 2002, Schmidly 2004, Merritt et al. 2008, USDA 2009). These works are also valuable for the literature citations they contain that can lead to more specific habitat and life history information.

Other sources of habitat requirement data are published habitat models and species profiles. Species profiles have been compiled and are a useful source of habitat information (Edwards 1997, USFWS 2000). Habitat suitability index (HSI) models are another useful source of habitat information. HSI models can also be used to quantify the suitability of a habitat for a particular species, thus allowing comparison of different time periods, locations and flow conditions. Similar to survey books, species profiles and HSI models are valuable for the well-documented references they contain, which are very useful for in- depth studies of organism habitat requirements. Many of these profiles address habitat suitability of freshwater fish.

Peer-reviewed journal articles will contain information concerning habitat requirements and preferences. Locating information for a specific habitat characteristic or species is now relatively easy by simply searching for keywords on the websites of the major publishing companies (e.g., sciencedirect.com, springerlink.com, informaworld.com, esajournals.org, or bioone.org, to name a few), or using search engines such as Google Scholar. Life history data for specific taxonomic groups have been compiled in various symposium proceedings and books (Carlander 1969 and 1977, Lee et al. 1980, Kuhn and Barbour 1983, Page 1983, Matthews and Heins 1987, Mayden 1992, Hubbs 1996, Carlander 1997, Irwin et al. 2000, Simon and Wallus 2004, Cooke and Philipp 2009). An excellent electronic resource is FishBase which is maintained by FAO (Froese and Pauly 2000).

Even with all these resources, knowledge gaps on specific habitat requirements, preferences and specific life history data exist for many North American fish, aquatic and riparian organisms. Therefore, determining habitat requirements of species assemblages will usually require selecting and researching the requirements for key or focal species about which something is known. When feasible, representatives of each trophic level, habitat guild, and/or reproductive guild should be chosen for this analysis (Balon 1975 and 1981, Goldstein and Simon 1999, Gorman 1988, Linam and Kleinsasser 1998, Simon 1999). For aquatic and riparian biota, key variables that should be evaluated include streamflow and water velocity, water temperature, depth, instream cover, river size, substrate type, instream vegetation, riparian vegetation, floodplain habitat, migration barriers, and dissolved oxygen.

2.2.1 Current Velocity and Depth

Much of the following discussion is taken from a review on fish habitat requirements conducted by Morrow and Fischenich (2000). Fishes occupy habitats ranging from rapids to stagnant pools, but a given life stage of a given species will tend to prefer a relatively

narrow range of velocities and depths. The species that make up a stream/river community of organisms will encompass a great range of habitat preferences, and thus, a mosaic of habitats with variable depths and flow velocities is desirable for maintenance of species diversity. In most fluvial systems, spatially-uniform velocities and depths constitute poor fish habitat. This is often the case in channelized streams. In most cases, a velocity regime that is nearest to the unaltered state for a river or stream will provide the best habitat for the native fish assemblage (Bain et al. 1988, Morrow and Fischenich 2000). Regulated rivers with flow velocities that vary widely on a daily or hourly basis (such as those observed in many hydropower operations) can be extremely detrimental to fish populations, because the organisms are repeatedly disrupted and forced to seek new areas with suitable conditions for resting, feeding, or activities associated with reproduction, such as courtship, nesting and brood guarding.

2.2.2 Instream Cover

Instream cover, such as large woody debris, is an important component of most lotic habitats and provides velocity refugia, hiding places from predators, and attachment sites for adhesive fish eggs for aquatic invertebrates and fishes. Because depth and current velocity can be closely related to certain types of cover features, increasing the amount of cover may increase the diversity in depth and velocity distributions and overall habitat complexity.

2.2.3 Substrate Composition

As a general rule, substrate particle size decreases with increasing stream order (i.e. headwater streams are of the lowest order, and downstream, mainstem reaches are higher order), with substrate in the largest rivers usually consisting of sand, silt, and clays. Many fishes, including some recreationally and economically important species, cannot reproduce successfully unless gravel or larger substrate is available and maintained free of siltation. Thus, coarser substrates often are very important habitat components. Substrate composition and spatial distribution are also dependent on the flow regime.

2.2.4 Instream Vegetation

Instream vegetation can be an important component of fish habitat in fluvial systems, especially those with relatively low water velocities and fine substrates. Instream vegetation can provide the same benefits as instream cover. As a general rule, native aquatic plant species are desirable and introduced species are not. Most problems with excessive aquatic vegetation involve introduced species.

2.2.5 Riparian Vegetation

Riparian vegetation is an important component to maintain the health of habitats in fluvial ecosystems. Riparian vegetation increases bank stability, reduces sedimentation, reduces summer water temperatures through shading, and facilitates the recruitment of large woody debris (Morrow and Fischenich 2000, Naiman et al. 2005). Riparian vegetation can also absorb nutrients from agricultural and urban runoff and thus mitigate some negative impacts of anthropogenic nutrient loading.

2.2.6 Floodplain Habitat

Many fish species require floodplain habitats for successful reproduction and some utilize floodplains during all phases of their life cycles (Morrow and Fischenich 2000, Winemiller et al. 2004, Zeug and Winemiller 2007 and 2008). Healthy floodplains serve as nutrient and sediment sinks resulting in improved water quality in the river. Healthy floodplains also attenuate high flow pulses and lessen the magnitude of floods. Water receding from floodplains often contains a substantial amount of food consumed by river fauna. Clearing floodplain habitat for human uses often causes excessive sedimentation and turbidity, excessive nutrient inflows and associated problems with water quality. This may lead to reduced reproductive success of some fish species (Morrow and Fischenich 2000). As a general rule, if a river or stream had extensive floodplain habitat in its pristine state, alterations to, or reduced access to, floodplain habitats will result in losses of fish diversity and abundance overall (Junk et al. 1989). Since floodplains act as sediment traps, alterations in river flows or land use that increase sedimentation and turbidity in the river can adversely impact floodplain habitats.

2.2.7 Fish Migration Barriers

The most common structures that impede upstream and downstream migration by aquatic organisms are dams (Rinne et al. 2005). Water diversions, physical barriers, or structures that reduce flow velocity can also impede longitudinal migration. In most cases, barriers to fish migration greatly degrade fish habitat, however some species are more affected by barriers to longitudinal movement than others. Barriers to fish (and other aquatic fauna) movement may also be created under low flow conditions and could lead to alteration in reproductive and recruitment success, predation and mortality rates, and assemblage composition.

2.3 Water Quality

Water quality is an integral component of aquatic ecosystems and should be addressed when evaluating instream flow needs. Sufficient instream flows are needed to maintain the physical, chemical, and biological integrity of rivers and streams. Water quality parameters, including temperature, dissolved oxygen, pH, conductivity, turbidity (fine sediment), and other parameters, are important to growth, survival, and reproduction of aquatic organisms and vary with changes in stream flow. This section briefly discusses water quality issues that impact aquatic organisms. Additional information on water quality can be found in the Water Quality Overlay document (in preparation by the SAC) and in future updates to this document.

Rivers and streams exhibit seasonal variations in water quality. For example, the warmest temperatures (late summer) typically coincide with the lowest flows of the year, causing stressful water quality conditions that may lead to assemblage changes. Because freshwater fishes and macroinvertebrates are cold-blooded, water temperature has a significant influence on their growth (metabolic rate), survival (lethal temperatures), and reproduction (spawning cues and egg incubation) (Armour 1991). Temperature ranges tolerated by organisms vary by taxa and life-stage. Factors that influence temperature

include flow, channel width in combination with riparian shading, thermal inputs, turbulence, and current velocity.

Freshwater fishes can be divided into several categories based on temperature requirements including cold-water, warm-water and cool-water fishes. Cold-water fishes have an upper lethal limit of approximately 25° C. This includes salmonids, which are largely absent in Texas except in a few fisheries downstream of reservoirs with hypolimnetic releases. Most fishes and other aquatic organisms in Texas are considered warm water fauna. Most warm water fishes and aquatic organisms can tolerate water temperatures as high as 36° C for limited times. Changes in mean or peak water temperatures can greatly alter the species composition of a stream or river when thermal maxima are exceeded for extended periods of time and no refugia are available. As a result of elevated temperatures dissolved oxygen can be depressed resulting in the loss of additional species or populations.

As a general rule, low dissolved oxygen (DO) in warm-water streams is harmful to most aquatic animals. To address that issue, the TCEQ has established criteria for DO in the Surface Water Quality Standards, Title 30, Chapter 307. These DO criteria are used in setting permit limits for wastewater discharges to ensure that low DO levels from wastewater discharge are rare. However, low DO can occur in other situations or locations such as the hypolimnion of reservoirs and can be a problem in tailraces of dams with hypolimnetic releases. DO levels are usually lowest during the summer when temperatures are warmer. In addition, DO levels tend to be lowest during the early morning hours, reflecting diurnal photosynthetic activity. If historical data are being reviewed, care should be taken to insure that time of day is factored into any time of time series analysis. Some species are less tolerant to low DO than others (Linam and Kleinsasser 1998).

High concentrations of suspended sediments, humic substances, phytoplankton, and industrial discharges can cause turbidity in rivers and streams. "Natural" levels of elevated turbidity can exist in east Texas, prairie streams and coastal rivers, and these are usually caused by high amounts of humic substances or suspended clay particles. Most turbidity in lotic habitats is due to suspended sediments that typically occur during higher flows. Although some species are adapted to life in turbid waters, excessive levels of suspended sediments can be extremely harmful to certain species of fishes, mussels, and other aquatic organisms.

2.4 Strategies for Synthesis of Available Information

Each document included in the literature review should be assessed for its likely relevance in formulating flow recommendations, noting in particular any statements that specifically link aspects of the flow regime with biota or key ecological processes.

When reviewing pertinent literature, it is very important to note the time of year at which the flow condition needs to occur, such as the occurrence of overbank flows during the spawning season. It is also helpful to distinguish whether the relationship being described

needs or tends to occur every year, or only during wet or dry years. The flow regime recommendations should also be developed using the four instream flow regime components, their seasonal timing, and water year types.

In performing the literature review, the investigator should look for both direct and indirect connections between the components of a flow regime and a variety of biota (see examples of these connections in Table 1). Species-specific information can be extremely useful in developing flow recommendations, particularly if the species is known to be a keystone species, or if its flow needs are representative of a habitat guild, or if some phase(s) of its life cycle is strongly tied to specific flow conditions.

Many of these flow-ecology relationships will reflect direct connections, such as the flow levels needed to enable fish spawning migrations. However, other relationships will be indirect, such as the influence of stream flows on water quality that can affect aquatic and riparian organisms. Because flows of various levels influence physical habitats, water chemistry, energy supplies, connectivity among different habitats, and species interactions, any information describing the inter-relationship of flow with these other ecosystem variables could be useful in developing instream flow recommendations.

Attention also should be paid to the necessary intra- and inter-annual variability in each of the four flow regime components. For example, sustaining a population of fish may require large floods that enable access to floodplain spawning areas during the spring season, but the species may not need such access every year. Some of the primary questions pertaining to the instream and riparian ecology, as well as related hydrological, water quality and geomorphology information, that should be assessed and documented are summarized in Table 2.

2.4.1 Preliminary Data Synthesis and Analysis

It is recommended to outline the interrelationships between flow components and biotic responses or ecological processes in a conceptual model. Conceptual models provide a concise way to portray ecological knowledge and show hypothesized linkages between flow and various aspects of ecosystem health, or a species' dependence upon certain flow conditions to complete a particular life history stage. The process of conceptual modeling usually results in identification of key uncertainties and information gaps in flow-ecology relationships which should be documented for future use. If possible and time permits, the conceptual model should be developed through a "mediated modeling" process that obtains input from experts during the conceptualization and later quantification phases (van den Belt and Dietz 2004). This can serve as the basis for future development of quantitative models or approaches that will be used to evaluate biological responses to changing flow regimes in an adaptive management framework (Locke et al. 2008). When possible, statistical correlations between flow conditions and various ecosystem components or species should be explored to provide a cursory evaluation of the strength of these relationships. However, such analyses may not be possible at the beginning of a study.

These types of conceptual modeling and correlative approaches provide fast and cheap alternatives when quantitative ecological simulation and instream habitat models are not options due to time and funding constraints. Quantitative simulation models can be very expensive and/or data elements or parameters required to run them often are lacking at the outset. The BBESTs may have to adopt qualitative methods to estimate environmental flows. This will be true particularly for the initial efforts by the first BBESTs; later efforts may benefit from ongoing or future quantitative research.

2.4.2 Confounding Factors

It is important for the biological analyses to identify other sources of ecological degradation that may affect ecosystem health even in the absence of flow alteration. This may include point and non-point source releases of contaminants and non-flow related habitat degradation (e.g., urbanization and channelization). This will help clarify how much conservation and/or restoration should be anticipated from improving the flow regime.

Table 2. Selected key ecological related questions that should be assessed and documented and suggested resources needed to address these information needs (based in part on Table II. Richter et al. (2006)). Additional references in Section 7.

Instream Ecology	Example Source	Description
1) Summarize biological data that have been collected in the study area. Who collected these data, over what time frame, how often, and by what methodology?	University of Texas at Austin, 2009. Texas Natural History Collections Fishes of Texas Project database (http://www.utexas.edu/tmm/tnhc/fish/index.html)	Georeferenced database of historical fish collections primarily from museum records
2) Has the abundance or distribution of certain species changed over time? Are these changes thought to be linked to changes in river flow? Are data available to document these trends and linkages?	Bonner, T. and D. Runyan. 2007. Fish Assemblage Changes in Three Western Gulf Slope Drainages. Report to TWDB, Austin, TX. Literature surveys on Sabine, Brazos and San Antonio Rivers available on DVD <http://www.twdb.state.tx.us/RWPG/rpgm_rpts/IndividualReportPages/2004483015_dvd.asp>	Reports developed as part of the Texas Instream Flow Program include analysis of temporal trends in species relative abundance. NOTE: TPWD routine monitoring program focused on reservoirs and estuaries, limited river data. USGS and TCEQ data largely water quality or hydrology only.
	Anderson, A.A., C. Hubbs, K.O. Winemiller, and R.J. Edwards. 1995. Texas freshwater fish assemblages following three decades of environmental change. *Southwestern Naturalist* 40(3):314-321.	Analysis of long-term database that reveals general patterns of fish faunal change in Texas river basins.

Instream Ecology	Example Source	Description
3) What species (fishes, reptiles, birds, mammals, invertebrates, aquatic plants) are of greatest concern from either ecological, socioeconomic or recreational standpoints?	Texas Parks and Wildlife website on Rare, Threatened, and Endangered Species (http://www.tpwd.state.tx.us/huntwild/wild/species/endang/index.phtml) Campbell, L. 2003. Endangered and threatened animals of Texas: their life history and management. Texas Parks and Wildlife Department. Austin, Texas.	Search T&E species by county, evaluate potential influence of flow regime on T&E species.
4) What is known about the linkages between flow variations and life histories of focal species? What times of year are most critical for these species, their life stages, and species assemblages?	Winemiller, K.O., A. Chin, S.E. Davis, D.L. Roelke, L.M. Romero, B. Wilcox. 2005. Summary Report Supporting the Development of Flow Recommendations for the Stretch of Big Cypress Creek below Lake O' the Pines Dam. Report to The Nature Conservancy/Caddo Lake Institute. p 65-91.	Caddo report developed a list of focal species based on their dependency on flowing water. Report also includes annotated bibliography including historical collection, available life history information, species lists with supplemental information.
	Hasson-Willimas, C. and T. Bonner. 2009. Texas Freshwater Fishes Website (http://www.bio.txstate.edu/~tbonner/txfishes/index.htm)	Texas State web site includes life history and habitat association data for species by basin.
	Linam, G.W. and L.J. Kleinsasser. 1998. Classification of Texas Freshwater Fishes into Trophic and Tolerance Groups. River Studies Report 14. Texas Parks and Wildlife Department. Austin, Texas. Appendix J in Linam et al. 2002 available at http://www.tpwd.state.tx.us/publications/pwdpubs/media/pwd_rp_t3200_1086.pdf	Information on trophic level and environmental tolerances of native Texas fish taxa. May be useful in creation of guilds

Instream Ecology	Example Source	Description
	Goldstein, R.M. and T.P. Simon. 1999. Toward a united definition of guild structure for feeding ecology of North American freshwater fishes. pp: 123-202. In: Simon, S.P. ed. Assessing the sustainability and biological integrity of water resources using fish communities. CRC Press.	Information on reproductive guild of fish taxa, some native to Texas. May be useful in creation of guilds
	USFWS (U.S. Fish and Wildlife Service). 2000. Habitat suitability index models, FWS/OBS/Available from: Information Transfer Specialist National Wetlands Research Center, U. S. Fish and Wildlife Service, Lafayette, LA. www.nwrc.gov/publications/specintro.html	Habitat suitability curves for many species of fish and wildlife
	Froese, R. and D. Pauly. Editors. 2000. FishBase 2000. Concepts, design and data sources. FAO Makati City, Philippines. Electronic Source: http://www.fishbase.org	Electronic database on critical life history information for many freshwater fishes
	Freeman, M.C., Z.H. Bowen and J.H. Crance. 1997. Transferability of habitat suitability criteria for fishes in warmwater streams. North American Journal of Fisheries Management 17(1): 20-31.	Discussion of critical issues affecting the use of suitability criteria derived in other areas

Instream Ecology	Example Source	Description
	1) Edwards, R.J. 1997. Ecological profiles for selected stream-dwelling Texas freshwater fishes. TWDB Report. Contract 95-483-107. UT Pan American. Edinburg, Texas. 2) Irwin, E. R. , W.A. Hubert, C.F. Rabeni, H.L. Schramm, Jr., and T. Coon. Eds. 2000. Catfish 2000: Proceedings of the Ictalurid Symposium. AFS Symposium 24. 3) Cooke, S.J. and D.P. Philipp. 2009. Centrachid fishes: diversity, biology, and conservation. Wiley-Blackwell. West Sussex, UK. 4) Simon, T.P. and R. Wallus. 2004. Reproductive biology and early life history of fishes in the Ohio River Drainage: Ictaluridae. Vol. 3. CRC Press. Boca Raton, FL. 5) Carlander, K.D. 1997. Handbook of Freshwater Fishery Biology. Volume Three. Life History Data on Ichthyopercid and Percid Fishes of the United States and Canada by K. D. Carlander (Hardcover - 1997) 6) Hubbs, C. 1985. Darter reproductive seasons. Copeia 1985(1):56-68.	Examples of various species specific or taxonomic group profiles that may contain some information on life history requirements including flow regime. See references in Section 7 for complete list. Note there is also a need to assemble similar information for other instream and riparian biota. This data may be more limited with the exception of wetland plants and major groups of aquatic vertebrates.
5) Can the flow needs of certain indicator species be used to represent the flow needs of assemblages of organisms (e.g., fish, crustacean or mussel assemblages)?	USACE. 1994. Red River Waterway Project, Shreveport, LA, to Daingerfield, TX, Reach, Reevaluation Study In-Progress Review: Appendix 6. Aquatic Resources.	Dominate species within habitat guilds (based on preferred velocities and spawning substrate) selected as indicator species.

Instream Ecology	Example Source	Description
	Goldstein, R.M. and T.P. Simon. 1999. Toward a united definition of guild structure for feeding ecology of North American freshwater fishes. pp: 123-202. In: Simon, S.P. ed. Assessing the sustainability and biological integrity of water resources using fish communities. CRC Press	General classification of fishes by reproductive guilds
	Freeman, M.C., Z.H. Bowen and J.H. Crance. 1997. Transferability of habitat suitability criteria for fishes in warmwater streams. North American Journal of Fisheries Management 17(1): 20-31.	Discussion of critical issues affecting the use of suitability criteria derived in other areas
6) If the instream flow regime has been altered by human influences, are necessary flow conditions still properly sequenced to enable successful life cycle completion for indicator species?	Long-term USGS data at critical sites where fish/biota collections have been made	Requires either detailed instream flow studies or comparison of flow regimes to biota population data and habitat use, or comparison to published suitability criteria.
7) Which habitats are most limiting, and what is the importance of flow regime components for developing and maintaining these habitats?	BIO-WEST. 2009. Instream Flow Guidelines - Relationships to Aquatic Habitat and State Threatened Species: Blue Sucker.	Hydrodynamic models used to predict habitat flow relationships
	Mosier, D. T., and R.T. Ray. 1992. Instream flow for the lower Colorado River: reconciling beneficial uses with the ecological requirements of the native aquatic community. Lower Colorado River Authority.	Instream flow assessment

Instream Ecology	Example Source	Description
8) Are aquatic floodplain habitats critical for maintaining fish populations in rivers?	Winemiller, K., F. Gelwick, T. Bonner, S. Zeug, and C. Williams. 2004. Response of Oxbow Lake Biota to Hydrologic Exchanges with the Brazos River Channel	Approach for assessing connectivity.
9) Is the aquatic ecosystem dependent upon material subsidies (e.g., detritus, nutrients) that are brought into the river from the floodplain during floods?	Developing a coarse woody debris budget for Texas Rivers. January 2010. TWDB Contract #0604830632. Stephen F. Austin University.	Study will provide information on coarse woody debris.
	Historical TCEQ and USGS combined flow and nutrient data	Data can be combined to estimate nutrient loads from upper to lower basin
	Piegay, H. 2003. Dynamics of wood in large rivers. American Fisheries Society Symposium 37:109-133.	Part of a symposium dealing with wood in world rivers.
10) What specific instream flows are required by certain species during particular periods (e.g., seasonal) in order to facilitate movements within the riverscape?	Long-term USGS data at critical sites where fish/biota collections have been made	Requires either detailed instream flow studies or comparison of flow regimes to biota population data and habitat use, or comparison to published suitability criteria.

Riparian Ecology	Example Source	Description
1) What is the extent and distribution of riparian areas in the study area?	To be determined for Texas - good start with the Texas Parks & Wildlife/Nature Serve System (TPWD GIS Lab, in progress)	vegetation classification database

Riparian Ecology	Example Source	Description
	Analysis of Riparian Area Survey Methodology on the Sabine River. April 2009. TWDB Contract #0704830738. Stephen F. Austin	Using the lower Sabine River sub-basin as a test case, will develop procedures to incorporate flow requirements of riparian areas into instream flow studies in Texas
2) What is known about relationships between river flows, alluvial water table levels, floodplain inundation patterns, and the influence of these hydrologic conditions on riparian areas?	Busch, D.E. and Scott, M.L., 1995, Western riparian ecosystems, in LaRoe, E.T., Farris, G.S., Puckett, E.E., Doran. P.D., and Mac, M.J., eds., Our living resources- a report to the nation on the distribution, abundance, and health of U.S. plants, animals, and ecosystems: U.S. Department of the Interior, National Biological Service, p. 286-290.	General theoretical framework with limited studies that document linkages between riparian zones and rivers.
	Naiman, R.J., H. Décamps, and M.E. McClain. 2005, Riparia: ecology, conservation, and management of streamside communities. Elsevier Academic Press. San Diego, California	General theoretical framework with limited studies that document linkages between riparian zones and rivers.
3) How does the riparian corridor depend upon physical habitat conditions that are shaped by river flows? Is lateral channel migration or bar formation important in forming these physical habitats?	National Research Council. 2002. Riparian areas-functions and strategies for management: Washington, D.C., National Academy Press.	General theoretical framework with limited studies that document linkages between riparian zones and rivers.
	Naiman, R.J., H. Décamps, and M.E. McClain. 2005, Riparia: ecology, conservation, and management of streamside communities. Elsevier Academic Press. San Diego, California	General theoretical framework with limited studies that document linkages between riparian zones and rivers.

Riparian Ecology	Example Source	Description
	Knighton, D. 1998. Fluvial forms and processes: a new perspective. Oxford University Press	General theoretical framework that document linkages between riparian zones and rivers.

Synthesis with Hydrology, Water Quality and Geomorphology	**Example Source**	**Description**
1. Are there locations or studies where hydrology, geomorphology, hydraulics, water quality and biological data were collected? These locations provide the richest sources of information for conducting comparisons and constructing predictive "models".	Kleinsasser, L.J. and G.W. Linam. 1989. Water quality and fish assemblages in the Trinity River, Texas between Forth Worth and Lake Livingston. TPWD River Studies Report 7. Austin, Texas.	Special study that evaluated the relationship of fish communities and water quality. Includes flow data near collection sites
	Arnold, W.R. 1989. Effects of water quality, instream toxicity and habitat variability on fish assemblages in the Trinity River, Texas. Ph.D. Dissertation. University of North Texas.	Special study that evaluated the relationship of fish communities and water quality. Includes flow data near collection sites
2. What long term combined biological, hydrology and water quality data sets exist in the basin?	Largely absent. Possible sources: 1) TPWD River Studies 2) Inland Fisheries Reservoir studies and 3) TCEQ ongoing aquatic life monitoring at water quality sites;	Long term combined biota, hydrology and water quality studies are largely lacking in Texas.

Synthesis with Hydrology, Water Quality and Geomorphology	Example Source	Description
3. Have there been any past instream flow studies conducted in the study area or basin?	Mosier, D. T., and R.T. Ray. 1992. Instream flow for the lower Colorado River: reconciling beneficial uses with the ecological requirements of the native aquatic community. Lower Colorado River Authority.	Instream flow assessment

SECTION 3. DEVELOPMENT OF GEOGRAPHIC SCOPE FOR FLOW REGIME RECOMMENDATIONS

The Geographic Scope of Instream Flow Recommendations (SAC 2009c) provides a review of the spatial diversity of data within a river basin. It displays the larger components of the basin; in this case the Trinity River Basin was used as the example. The report reviews the distribution of stream flow gages and locations and shows major sub-basins and major flow determinants such as in-channel dams.

This section is an extension of The Geographic Scope of Instream Flow Recommendations (SAC 2009c) to focus on the biological implications of geographic subregions. It reviews the utility of increasing the visual resolution and detail of geographically oriented biological data in support of a flow regime analysis. Examples of illustrative spatial information would be perennial vs. intermittent stream distribution, location, location of riparian vegetation types (with regard to the need for overbanking flows for connected habitats such as adjacent marshes or oxbows), and distribution maps of aquatic species.

As noted in Section 1, HEFR input data should be developed without regard for the presence of USGS gages in a particular area sampled. While the ultimate level of analysis may be hampered by the lack of gaged flow data, the geographic distribution of important biological inputs still needs to be determined to develop a baseline data set. Ultimately, that database will allow the BBESTs to assess the adequacy and spatial scope of their flow regime recommendations in representing the basin.

The essential elements in developing the geographic data are input data development and map construction.

Input Data – Data reports and geographically descriptive analyses from the results of work described in Section 2 should be compiled in a map format. For instance, field sampling efforts that provide species lists, especially wide-ranging studies should be included on maps of appropriate visual resolution. The distribution of identified river types should be included. Existing maps such as National Hydrographic Dataset (NHD) maps should to be utilized as base maps since they already contain layers of useful non-biological data such as location of perennial streams, riparian and floodplain areas susceptible to flooding under overbanking flows and locations of contiguous habitat areas such as marshes, oxbows, and abandoned channel lagoons. In addition to the above data types, such useful overlays as cropland, urban areas, dams and reservoirs, and stream segment lengths, etc. are also included. All these data can assist in assessing the state of the habitat throughout the basin.

Map Construction – Data should be assembled on base maps at appropriate visual resolution. Data such as species distribution throughout the basin or portions thereof, the geographic range of state and federally listed threatened or endangered fish species and species of concern, and location of any critical habitat or sensitive areas should be

included. The maps should include riparian areas containing vegetation requiring overbanking flows or high flow pulses, and associated connected habitats in floodplain areas that would benefit from pulsed or overbanking flows. Areas of significant geomorphic activity due to increased flows should be mapped. In order to see the data portrayed at the map scale chosen, both the resolution and the size of the plot files should be sufficiently scaled. In the examples presented in this section, the resolution is 300 DPI and the plot files are 24 by 36 inches.

The ultimate goal is to produce high visual resolution maps of a watershed containing important physiographic and biological overlays which can inform the flow regime analysis.

3.1 Realistic Expectations Concerning Geographic Input

The SAC recognizes that the BBESTs have both time and budget constraints. Hence, recommendations as to data inputs and analytical methodologies to establish geographic input data for HEFR relies almost exclusively on published information and readily available mapping data and techniques. The BBEST can peruse the data and maps to assess how much useful input is likely to be developed from those sources. It is important to establish and itemize input data goals early in the process.

Later in this section recommendations will be made as to how to best utilize the data and analytic mapping techniques, but to underscore the realistic expectation of results, the goals need to stay as close to available data as possible, since budget and time constraints will not likely allow much in the way of new studies to develop additional data.

The example below examines one type of geographic information of sufficient import as to require additional effort to complete.

The distribution of individual fish and mussel species throughout the basin may require convening a panel of experts to provide input on the distribution of the species where only vague references are currently available in the literature. Of all the species listed for a given river basin, many will be listed as occurring statewide, others may be endemic to a specific location or stream, and Texas Parks and Wildlife Department (TPWD) currently lists threatened or endangered species by county. It is the remaining species, often habitat specialists, whose distribution needs additional definition. Absent actual sampling to determine species distributions, a team of experts can use available publications, perhaps museum records and individual scientists' opinions to attempt to develop these distributions. The resultant maps would definitely help shape flow regime recommendations. Variants of this technique are used to develop species lists for water-related projects when species lists are important in assessing project impacts during permitting. Remember the BBEST will be developing through the use of maps much of the physical and some of the chemical data needed to assess whether appropriate habitat may be present for a given species. This process should not take that long to accomplish and, where access to appropriate data is not available, the analysis for a given species should be terminated and the result so noted. The objective is not to get bogged down.

3.2 Specific Procedures for Developing Geographic Input

Whereas Section 2 is thorough regarding the types of information that should be assembled as a first step in any BBEST analysis, this section will deal with the type and scale of geographic analyses that can be employed to make this data useful. The initial step in assessing a river basin deals with determining what type(s) of systems are represented in the river basin studied (3.2.1). Section 3.2.2 then deals with the extraction of geographic data from available data sources. Finally, Section 3.2.3 provides examples of maps and the procedures to develop these maps. The ultimate objective is to overlay the available biological information on to the maps presented in SAC 2009c.

3.2.1 River Type

Classification of river type may be an aid to the BBESTs in developing flow requirements, particularly in parameterization of HEFR and development of biological or other overlays. Flow versus ecology relationships often differ from one river ecosystem type to another (Lytle and Poff 2004, Arthington et al. 2006). Thus, consideration of the structure, function, and other aspects of each river type's ecology helps assure that flow recommendations developed for each river represent the factors most important to its sound ecological environment (Arthington et al. 2006, Apse et al. 2008, Poff et al. in press).

Benefits of considering river type in development of environmental flow requirements include:

- Hydrological, biological, and other types of data may not be available for every river for which the BBEST desires to develop recommendations. Consideration of river type maximizes the effectiveness of transfer of knowledge (e.g. flow-ecology relationships) from rivers with available data and site-specific flow studies to rivers with no such information.
- The most important flow components and thresholds in alteration of these components may vary across river types. Thus, the parameterization of HEFR, for example, should incorporate ecological considerations by river type.
- The most important biological overlays may vary across river type as well. So, river type should be considered in selection of focal species, indicator variables, and other factors for use in biological overlays.
- As discussed by the SAC (2009c), consideration of river type helps ensure inclusion of the full diversity of river ecosystem types in determination of the geographic scope of flow recommendations.

Classifications of river types come in many shapes and sizes. River classifications may be based on hydrology (e.g., Poff and Ward 1989, Harris et al. 2000, Olden and Poff 2003, Henriksen et al. 2006), geomorphology (e.g., Brierly and Fryirs 2000), ecology (e.g., Walsh et al. 2007), or a combination of factors (e.g., Higgins et al. 2005, Snelder et al. 2005, Michigan Groundwater Conservation Advisory Council 2007). The Texas Instream Flow Program (TCEQ et al. 2008) provides a review of classification approaches and makes recommendations on factors to consider in selection of a scheme for Texas rivers. A literature review of river classifications and their use in development

of instream flow requirements is available at the Ecological Limits of Hydrologic Alteration Toolbox website: http://www.conserveonline.org/workspaces/eloha/documents/bibliography.

An important consideration is that if a river classification scheme is to be used to inform biology overlays and/or HEFR parameterization, then it should incorporate at least a coarse consideration of biological and ecological variability. Ultimately, the BBESTs will determine the classification to be used based on their considerations of the most important factors in their basin.

A variety of river classification schemes are available either statewide or in specific areas of the state. Some statewide classifications include:

- Ecoregions (e.g., Griffith et al. 2007) and physiographic provinces (e.g., Johnson 1931)
- Wolock (2003) Hydrologic Landscape Regions of the United States – a classification of 43,931 small watersheds in the United States into 20 categories (the HLRs) on the basis of similarities in land-surface form, geologic texture, and climate characteristics.
- Edwards et al. (1989) classification of aquatic communities – not mapped
- Hersh and Maidment (2007) classification of streams integrating hydrography, water quality, climatology, hydrology and hydraulics, geomorphology and physical processes, and limited biology – mapped statewide at the scale of USGS sub-basins (HUC8's)
- US Geological Survey's Stream Classification Tool for Texas (TxSCT) (Henriksen 2008) is a hydrologic classification based on a unique set of ten, non-redundant, hydrologic indices – available for 297 river gages in Texas
- The Nature Conservancy's hierarchical classification of freshwater ecosystems [methodology based on Higgins et al. (2005)] based on river size, physiography/ecoregions, slope, elevation, coarse hydrology, drainage network position, and geological characteristics – mapped statewide in 1:100,000 NHDPlus, except for portions of the Trans-Pecos (report to be available December 2009)

In addition, more detailed classifications based on geomorphology exist for some river segments and sub-basins, including the portions of the Brazos (Phillips 2006), Sabine (Phillips and Slattery 2007, Phillips 2008b), San Antonio (Engel and Curran 2008), and Trinity (Phillips 2008a) rivers using the River Styles framework (Brierly and Fryirs 2000).

3.2.2 Use of Available Data Sources and Maps

Since flow regime specification will only be applied to portions of any river basin, the BBESTs need to determine where in that system the results will be verifiable by other forms of data including biology.

One objective of the biological overlay is to assess the state of the biological data available in the basin to determine whether sufficient information would be available to

support the hydrologic analysis, especially whether recommendations for all four levels of flows in TIFP or perhaps only 2 or 3 could be developed for a proposed stream reach. A BBEST will have to rely on the sufficiency of existing data and the best professional judgment of those who best know their system. By way of example, the Instream Biology Workgroup has spent considerable time reviewing what is available in the Trinity River Basin and attempting to assemble basin overlays that will be of use to the SAC and ultimately the BBESTs. Hence, the remainder of this section uses the Trinity River Basin as a model for all river basin studies.

From a biological perspective, it is important to gather background information and biological data to define the distribution and abundance of species in the system. The current drafts of the Trinity River Basin Literature Reviews (Guillen and Wrast 2009) have been reviewed. While it is extensive and relatively complete, only 43 references pertained to fish in the Trinity River system. Of these, 23 were reservoir studies and six were studies of individual species in limited locations. Two studies were done for TCEQ use attainability analysis studies for segment 0805. Of the remaining 12 studies, four were large area mainstem river collections from the Dallas-Fort Worth area to Lake Livingston. Eight were river studies over smaller reaches but all on the main stem river. Most of these were TPWD collections ranging from the 1950s through the present. Most of the large surveys sampled approximately 10 stations along the river. It appears that suites of data have not been compiled for very many locations throughout the Trinity River Basin.

The United States Fish and Wildlife Service (USFWS) and TPWD both record the presence of threatened or endangered species. TPWD's website allows each county to be reviewed separately and includes rare or species of concern as well as federally and State-listed species. Few threatened or endangered fish species are listed for the Trinity River and most are at the edge of the range in the Trinity River. TPWD may provide more precise data upon request about a particular species range, or check their website for county-by-county listings <http://gis.tpwd.state.tx.us/TpwEndangeredSpecies/DesktopDefault.aspx>.

A total fish species list for the Trinity River is available from Thomas, Bonner, and Whiteside (2007) or the Texas Freshwater Fishes website (Hassan-Williams and Bonner 2009). This is an essential step in using fish data in support of the hydrological analysis. Hubbs et al. (2008) and Lee et al. (1980) provide some assistance in locating species distribution within the basin. These references also provide statewide coverage. From these sources and the general fisheries literature the BBESTs need to augment the habitat data from their literature report. Douglas (1974) and Miller and Robison (1973) are two excellent references that can add more detail concerning habitat, feeding, and reproduction for many of the species in the Trinity River and other rivers as well. Bonner is working upon a distribution of species within river basins in Texas. The information should be posted on their website by spring or summer 2010 (Bonner 2009). Since the Trinity-San Jacinto and Sabine Neches BBESTs must provide flow regime recommendations by November 2009, this work will not be available in time for their deliberations. For those BBESTs data will still be lacking on certain species. Those

BBESTs need to access widespread databases or articles that provide life history and habitat data for those species. The BBESTs should consider convening a group of knowledgeable biologists to determine the probable distribution of the species in their basin. The study group should also include individuals with knowledge of the current geomorphology of the river in question. They will provide important input upon which to base decisions as to presence/absence of species in portions of the basin.

Mussels that are strongly tied to substrate are another group of organisms the BBEST could attempt to geographically locate throughout their basins. While the reference documents are far fewer than for fish species, Howells et al. (1996) contains generalized distribution maps. TPWD lists many mussel species as species of concern. These are listed by county and habitat described on their website. Individual researchers would need to be contacted for more detailed data.

3.2.3 Maps

The Geographic Scope of Instream Flow Recommendations (SAC 2009c) presents many maps designed to define the geographic scope of the flow regime. However, additional information pertinent to developing biological overlays may be extracted by examining these map data at a greater scale. By way of demonstration, 6 example maps are presented below (Figures 1 to 6). The National Hydrograph Data Set (NHD) map files necessary to produce these maps require the use of a Cad/GIS program that is able to access the program. The PDF files, created by Cad/GIS programs, of the NHD file can be viewed on most computers. Zooming in and out with clarity is dependent on the size and resolution of the PDF file. Print or viewing quality is dependent on the resolution of the file processed and the size of the print output, e.g., an 8.5” x 11” print at 300 dpi is not as clear as a 36” x 36” print at 300 dpi. The PDFs of the example maps included in this report were developed at 300 dpi and present high visual resolution when printed on plotter paper at a format size of 36” x 36”. To view PDFs for the 6 example maps displayed at enhanced scale resolution, please access this site: http:// www.tceq.state.tx.us/permitting/water_supply/water_rights/eflows/resources.html.

The 6 example maps represent but a few of the possible maps that can be generated relatively easily. Figures 1 to 4 are figures showing the entire basin. Figures 5 and 6 depict areas roughly the size of a county within the basin. The geographic area included in a particular map is determined by the parameters being examined and resolution required to view it adequately.

Below is an annotated description of Figures 1 to 6 intended to demonstrate their utility to the BBESTs.

> Figure 1 is the NHD map for the Trinity River Basin at a high resolution output that shows all perennial streams, county boundaries, and city boundaries. The map also contains the location of 10 sub-basins throughout the Trinity River Basin. The sub-basin delineations assist in putting perspective on the areas to be considered in the development of a representative recommended flow regime. Even then, for instance,

examination of the mainstem Trinity River Basin (#6) reveals numerous perennial creeks entering the river in this sub-basin, some of which have unique characteristics such as areas requiring overbanking or that contain substantial marsh and swamp areas.

Figure 2 presents the Trinity River Basin map showing the reservoir and perennial streams overlain by Blair's (1950) biotic province designations and the TPWD Level 3 Ecological Zones (TPWD 2009c). A useful addition is the inclusion of county lines. Both of the map overlays are useful in determining the distribution of species typical of those areas.

Figure 3 displays the distribution of vegetation types that benefit from overbanking flows. In the Trinity River Basin, 4 vegetation associations would require such overbanking flows. Overbanking flows are a major consideration in the development of a flow regime process, and this figure provides support for such flows in the indicated areas. The types of vegetated areas requiring overbanking flows in the Trinity River Basin include bald cypress-water tupelo, elm hackberry parks/woods, water oak-elm-hackberry forests, and willow oak-water oak-black gum forests. The vegetation map overlay was downloaded from the TPWD website (TPWD 2009a).

Figure 4 overlays the TPWD vegetation map from which the data in Figure 3 was obtained. The BBESTs can view land use categories such as crops, urban areas, and lakes from this map. In the Trinity River Basin the Dallas-Fort Worth area, and large adjacent croplands as well as reservoirs consume much of the land in the upper half of the basin. All these land uses are presented at a scale useful to the BBESTs when assessing stream flow regimes in those regions.

Figure 5 shows an area of the basin (Kaufman Co.) where existing ponds on intermittent creeks possess relatively large areas of potential storage. Similar areas appear in other portions of the basin (e.g., Navarro Co.). Such areas deserve scrutiny concerning what fish species inhabit the area. These ponded areas may be acting as detention ponds supporting aquatic habitat downstream of these ponds on intermittent streams. Such areas would also be useful for riparian aquifer recharge. While most of these areas are in cropland areas, they were often formerly wetland drainages.

Figure 6 displays the distribution of swamps and marshes in Anderson County. Other such areas occur in Sub-basin 6, as well, and Sub-basin 5 is replete with such areas (Figure 1). These areas are almost always associated with perennial streams and will likely be different from the mainstem river regarding the diversity and abundance of species. These areas are very dependent upon connectivity links in their specific watersheds. These systems should be examined, quantified, and their species mix determined because the species list may vary from the mainstem river; such areas will add to the

diversity of the system. These areas are also important support areas for reptiles, birds, and mammals. Without examination of the watershed at an enhanced scale such areas, not in the mainstem channel area, might be overlooked.

As noted above, many more maps can be generated that would prove useful to the BBESTs. These would be most useful as overlays on the base NAD map, which shows the perennial streams in the river basin. Some possible additional maps are listed below.

- Species distribution maps for fish.
- Species distribution maps for mussels.
- Maps of the distribution of threatened or endangered species (fish, mussels)
- Overlay location of aquatic areas historically sampled based upon the literature review.
- Plot geomorphic zones on tributaries as available from literature reviewed.
- Plot coverage of available hydrologic stream rating studies, cross-section analyses or other potentially useful locational data, especially for ungaged areas of the basin.

3.3 Summary and Recommendations

1. Organize and classify existing basin geographic data and maps and determine the visual resolution scale required for different areas.

   The BBESTs can take the following specific steps in evaluating the utility of river type in development of flow regime analysis, e.g., HEFR parameterization and/or overlays and selecting a classification scheme to provide the context of river types in a given basin:

   a. Consider variability of river types in your basin (e.g., Central Plains versus Coastal Plain rivers in the Trinity River basin).
   b. Determine factors that structure this variability (e.g., is hydrology alone sufficient? Also need ecology? Geomorphology?).
   c. Determine, based on SAC (2009c) and this document, the river segments for which flow recommendations will be developed.
   d. Select a classification that best represents the ecological, hydrological, geomorphological, and other relevant considerations in the selected river segments.
   e. Select overlays and/or parameterization guidelines for each river type determined to be significant in the river basin.

2. Use ArcView/ArcGIS to develop map overlays on NHD maps, containing as many useful parameters as practical. Add to the base map layers from the literature search results and other existing maps.

3. Attempt to compile similar areas in the basin based upon geographic overlap and similarity of map features useful to the hydrological analysis.

4. Determine basin areas where sufficient data supports hydrological analysis.

5. Highlight areas with deficient mapping data to support hydrological analysis.

6. Provide the maps to those performing the hydrological analyses to help refine the model run settings and/or parameterization.

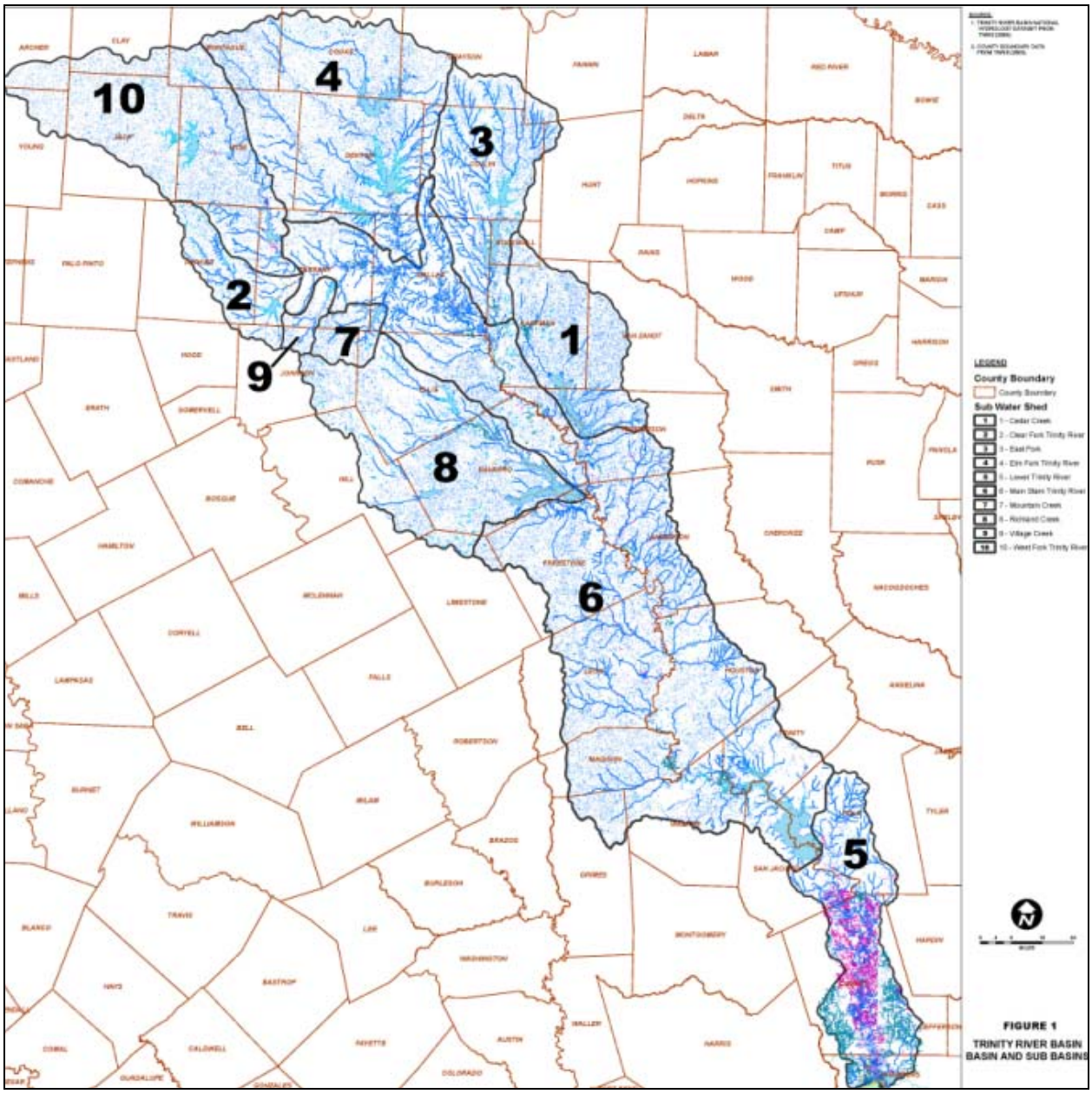

Figure 1. Trinity River Basin- Basin and Sub Basins

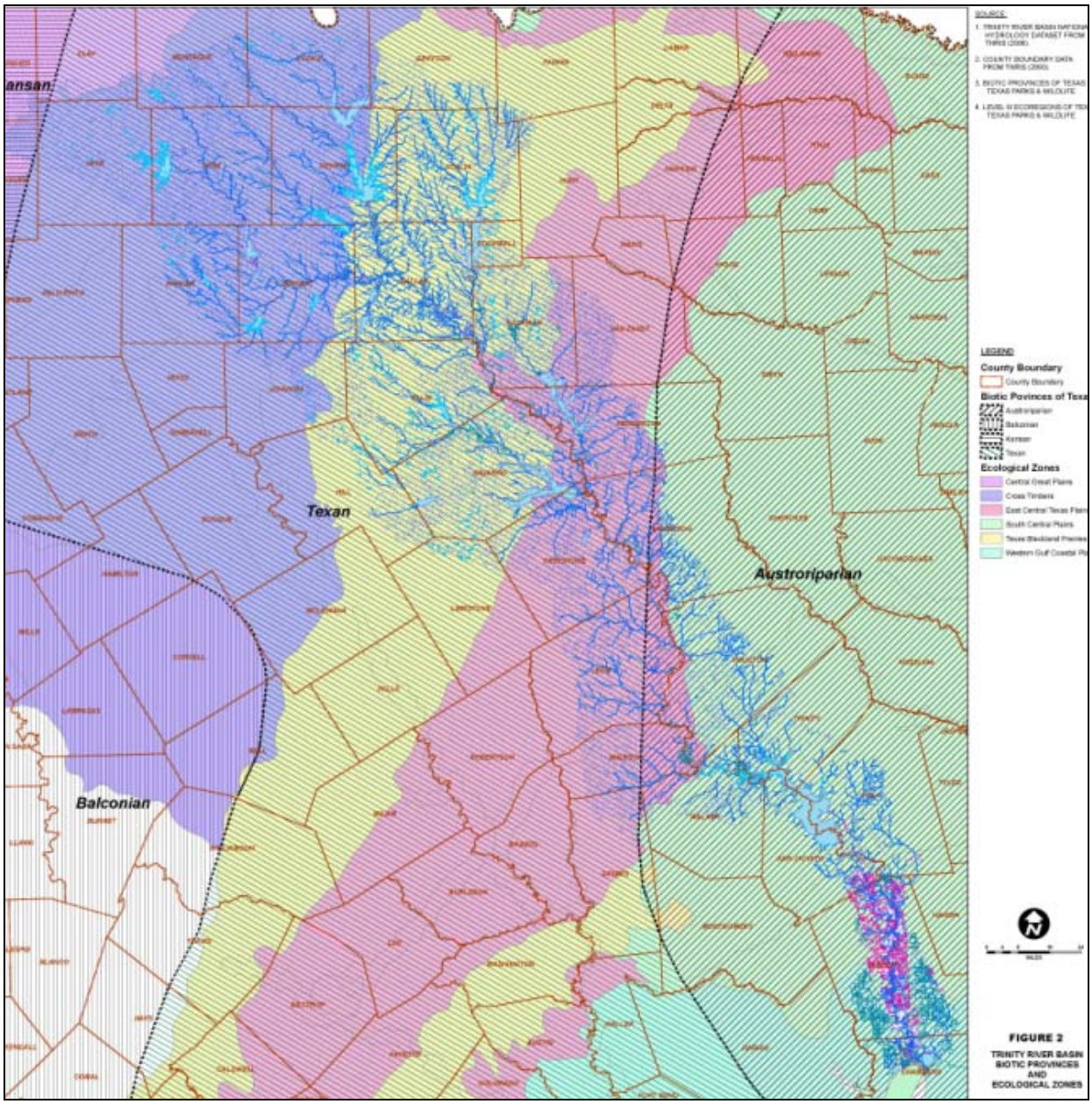

Figure 2. Trinity River Basin- Biotic Provinces and Ecological Zones

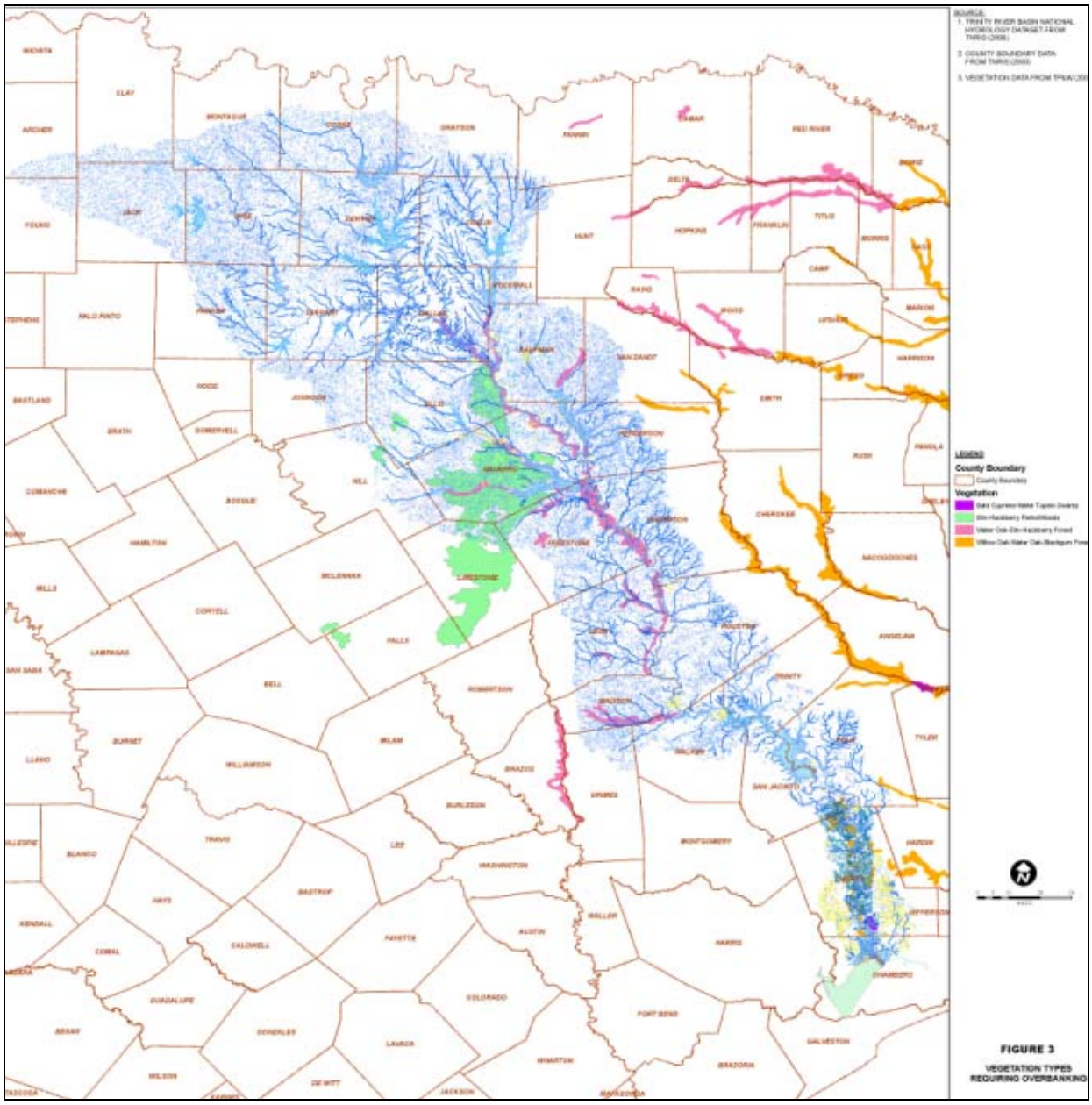

Figure 3. Vegetation Types Requiring Overbanking

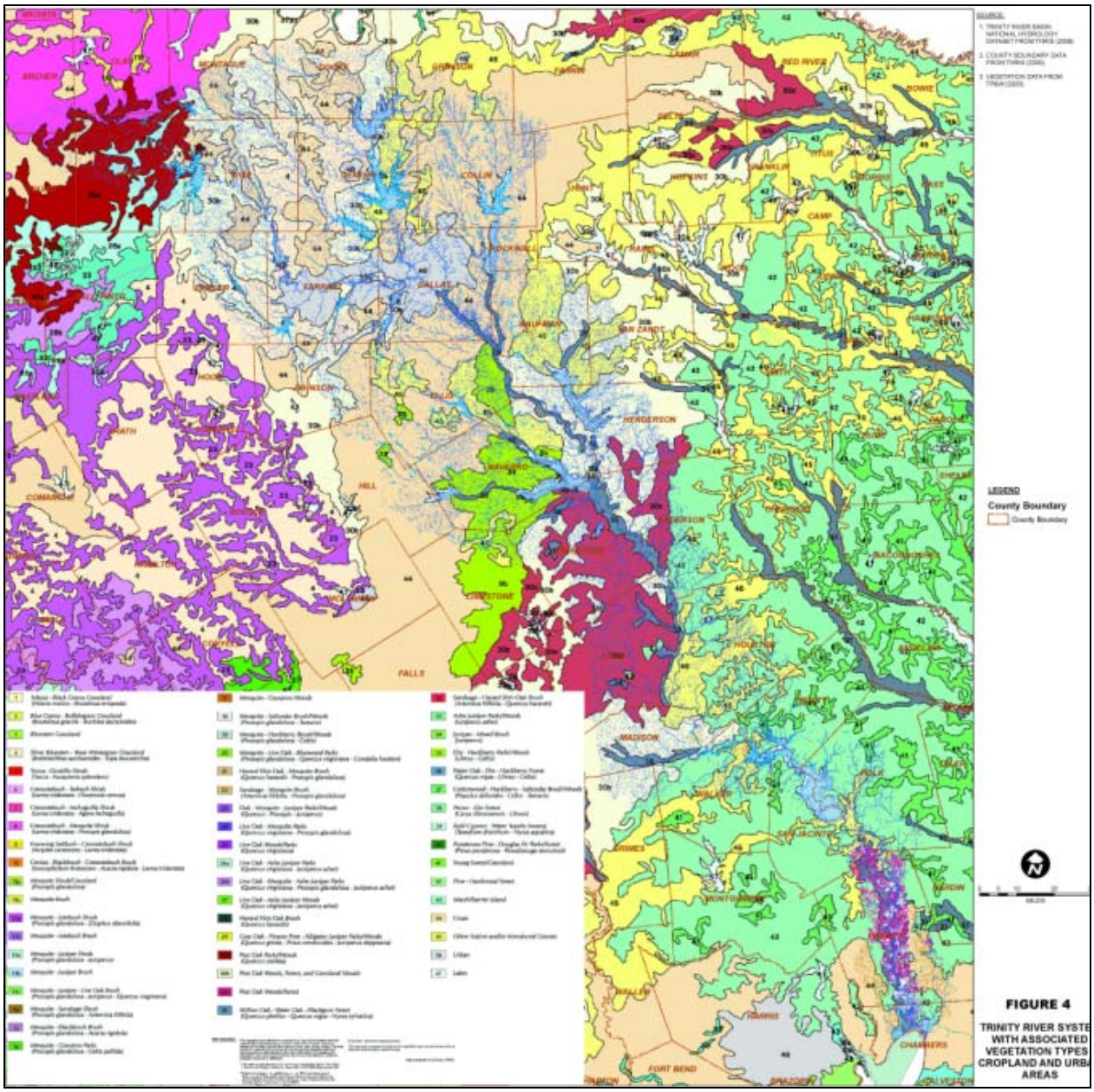

Figure 4. Trinity River System with Associated Vegetation Types Cropland and Urban Areas

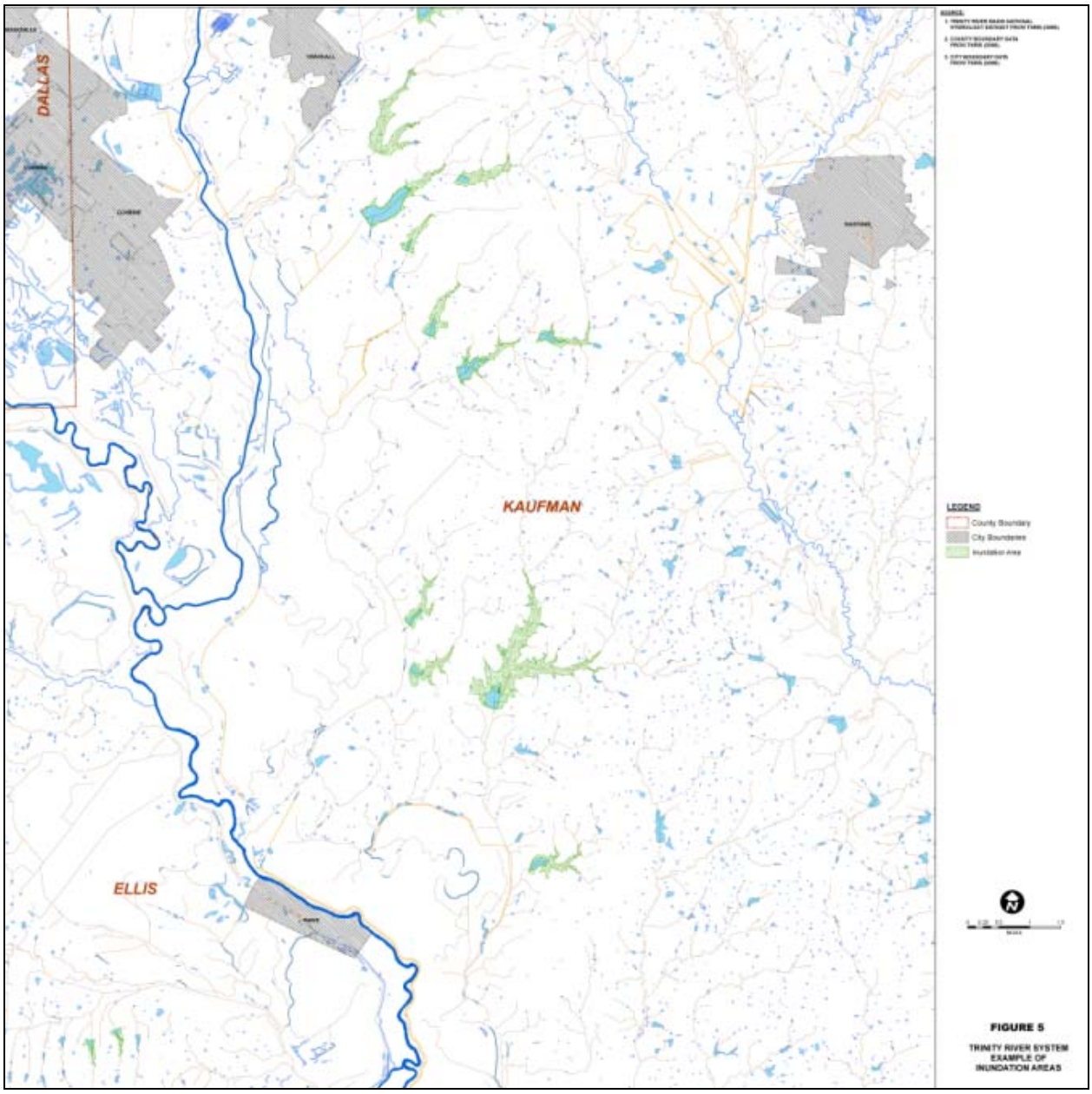

Figure 5. Trinity River System- Example of Inundation Areas

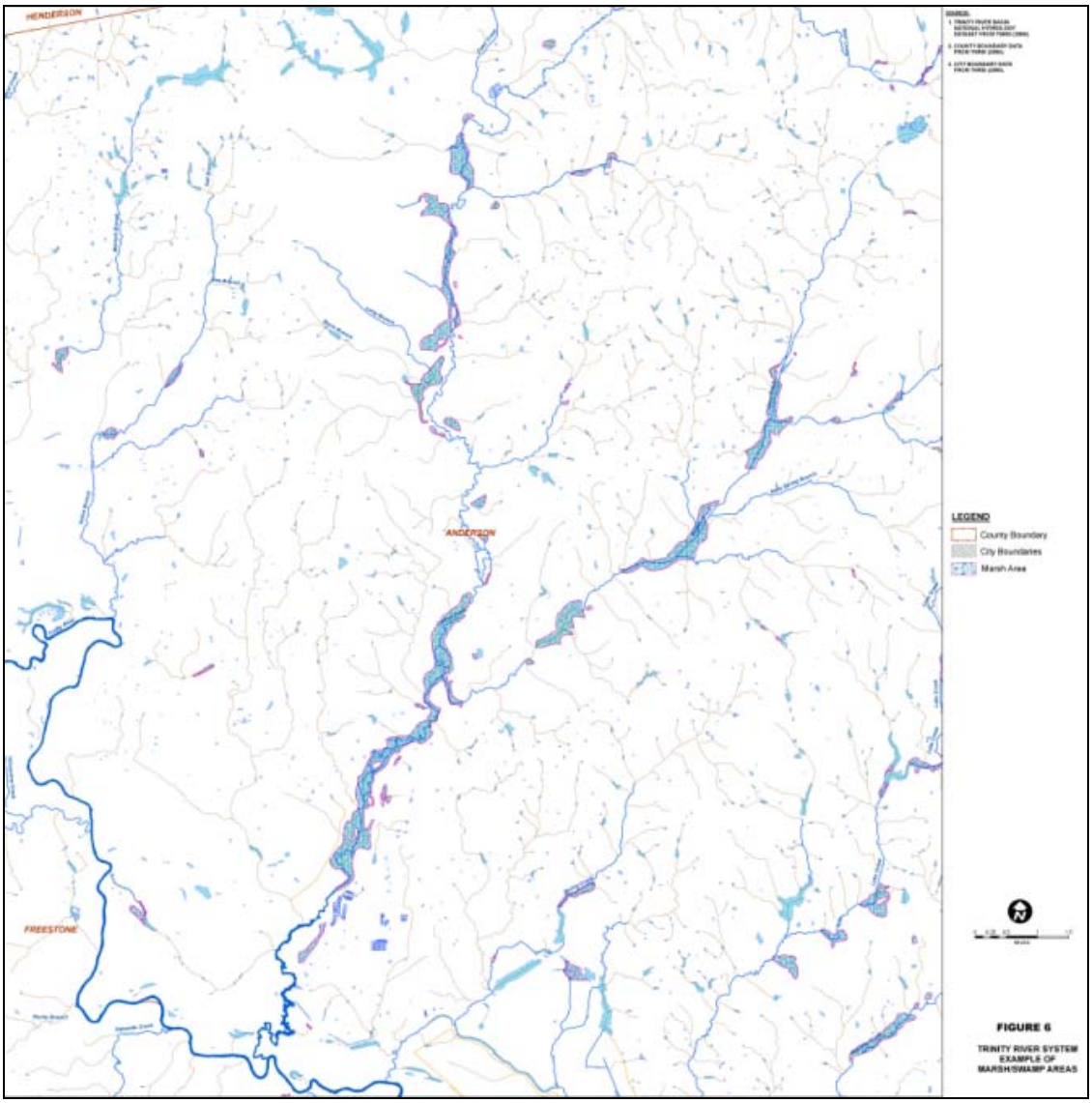

Figure 6. Trinity River System- Example of Marsh/Swamp Areas

SECTION 4. BIOLOGICAL INPUT FOR HEFR

The Hydrology Based Environmental Flow Regime (HEFR) method uses hydrologic statistics to populate a flow regime matrix that is consistent with the TIFP framework (SAC 2009a). Although this method is, at its core, a hydrologic method, there are decision points involved in generation of the flow regime matrix and some or all of those decisions can employ biological input.

This section presents the decision points required for HEFR and identifies those which lend themselves to the use of biological input. The relationship of the decision points to ecosystem functions is not well documented and prudence is required. However, Tables 4 through 7 in this section present a biological rationale for the relationship between the decision points and their related ecosystem functions that can be used by the BBESTs to include biological input in the parameterization of hydrologic models such as HEFR.

The decision points are separated into those that should occur prior to generation of the flow regime matrix (pre-processing) and those that are needed to parameterize both the hydrographic separation method and the HEFR analysis (processing). After the matrix is generated, there are also biological considerations that could further refine the flow regime characteristics. These post-processing decisions are addressed in detail in Section 5.

4.1 HEFR Decision Points

The SAC (2009a) lists a series of decision points for HEFR applications. Some of these decision points have potential biological relevance and can be readily categorized based on where those decisions occur during the process of generating a HEFR based flow regime matrix. Prior to processing a hydrologic dataset, some decisions are needed to guide the analysis as a whole.

For example, in the context of selecting a period of record of gage flows for analysis, the desired ecological condition would need at least some preliminary discussion. In light of the mandate for environmental flow regimes that support a sound ecological environment, just what this environment should look like is a subject of great importance. Within this discussion, consideration should be given to the existing biological and habitat conditions of the river system (factoring in significant alterations that have occurred over time), the historical conditions as best as can be determined, and whether either of these conditions reflect "…a balanced, integrated, and adaptive community of organisms comparable to that of the natural habitat of [the] region" (TCEQ et al. 2008). Examples of sources of information to help make comparisons of historical and current conditions are referenced in Section 2 of this document. (e.g., Bonner and Runyan 2007). Other sources to aid in the discussion of existing ecological conditions and consideration of high-level determinations of ecosystem health include TCEQ aquatic life use

designations (30 TAC 307)[1] and any known impairments to these uses (TCEQ 2008), the descriptions of the TCEQ aquatic life use subcategories (Table 3), TPWD's ecologically significant stream segments (TPWD 2009b), and the concept of a biological condition gradient (Figure 7).

Table 3. Characteristics of Aquatic Life Use Subcategories (from Table 4, 30 TAC 307)

	Habitat Characteristics	Species Assemblage	Sensitive species	Diversity	Species Richness	Trophic Structure
Exceptional	Outstanding natural variability	Exceptional or unusual	Abundant	Exceptionally high	Exceptionally high	Balanced
High	Highly diverse	Usual association of regionally expected species	Present	High	High	Balanced to slightly imbalanced
Intermediate	Moderately diverse	Some expected species	Very low in abundance	Moderate	Moderate	Moderately imbalanced
Limited	Uniform	Most regionally expected species absent	Absent	Low	Low	Severely imbalanced

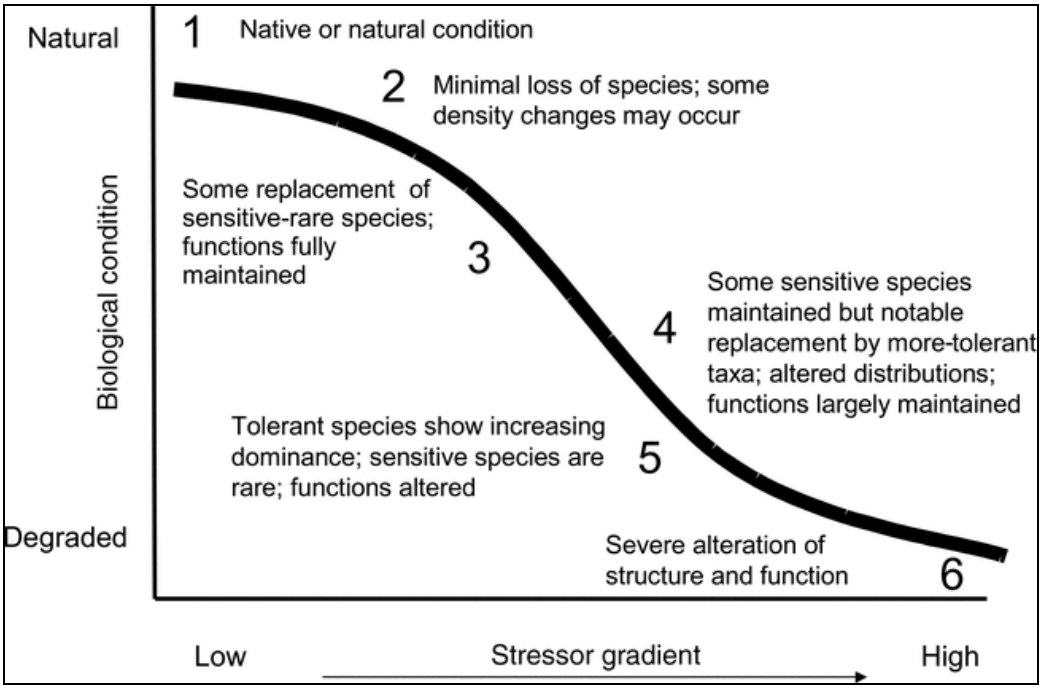

Figure 7. Conceptual Model Depicting Change in Biological Conditions in Response to an Increasing Stressor Gradient (from Davies and Jackson 2006)

[1] Aquatic life use designations typically reflect existing water body conditions and may not represent the desired or attainable use (30 TAC 307.3(a)(3)). In addition, the adoption of these designations require provisions for public notice and hearing (30 TAC 307.2(d)(3) as well as the review and approval of EPA to become effective.

A decision on the desired ecological condition is directly tied to the determination of which set or subset of gage flows would be used in the analysis. For example, in a system where flows are affected by a reservoir, should pre-impact or post-impact flows be used? It is acknowledged, however, that absolute consensus may not be reached on the desired ecological condition of a given river system. In that case, multiple periods of record, such as before and after a reservoir/diversion is in place, can be processed to generate pre-impact and post-impact flow regimes. These regimes could then be compared and the comparison could be used to characterize the degree to which the flow regimes have been altered. Other decisions that occur prior to processing include determination of the number of flow components, and the choice of hydrographic separation tool and episodic event method. Table 4 presents these pre-processing decision points and their potential biological significance.

Table 4. Pre-Processing Decision Points

Pre-Processing Decision Points	**Potential Biological Significance**
Period of Record	Define Desired Ecological Conditions. For example, what are we trying to protect or restore? What is the base period? What are the reference conditions?
Number of Instream Flow Components	Are there any areas where overbanking flows are not ecologically important? Are there any reasons not to include all four flow components in the initial HEFR analysis?
Daily average versus instantaneous flow data	Is mean daily data sufficient? What situations exist (for example species life history concerns) where instantaneous flow data are more important? For example, diurnal feeding patterns and/or migration triggers may be triggered at specific flows within a day……or night?
Hydrographic Separation Tool	Identify the ecologically and biologically important components of the flow regime. For example, do small runoff events provide any of the ecological benefits associated with high flow pulses without necessarily meeting the criteria of a high flow pulse? Is the ecological role of leading and trailing limbs more akin to base flows or high flow pulses? Do very high flows, even if sustained for a period, serve the habitat functions of base flows? Note that high flows and base flows can also serve different habitat functions.
Episodic Event Method	Which flow characteristic(s) should be considered? Duration, volume, and/or peak (magnitude) flow of high flow pulses (HFP) and overbank events? Which method best identifies the flows needed to maintain the ecological functions of a river system? Can only one of the flow characteristics adequately deliver ecological benefits to the riverine ecosystem?

4.2 Biological Input to IHA and MBFIT

Once the pre-processing decisions are made, additional decisions are required to separate the hydrograph into the TIFP flow components (i.e. subsistence flows, base flows, high flow pulses and overbanking flows). Some decisions may be more appropriately made during post-processing, such as whether or not to include overbanking flows or how many hydrologic conditions to include.

For example, from the biological perspective, the percentile values used to separate base flows conditions are largely defined by requirements for aquatic habitats (e.g. runs, riffles, pools). In cases where no habitat data exists, the default separation values can be used, although there is little evidence of a relationship between the default parameters and ecosystem attributes. With respect to overbanking flows, the SAC (2009a) notes that in highly altered areas some components of a natural flow regime may not be appropriate. For preliminary flow regime matrices, all flow components and hydrologic conditions should be included. Decisions regarding which elements, if any, should be eliminated or combined should be made in the post-processing phase using inputs from all disciplines. Tables 5 and 6 indicate the pre-processing decision points for hydrographic separation and their potential biological significance.

Table 5. Biological Input for the IHA Hydrographic Characterization

Decision Points for IHA	**Potential Biological Significance**
HFP upper threshold and lower threshold	Maintain important physical features and riparian connectivity, Provide migration and spawning cues for fish, Community Diversity, Habitat Quality and Quantity
HFP ascending and descending rate of change	Rise rates that are too rapid may wash aquatic organisms downstream before they can find shelter along the river margins. Rapid flow increases can also serve as spawning cues Fall rates that are too rapid may lead to stranding of aquatic organisms in shallow areas.
Small and large flood recurrence interval	Maintain important physical features and connectivity to riparian areas. Provide water and nutrients to floodplain depression pools or backwater sloughs used as spawning areas.
Extreme low flow threshold (subsistence flow threshold)	Is there a flow level below which there would be ecological impacts associated with water quality or significant habitat reduction? Consider Water Quality Concerns, Life Cycle Cues, Provision of Refuge Habitat

Table 6. Biological Input for the MBFIT Hydrographic Characterization

Decision Points for MBFIT	Potential Biological Significance
HFP upper threshold (same as IHA EFC) HFP lower threshold (same as IHA EFC)	Maintain important physical features and connectivity, Provide migration and spawning cues for fish
Extreme low flow threshold	Is there a flow level below which there would be ecological impacts associated with water quality or significant habitat reduction? Consider Water Quality Concerns, Life Cycle Cues, Provision of Refuge Habitat

4.3 Biological Input to HEFR

The final step required to generate a flow regime matrix is to process the outputs from the hydrographic separation through HEFR. The parameters chosen during this phase of the analysis also have biological implications (Table 7). In particular, the choice of seasonal assignments can influence the resulting matrix values both for base flows and for high flow pulses.

The subsistence flow threshold percentile impacts the resulting matrix not only with respect to subsistence flow recommendations, but also for lower base flows. The default method substitutes a 7Q2 value for subsistence flows. In some river systems, particularly when pre-impact flows are used in the analysis, the 7Q2 value can exceed not only the default threshold value (10th percentile) but also the percentile values generated for base flow conditions. HEFR includes an option where the 7Q2 is not substituted for subsistence flow values. It is recommended that the 7Q2 value not be substituted in the preliminary matrix. Issues related to water quality can be addressed as part of post-processing (discussed in Section 5) or as discussed in the Water Quality Overlay document (in preparation).

Table 7. Biological Input to HEFR

Decision Points for HEFR	Potential Biological Significance
Subsistence Flows Threshold Percentile	Is there a flow level below which there would be ecological problems? Water Quality Concerns, Life Cycle Cues, Provision of Refuge Habitat
Multipeaks-Multiplier	Are there ecological justifications to recommend a very long pulse, or should the long pulses be disaggregated into multiple pulses?
Hydrologic Conditions (wet dry, average)	From an ecological perspective are all three conditions needed? (see Colorado IF study) If all three are needed is there specific biological information that should guide the choice of the percentiles?
Water Quality Protection Flow	Can the Subsistence flows be less than published 7Q2? Is it appropriate to recommend flows that may result in the contravention of water quality standards? Are there data reflecting healthy communities at flows below 7Q2?
Seasonality	Provide migration and spawning cues for fish and seasonal flux in water quality (temp, DO). and invertebrates (e.g., mussels, prawns), Examine life cycle length and milestones (reproduction, egg and larval development/diapause, growth, maturity, etc.) of key species and/or assemblages for seasonal alignments, Riparian connectivity may also be more important at certain times of the year.

4.4 Example Application

To illustrate the decision point process described above, the following example details how biological input could be used to parameterize HEFR. This section describes a comparison between a flow regime matrix generated using the HEFR default values (SAC 2009a), and a flow regime matrix generated using site specific data for a particular location. This example is intended as a proof of concept to illustrate how biological information could inform the parameterization of HEFR (or other hydrologic methods), and the underlying decision points needed to produce a flow regime matrix. Note that the flow regime matrix derived from the biological parameterization has not been approved by any BBEST or BBASC, and is simply presented here to facilitate discussions of how biological information could be used in the pre-processing and processing phase of flow regime matrix generation. Additionally, the following example assumes only biological input and does not consider integration with other disciplines such as hydrology, water quality and geomorphology.

4.4.1 Default Method

This example uses USGS Gage 08183500, San Antonio River at Falls City, TX. Figure 8 presents the default flow regime matrix (See Appendix A. of SAC 2009a for the default parameters). For example, IHA was used for flow classification and the 7Q2 value (189 cfs) set the floor for low flows. This 7Q2 value was calculated using a period of record from 1971 through 1996. The full period of record (1926-2008) was used in this default run.

Overbank Flows	Return Period (R) : 2.4 (years)			Duration (D) : 19 (days)		
	Volume (V) : 57323 (ac-ft)			Peak Flow (Q) : 4450 (cfs)		
High Flow Pulses	F: 1	F: 1		F: 1	F: 1	
	D: 6	D: 6		D: 6	D: 6	
	Q: 913	Q: 1000		Q: 986	Q: 1030	
	V: 6957	V: 6433		V: 6987	V: 6060	
	F: 2	F: 2		F: 2	F: 2	
	D: 4	D: 4		D: 4	D: 4	
	Q: 582	Q: 643		Q: 617	Q: 617	
	V: 4217	V: 3763		V: 3283	V: 3599	
	F: 3	F: 3		F: 3	F: 3	
	D: 3	D: 3		D: 3	D: 3	
	Q: 410	Q: 474		Q: 372	Q: 414	
	V: 2063	V: 2335		V: 1684	V: 1881	
Base Flows (cfs)	313	307		253	274	
	230	222		189	192	
	189	189		189	189	
Subsistence Flows (cfs)	189	189		189	189	
	Dec Jan Feb	Mar Apr May		Jun Jul Aug	Sep Oct Nov	
	Winter	Spring		Summer	Fall	

Hydrologic Conditions	
	Wet (75th %ile)
	Average (50th %ile)
	Dry (25th %ile)
	Subsistence

High Flow Pulse Characteristics	
	F = Frequency (per season)
	D = Duration (days)
	Q = Peak Flows (cfs)
	V = Volume (ac-ft)

Figure 8. Flow Regime Matrix Generated With Default Values

4.4.2 Available Biological Data

The modified example uses information from a study of the San Antonio River conducted to assess low flow needs (BIO-WEST 2008). This study did not evaluate the full spectrum of instream flow components. However, sufficient information is available relative to low flows to illustrate how biological input to HEFR pre-processing could be accomplished.

The BIO-WEST study recommended preliminary subsistence guidelines based on habitat mapping and fish habitat modeling. For subsistence flows, backwater habitat disappears below 89 cfs. The 20th percentile flow in the summer months was calculated as 89 cfs. The maximum of the 20th percentile flows (in each month) and 89 cfs was selected so that none of the monthly target flows would drop below 89 cfs. For Base-Dry conditions, the study recommended the 50th percentile flow. The preliminary recommendations are shown in Table 8 below.

Table 8. Lower San Antonio Instream Flow Guidelines (adapted from BIO-WEST 2008, Table 7.1, Page 90)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Subsistence (cfs)	119	124	119	117	115	95	89	89	90	89	102	112
Base Dry (cfs)	197	215	198	202	211	185	150	134	160	163	174	188

In addition, the BIO-WEST study further relates habitat to discharge. For example, runs, riffles and backwaters were maximized when flows exceeded 535 cfs while pools were maximized at around 89 cfs as shown in Figure 9.

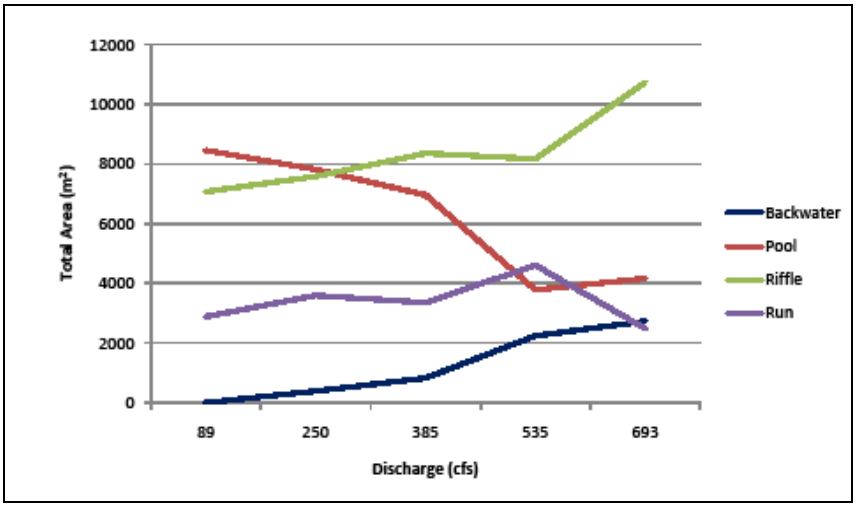

Figure 9. Habitat Types vs. Discharge (from BIO-WEST 2008, Figure 5.5, Page 36)

The study also notes an inverse relationship between available habitat for most guilds and two distinct species identified in the study at flows between 89 cfs and 385 cfs as indicated in Figure 10 below. These analyses were derived from habitat suitability determinations based upon fish collections and associated habitat mapping and modeling, and could help inform decisions about separation of low flow components and their thresholds.

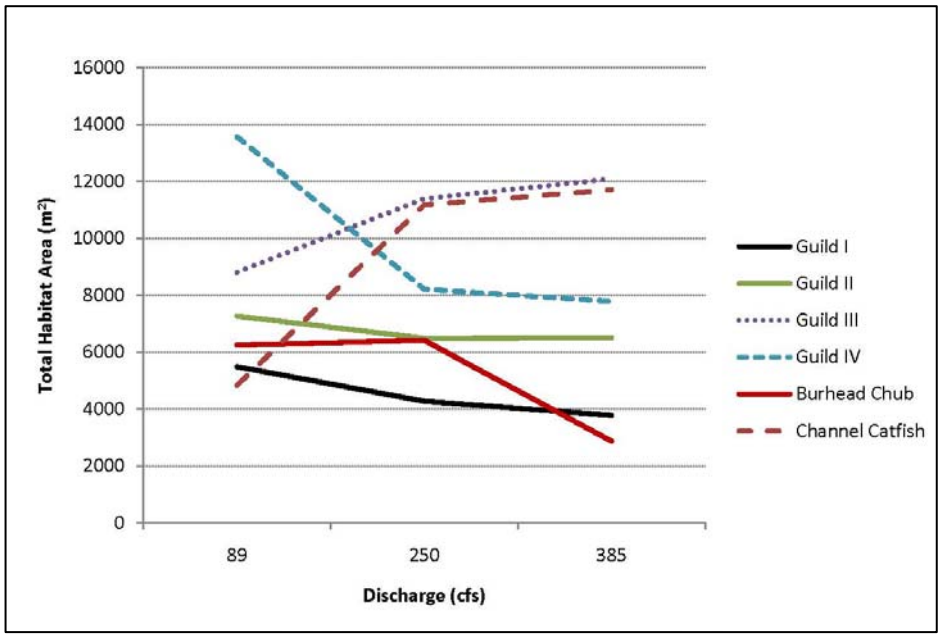

Figure 10. Predicted Fish Habitat per Guild or Species (from Bio-West 2008, Figure 6.8, Page 77)

4.4.3 Application of Biological Data During Pre-Processing

Pre-processing decision points are identified in Table 4 above. At present, flows in the San Antonio River are characterized by elevated base flows resulting from wastewater treatment plant discharges. In a preliminary assessment of the subsistence and dry instream flow components, BIO-WEST (2008) identifies a break point in the hydrologic period occurring in 1971. The flow regime prior to 1971 is more representative of natural conditions and therefore the pre-impact period (1926-1971) was chosen as the period of record for generation of the flow regime matrix. Although the BIO-WEST study did not address the full spectrum of flows, it does, following the TIFP guidance (TCEQ et al. 2008), acknowledge that these flows are "extremely important" and will be addressed in a more complete evaluation. Therefore, there is no reason to modify the number of flow regime components at this time, although this could occur during the post-processing phase as discussed in Section 5, or during the integration of information from various overlays such as sediment transport (SAC 2009b) and Water Quality (in preparation). Daily mean data was deemed sufficient for this proof of concept due to a lack of biological data focusing on the importance of flow differences at the sub-daily level.

Additional decisions during the pre-processing phase include choosing both a hydrographic separation method and an episodic event method. From a biological perspective, the primary considerations for the selection of flow separation have to do with the ecological function that a given flow magnitude is intended to provide and how short term variability or fluctuation may impact these functions. For instance, flows above some threshold may produce unsuitable instream habitat conditions for much of the available area. Above this threshold the instream habitat function generally associated with low flows is no longer of primary importance as many species retreat into velocity shelters or are swept downstream. Likewise, if high flows persist, the initial channel maintenance benefits associated with sediment transport may diminish. Biological information may help to define threshold and variability ranges used to parameterize the flow separation algorithms. The San Antonio River study, (BIO-WEST 2008) because it is focused on low flows, does not bracket preferred instream habitat conditions. However, a previous study on the Colorado River (BIO-WEST 2007) does bracket these conditions (Figure 11).

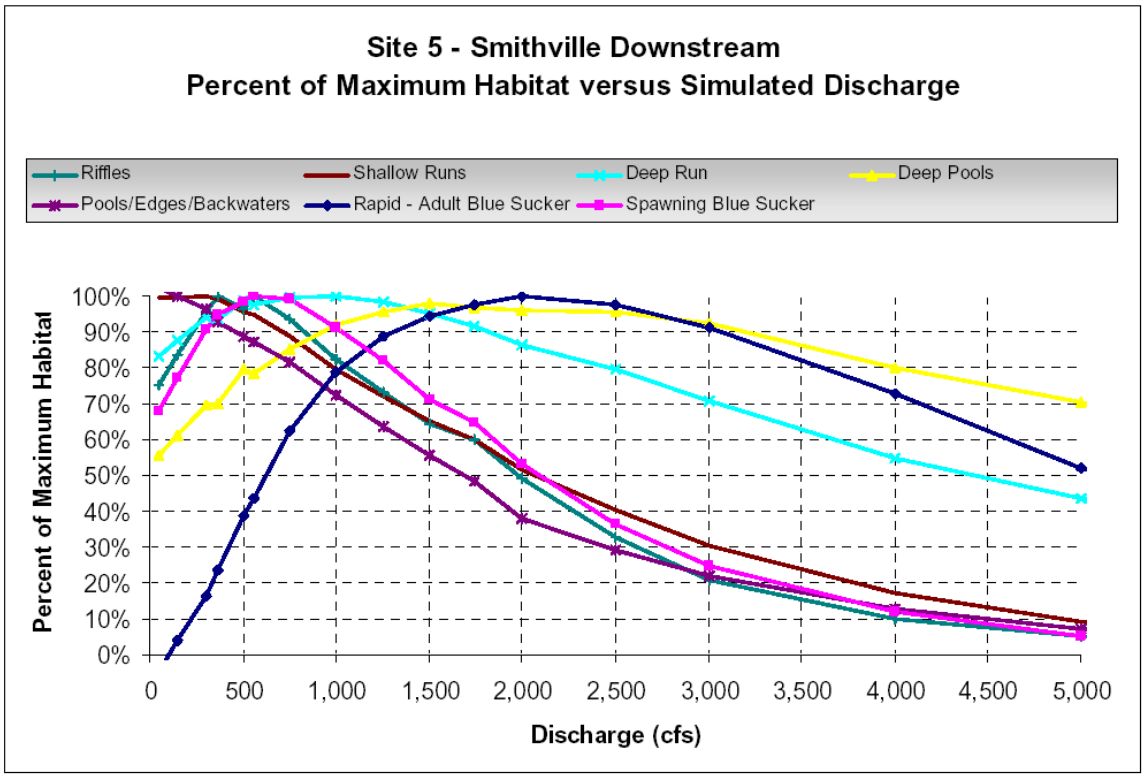

Figure 11. Percent of Maximum Habitat vs. Simulated Discharge at Smithville (from BIO-WEST 2007, Figure C10, Page C6)

For the Smithville site, the majority of mesohabitats become less available above 2000 cfs, which might suggest an upper threshold on baseflow somewhere around and slightly above this level. It should be noted that this example relies on a detailed site specific study. However, this knowledge may also be available from long term experience working in a particular river system.

For the Falls City application, either IHA or MBFIT could be used. There was no biological reason to choose one over the other, therefore the default method (IHA) was selected. The existing instream flow study (BIO-WEST 2008) does provide indication of correlation between habitat, species and flows and therefore provides some indication of specific flow threshold values.

Figure 9 indicates that when flows rise above 535 cfs, runs, riffles, and backwater habitats increase and pools are decreased. Figure 10 indicates an inverse relationship between the availability of various fish habitats when flows are between 89 cfs and 385 cfs. For this application, moderate pulses of 385 cfs and 535 cfs were selected. The alternate method, or frequency-based approach allows the user to select specific flow values and determine the frequency of those particular flow values. Therefore the frequency-based approach was used to compute episodic events.

4.4.4 Biological Input to Hydrographic Separation

Potential biological input to hydrographic separation is identified in Tables 5 and 6 above. As mentioned previously, IHA was used for hydrographic separation. The IHA input was modified to reflect the study information discussed in Section 4.4.2. For example, the HFP lower threshold and the extreme low flow definition were modified so that the flows would be separated based on biological information from the BIO-WEST study. This separation results in subsistence flows that represent an approximation of the 20th percentile flows. In other words, IHA parameters were set so that subsistence flows equaled 40% of both the lowest 50% of flows and a portion of the flows between the 50th and 75th percentile flow that did not meet all high flow criteria. This separation results in subsistence flows that approximate but are just slightly higher than the 20th percentile of all flows. A more in depth statistical approach could produce an exact value but an in depth computation was not conducted for this proof of concept.

The small flood event was designated with the recurrence interval of bankfull discharge. The National Weather Services Advanced Hydrologic Predictions Services (NWSAHPS) describes a stage of 10ft at the Falls City gage as overbank conditions (NWSAHPS 2009). The graph provided by NWSAHPS was used to generate a relationship between river stage and discharge. The 10 ft stage has a corresponding discharge of 6770 cfs. To place small floods near overbank flow in IHA, a maximum annual flow duration curve was used to determine the return interval of a 6770 cfs flood. This return interval was input in IHA and is indicated in Figure 12. In HEFR, the worksheet "Charts_Freq" was used to determine the frequency of an event near bankfull. The value of 6830 cfs was chosen, with a return interval of 5 per 17 years.

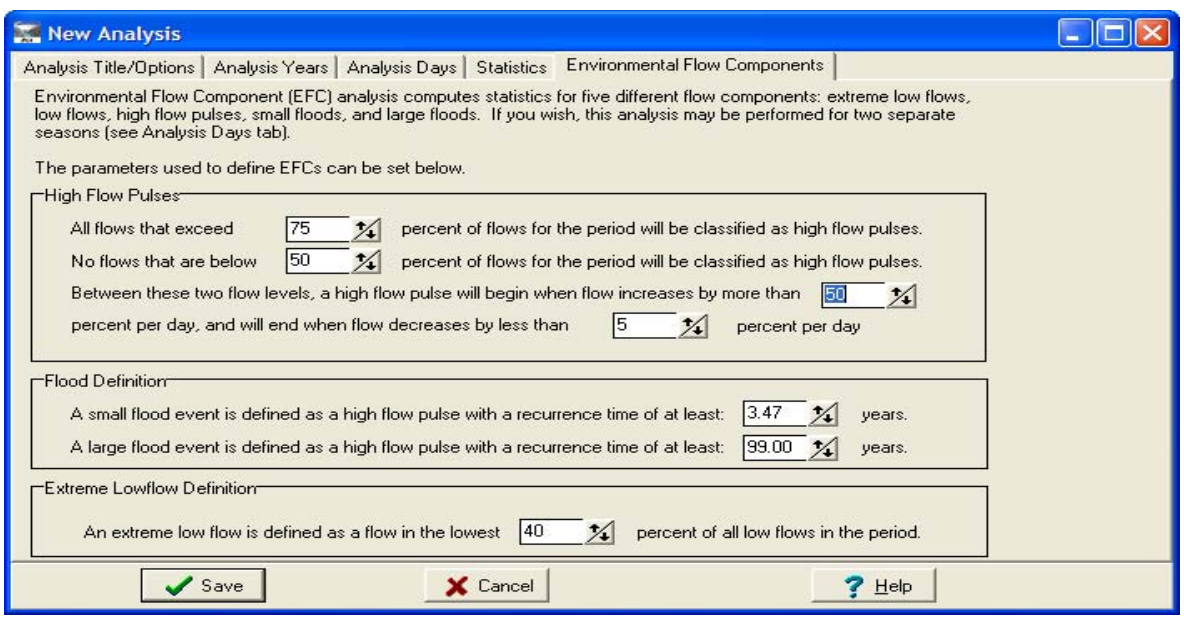

Figure 12. Input for IHA Hydrographic Separation

4.5 Biological Input to HEFR

HEFR provides a user specified seasonality if the default seasonality is not used. However, options in HEFR allow a user specified range of seasons (SAC 2009a). For this application, there was no available biological information that indicated a need to modify the default number of seasons (four seasons). However, for consistency with the approach used in the existing study (BIO-WEST 2008), the default seasonality was modified so that the months were assigned to seasons beginning with January (i.e. January through March, April through June, etc.). Based on the preliminary study recommendations, the 7Q2 value of 189 cfs was not substituted. Instead the subsistence flow threshold was set to 0.5 (the seasonal median) and 89 cfs was inserted for 7Q2 so that the resulting flow regime matrix did not produce recommendations below 89 cfs. There was insufficient information to make a decision with respect to the multipeaks-multiplier. Figure 13 shows the HEFR inputs and Figure 14 presents the flow regime matrix.

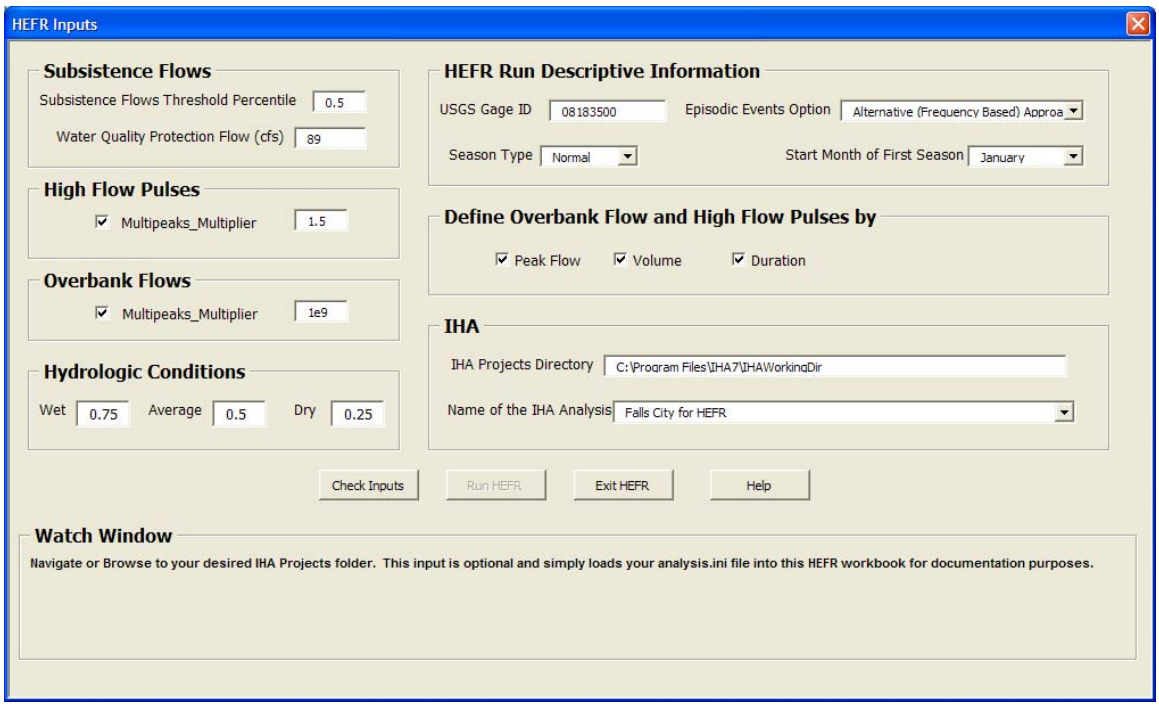

Figure 13. Modified HEFR Inputs

Overbank Flows	Qp: 6,830 cfs with Frequency 5 per 17 years Volume is 67,424 to 99,563 (83,494) Duration is 13 to 43 (23)											
High Flow Pulses	Qp: 535 cfs with Frequency 8 per year Volume is #N/A to 18,718 (2,715) Duration is 2 to 7 (4)											
	Qp: 385 cfs with Frequency 10 per year Volume is #N/A to 16,785 (782) Duration is 2 to 5 (3)											
Base Flows (cfs)	223			221			200			213		
	178			178			170			178		
	144			148			145			152		
Subsistence Flows (cfs)	102			92			89			89		
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Winter			Spring			Summer			Fall		

Hydrologic Conditions	
	Wet (75th %ile)
	Average (50th %ile)
	Dry (25th %ile)
	Subsistence

High Flow Pulse Characteristics	
	F = Frequency (per season)
	D = Duration (days)
	Q = Peak Flows (cfs)
	V = Volume (ac-ft)

Figure 14. Modified Flow Regime Matrix

4.5 Summary

The preceding example illustrates biological input to generation of the flow regime matrix. Figures 15 and 16 below illustrate the differences between the values generated by the default method and those generated with preliminary biological input to HEFR processing. The modifications based on available biological information for low flows did result in a different flow regime, more consistent with the available study results. Note that additional biological information could be available to further modify both the hydrographic separation and processing of the hydrograph by HEFR. This example only used biological data from a preliminary assessment of lower flows and the results could be different if additional data on a full range of flows were considered. The application above was only intended to show how a hydrologic method could be parameterized to reflect biological data. The flow regime matrix resulting from parameterization of HEFR may still need to be modified, refined and confirmed using "overlay" information from all disciplines. Thus, once the flow regime matrix is generated, additional modifications can be made as discussed in Section 5.

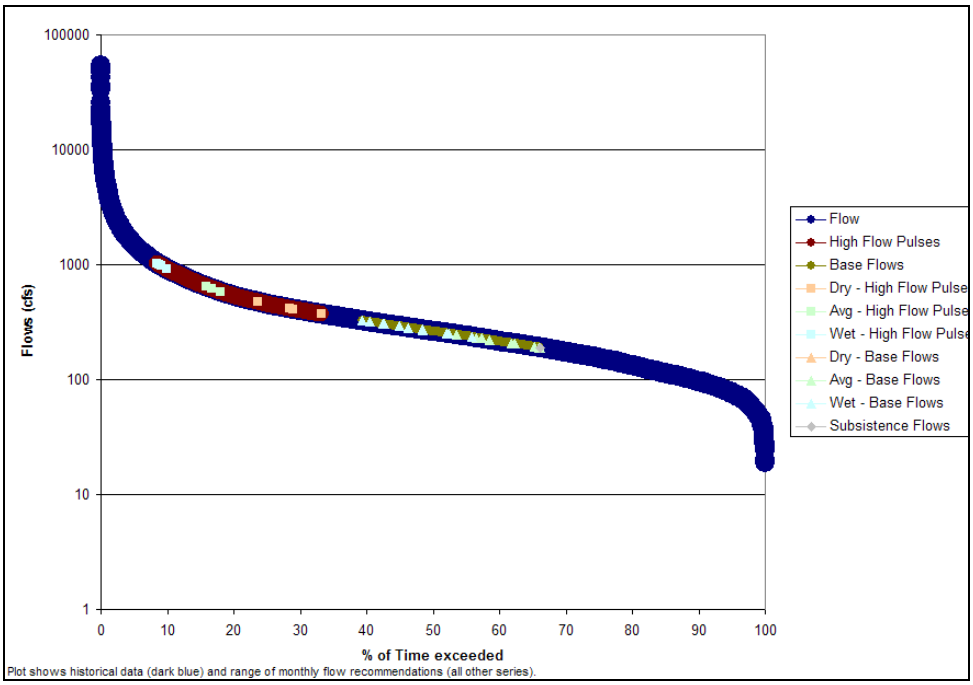

Figure 15. Flow Duration Curve Generated Using the Default Method

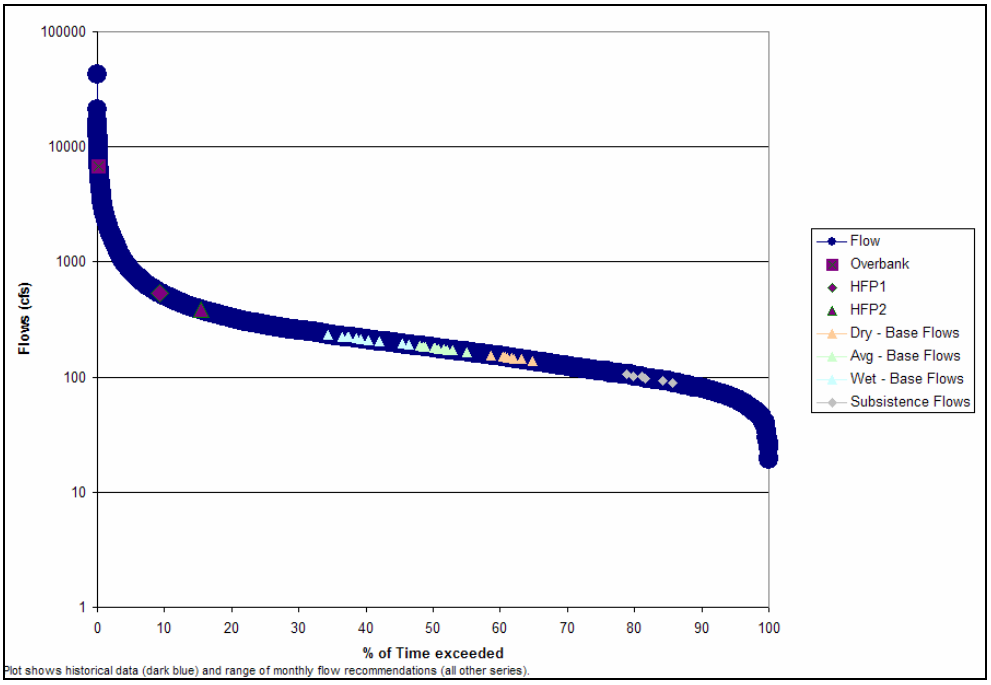

Figure 16. Modified Flow Duration Curve Based on Biological Input

SECTION 5. OVERLAY OF BIOLOGICAL INFORMATION: REFINING THE FLOW REGIME MATRIX

While the previous three sections have described biological information needs and sources, geographic scoping, and pre-processing of biological information for running hydrologic analyses, this section describes the "overlay" process leading to adjustments to the initially populated flow regime matrix (post-processing).

HEFR is one tool that can produce an initial flow regime matrix. Although there are several variations of the HEFR matrix (as presented in Section 4), the basic principle is that the HEFR matrix is consistent with the TIFP framework and comprises instream flow need estimates for four flow components: subsistence flows, base flows, high flow pulses, and overbank flows (SAC 2009a). As appropriate, flow estimates can be produced at different time scales such as monthly, seasonal, and annual and for different hydrologic conditions such as dry, average and wet. The duration, magnitude and frequency of episodic events may also be specified. The initial matrix and its characteristics provide the foundation for overlaying biological information resulting in a refined matrix that better addresses the flow needs of important biological resources, water quality, and geomorphic processes.

5.1 Integration is a Multi-disciplinary Process

Due to the diversity and wide range of stream types and communities in Texas, it should be recognized that application of any hydrologic tool such as HEFR is not a "one size fits all" exercise for estimating instream flow needs. The initial flow regime matrix serves as a surrogate for addressing a myriad of environmental flow requirements, and biological information from the area of interest should be used beforehand to help parameterize a hydrologic analysis and afterwards to refine the initial output. Following the initial calculation of flow regime values at representative points throughout the river basin, a multi-disciplinary integration process should be developed to systematically review those values and assess their efficacy in addressing specific biological, water quality, and geomorphic flow related objectives, concerns and issues. Overlay information from all disciplines should be used to make necessary adjustments and refinements in a systematic manner that would meet the needs of key species in the system. This requires getting the right flow regime to create and maintain habitat, maintain suitable water quality, and to provide the appropriate life cycle environmental cues and opportunities for survival, growth, and reproduction. It is recognized that best professional judgment will likely be a necessary element of this approach, and the rationale for all evaluations and refinements should be clearly and consistently documented. An integration workshop is an efficient option to consider.

Workshop objectives could include:

- Review initial matrix and its characteristics
- Review summary reports including conceptual models

- Review representative focal species or guilds (aquatic and terrestrial) and their life histories
- Review linkages between flow components and biotic tolerances (e.g., dissolved oxygen) and dependencies (e.g. habitat)
- Identify important seasonal (or other temporal scale) cycles and timing of life history events
- Confirm or refine flow estimates using these linkages, relationships and professional biological judgment
- Assess whether both short-term and long-term dynamics of habitats, as affected by hydrology, will be sufficient to maintain focal species or guilds
- Identify major uncertainties and data gaps and prioritize research needs.

Biological information selected for refining the flow matrix should be organized relative to the four flow regime components using the suite of questions articulated in Section 2 to help guide inquiries. Table 1 (Section 1) provides an overview of some ecological roles of the four flow regime components.

5.2 Subsistence Flows

Two of the key objectives in identifying subsistence flows are ensuring that water quality is maintained and key habitats are available and accessible by focal species and/or guilds. Data from water quality monitoring programs and water quality models can be used to double check flow values produced through hydrologic analysis. If flow values in the subsistence component will not maintain important water quality parameters at all times, then stream flows during specific months or seasons in which they are deficient need to be discussed and refined. Some water quality models can be used to determine flows that maintain water quality standards or other important parameters. Output deemed reliable can be used to justify revisions. Important water quality parameters might include temperature criteria for different life history stages including survival, growth, and reproduction; dissolved oxygen concentrations relative to known tolerances or standards; and others. For example, in a study of the San Marcos River, Saunders et al. (2001) used the SNTEMP temperature model to evaluate spring flows needed to maintain spring run characteristics including temperature criteria for the endangered fountain darter *Etheostoma fonticola*. They found that at spring flows less than 65 cfs those characteristics were not maintained.

Another example involves using available habitat information such as observation, data, or modeling. In the San Antonio River example discussed in Section 4, habitat area-streamflow relationships (Figures 9 and 10) were evaluated to identify preliminary subsistence flows. Those specific recommendations could be used to replace, confirm, or refine hydrology-derived subsistence flows as needed and where possible. Alternatively, the specific habitat area-streamflow relationships and even the underlying modeling can be re-evaluated or re-interpreted to construct new recommendations and refinements. In other river systems or segments, habitat-based instream flow assessments targeted at very low flows may not be available. In those cases empirical visual observations, cross-section ratings, and other hydraulic methods may be used. The availability and reliability

of cross-sections and associated rating curves will need to be critically evaluated to ensure cross-sections accurately represent some form of important or limiting habitat. It is also important to understand biotic relationships to that habitat to provide insight on seasonal or environmental factors that may be most important. Cross-section ratings can be used to evaluate relationships between wetted perimeter or width and stream flow; important breaks or inflection points in those relationships may indicate a critical flow level. Figure 17 illustrates a normalized wetted width-spring flow relationship for three habitat types in the San Marcos River (Saunders et al. 2001). In the main channel, the curve for riffle habitat begins declining rapidly at flows beginning around 100 cfs. This flow level was used to help describe spring flow effects on ecosystem characteristics. Similar analyses could be used to refine hydrology-derived recommendations. A discussion of the advantages and disadvantages of hydraulic rating methods can be found in Annear et al. (2004).

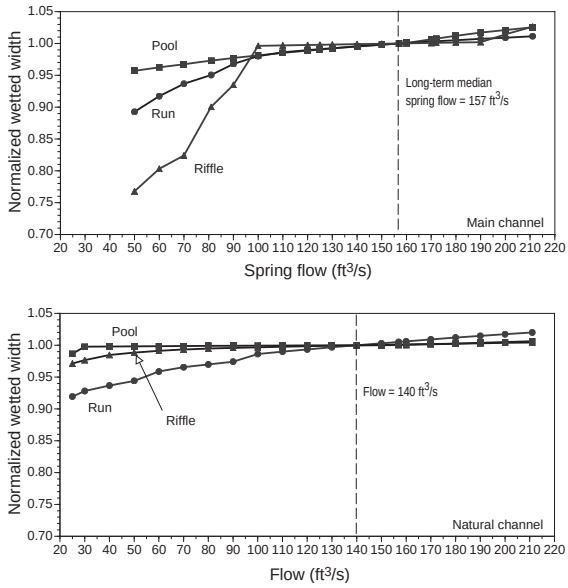

Figure 17. Wetted Width Relationships to Spring Flow in the San Marcos River (from Saunders et al. 2001)

Surveys and hydraulic models of longitudinal profiles can also be used to assess longitudinal connectivity. Information needs to address other important ecological roles can be developed and evaluated in a similar manner.

5.3 Base Flows

Ecological roles of base flows include providing suitable habitat, maintaining habitat diversity, and supporting the survival, growth, and reproduction of aquatic organisms. Base flows are also important for riparian areas (Table 1).

Information on indicator or focal species can be used to confirm and refine base flow estimates. Specifically, quantified flow-ecology relationships discovered in literature reviews can be used directly by comparing hydrology-derived estimates with specific

flow requirements. Qualitative life history information and conceptual models of focal species' life cycles can also be used (see Section 2 and Winemiller et al. 2005). For example, data on fish spawning seasons can be used to evaluate the timing of higher base flows and other flow components. Information on basic habitat use for different life stages of a species can indicate the pattern and range of flows needed across seasons. As a suite of focal species is evaluated in this and other ways, patterns may emerge supporting validation or highlighting concerns with base flow estimates in different months or seasons or across dry, average, and wet hydrologic conditions.

The variety of tools that can be used in determining instream flows needed to support suitable habitat (i.e. quantity and quality) range from desktop methods such as the Lyons Method (TRG 2008), hydraulic habitat rating methods, and incremental methods that relate habitat quality, quantity, and diversity to stream flow (Annear et al. 2004, NRC 2005, Locke et al. 2008, TCEQ et al. 2008). Many field-based instream flow studies have been performed across the state of Texas at varying levels of complexity; often these studies were performed in support of a regulatory process or proposed water development project. Before results from these studies are used in a biological overlay process, an evaluation of the scope and purpose of individual studies should be conducted to ensure that the studies are focused on maintenance of a sound ecological environment. Study limitations should be critically evaluated to ascertain the utility of the study results in refining hydrology-derived estimates.

Habitat-flow assessments produce a measure of habitat such as weighted usable area or diversity as a function of stream flow and may be useful in evaluating hydrology-derived base flows. There are numerous ways to explore these datasets (see TCEQ et al. 2008 for a discussion). As a recent example, habitat models were reconstructed for use in the Environmental Flows Project for Caddo Lake and its tributaries. These models were evaluated at a December 2008 workshop as to their utility for updating flow prescriptions.[2] Although no adjustments were made at that time, research needs were identified to improve model accuracy and utility.

If habitat models are available, then at least two approaches can be used to assess biological response. One approach compares recommendations from the model directly with hydrology-based estimates. The second approach uses hydrologic time series to run through the habitat model to get habitat time series. Time series analysis can highlight the location of habitat bottlenecks and the distribution of habitat availability through time, among other analyses (see Stalnaker et al. 1996 and TCEQ et al. 2008 for more discussion). Such tools could also be used to compare habitat time series using different HEFR settings, hydrologic records, and algorithms.

Again, not all river basins, tributaries or segments will have site-specific instream flow evaluations. As with subsistence flows, hydraulic rating methods may be used if "quality" cross sections can be located or new data collected; ratings for limiting or key habitats would be most critical and could be collected in a relatively short period of time if a wide range of flow levels were available. Additionally, information from instream

[2] Trungale 2008. http://www.caddolakeinstitute.us/decflowsmeeting08.html

flow assessments on nearby systems or similar river types can be evaluated to ascertain if similar habitat-flow relationships would be expected. If so those models may be relevant sources to evaluate initial flow regime estimates. Habitat suitability criteria can also be transferred, although with caution as noted in Section 2.

5.4 High Flow Pulses

Some ecological roles of high flow pulses are outlined in Table 1. High flow pulses shape physical habitat of the river channel, contribute to sediment transport and flushing of silt and fine particulate matter and provide other geomorphic and water quality functions. Biological roles include providing spawning cues and habitat for some species of fish and facilitating connectivity to oxbows and other wetlands. The timing of high flow pulses may be critical for triggering spawning migrations or actual spawning events. The magnitude and duration of high flow pulses can also be double checked with known life history requirements. For example, pulse characteristics for paddlefish *Polyodon spathula* spawning were developed in the Caddo Lake Environmental Flow Project using qualitative information summarized in Figure 18. (Winemiller et al. 2005) . Specifically, a pulse of 1500 cfs lasting 2-3 days to occur every March was identified to support paddlefish.[3]

Another example, well documented in Mosier and Ray (1992) and BIO-WEST (2007), involves blue sucker *Cycleptus elongatus* spawning on the Colorado River, Texas. Information from these studies could be directly used in assessments on the lower Colorado River but could also be used to inform flow requirements in other river systems where blue sucker currently exist or have historically occurred.

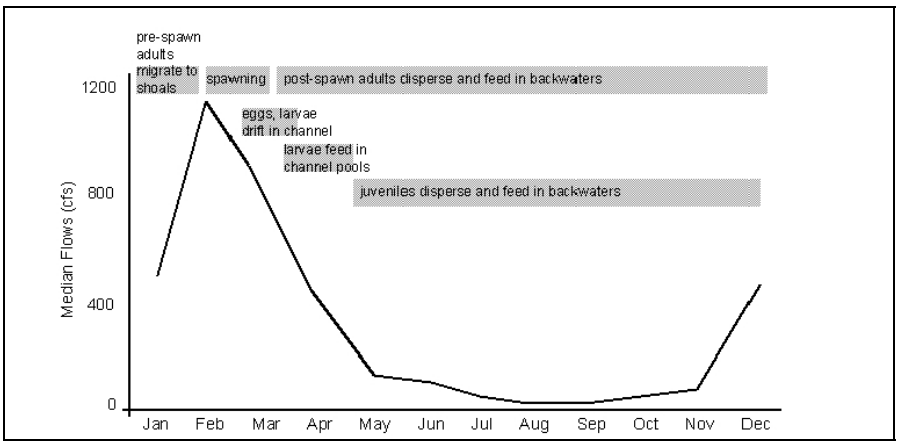

Figure 18. Paddlefish Life Cycle in Relation to Seasonal Flow in Big Cypress Bayou (from Winemiller et al. 2005)

Approaches to address lateral connectivity to oxbows include reviewing available life history information, conducting targeted sampling, and hydraulic modeling to identify flow levels needed to provide connections. Other ecological roles can be addressed by identifying information relating that role to stream flow.

[3] http://www.caddolakeinstitute.us/may05.html

5.5 Overbank Flows

In addition to supporting major geomorphic processes (SAC 2009a), overbank flows provide lateral connectivity for aquatic organisms to floodplain areas and maintain the balance and diversity of riparian zones. Assessments of lateral connectivity include reviewing available life history information of aquatic and riparian species, constructing conceptual models depicting flow-ecology relationships and needs, and evaluating the performance of overbank flow estimates in meeting those needs. Studies of fish assemblages using floodplain habitat such as oxbow lakes for different life stages are available for some Texas rivers (Winemiller et al. 2004). Information on the hydraulic conditions needed to spill onto the floodplain can be derived from field based or desktop hydraulic assessments or by using flood stages identified by the National Weather Service, for example. Desktop approaches using digital elevation models have been used to relatively quickly develop relationships between magnitude and inundated floodplain area. More complex hydraulic approaches include the area of inundation approach outlined in TCEQ et al. (2008). Hydraulic information coupled with life history information for riparian species and their inundation characteristics (timing, duration, frequency, etc.) can be used to check and refine hydrology-derived characteristics of overbank flows.

5.6 Adaptive Management

SB 3 envisions an adaptive management process for revisiting the environmental flow standards and environmental flow set-asides derived through the TCEQ rulemaking procedure. The TCEQ is responsible for establishing a schedule for considering modifications to adopted environmental flow standards and set-asides and must take into account the work plans devised by the bay/basin area stakeholder committees that are required to be prepared under SB 3. It is these work plans that establish the scope and schedule (at least once every 10 years) for reviewing, validating, and/or refining through an adaptive management process, the environmental flow analyses and flow regime recommendations and the environmental flow standards and set-asides for each bay and basin area. To the extent that water rights permits issued or amended on or after September 1, 2007 may contain environmental flow provisions, these environmental flow requirements may be adjusted by the TCEQ based on the adoption of environmental flow standards or the outcome of the adaptive management process; however, any increase, in combination with similar previous increases, in the requirement for bypassing or releasing flows for environmental purposes is limited to 12.5% of the annualized amount of the originally permitted requirement.

The SB 3 adaptive management process envisions that additional data, information, and studies will be necessary in order to make informed decisions regarding any future changes to the environmental flow standards and set-asides. Provisions for how this continuing work will be undertaken will be described and outlined in the work plans developed by the bay/basin area stakeholders committees assisted by their BBESTs. The on-going TIFP studies will provide useful information, but more will likely be needed.

In particular, dependence upon hydrology-based environmental flow recommendations, which may be largely required to meet the aggressive time frames specified in SB 3, highlights the need for future adaptation of the adopted flow standards. Basing a recommended flow regime solely on analysis of a selected historical hydrology period presumes that maintenance of these flow regime components will achieve the sound ecological environment objective. This should be viewed as a “default” approach. While application of the pre- and post-biological overlay process described herein can substantively improve the hydrology-based recommendations, future refinements and validation will accrue only from the use of new and better science envisioned through the adaptive management process.

SECTION 6. SUMMARY AND RECOMMENDATIONS

The focus of this document is on the importance of instream flows for protecting aquatic resources in the streams and rivers of Texas. This document reviews the types of biological information and data that should be used by the BBESTs in developing and refining an environmental flow regime pursuant to the requirements of Senate Bill 3.

Senate Bill 3 provides that the BBESTs develop an environmental flow analysis and a recommended environmental flow regime that is defined as a "schedule of flow quantities that reflects seasonal and yearly fluctuations that typically would vary geographically, by specific location in a watershed, and that are shown to be adequate to support a sound ecological environment and to maintain the productivity, extent, and persistence of key aquatic habitats in and along the affected water bodies." Such instream flow regimes will have to be developed by BBESTs recognizing the inherent variability in stream systems and river type within basins and throughout the state.

Due to the range of temperature and precipitation in the state, and the geographic expanse of Texas, there can be large differences between streams in the upper and lower part of a river basin, and between streams in different river basins. Flow regimes can generally have regional patterns that are determined largely by river size and by geographic variation in climate, geology, topography, and vegetative cover. A river or stream's flow regime is key to variation in other physical and biological components of the stream ecosystem. Flow regimes that contain the most critical components (magnitude, frequency, duration, timing, and rate of change) of the fluvial system's natural flow regime have the greatest probability of sustaining the integrity of the natural ecosystem, while post-development flow regimes have no doubt resulted in altered ecosystems.

The time frame specified by SB 3 for the BBESTs to develop environmental flow recommendations is aggressive and necessitates the use of existing data and information. Furthermore, without site-specific and detailed data describing and quantifying important relationships between flow and aquatic organisms, as is the case for most of the river and bay systems across the state, the SB 3 approach to developing recommended environmental flow regimes often may have to rely on assuring that some selected historical hydrologic period characteristics of an aquatic system are maintained. This, of course, is one of the primary reasons for the development and use of HEFR as a tool to quickly develop environmental flow recommendations consistent with the TIFP framework and current trends in instream flow science. The environmental flow recommendations, and the environmental flow standards and flow set-asides that originate through the SB 3 process will be subject to continual review, validation and refinement through the adaptive management process that is contemplated and required by the SB 3 legislation.

The previous sections of this document provide information on the diversity of stream types in the state, current concepts in instream flow science, and the development of an instream flow regime framework (Section 1); the information needed to develop a biological overlay within the context of SB 3 (Section 2); the application of biological information to inform the geographic scope of instream flow recommendations (Section 3); development of input for addressing decision points used in hydrologic evaluations including HEFR (Section 4); and the application of a biological overlay process to further refine the initially populated flow regime matrix (Section 5). The SAC offers the following summary and recommendations from the information presented herein:

Recommended Procedure

STEP 1. Establish clear, operational objectives for support of a sound ecological environment and maintenance of the productivity, extent, and persistence of key aquatic habitats in and along the affected water bodies.

Section 4.1 includes a brief discussion of factors that could be considered during the BBEST's deliberations on operational objectives. This step should also address input from all disciplines.

Suggested operational objectives include:

a. Maintain native biodiversity to the extent that is reasonable given recent climatic conditions, major infrastructure developments, and biological invasions.
b. Maintain environmental quality and ecosystem productivity in support of this biodiversity and the recreational, commercial, and aesthetic uses of the renewable natural resources that it provides.
c. Maintain both short-term and long-term dynamics of habitats that support native biodiversity.

STEP 2. Compile and evaluate readily available biological information and identify a list of focal species.

Review readily available information for important species in the basin of interest. Early in this process, a list of focal species should be identified, and these species will be the focus of the biological overlays. Care must be taken to identify a suitable set of species that, when their ecological requirements are met, will provide broad protection for most of the biological components of the ecosystem including instream and riparian resources. When reviewing and summarizing studies and findings for the basin of interest, certain kinds of biological and other ecological information desired for the analysis may be sparse or completely lacking. In such instances, the options include use of biological data from adjacent river systems, inferences based on life history information compiled from the literature, and reliance on general habitat suitability criteria developed for species from multiple regions. A detailed discussion of these issues and information sources can be found in Section 2.

STEP 3. Obtain and evaluate geographically-oriented biological data in support of a flow regime analysis.

Data reports and geographically descriptive analyses from the results of work described in Section 2 should be compiled in a map format. The geographic distribution of identified river types should be estimated. Existing maps such as NHD maps should be utilized as base maps since much useful non-biological data is available such as location of perennial streams, riparian and floodplain areas that flood under overbanking flows, and locations of contiguous habitat areas such as marshes, oxbows, and abandoned channel lagoons. To view the example maps displayed in Section 3 at enhanced scale resolution, please access this site:
<http://www.tceq.state.tx.us/permitting/water_supply/water_rights/eflows/resources.html>.
Data should be assembled on base maps at appropriate scales of resolution. Such data may include species distribution throughout the basin or portions thereof, the geographic range of state and federally listed Threatened or Endangered fish species and species of concern, and location of any critical habitat or sensitive areas. Set goals in map creation such that the maps produced will provide input to the flow regime analysis.

STEP 4. Parameterize the flow regime analysis using ecological and biological data

Biological information should inform the flow regime analysis, e.g. parameterization of HEFR (or other hydrologic methods), and the underlying decision points needed to produce a flow regime matrix. Some decisions should occur prior to generation of the flow regime matrix (pre-processing). These include the period of record for the analysis, the number of instream flow components and choice of hydrographic separation method. Once pre-processing decisions are made, decision points for modification of default parameters for both the hydrographic separation method and the HEFR analysis (processing) can be accomplished with available biological data in order to generate a flow regime matrix. A specific example, using information from a low flow study is provided in Section 4.

STEP 5. Evaluate and refine the initial flow matrix

The initial flow regime matrix produced by the flow regime analysis should be evaluated to ensure that the components of the biological system, their water quality requirements, and geomorphic processes that create and maintain their habitats are maintained. This final step is perhaps the most critical one in the environmental flow evaluation process. Table 1 (Section 1), Table 2 (Section 2) and Tables 5 through 7 (Section 4) all provide guidance to maximize the probability of success in protecting key biological components and the essential ecosystem dynamics that support them. A multidisciplinary integration workshop is one option to efficiently evaluate and refine the flow regime matrix (Section 5.1).

General Recommendations

1. Quantification of biology based flow parameters

The BBESTs should examine sources from the literature review, assess them for relevance and identify any statements, data, or graphs that specifically link aspects of the flow regime with biota or key ecological processes. It is important to document key habitat requirements and preferences of focal biological species and assemblages.

2. Causal connections based on available data and known relationships

It is recommended that the BBESTs portray the flow-ecology relationships and ecological processes in a conceptual model. Conceptual models provide a concise way to portray ecological knowledge and show hypothesized linkages between flow and various aspects of ecosystem health, or a species' dependence upon certain flow conditions to complete a particular life history stage. The process of conceptual modeling usually results in identification of key uncertainties and information gaps in flow-ecology relationships. When possible, statistical correlations between flow conditions and various ecosystem components or species should be explored to provide a cursory evaluation of the strength of these relationships.

3. If there is existing data that links aspects of the flow regime with biological information, this information should be used to parameterize the flow regime analysis, e.g. HEFR

Based on the quantification of flow parameters, development of causal connections and geospatial information, information may be available that specifically links biological information to aspects of the flow regime. Biological input for some pre-processing decision points, such as number of flow regime components and period of record for the analysis, should be considered by the BBESTs in the process of generating preliminary flow regime matrices. Even if specific biological information is not available to inform all decision points in the hydrographic separation, any available information should be used. For generation of the flow regime matrix, the BBESTs should consider both specific and more general biological information, particularly with respect to seasonality, to modify the default parameters and generate the initial flow regime matrix.

4. Subsistence flows should maintain water quality and key habitat considerations

Subsistence flows need to be sufficient to support key habitats and habitat needs for focal species, populations, or guilds of representative flowing-water organisms and adjustments should be made to minimize or avoid loss of key habitats and needs, to the extent possible. Flows should be evaluated and adjusted to ensure water quality parameters (e.g. DO and temperature) are maintained in a suitable range to ensure aquatic life persists/endures. Relationships between water quality parameters and flow should be quantified to the extent that information is available. Available water

quality models should be evaluated and updated, if warranted and possible, for examining site-specific DO and temperature relationships.

5. **Base flows should be identified that provide suitable and diverse habitat conditions and support the survival, growth, and reproduction of aquatic organisms**

   To the extent available, information on focal species can be used to confirm and refine base flow estimates. Specifically, quantified flow-ecology relationships discovered in literature reviews can be used directly by comparing statistical (e.g. HEFR-derived) estimates with specific flow requirements. Qualitative life history information and conceptual models of species' life cycles can also be used. The Freshwater Fishes of Texas website has compiled much of this information for many Texas fishes and can be accessed here http://www.bio.txstate.edu/~tbonner/txfishes/.

   A variety of tools can be used to evaluate suitable habitat. Desktop methods can be used where limited information is available. Where cross-sections and rating curves are available, hydraulic rating methods can be used to relate habitat-flow relationships. Incremental methods that relate habitat quality, quantity, and diversity to streamflow may be available for some rivers.

6. **High flow pulses have important roles in maintaining water quality, physical processes, connectivity, and biological processes.**

   Pulse characteristics (such as the magnitude, timing, duration, and frequency) should be evaluated and refined relative to life history information for focal species, to the extent available. Approaches to address lateral connectivity to oxbows or other riparian habitats include reviewing available life history information, conducting targeted sampling and hydraulic modeling to identify flow levels needed to provide connections.

7. **Overbanking flows support geomorphic processes, provide lateral connectivity, and maintain the balance and diversity of riparian areas.**

   Assessments of lateral connectivity include reviewing available life history information of aquatic and riparian species, constructing conceptual models depicting flow-ecology relationships and needs, and then evaluating the performance of the HEFR matrix overbank flows in meeting those needs.

   Studies of fish assemblages using floodplain habitat, such as oxbow lakes, for different life stages are available for some Texas rivers and can be used to identify important overbank flow-ecology relationships.

   Information on the hydraulic conditions needed to spill onto the floodplain can be derived from field based and desktop methods (Section 5.5.).To the extent available, hydraulic information coupled with life history information for riparian species and

their inundation characteristics (timing, duration, frequency etc.) can be used to check or refine statistically derived characteristics of overbank flows (e.g., from HEFR runs).

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May 29, 2009

Transmittal to Basin and Bay Expert Science Teams (BBESTs)

Report # SAC-2009-04

Title: Fluvial Sediment Transport as an Overlay to Instream Flow Recommendations for the Environmental Flows Allocation Process.

The attached document constitutes another deliverable from the Senate Bill 3 Science Advisory Committee (SAC) to assist the BBESTs in carrying out their responsibilities to develop instream environmental flow regime recommendations. This document deals with the issue of sediment transport, and presents information for the BBESTs to consider as a possible overlay to HEFR-based results, in particular to assess impacts on sediment loads resulting from HEFR-based hydrologic evaluations.

The document reviews various methods for assessing suspended-load and bedload transport, and recommends that the BBESTs consider application of the SAM Hydraulic Design Package for estimating effective discharge. A detailed example is presented, cautioning that it presents a worst-case scenario in which annual flow volumes are strictly limited to the HEFR-prescribed results in all respects.

While the SAC does not believe that sufficient data exists to directly prescribe a "sediment load regime" that would maintain instream ecology, we do suggest that the information contained in this report, in particular the SAM model, can be used to validate HEFR-based flow regimes from the perspective of sediment transport impacts.

The SAC is hopeful that the BBESTs will find this information useful in their deliberations, and we invite feedback as we all move forward with our respective responsibilities under SB3.

Robert J. Huston, Chairman, SB3 Science Advisory Committee

WORKING DRAFT

Fluvial Sediment Transport as an Overlay to Instream Flow Recommendations for the Environmental Flows Allocation Process

Senate Bill 3 Science Advisory Committee for Environmental Flows

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Report # SAC-2009-04

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SECTION 1
FLUVIAL SEDIMENT TRANSPORT

The fluvial system commonly is conceptualized on the basis of three dominant processes that operate at various spatial and temporal scales: (1) erosion in the upper source zone, (2) transport in the middle transfer zone, and (3) deposition in the lower accumulation zone (Schumm, 1977) (Figure 1). This macroscopic conceptual model is applicable to many coastal-draining river systems, and all three of the processes; erosion, transport, and deposition; occur to varying degrees in each zone. Sediment-transport processes associated with flowing water begin when earth material is entrained from hillslopes or channel margins and terminate when the material either is deposited or dissolved. Fluvial deposits, including instream bars and benches, floodplains, and deltas, can be either temporary and remobilized or permanent and converted to sedimentary rock over geologic timescales.

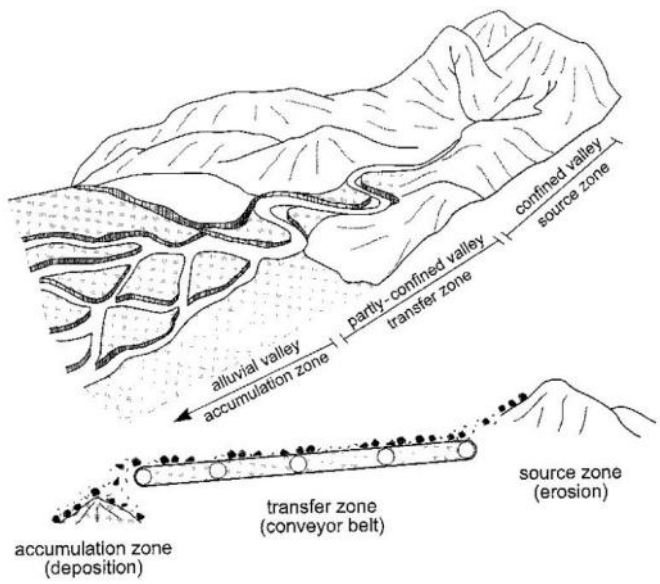

Figure 1. Conceptual diagram of a large fluvial system, with an emphasis on sediment erosion transport, and deposition (from Kondolf, 1994; scanned from Brierley and Fryirs, 2005).

The transport of material in fluvial systems is segregated into three general modes: (1) dissolved load, (2) suspended load, and (3) bedload (Figure 2). Dissolved load includes chemical constituents moving through the system, and suspended load and bedload are mechanisms of sediment transport. Suspended load refers to particles that are continuously entrained in the water column, and mostly consists of clay and silt, with varying amounts of sand derived from the channel bed during turbulent flows. Sand-sized particulates can either be transported along the bed during low- or moderate-flow conditions or in suspension during turbulent flows, thus a sub-category termed wash load is defined by only those particles continuously entrained in the water column (e.g., clay, silt, and organic matter) at all times. Suspended load is important for natural floodplain deposition processes and maintenance of deltaic and estuarine wetland environments.

Bedload refers to sand grains, gravels, or larger particles that move along or near the channel bed by various mechanisms (Figure 2). Some references segregate bed-material load from bedload (e.g., Stevens and Yang, 1989), where the former is defined as all particles originating from and exchanging with the channel bed irrespective of the transport mode. Bedload transport is responsible for instream habitat complexity and maintenance, as well as deltaic accretion (formation). The amount of bedload transported by a river assists in forming its channel geometry and its ability to recover from natural or anthropogenic disturbances, including floods and upstream impoundments.

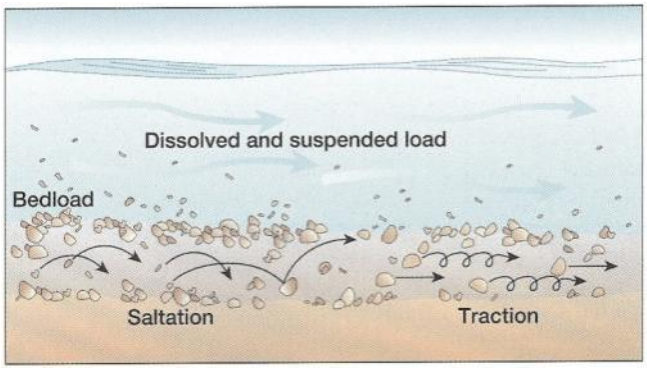

Figure 2. Generalized mechanisms of fluvial transport (from McKnight and Hess, 2000).

SECTION 2
PURPOSE AND SCOPE

This report provides guidance for the inclusion of fluvial sediment transport as a possible overlay to the HEFR approach for determination of an environmental flow regime required by Texas Senate Bill 3 (Senate Bill 3 Science Advisory Committee for Environmental Flows, 2009). Although numerous sources associate the majority of fluvial sediment transport with high-pulse flows, the discussion and guidance provided below are not contingent on an exclusive association of sediment transport with HEFR-based high-pulse flows. In many cases, a healthy sediment regime could be associated either with overbank, high-pulse, or even base flows. Further, it should be recognized that sediment transport processes do not encompass the full breadth of fluvial geomorphic investigation, but can be readily associated with an environmental flow regime.

Section 3 of this report provides a rationale and context to justify inclusion of a sediment transport overlay to the environmental flows allocation process mandated by Texas Senate Bill 3. Section 4 discusses various methods of assessment, including the use of historical data, model equations, and computation of effective discharge. Strengths and weaknesses of various methods are presented. Section 5 recommends the effective discharge approach to assess sediment transport at gaging stations and discusses some limitations of this approach. Further, a step-by-step example of the effective discharge approach at a long-term USGS streamflow-gaging station is provided and the use of the SAM hydraulic design model for estimation of effective discharge is advocated. Section 6 identifies several decision points that a practitioner tasked with a sediment-transport analysis will encounter. Section 7 provides a step-by-step example of SAM sediment-transport analyses of historically observed flows and HEFR-adjusted flows for the Sabine River near Bon Wier, Texas. Importantly, the HEFR-based SAM analysis assumes a "worst-case scenario" where the annual flow volume in excess of the HEFR-prescribed flow regime is removed (e.g., a new reservoir is constructed and flows are regulated to not exceed the HEFR-prescribed flows). Section 8 draws some general conclusions and reinforces various limitations of an effective discharge analysis.

This report originally was prepared by the Science Advisory Committee, with contributions and comments from the Texas Water Development Board (TWDB). Members of the Science Advisory Committee have reviewed, edited, and expanded the document and have provided recommendations regarding the application of the information and procedures presented in the document pursuant to the requirements of SB 3.

SECTION 3
RATIONALE AND CONTEXT

As flows increase from base flow to high-pulse flows to overbank floods, rates of sediment transport in the water column and at the channel bed greatly increase. The erosion, transport, and deposition of sediment are as important to the complexity and structural diversity of rivers, riparian zones, deltas, and estuaries as the conveyance of water itself. The balance between the force of water and the resistance of sediment sculpts the many fluvial patterns and shapes that provide habitats and conditions to which aquatic and riparian species uniquely adapt over time. If only flows are considered, without the associated sediment, then an incomplete assessment of the state's rivers and bays reduces the likelihood of conservation or rehabilitation. A worst-case scenario might involve high-pulse flow releases that increase rates of habitat degradation.

3.1 TEXAS SENATE BILL 2

The importance of sediment and river channel morphology has been highlighted by instream-flow activities associated with Texas Senate Bill 2. Also, in a National Research Council review of the Texas Instream Flow Program (TIFP) (2005), it was stated that the section considering physical processes and sediment required "significant augmentation" to relate them to the hydrologic regime, and that a "thin, single set of analytical approaches" would be insufficient to "address the range or complexity of physical processes." In response to these comments, the state agencies responsible for the TIFP further addressed physical processes and sediment in the revised technical overview document (TOD) of the TIFP (2008), which contains the following statements:

> *"Geomorphic studies will assess the active channel processes responsible for developing physical habitats."*
>
> *"Agencies will develop sediment budgets…"*
>
> *"…geomorphic studies need to be tailored to the specific sub-basin being investigated"*
>
> *"…the lack of geomorphic data for Texas' rivers is problematic."*
>
> *"…a monitoring program that collects geomorphic data for major rivers will be required."*

The TOD goes on to recommend specific lines of inquiry to address these problems and achieve programmatic goals.

3.2 TEXAS SENATE BILL 3

Texas Senate Bill 3 mandates that locally based basin and bay expert science teams (BBESTs), with consultations and support from the Environmental Flows Science Advisory

Committee (SAC) and basin and bay area stakeholder committees, "*develop environmental flow analyses and a recommended flow regime*" that "*maintain(s) the viability of the state's streams, rivers, and bay and estuary systems*" using "*reasonably available science*." BBESTs are responsible for flow recommendations required by Senate Bill 3. It is thus within their purview to consider reasonably available scientific methods to account for instream sediment and its delivery to bay and estuary systems. The imminent deadlines for which the BBESTs must provide flow-regime recommendations exclude the possibility of making present-day sediment-load measurements and analyses for the short-term requirements. However, estimates or predictions of sediment transport for various flows would serve as a benchmark from which to assess programmatic goals, and adaptive management practices might consider sediment data as they become available.

Measurable objectives that link sediment to healthy rivers and floodplains include achieving optimized: (1) channel-bed elevations and rates of bank erosion; (2) instream geomorphic unit structure and function, including composition and adjustment frequency of units such as pool-riffle sequences, bars, and benches, among others (see Brierley and Fryirs, 2005); (3) turbidity; and (4) floodplain accretion rates. Measureable objectives that link sediment to healthy estuaries include achieving optimized: (1) rates of deltaic accretion, (2) rates of estuarine shoreline erosion, and (3) turbidity. Achieving these objectives would promote healthy aquatic and riparian habitats by supporting the abiotic conditions to which native species have successfully adapted over time.

Although some objectives associated with sediment transport can be measured, little can be done using readily available desktop methods to prescribe a "sediment-load regime" that would adequately maintain instream ecology. The chief reason for this is the paucity of historically-observed geomorphic and sediment-transport data for rivers in Texas, contrasting with the availability of streamflow data for HEFR-based flow-regime analyses. Further, various fluvial processes (e.g., channel bar deposition and modification, channel migration, floodplain sedimentation) initiate and/or occur over a range of flows and, therefore, are dependent on sufficient rates of sediment transport during those flows. The unavailability of data for Texas rivers obfuscates the determination of optimized sediment concentrations or loads for these physically-relevant flows.

As an alternative to determining a "sediment-transport regime" to maintain instream ecology, methodological approaches are outlined below that would facilitate quantification of sediment loads for observed flows or HEFR-adjusted flow prescriptions. Using these methods, "what if" hydrologic scenarios could be analyzed to infer changes in sediment loads. Further, these methods can be applied using historical data, including sediment-load measurements (e.g., suspended load) or river channel dimensions (e.g., cross sections), thereby providing a context for contemporary conditions. Evaluations of sediment load in Texas eventually need to be related to habitat structure, function, and change, which would require interdisciplinary research among specialists in biology, geomorphology, and hydrology. Many of these efforts fall under the auspices of the Texas Instream Flow Program mandated by Senate Bill 2.

SECTION 4
METHODS OF ASSESSMENT

Suspended load and bedload are measured or estimated separately because the physical processes that govern their rates of transport are contingent on different factors. The sum of suspended load and bedload is the total sediment load. Methods to assess suspended load and bedload in Texas rivers and streams can be separated into two categories: (1) historical data analyses and (2) model estimates.

4.1 HISTORICAL SUSPENDED-SEDIMENT DATA

Historical suspended-sediment load data are available until the early 1980s for various streamflow-gaging stations in Texas, and are derived from two general sources: (1) reports published by the Texas Water Development Board (TWDB) and predecessor agencies and (2) the U.S. Geological Survey (USGS). Suspended-sediment load measurements commonly are associated with discharge to generate a sediment-discharge rating curve. This, however, is problematic because suspended-sediment concentrations are known to be variable for a given discharge. Stormflow hydrographs usually, but not always, are characterized by higher suspended-sediment concentrations during the rising limb than the falling limb, referred to as a type-I hysteresis loop (Figure 3). Further, the timing between storm events also influences availability of sediment from the watershed, such that an initial stormflow following relatively dry conditions usually has a greater suspended-sediment concentration than subsequent flows of similar magnitude. Aside from these complications, assessments of suspended-sediment load for various flows are encouraged.

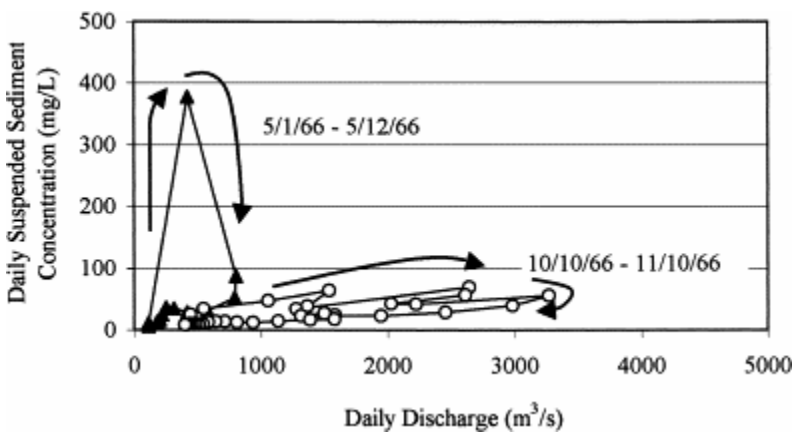

Figure 3. Type-I hysteresis loop of suspended-sediment concentrations for two stormflow events, showing (1) concentrations higher on the rising limb than the falling limb and (2) sediment exhaustion effects for the second, larger flood (from Hudson, 2003).

A series of reports by the TWDB and predecessor agencies (Stout et al., 1961; Adey and Cook, 1964; Cook, 1967; Cook, 1970; Mirabal, 1974; Dougherty, 1979; Quincy, 1988) summarize daily suspended-sediment concentration and load measurements into monthly values at various

stations in Texas over various periods of record. The data were collected by the "Texas-sampler method". Historic suspended sediment samples were obtained in an 8-oz narrow-neck bottle held in a 10-lb torpedo-shaped frame, positioned no more than one foot below the water surface. Samples were obtained daily at one-sixth, one-half, and five-sixths of the water-surface width (Stout et al., 1961). To account for increasing suspended sediment concentrations with depth, the measured percent of suspended sediment by weight was multiplied by 1.102 to obtain the mean percentage of suspended sediment in the vertical profile (Quincy, 1988). The data summarized in these reports were collected to estimate reservoir siltation and should be used with caution for determining an environmental flow regime.

The USGS also collected suspended-load data at various stations in Texas and for various periods of record. Data typically were collected 5 to 10 times per year for various flow magnitudes. The data can be accessed through the National Water Information System (NWIS) at *http://waterdata.usgs.gov/tx/nwis/qwdata*. USGS suspended-sediment data were collected by one of two methods: (1) equal-discharge-increment (EDI) or (2) equal-width-increment (EWI) (Edwards and Glysson, 1999). In simple terms, the EDI method obtains depth-integrated samples of suspended sediment from the centroids of equal-discharge increments across the channel. The EWI method obtains depth-integrated samples of suspended sediment at equally-spaced increments across the channel. Both methods provide similarly accurate results.

A comparison of the "Texas-sampler method" and the USGS method was made by Welborn (1967). For sand-bed rivers, including the Sabine, Neches, Trinity, and San Jacinto, correlations could not be formulated between the two methods and preference is given to the more accurate USGS method because of highly-variable ratios of the two estimates along different rivers. However, for rivers with mixed or gravel beds, it was found that suspended-sediment load (in tons/year) computed by the former method closely matches loads computed by the USGS method.

Strengths: representative of historical conditions; measured data; easily coupled with streamflow measurements

Weaknesses: USGS data not available since mid-1990s; TWDB data not available since mid-1980s; Texas-sampler method not as accurate as USGS depth-integrated method; restricted to selected streamflow-gaging stations; restricted to the measurement period of record

4.2 HISTORICAL BEDLOAD DATA

Historical bedload data for Texas rivers are practically unavailable. Discrete measurements of bedload probably are available in isolated sources associated with one-time investigations. However, the great difficulties in accurately measuring bedload, especially in sand-bed channels, should be considered if data sources are found. If sufficient historical bedload data are identified and their quality deemed acceptable, then computations of effective discharge for bedload transport can be made with available streamflow data.

Strengths: representative of historical conditions; measured data

Weaknesses: mostly unavailable, unless embedded within published or unpublished project-specific reports; restricted to measurement stations; restricted to the measurement period of record

4.3 SEDIMENT TRANSPORT MODELS

Bedload models, usually based on hydraulic principles, are notoriously inaccurate (Gomez and Church, 1989), uncertain (Gomez and Phillips, 1999), and applicable to rivers that exhibit steady-state equilibrium, but offer the most rapid approach to estimate transport. The various formulas for estimating bedload transport commonly require values for bed-material particle size, channel slope (energy gradient), flow depth, among other measureable or estimated factors. Common bedload transport equations include Meyer-Peter and Müller (1948), Einstein (1950), Ackers and White (1973), Bagnold (1980), Parker et al. (1982), and Gomez (2006), among others. The choice of bedload equations should be based on: (1) the composition of the bed material, (2) channel geometry, and (3) the hydraulic conditions under consideration. If changes in channel-bed and bank positions over time are known, another approach is Exner's equation used in a morphodynamic model. The following sources provide useful bedload transport model equations and explanations: (1) Gomez and Church (1989), (2) Stevens and Yang (1989), and (3) Robert (2003).

A very useful application to estimate bedload and suspended-load transport is SAM – Hydraulic Design Package for Channels, which includes various sediment transport equations that accompany a one-dimensional hydraulic computation model. User input to SAM includes channel cross-sectional data, energy gradient (channel slope), bed-material particle size distributions, and a roughness value, among other limited data. The SAM application assesses the user input to determine which sediment transport equations are most applicable, and then computes sediment transport loads by coupling the model output with the cross-sectional geometry data. Further, flow-duration curve data can be included to determine which flows cumulatively transport the most sediment over time, referred to as the effective discharge. A final comment should be made that personnel involved with application of sediment transport models or SAM should have considerable background or training, and caution should be given to computed estimates. For some rivers in Texas, a source of data to parameterize sediment-transport models is provided in a 4-CD set of data published by the National Cooperative Highway Research Program (2004). Further, cross-sectional data from streamflow measurements can be requested from the U.S. Geological Survey (USGS) water-science centers in Texas.

Strengths: not contingent on sediment-load measurements; flexibility over space and time (e.g., model parameters could be from any station along a river, or could be historical)

Weaknesses: result accuracy; requires accurate model parameters (e.g., cross-sectional data, channel slope, bed-material size distribution)

4.4 EFFECTIVE DISCHARGE

Sediment load is a measure of mass transport over time and, with a reasonably extensive dataset, one could formulate sediment-flow prescriptions in the same manner as streamflow. However, the most commonly applied method to associate sediment load with streamflow is through an analysis of effective discharge. Effective discharge is the flow that cumulatively transports the majority of sediment, usually bed-material load, at a channel cross section over time (Figure 4). It is usually a flow of moderate magnitude and frequency. Although high-magnitude floods can transport substantial quantities of sediment, their relatively infrequent occurrence often is outpaced by the sediment transport of more frequent moderate flows. Although effective discharge is informative with respect to sediment transport, it is less predictive for assessments of channel form or adjustment over time.

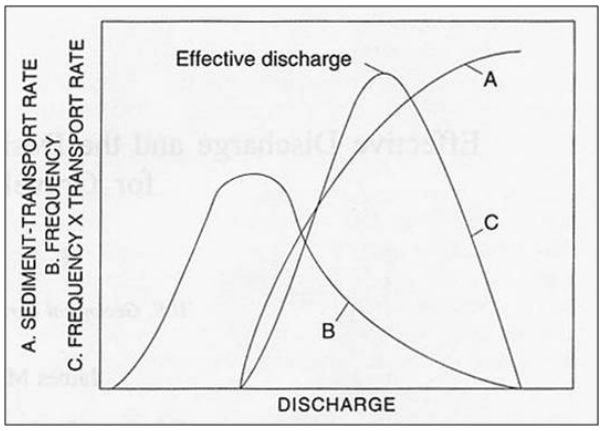

Figure 4. Effective discharge, in its graphical form, is the largest product of the sediment transport rate and the frequency of transport (from Wolman and Miller, 1960; scanned from Andrews and Nankervis, 1998).

Although a number of investigations confirm that relatively frequent, moderate flows (Hudson and Mossa, 1997) or bankfull flows (Andrews and Nankervis, 1995; Biedenharn et al., 1999; Torizzo and Pitlick, 2004) are responsible for the majority of cumulative sediment transport over time (Figure 5), others have shown that infrequent, high-magnitude floods equate to the effective discharge (Gupta, 1988; Bourke and Pickup, 1999), especially in fluvial systems with highly variable flow regimes. Generally, effective discharge is less frequent as the average annual precipitation and regularity of flooding decreases. A further complication associated with applications of effective discharge is the tendency to rely solely on one flow value to transport sediment over time. Instead, an emphasis on flow variability and the range of flows necessary to transport sediment over time should be embraced. For example, average flow conditions are known to transport appreciable quantities of sediment in sand-bed river systems.

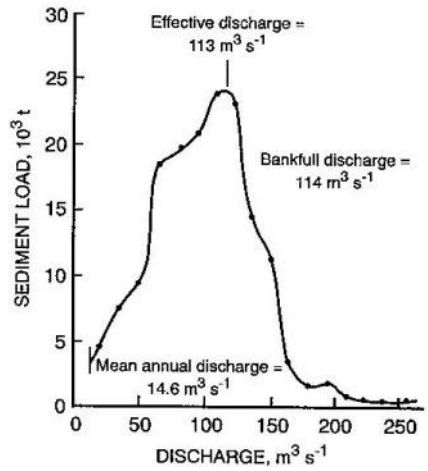

Figure 5. Effective discharge in this example approximately is equal to the bankfull discharge (from Andrews, 1980; scanned from Knighton, 1998).

A process to compute effective discharge at gaged or ungaged stations is provided in Biedenharn et al. (2000). Effective discharge requires an annual flow-duration curve and a sediment-discharge rating curve. Discharges are divided into a range of equal arithmetic classes and the total sediment load is computed for each class. This is done by multiplying the frequency of each flow class by the median sediment load of that class. The average of the flow class with the highest load is the effective discharge. Further, the quantification of sediment load by flow classes enables an assessment of the relative importance of the effective discharge compared to lesser and greater flows. For purposes of instream channel maintenance, the method is suggested for bed-material load only. However, the method could independently be applied to determine effective flows for suspended load or bedload.

The actual concept of effective discharge should be taken into consideration when evaluating its potential to prescribe various channel-maintenance flows. First, its application assumes steady-state equilibrium of the river channel, or the tendency to fluctuate around an average geometric condition (e.g., bankfull width-to-depth ratio) (Figure 6). If the channel does not display equilibrium, such as would be the case for an actively incising channel-bed, then a computation of effective discharge does not describe the condition acceptable for conservation or restoration efforts. Further, the effective discharge is a product of flow frequency; therefore a regulated adjustment of the flow regime would result in a different value.

Strengths: adaptable to both measured and model-estimated data; adaptable to bedload, suspended-load, or total load

Weaknesses: assumes steady-state equilibrium; restricted to streamflow-measurement stations; restricted to the streamflow-measurement period of record

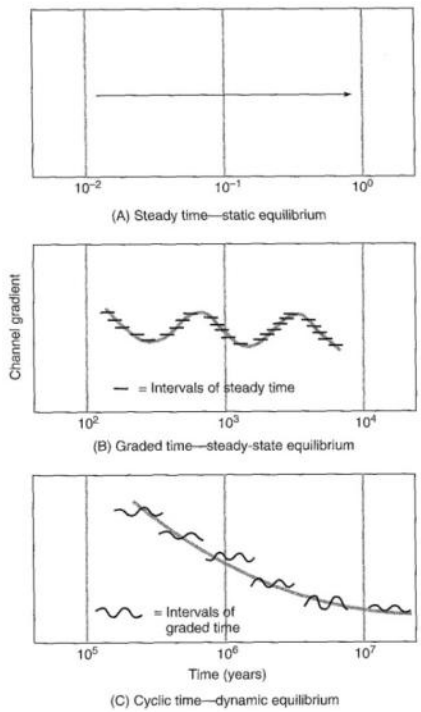

Figure 6. Concepts of equilibrium in fluvial geomorphology (from Schumm, 1977; scanned from Ritter et al., 2002). Channel rehabilitation or engineering applications focus on graded time scales, and efforts are usually made to promote a steady-state channel condition that is resilient to disturbances (e.g., floods).

SECTION 5
RECOMMENDATIONS AND EXAMPLE COMPUTATION OF EFFECTIVE DISCHARGE

An analysis of the effective discharge of sediment transport at gaging stations with a sufficient period of record (20 or more years) could serve as an overlay to modify HEFR-based flow prescriptions (mostly high-pulse flows or overbank flows). For gaging stations with accurate suspended-load data, effective discharge can be computed using the methodology described in Biedenharn et al. (2000). Bedload transport can be accounted for with a model equation, which requires inputs of bed-material size, channel slope, cross-sectional geometry, and flow depth, among other hydraulically relevant parameters. The caveat of using measured suspended-load data is that the values represent conditions during the period of measurement, which might have been degraded or not representative of desired conditions for many rivers in Texas, especially for stations downstream of reservoirs.

It should be recognized that an analysis of effective discharge does not encompass nor entirely explain the breadth of fluvial geomorphic processes. Sediment transport, however, is a fairly straightforward process to relate with streamflow, and collection of sediment-transport data commonly occurs simultaneous with streamflow at a gaging station. Furthermore, computation of effective discharge based on bed-material load is the widely accepted method (Biedenharn et al. 2000) for evaluating changes in channel morphology. Effective discharge of suspended load offers comparatively less insight toward assessments of instream habitat conditions and dynamics.

5.1 EXAMPLE OF EFFECTIVE DISCHARGE ANALYSIS

An illustrative example is provided below for the Brazos River near Richmond, Texas, using streamflow and suspended-load data from the USGS National Water Information System (NWISWeb) (U.S. Geological Survey, 2009) and supporting data from the National Cooperative Highway Research Program (2004). Further, a procedural flowchart of effective discharge analysis is shown in Figure 7.

Data required for an analysis of effective discharge at 08114000 Brazos River at Richmond, Texas, are summarized in Table 1.

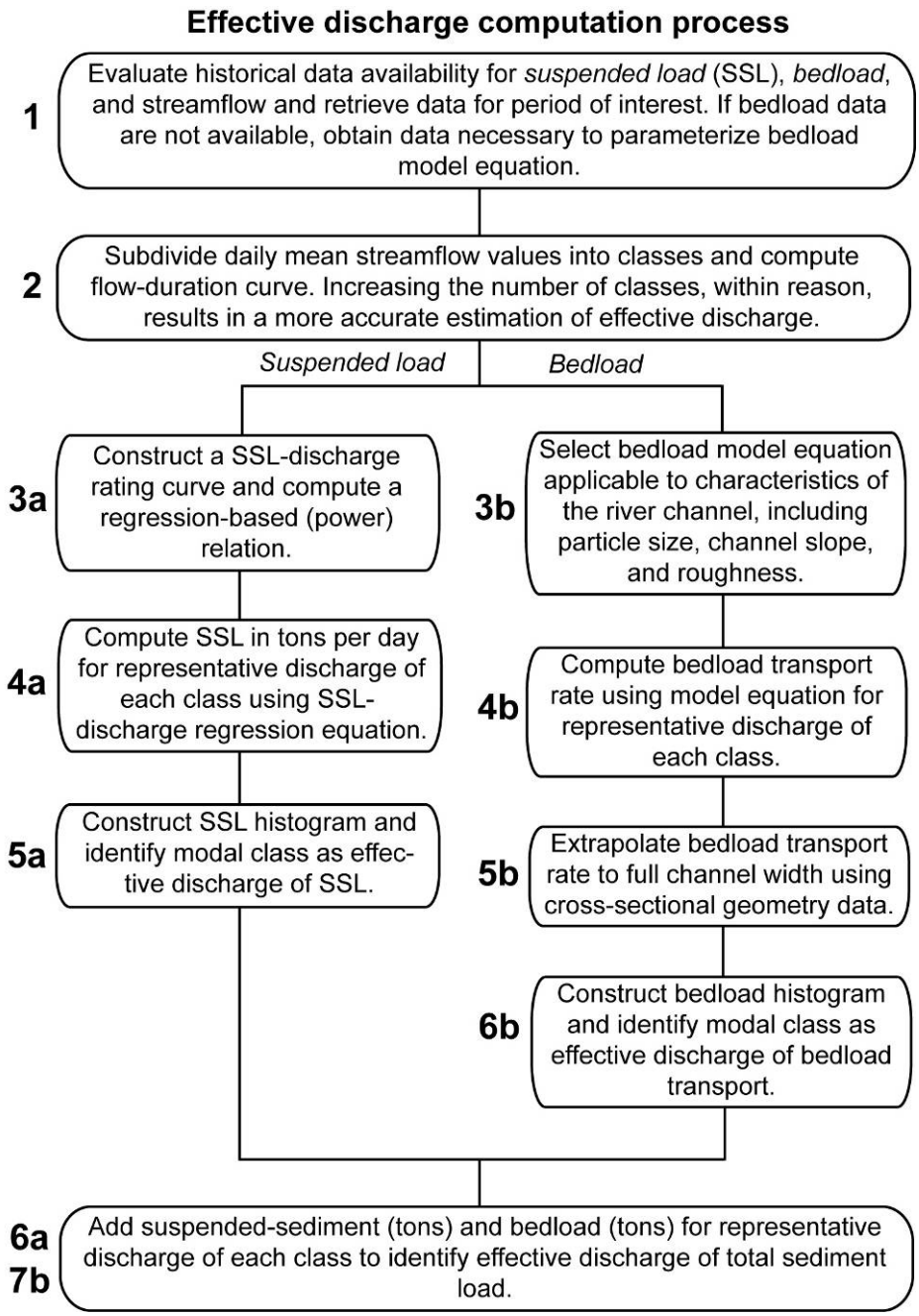

Figure 7. Procedural flowchart for computation of effective discharge for suspended-sediment load, bedload, and total load.

Table 1. Data required for effective discharge analysis at 08114000 Brazos River at Richmond, Texas.

Data	Source
1. Daily mean streamflow (ft^3/s)	USGS NWISWeb
2. Suspended sediment load (tons/day)	USGS NWISWeb water-quality data
3. Bed-material particle size (in)	National Cooperative Highway Research Program (2004)
4. Dimensionless channel slope	National Cooperative Highway Research Program (2004)
5. Manning's *n* coefficient	National Cooperative Highway Research Program (2004)
6. Cross-sectional channel geometry data	Hard-copy USGS streamflow measurement notes (available at USGS water science centers)

5.1.1 Flow-Duration Curve

1. Daily mean streamflow for the period of record were downloaded from USGS NWIS and exported to a spreadsheet. Days with missing values were deleted from the dataset, and streamflow values were sorted in descending order. Intervals of discharge were subdivided into 36 classes, the last class being 100,000 ft^3/s (Table 1). A simple quantitative method to determine class intervals is provided in Biedenharn et al. (2000), but was not used for this analysis. Exceedance frequencies were computed using the number of days in the period of record, and plotted data are shown in Figure 8.

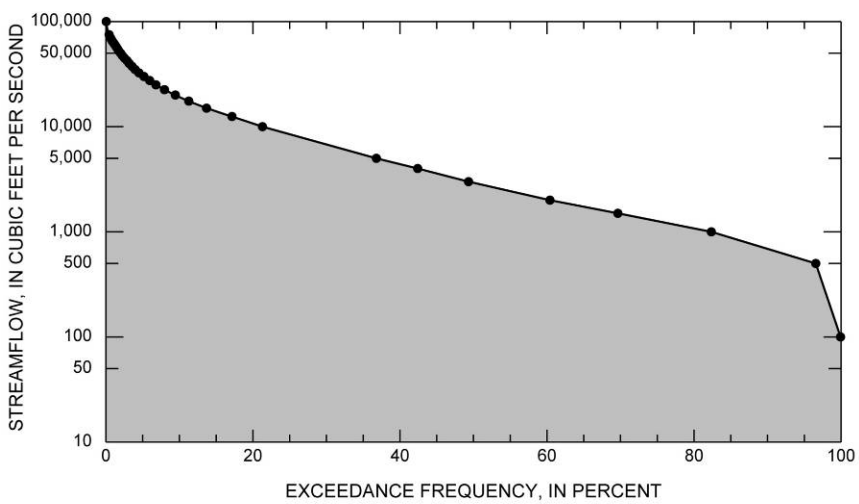

Figure 8. Flow-duration curve for 08114000 Brazos River at Richmond, Texas, for the full period of record using daily mean values. The high density of points at the upper tail is for a more accurate determination of effective discharge.

5.1.2 Suspended-Sediment Load

2. Suspended-sediment-load (SSL) data (period of record: February 1966 to September 1995) (tons/day) were downloaded by selecting the water quality / sediment measurements from USGS NWIS, and were exported to a spreadsheet. Records were sorted by the parameter code, and only data for suspended-sediment load were retained (USGS parameter code 80155). For days with multiple measurements of SSL, the mean value was used for that day. SSL (in log-10 space) for each day was plotted against its corresponding daily mean streamflow (in log-10 space), and a power function was fit to the data (Figure 9). The power function fitted to predict SSL from streamflow (Q) (ft^3/s) is:

   - $\boldsymbol{SSL = (0.0000527)Q^{2.1463}}$, where SSL is suspended-sediment load (tons/day) and Q is discharge (ft^3/s).

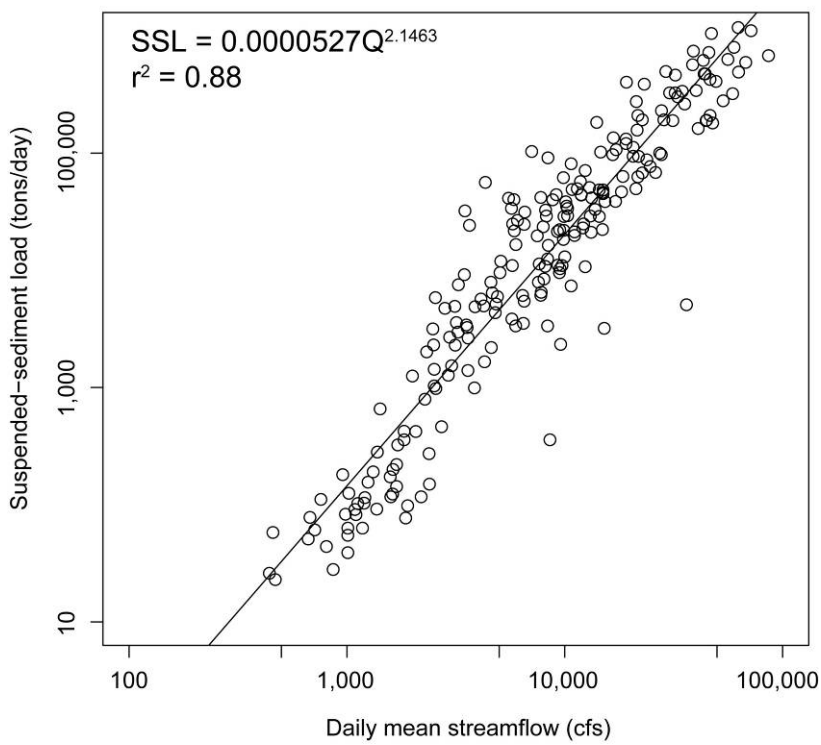

Figure 9. Suspended-sediment-load and streamflow rating curve for 08114000 Brazos River at Richmond, Texas. Scatter about the power trendline is attributed to sediment availability and hysteretic behavior of suspended-sediment concentrations over time.

3. A representative streamflow for each discharge class interval was computed as the mean discharge between two classes. The representative discharge was used in the power function determined in step #2 to compute SSL in tons/day for each discharge class. The result was multiplied by the discharge exceedance frequency to obtain the load

transported by each discharge class. Finally, the load values were plotted as a histogram for each class, using the discharge value originally used in the flow-duration curve (Figure 10). Results of the entire analysis are also presented in Table 2. It takes some iterations of this step to ensure that discharge class intervals are appropriate to accurately determine the effective discharge.

4. The effective discharge is determined by evaluating the modal class of the histogram. In this case, four discharge classes exhibited the highest suspended-sediment loads, and the mean discharge representing their bounds was selected and approximates 46,000 ft^3/s, which is the effective discharge for suspended-sediment transport. Thus, for the period February 1966 to September 1995, the Brazos River at Richmond transported the cumulative majority of suspended sediment at about 46,000 ft^3/s. However, this does not include bedload transport. According to the National Weather Service (NWS) West Gulf River Forecast Center (http://www.srh.noaa.gov/wgrfc/), flood stage occurs at a USGS stage of 48 feet, or 81,800 ft^3/s based on the current expanded stage-discharge rating table. Therefore, effective discharge of SSL is substantially less than flood stage.

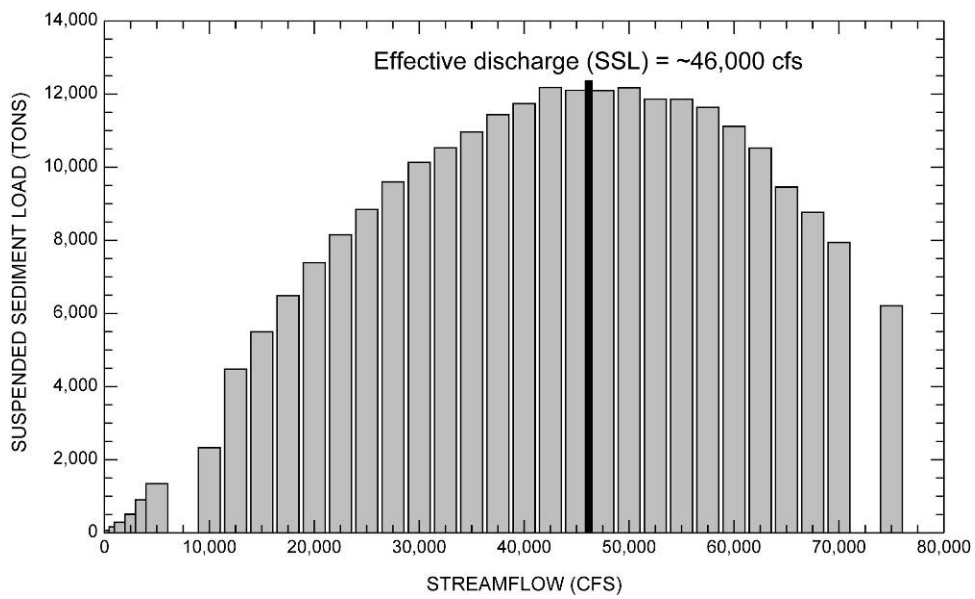

Figure 10. Suspended-sediment load (SSL) histogram showing effective discharge for SSL at 08114000 Brazos River at Richmond, Texas, approximately is 46,000 ft^3/s.

Table 2. Computations for the flow-duration curve and histogram for determination of effective discharge for suspended-sediment load (SSL). Gray columns were used to generate an SSL histogram.

(ft^3/s; cubic feet per second; %, percent; SSL, suspended-sediment load)

Streamflow (ft^3/s)	Days exceeded	Exceedance frequency	Representative streamflow (ft^3/s)	SSL (tons per day) via power function	SSL (tons)
0	32,796	100.00%	0	0	0
100	32,774	99.93%	50	0	0
500	31,669	96.56%	300	11	11
1,000	27,009	82.35%	750	78	64
1,500	22,838	69.64%	1,250	234	163
2,000	19,809	60.40%	1,750	481	291
3,000	16,177	49.33%	2,500	1,035	510
4,000	13,908	42.41%	3,500	2,130	903
5,000	12,066	36.79%	4,500	3,653	1,344
10,000	6,987	21.30%	7,500	10,936	2,330
12,500	5,624	17.15%	11,250	26,110	4,477
15,000	4,489	13.69%	13,750	40,165	5,498
17,500	3,700	11.28%	16,250	57,486	6,486
20,000	3,100	9.45%	18,750	78,154	7,387
22,500	2,615	7.97%	21,250	102,240	8,152
25,000	2,234	6.81%	23,750	129,807	8,842
27,500	1,956	5.96%	26,250	160,912	9,597
30,000	1,699	5.18%	28,750	195,607	10,133
32,500	1,476	4.50%	31,250	233,941	10,529
35,000	1,303	3.97%	33,750	275,959	10,964
37,500	1,166	3.56%	36,250	321,702	11,437
40,000	1,037	3.16%	38,750	371,209	11,738
42,500	941	2.87%	41,250	424,517	12,180
45,000	824	2.51%	43,750	481,661	12,102
47,500	731	2.23%	46,250	542,675	12,096
50,000	657	2.00%	48,750	607,590	12,172
52,500	575	1.75%	51,250	676,436	11,860
55,000	519	1.58%	53,750	749,242	11,857
57,500	462	1.41%	56,250	826,035	11,636
60,000	402	1.23%	58,750	906,843	11,116
62,500	348	1.06%	61,250	991,691	10,523
65,000	287	0.88%	63,750	1,080,604	9,456
67,500	245	0.75%	66,250	1,173,605	8,767
70,000	205	0.63%	68,750	1,270,718	7,943
75,000	143	0.44%	72,500	1,424,145	6,210
100,000	18	0.05%	87,500	2,132,271	1,170

5.1.3 Cross-Sectional Data

5. In order to apply a bedload transport model, cross-sectional data are required to parameterize various steps in the model development. The choice of a cross section is very important because it represents the condition of the channel at a given time and place, such that the choice of an incised, degraded cross section downstream of a reservoir would provide results inappropriate for assessment of naturalized conditions.

For this exercise, hard-copy USGS streamflow measurement notes for two measurements in February 1998 (moderate flow) and November 2004 (high flow) were used to construct a cross-section on the upstream side of the bridge at Richmond. The moderate flow in 1998 was used to construct the channel bed and base of the bank, and the 2004 flow was used to vertically extend the banks to a maximum stage of 33.8 feet. Based on the observed bank angle, banks were artificially extended to the NWS flood stage of 48 feet (Figure 11) The reason for using a composite of two flows was to avoid excessive bed scour during the high flow but, nonetheless, capture as much of the bank morphology as possible.

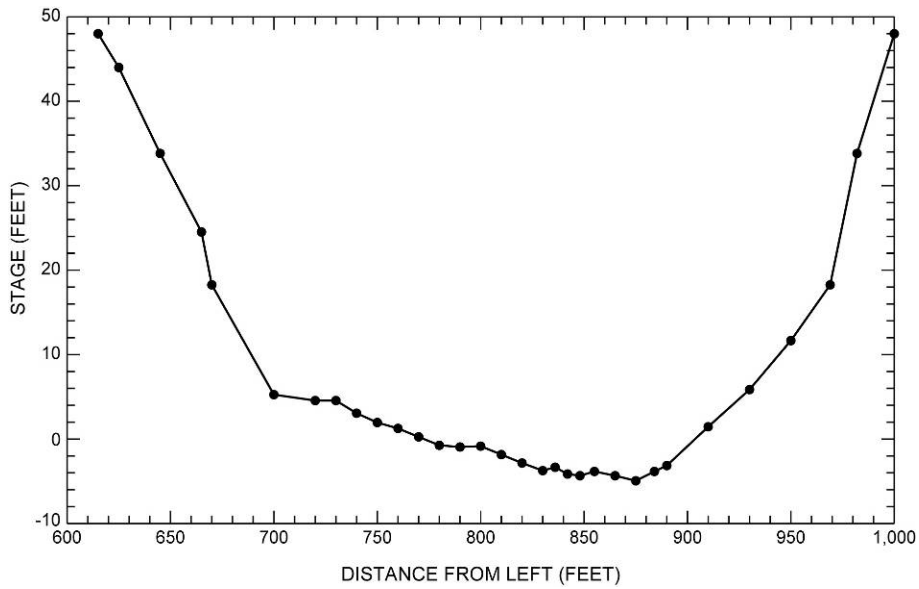

Figure 11. Cross section of 08114000 Brazos River at Richmond, Texas, based on USGS streamflow measurements in February 1998 and November 2004, and extended to NWS flood stage of 48 feet. The moderate flow of 1998 was used to construct geometry up to about 18 feet and the high flow of 2004 further extended geometry to about 34 feet.

6. The cross section was imported into WinXSPRO, a free software package available online from the U.S. Department of Agriculture Forest Service (2009). Care should be taken to correctly associate WinXSPRO results with the appropriate USGS stage because the software automatically sets the lowest point in the section to "0". Hydraulic values, including hydraulic radius and mean velocity, for 0.25-ft stage increments were computed using the following hydraulic data for the Brazos River at Richmond, Texas, from the National Cooperative Highway Research Program (2004) CD set:

   Dimensionless channel slope: 0.00012
   Manning's *n*: 0.03

5.1.4 Bagnold's (1977) Bedload Model

7. For all discharge class intervals used to compute suspended-sediment load above, a series of computations were made to estimate bedload transport (Table 3). English units were used. First, mean velocity (U) (ft/s) and hydraulic radius (R) (ft) for each discharge were entered from the WinXSPRO results. Stream power per unit area (ω) (lb/s^3) for each discharge class interval was computed from the following equation:

   - $\boldsymbol{\omega = \rho g d S U}$, where ρ is the mass density of water (62.28 lb/ft^3), g is acceleration due to gravity (32.17 ft/s^2), d is mean flow depth (ft) which is considered analogous to R, S is dimensionless channel slope (0.00012), and U is mean velocity (ft/s).

   Using the median particle size (D_{50}) (ft) of bed-material for the Brazos River at Richmond from the National Cooperative Highway Research Program (2004) CD set (see below), the critical shear stress (τ_c) (lb/ft^2) for entrainment was computed from the following equation:

   - $\boldsymbol{\tau_c = \tau^*(\rho_s - \rho) D_{50}}$, where $\tau^*$is the dimensionless Shields parameter (0.03 for sand-bed channels), ρ_s is the mass density of sediment (164.98 lb/ft^3 for quartz), and D_{50} is the median particle size (0.00075 ft).

   Average Bed Material D_{16}, D_{50}, D_{84} (in) (or the diameter at which 16, 50, and 84 percent of the sediment is finer than): 0.006, 0.009, 0.013

   Next, the mean flow depth (ft) required to entrain the median particle size (D_{50}) (ft) was computed from the following equation:

   - $\boldsymbol{d = \tau_c / (\rho S)}$

   From this value, Manning's equation was used to compute the critical flow velocity (U_c) (ft/s) required to entrain the median particle size (D_{50}) (ft):

   - $\boldsymbol{U_c = (1.49 d^{2/3} S^{1/2})/n}$, where n is Manning's coefficient (0.03).

   Next, the critical stream power (ω_c) (lb/s^3) required to entrain the median particle size (D_{50}) (ft) was computed from the following equation:

   - $\boldsymbol{\omega_c = U_c \tau_c}$

   The Bagnold (1977) formula to estimate the bedload transport rate (I_b) (lb/ft/s) for each discharge class interval was computed from the following equation:

   - $\boldsymbol{I_b = (\omega - \omega_c)^{3/2} (d/D_{50})^{-2/3}}$

Finally, the bedload transport rate (I_b) (lb/ft/s) was multiplied by the wetted perimeter (from WinXSPRO) for each discharge class interval to estimate a channel-wide bedload transport rate (lb/s), and the value was converted to tons/year.

Table 3. Computations for bedload transport using the Bagnold (1977) model and effective discharge for bedload. Critical stream power (ω_c) was computed to be 0.00057 lb/s^3 for this example. Gray columns were used to generate a bedload histogram.

(ft^3/s; cubic feet per second; %, percent; ft, feet; ft/s, feet per second; ω, stream power per unit bed area; lb/s^3, pounds per cubic second; lb/ft/s, pounds per foot per second; yr, year)

Streamflow (ft^3/s)	Exceedance frequency	Stage (ft)	Mean velocity (ft/s)	Mean depth (ft)	Stream power (ω) (lb/s^3)	Bedload transport (lb/ft/s)	Bedload transport (tons/yr)	Bedload (tons)
100	99.93%	7.8	2.1	7.6	3.837	0.01605	62,039	61,998
500	96.56%	8.87	2.3	8.4	4.645	0.02000	79,191	76,470
1,000	82.35%	9.75	2.4	9.1	5.251	0.02278	92,393	76,090
1,500	69.64%	10.45	2.5	9.7	5.830	0.02555	105,209	73,264
2,000	60.40%	11.06	2.5	10.1	6.071	0.02642	110,481	66,731
3,000	49.33%	12.11	2.7	10.9	7.076	0.03160	135,127	66,653
4,000	42.41%	13.02	2.8	11.6	7.809	0.03515	153,075	64,916
5,000	36.79%	13.89	2.9	12.2	8.506	0.03864	171,324	63,032
10,000	21.30%	17.66	3.3	14.9	11.822	0.05541	264,034	56,251
12,500	17.15%	19.24	3.5	16.2	13.632	0.06489	315,365	54,080
15,000	13.69%	20.78	3.7	17.5	15.568	0.07522	370,302	50,686
17,500	11.28%	22.26	3.8	18.7	17.085	0.08274	412,541	46,542
20,000	9.45%	23.68	4.0	19.9	19.138	0.09411	473,693	44,775
22,500	7.97%	25.01	4.1	20.9	20.602	0.10173	518,490	41,342
25,000	6.81%	26.31	4.2	21.8	22.013	0.10925	565,418	38,515
27,500	5.96%	27.56	4.4	22.7	24.014	0.12116	636,631	37,970
30,000	5.18%	28.76	4.5	23.5	25.425	0.12899	685,881	35,532
32,500	4.50%	29.94	4.6	24.4	26.985	0.13755	737,935	33,211
35,000	3.97%	31.08	4.7	25.2	28.476	0.14593	796,713	31,654
37,500	3.56%	32.2	4.8	25.9	29.890	0.15409	850,992	30,255
40,000	3.16%	33.28	4.9	26.6	31.337	0.16250	907,706	28,701
42,500	2.87%	34.35	4.9	27.4	32.280	0.16657	940,913	26,997
45,000	2.51%	35.38	5.0	28.0	33.660	0.17482	998,564	25,089
47,500	2.23%	36.4	5.1	28.7	35.191	0.18383	1,061,660	23,664
50,000	2.00%	37.42	5.2	29.3	36.631	0.19256	1,118,126	22,399
52,500	1.75%	38.4	5.2	30.0	37.506	0.19638	1,155,837	20,265
55,000	1.58%	39.36	5.3	30.6	38.992	0.20544	1,222,095	19,340
57,500	1.41%	40.28	5.4	31.2	40.507	0.21473	1,287,515	18,137
60,000	1.23%	41.12	5.4	31.7	41.156	0.21759	1,318,420	16,161
62,500	1.06%	41.95	5.5	32.2	42.579	0.22660	1,383,729	14,683
65,000	0.88%	42.78	5.6	32.7	44.027	0.23582	1,451,174	12,699
67,500	0.75%	43.58	5.6	33.2	44.700	0.23882	1,480,947	11,063
70,000	0.63%	44.38	5.7	33.7	46.183	0.24832	1,551,610	9,699

8. A bedload histogram was plotted in the exact same manner as the suspended-load exercise (Figure 12), multiplying the final bedload (tons/year) by the exceedance frequency of the discharge for which it was modeled. The results show that effective

discharge for cumulative bedload transport occurs at relatively low flows. This, however, is an inaccurate assessment of bedload transport in reality. The Bagnold (1977) model is dependent on excess stream power, which is generated to a large measure by depth and velocity. The flaw in this example occurred because the stage for very low flows according to the USGS, for instance 100 ft^3/s, filled up the cross section to a mean depth of 7.6 feet at a mean velocity of 2.1 ft/s according to hydraulic computations modeled in WinXSPRO. These modeled hydraulic conditions are more than adequate at transporting sand-sized bedload, and their almost constant occurrence over time ensured low flows outpaced moderate to high flows with respect to cumulative transport. In reality, the hydraulic conditions at 100 ft^3/s at this cross section are sluggish and pond-like, not capable of transporting sand-sized bedload. Furthermore, it is very unusual for bedload to exceed suspended-load transport, thereby providing additional evidence for the problematic data used to compute bedload. This example underscores the importance of selecting an appropriate cross section to model bedload transport using any given equation. For appropriate cross sections with adequate data, however, the Bagnold (1977) equation has worked well for other investigations.

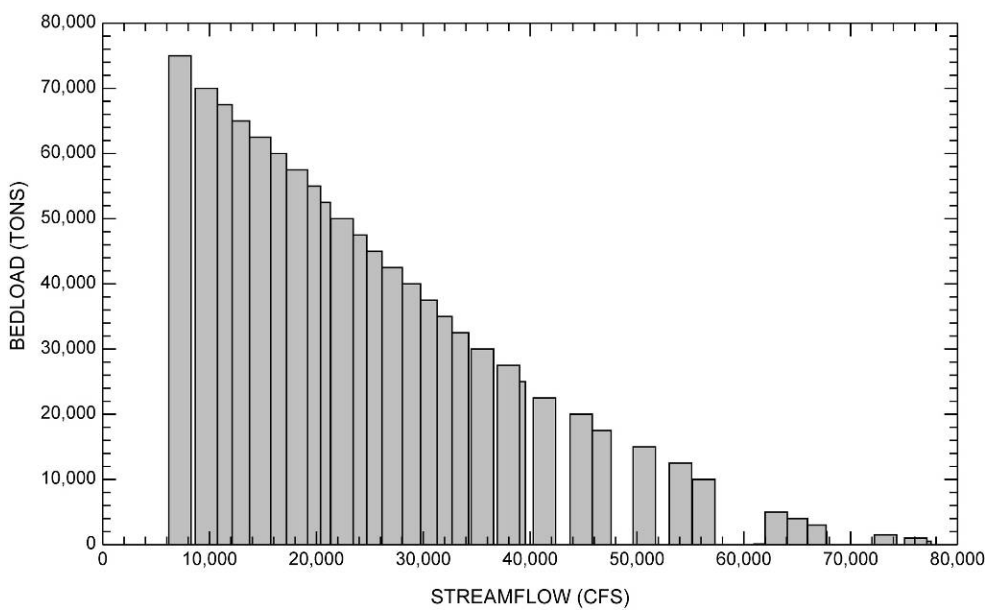

Figure 12. Bedload histogram showing an inaccurately low estimate of effective discharge for bedload at 08114000 Brazos River at Richmond, Texas.

9. Finally, the practitioner can combine suspended load (tons) and bedload (tons) for a given flow to evaluate the effective discharge for total sediment load.

5.2 ADVOCACY OF THE SAM HYDRAULIC DESIGN MODEL

The SAM hydraulic design model efficiently computes the exercises shown above when parameterized with sufficient data. Furthermore, SAM can recommend appropriate sediment transport formulae for the given input, such as channel slope and bed-material particle size. The use of the SAM hydraulic design model is a tool that can be used to establish effective discharge at gaging stations, but should be done by an expert in the field of fluvial geomorphology or sediment transport dynamics.

As discussed above, effective discharge should be applied with caution for rivers that do not exhibit steady-state equilibrium. The SAM model requires cross-sectional geometry data for the location of interest. For rivers that are degraded, such as those that have incised immediately below reservoirs, cross-sectional channel geometry probably is not representative of any natural condition. As a hypothetical example, cross-sectional area of a river channel immediately downstream of a reservoir is greatly enlarged as a result of channel incision and bank retreat, and SAM computes a sediment load much greater for the enlarged channel than would be expected naturally. Because the sediment transport models embedded within SAM are based on equilibrium-based theoretical constructs, however, the output of the model provides the analyst with a reference condition of sediment transport. As such, SAM output can be used in conjunction with field measurements of suspended load and bedload to determine if the river is over- or under-achieving with respect to sediment transport.

Regardless of the analysis employed, values of effective discharge should be considered with respect to desired conditions of particular river systems. For some rivers, it might be desirable to transport less sediment load than that computed by an effective discharge analysis. As a hypothetical example, a river reach 25 miles downstream of a reservoir receives much less sediment than it did during pre-impoundment conditions. In order to prevent channel incision and associated bank failure over time, it would be desirable for sediment transport to underperform that predicted by a SAM analysis of steady-state conditions. Another serious concern related to the practicality of effective discharge for environmental flow programs is the stasis of its approach. If an existing flow regime is modified to satisfy a prescription, then it is likely that the magnitude and frequency of the effective discharge changes as well. Iterations of effective discharge overlays and subsequent modification of the flow regime becomes impractical at some level.

SECTION 6
DECISION POINTS

Similar to the HEFR-based approach to determine an environmental flow regime for Texas rivers, a variety of decisions are required to compute the effective discharges of sediment transport processes. One decision point not specifically discussed below regards computation of effective discharges for ungaged locations, which is beyond the scope of this report. The decision points include:

1. **Bedload, bed-material load, suspended load, <u>or</u> total sediment load:** The practitioner must decide if effective discharge will be required for bedload only, bed-material load only, suspended load only, or the combination of bedload and suspended load (total load). For objectives associated with instream-habitat structure, channel morphology, deltaic lateral accretion, and beach or shoreline maintenance, bed-material load is the most important sedimentary variable. For objectives associated with floodplain sedimentation, turbidity, or deltaic vertical accretion, suspended-load is the most important sedimentary variable. Finally, total load constitutes the most complete picture of sediment transport.

2. **Historically collected sediment-load data <u>or</u> model application:** The practitioner must decide whether to use previously collected sediment-load data or to apply a sediment-transport model equation to estimate load. In Texas, the USGS and TWDB have historically collected suspended-load data at a number of USGS streamflow-gaging stations. Bedload, however, has not historically been collected, unless done so on a project-specific basis. It is highly likely, therefore, that a model equation would have to be used for computation of effective discharge for bedload transport.

3. **USGS <u>or</u> Texas-sampler method for historical suspended-load data:** The USGS has historically collected depth-integrated suspended-load data at a number of streamflow-gaging stations in Texas prior to the mid-1990s. The TWDB has various published reports of historical suspended-load data obtained by the Texas-sampler method at selected streamflow-gaging stations prior to the mid-1980s. In general, USGS depth-integrated data are more accurate than the Texas-sampler method.

4. **Period of record:** The period of record is a twofold decision: (a) hydrologic data and (b) sediment-load data. The period of record for sediment-load data is not applicable if a sediment-transport model equation is used.

    a. Historical streamflow data are required to generate a flow-duration curve for computation of effective discharge. The choice of an appropriate period of record of streamflow data could reflect pre- or post-regulation conditions, among other historical changes to the river's flow regime.

    b. Sediment load is highly sensitive variable over space and time. Sediment concentrations in the water column are dependent on season, antecedent rainfall,

land-use, characteristics of the storm hydrograph, and upstream impoundments, among other variables. The period of record for measured sediment-load data could reflect pre- or post-regulation conditions, among other historical changes to the river's sediment-transport regime.

5. **Flow-duration class intervals:** A flow-duration curve requires the practitioner to establish "class intervals" which are related to exceedance frequency of that interval's representative flow. Although various published sources offer guidance on establishing class intervals, the choice is relegated to the practitioner. Accuracy of effective discharge increases if class intervals are shorter and more numerous (e.g., class intervals of 1,000 ft^3/s are more accurate than 5,000 ft^3/s).

6. **Sediment-transport model:** This decision is only required if the practitioner does not have or chooses not to use measured sediment-load data to determine effective discharge. A variety of model equations exist that estimate bedload or bed-material load transport rates for various flow conditions, and are based on measured or estimated parameters. Bedload and bed-material load equations commonly are suited to particular conditions, such as a low-gradient sand-bed channel, for example. Other model equations exist that estimate suspended-load transport rates using either measured or estimated parameters. The choice of an appropriate model equation is relegated to the practitioner, possibly with guidance from the SAM hydraulic design model.

7. **Channel cross-section dimensions:** This decision is only required if using a model equation to estimate sediment load. Cross-sectional data are needed to compute channel hydraulics (e.g., width, mean depth, mean velocity) based on a given slope and flow-resistance coefficient. Further, most model equations render sediment-load estimates for a given channel length, and require a wetted perimeter for extrapolation to channel-wide transport rates. As shown from the Brazos River at Richmond, Texas, example above, an unrepresentative cross section can lead to erroneous results. Cross-sectional dimensions could be chosen to represent pre- or post-regulation conditions, pre- or post-disturbance conditions, straight-reach or meander-bend conditions, among other complex arrangements of channel shape over space and time.

8. **Model parameters:** This decision is only required if using a model equation to estimate sediment load. Various parameters, including channel slope, particle size, mean depth, and water temperature, among others, are needed to parameterize sediment-transport model equations and compute selected hydraulics at a channel cross section. Various published and unpublished sources exist that provide this information. For certain applications, the practitioner could elect to estimate required parameters.

9. **Extrapolation of effective discharge to a channel reach:** As outlined above, computation of effective discharge is restricted to one channel cross section. Given this

restriction, environmental flow objectives associated with sediment transport are valid for one station. If desired, extrapolation to a channel reach should consider variability in sediment sources and sinks upstream and downstream of the station, including tributary inputs, distributary outputs, active bank erosion, channel incision or aggradation, overbank deposition, among other complex watershed and channel characteristics and processes.

SECTION 7
USING SAM TO DETERMINE THE EFFECTIVE DISCHARGE FOR ALLUVIAL STREAMS

The purpose of this example is show how the SAM[1] software can be used to compute the effective discharge for the existing hydrology and the adjusted hydrology resulting from an implementation of an environmental flow regime (e.g., HEFR-based analysis). Effective discharge is defined as the mean of the discharge increment that transports the largest fraction of the annual sediment load over a period of years (Andrews, 1980). It is computed by integrating the flow-duration curve and a bed-material load rating curve (Biedenharn et al., 2000). When using SAM to compute effective discharge, the sediment load is the total bed-material load (i.e., material that is found in the channel bed). Wash load (i.e., material finer than the bed-material load) is not included in the SAM computational procedures. For this example, the HEFR procedure (Senate Bill 3 Science Advisory Committee for Environmental Flows, 2009), as developed by the Texas Parks and Wildlife Department (TPWD), is used. Importantly, the HEFR-based SAM analysis assumes a "worst-case scenario" where the annual flow volume in excess of the HEFR-prescribed flow regime is removed (e.g., a new reservoir is constructed and flows are regulated to not exceed the HEFR-prescribed flows).

The SAM package was chosen for this example because of its ability to transition from computations of flow hydraulics to sediment transport capacity and sediment yield. Effective discharge is determined using SAM results for sediment yield. More information on the SAM software can be found in the users' manual (Copeland et al., 1997) and Thomas et al. (2002).

The computation of effective discharge requires the development of a bed-material load histogram. The histogram is generated by using representative discharge bins, obtained by dividing the discharge range into equal size arithmetic bins (discharge classes). The mean discharge of the flow bin is integrated with the bed-material load rating curve to find the bed-material load for each discharge class. The sediment load transported by each bin is computed by multiplying the bed-material load by the percentage of time represented by each discharge class. The results are plotted as a histogram representing the annual bed-material load transported by each discharge class. This computation is performed by the Sediment Yield Module in the SAM hydraulic design package. The bed-material load histogram should display a continuous distribution with a single mode (peak). If this is the case, the effective discharge corresponds to the mean discharge for the modal class (the peak of the histogram). If the modal class cannot be readily identified, the effective discharge can be estimated by drawing a smooth curve through the tops of the histogram bars and interpolating the effective discharge from the peak of the curve. If the modal class of the bed-material-load histogram is the lowest discharge class, it is likely that the indicated effective discharge is erroneous. In this case it may be necessary to modify the procedure by either increasing the number of discharge classes or modifying the bed-

[1] Two versions of this system currently exist, SAM and SAMwin. SAMwin is the Windows version of the older DOS-based SAM. The SAM Hydraulic Design Package for Channels is a result of research conducted through the Flood Damage Reduction and Stream Restoration Research Program, starting in the late 1980s, at the Coastal and Hydraulics Laboratory (CHL) of the Engineer Research and Development Center (ERDC), Vicksburg, Miss. Recently, under Cooperative Research and Development Agreement (CRDA) number CRDA-01-CHL-04, Owen Ayres & Associates, Inc., Ft. Collins, Colo., developed a modern, user-friendly, graphical user interface. In this report, SAM refers to the Windows version known as SAMwin. The software is available from Owen Ayres & Associates, Inc., Ft. Collins, Colo.

material rating curve, noting that caution should be exercised in each case (Biedenharn et al., 2000).

The Sabine River at Bon Wier, Texas was selected to show how SAM can be used to determine effective discharge for pre- and post-implementation of a HEFR-based environmental flow prescription. Determination of the effective discharge also produces two additional outputs that are important in assessing geomorphic stability of streams: (1) average annual water yield and (2) average annual sediment yield.

The steps required to do an effective discharge computation are as follows:

1. Development of the hydraulic parameters needed to compute a bed-material load rating curve, which include effective width, effective depth, discharge or velocity, and channel slope.
2. Development of the bed-material load rating curve, which requires knowledge of the bed-material gradation.
3. Computation of the existing sediment yield and the bed-material load histogram, which requires the integration of the bed-material-load rating curve with the existing flow-duration curve.
4. Development of a flow-duration curve that reflects the hydrologic conditions expected to exist following the implementation of HEFR-based flow prescriptions.
5. Computation of the sediment yield and bed-material load histogram for post-HEFR implementation conditions, which requires the integration of the bed-material-load rating curve with the post-HEFR flow-duration curve.
6. Comparison of pre- and post-HEFR water yield, sediment yield, and effective discharge computations.

For this example, it is assumed that data developed in steps 1 and 2 above will be the same and that only the flow-duration curves will be different between the existing conditions and a fully implemented HEFR-based environmental flow regime. This constitutes the condition that would exist in year 1 of the implemented flow regime, assuming there is sufficient infrastructure and water demand to remove flows above those protected by HEFR. The conclusions reached by analyzing pre- and post-HEFR conditions are the same whether the flow changes occur all at once or if the transition to a fully implemented flow regime occurs over a period of years. A slower transition to a fully implemented flow regime could make for a more manageable change in channel character. Detailed modeling of the system could provide beneficial insights into channel behavior as the flow reduction from existing conditions to an implemented HEFR-based flow regime occurs.

7.1 STEP 1

Step 1-A: The application of SAM to determine the effective discharge requires hydraulic parameters needed to compute a bed-material load rating curve, including effective width, effective depth, discharge or velocity, and channel slope. These data can be obtained for the

USGS streamflow-monitoring network and by using the computational capabilities of SAM. Figure 13 shows a cross section for the Sabine River near Bon Wier, Texas (USGS streamflow-gaging station 08028500). The cross section is from a discharge measurement on April 1, 2004. The original cross-section is simplified for input into the SAM Hydraulic Module.

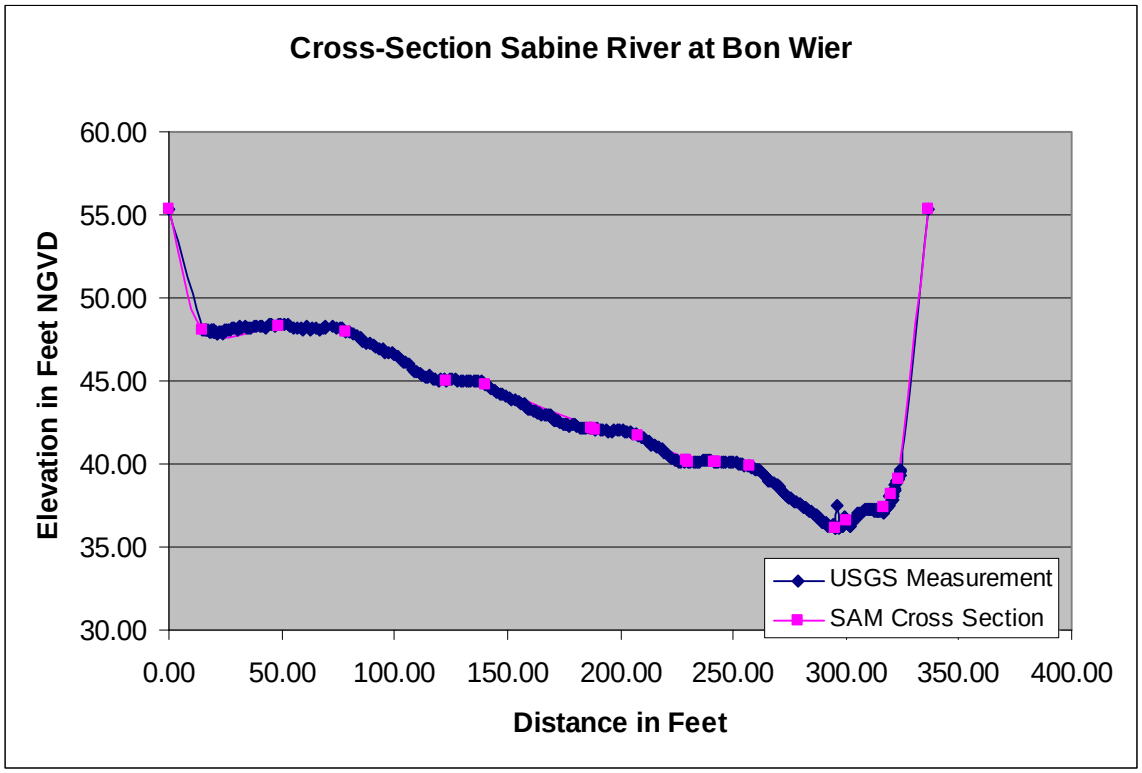

Figure 13. Cross section of the Sabine River near Bon Wier, Texas on April 1, 2004 (USGS streamflow-gaging station 08028500).

The SAM Hydraulic Module can solve for any one of the variables in the uniform flow equation (shown below). Water discharge is usually the dependent variable. However, SAM allows any of the variables on the right side of the equation to become the dependent variable, except side slope (z). The SAM Hydraulic Module inspects each input record type in a data set and determines which variables have been prescribed. The omitted variable becomes the dependent variable (Thomas et al. 2002).

- $\boldsymbol{Q = f(D, n, W, z, S)}$, where Q is water discharge (ft^3/s), D is depth (ft), n is Manning's roughness coefficient, W is bottom width (ft), z is side slope of the channel, and S is energy slope.

For this example, normal depth was computed by SAM. The input required for the normal depth computations include the cross section as shown in Figure 13, discharges, channel slope, and Manning's n values. The input data used for the normal depth computation is shown below:

```
T1 T1 Sabine River Demonstration Run
T1 T2 Using USGS data to create cross sections
T1
TR     1
X1  97.7      21       0  336.46
GR 55.36    0.00   48.02   15.00   48.27   48.27   47.98   78.69   44.95  123.14
GR 44.80  140.49   42.11  187.45   42.07  188.65   41.67  208.18   40.17  229.17
GR 40.16  230.30   40.17  241.61   40.16  242.69   39.83  257.09   36.11  295.01
GR 36.60  300.46   37.39  316.36   38.16  320.18   39.07  323.06   55.36  336.46
GR  67.2     485
NE     0       0       0       0       0       0       0       0       0       0
NE     0       0       0               0       0       0       0       0       0
KN  .030                             .030
KN                                                                   .030    .125
ES.00014  .00014  .00014  .00014  .00014  .00014  .00014  .00014  .00014  .00014
QW   300    1520    4135   10200   16500   19300   27600   38400   52400   98100
WT    60
$$END
```

Step 1-B: The results of the normal depth computations are compared to the current USGS rating curve for the Sabine River near Bon Wier, Texas. The comparison of the computed vs. observed rating curves (Figure 14) shows sufficient agreement between the measurements, thereby enabling us to move forward with this example. The practitioner performing these computations will need to determine when the agreement of the computed and observed measurements is satisfactory to move forward with the study.

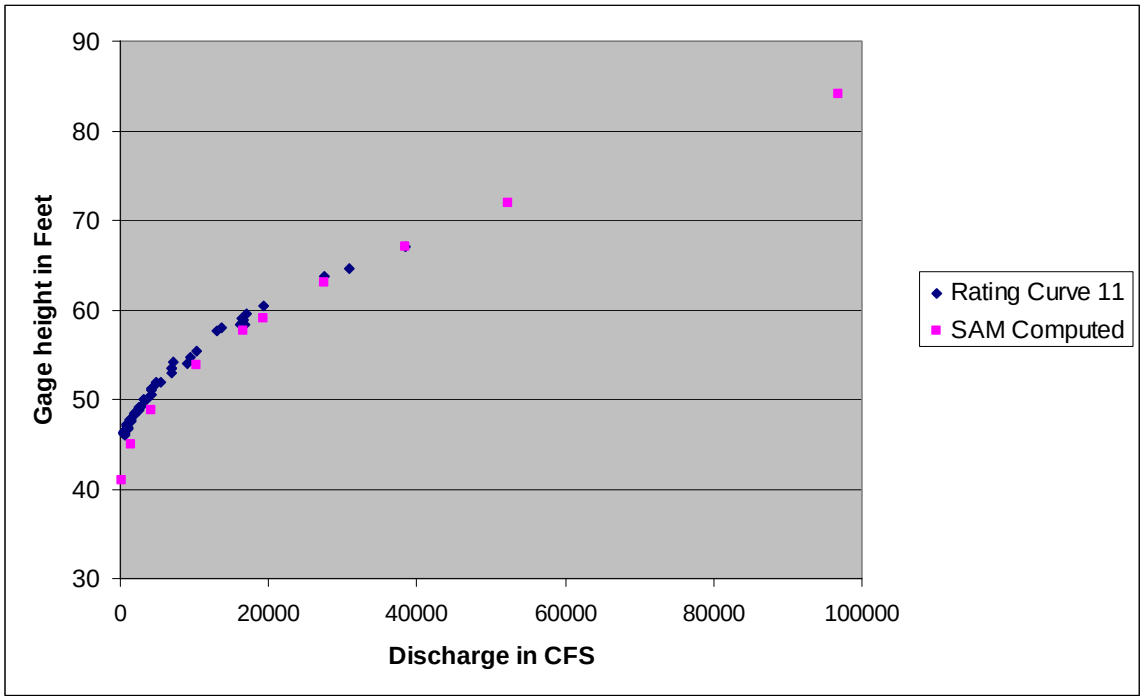

Figure 14. Comparison of current (2009) and SAM-computed stage-discharge curves for USGS streamflow-gaging station 08028500, Sabine River near Bon Wier, Texas.

7.2 STEP 2

The results of the SAM hydraulics computations are used with a bed-material gradation curve to compute the bed-material load rating curve.

SAM.HYD writes the following information into a file that used by SAM.SED to compute the Bed-Material Load Rating Curve:

```
T1      FILE WRITTEN BY SAM.hyd
T1
TF ACKERS-WHITE.        YES
TF COLBY                YES
TF ENGELUND-HANSEN      YES
TF VAN.RIJN             YES
TR
QW   300    1520    4135   10200   16500   19300   27600   38400   52400   98100
VE  1.31    1.97    2.53    3.18    3.69    3.89    4.39    4.92    5.50    6.92
DE  3.35    6.23    9.05   12.68   15.80   17.07   20.53   24.53   29.08   41.36
WI   69.   123.6   180.8   252.6   282.8   290.7   305.1   314.6   321.0   328.9
ES.00014  .00014  .00014  .00014  .00014  .00014  .00014  .00014  .00014  .00014
WT    60
```

The bed-material gradation for the Sabine River near Bon Wier, Texas is input into the SAM Sediment Module. The input data are found in the PF records (see below). For the Bon Wier gage, the data included a D_{16} (i.e., 16 percent of the material is finer than) of 0.0625mm, a D_{50} (i.e., median particle size) of 0.14 mm, and a D_{84} (i.e., 84 percent of the material is finer than) of 0.50 mm. For the Bon Wier gage, the bed-material data came from Soar and Thorne (2001).

```
PF                   1.0     .50      .5     100      .3      84     .14      50
PFC.0625      16   .0625       0
SP  2.65
$$END
```

The SAM Sediment Module allows the user to chose up to 20 sediment transport functions to compute the total bed-material load rating curve. These functions include equations developed for bed material from cobble and gravel to very fine sands. Some of the functions compute by grain-size class while others use only D_{50} for a single grain-size computation. A tool called SAM-AID is available in SAM to help the user pick out one or more appropriate sediment functions for the initial computations. The practitioner usually selects 3 or 4 sediment transport functions and then chooses one that falls in the middle of pack. If the practitioner has enough data to develop a total bed-material load rating curve from observed measurements, then the curve can be directly input into the sediment yield module and steps 1 and 2 are not required. The important thing to remember here is if you want to compare pre- and post-implementation conditions, you should use the same sediment transport function or use the same observed total bed-material load rating curve for both conditions. Figure 15 shows bed-material load rating curves developed for 4 sediment transport functions: (1) Ackers-White, (2) Engelund-Hansen, (3) Colby, and (4) Van Rijn. Based on input conditions of the Sabine River near Bon Wier, Texas, the SAM-AID tool recommended that the Engelund-Hansen function would most

accurately compute bed-material discharge. Therefore, the Engelund-Hansen function was used to compute sediment yield (bed-material yield) and effective discharge.

Figure 15. Sediment-load rating curves computed by SAM-AID using input parameters for USGS streamflow-gaging station 08028500, Sabine River near Bon Wier, Texas.

7.3 STEP 3

Step 3-A: The Sediment Transport Module develops an input file for the Sediment Yield Module. This file contains the total bed-material load rating curve, also known as QW and SC cards (see sediment yield input file 1 below). A second file is needed for the Sediment Yield Module that contains the flow-duration curve, the number of output class intervals, and the specific weight of sediment. This file can be developed using input boxes produced by the SAM program (see sediment yield input file 2 below). The flow-duration curve for existing conditions on the Sabine River near Bon Wier is shown in Figure 16. For the number of output class intervals, the default value is 20 but in some cases as many as 50 or more might be necessary to describe the flow regime. The default specific weight of sediment is 93 lbs/ft^3, which can be changed as required by the SAM practitioner.

The Sediment Yield Module input files are:

Sediment yield input file 1:

```
1      FILE WRITTEN BY SAM.hyd
T1
TI      FILE WRITTEN BY SAM.sed
TF     ENGELUND-HANSEN
QW   300    1520    4135   10200   16500   19300   27600   38400   52400   98100
SC74.100    150.    233.    346.    449.    492.    607.    738.    890.   1308.
$$END
```

Sediment yield input file 2:

```
T1 Sabine River at Bon Wier
T1 observed Flows
T1 After Toledo Bend 1972-2007
T1
JP    50             365             365              93
QQ   307     575     738     917    1270    1970    3180    4570    6150    8280
QQ 14300   17520   19016   21400   24400   29700   35604   98000
QD   100      98      95      90      80      70      60      50      40      30
QD    20      10       8       6       4       2       1       0
$$END
```

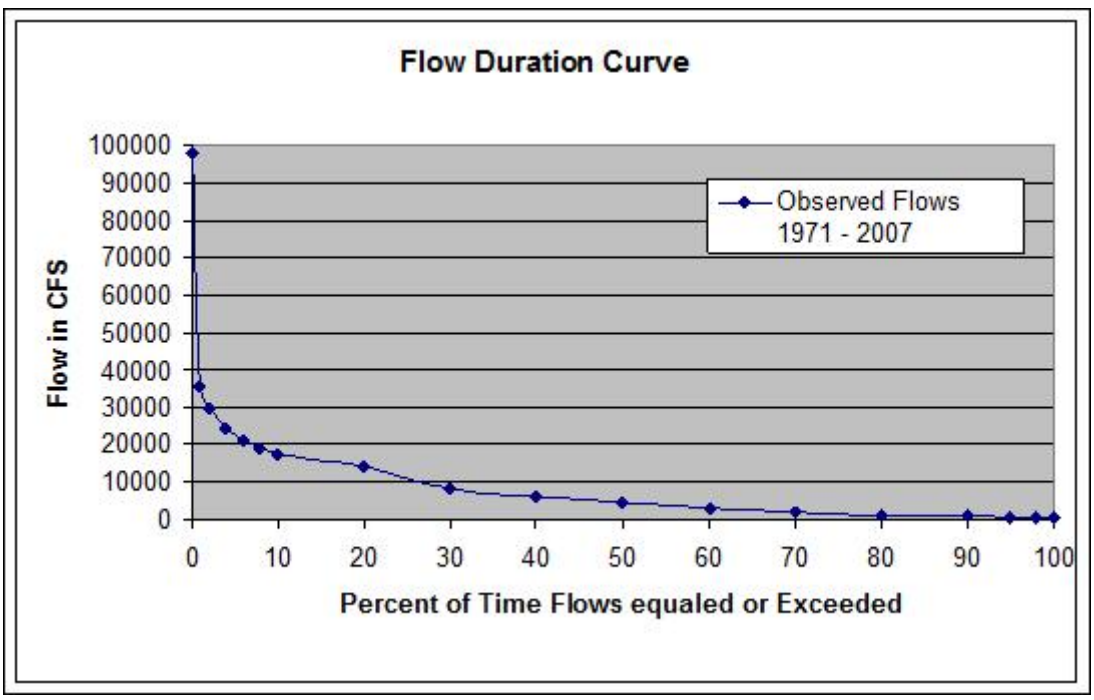

Figure 16. Flow-duration curve for USGS streamflow-gaging station 08028500, Sabine River near Bon Wier, Texas.

Step 3-B: Execution of the Sediment Yield Module for the existing hydraulic and hydrologic conditions shows:

Average annual water yield is:	5,465,145 acre feet
Average annual sediment yield is:	3,342,038 tons

Figures 17 and 18 show the bed-material load histogram generated by the SAM Sediment Yield Module. The bed-material load histogram shows the bin containing flows from 13,984 to 15,938 ft^3/s carries the largest percentage of the annual bed-material load. This bin has a midpoint of 14,961 ft^3/s and conveys about 412,000 tons of bed material annually. For existing conditions, the effective discharge would reference as 14,961 ft^3/s, but more importantly the practitioner should consider the effective discharge range for this computation to be between 14,000 and 16,000 ft^3/s.

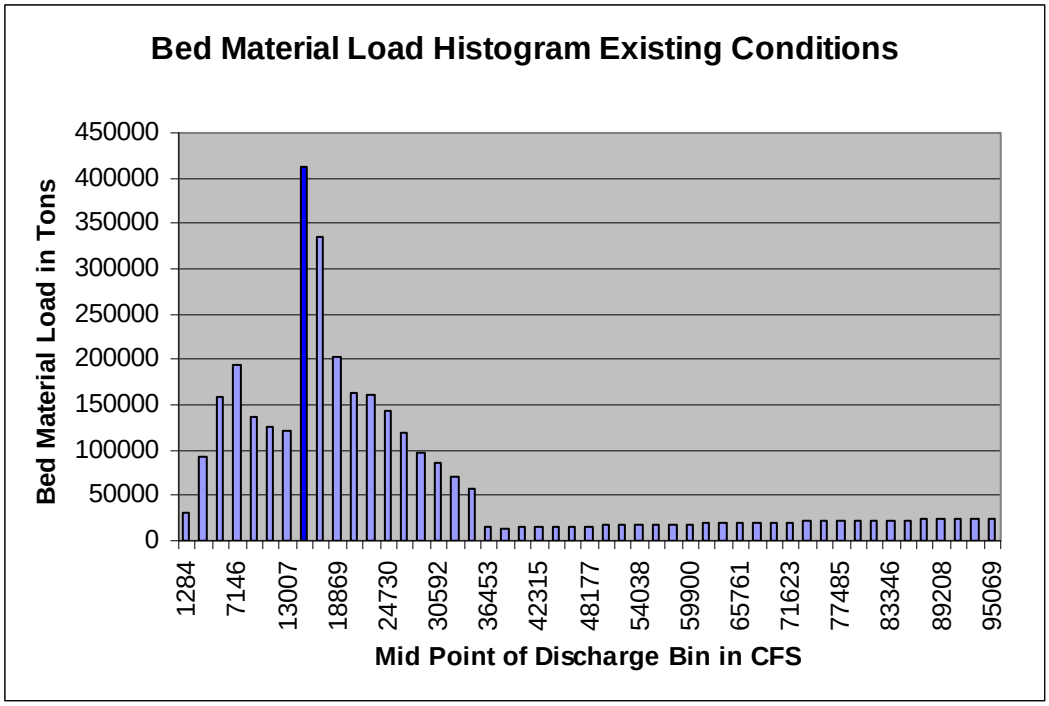

Figure 17. Bed-material load histogram for existing hydrologic conditions at USGS streamflow-gaging station 08028500, Sabine River near Bon Wier, Texas.

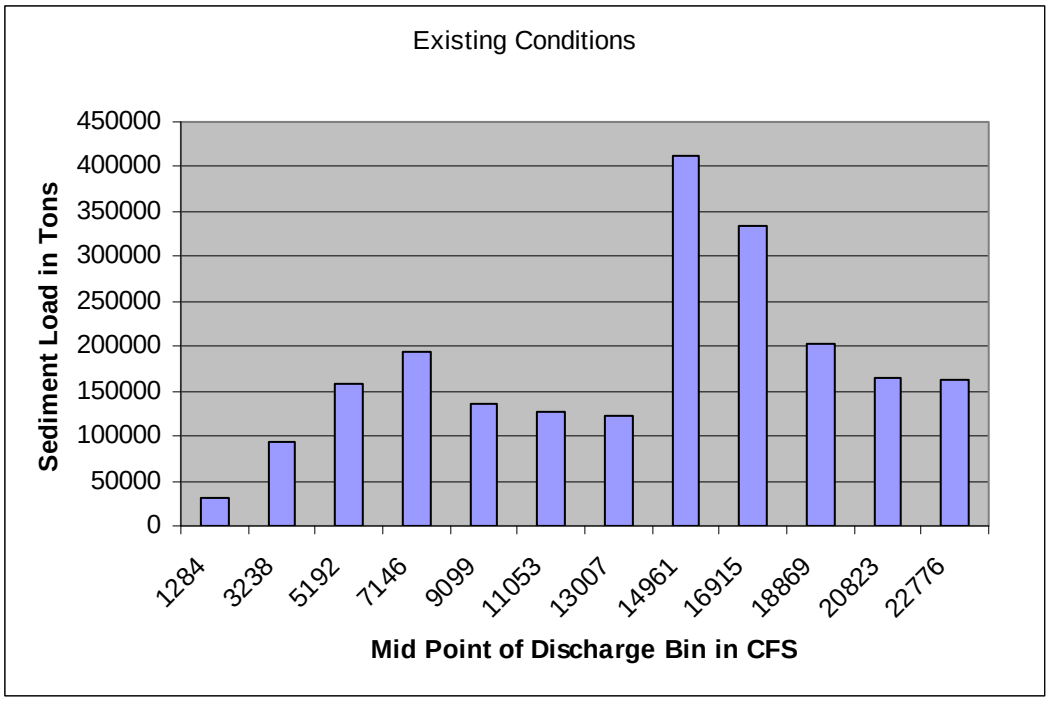

Figure 18. Bed-material load histogram for existing conditions less than 25,000 ft^3/s at USGS streamflow-gaging station 08028500, Sabine River near Bon Wier, Texas.

7.4 STEP 4

Step 4-A: Step 4-A is the development of the flow duration that will exist after the HEFR-based implementation. For this example, the HEFR-based flow regime was developed using the observed discharge measurements for the Sabine River near Bon Wier, Texas for water years 1924 to 1960. The water years 1924 to 1960 represent flow conditions that existed before the construction of any major reservoirs in Sabine River Basin. The HEFR-based flow regime is shown in Table 4.

Table 4. Results of HEFR-based flow regime analysis using water years 1924 to 1960 at USGS streamflow-gaging station 08028500, Sabine River near Bon Wier, Texas.

Overbank Flows	Return Period (R) : 0.8 (years)		Duration (D) : 32 (days)	
	Volume (V) : 1353987 (ac-ft)		Peak Flow (Q) : 31800 (cfs)	
High Flow Pulses	F: 1 D: 18	F: 1 D: 16	F: 0 D: 12	F: 0 D: 10
	Q: 19000 V: 416351	Q: 17400 V: 384814	Q: 11900 V: 120397	Q: 7135 V: 82354
	F: 1 D: 12	F: 1 D: 11	F: 0 D: 9	F: 1 D: 6
	Q: 13400 V: 207868	Q: 12900 V: 191207	Q: 5690 V: 67716	Q: 3705 V: 37964
	F: 1 D: 6	F: 1 D: 6	F: 0 D: 4	F: 1 D: 4
	Q: 8690 V: 87610	Q: 10700 V: 98500	Q: 2995 V: 24258	Q: 2350 V: 17009
Base Flows (cfs)	6110	6640	2190	1430
	2800	4000	1220	870
	1540	2340	770	703
Subsistence Flows (cfs)	703	703	703	703
	Dec Jan Feb	Mar Apr May	Jun Jul Aug	Sep Oct Nov
	Winter	Spring	Summer	Fall

Hydrologic Conditions
Wet
Average
Dry
Subsistence

High Flow Pulse Characteristics
F = Frequency (per season)
D = Duration (days)
Q = Peak Flows (cfs)
V = Volume (ac-ft)

Step 4-B: After the HEFR-based flow regime is computed (shown in Table 4), the next step is to adjust the observed flows for the analysis period 1971 to 2007 to reflect implementation of the prescribed flow regime. The adjustment to the observed hydrograph was accomplished as follows:

1. The total annual flow volume from December 1st to November 30th was computed. The lower 25% of the years were considered dry (lowest 9 of the 36 years). The upper 25% of the years were considered wet (highest 9 of the 36 years). Flows between 25% and 75% were considered average flow years.
2. Based on the hydrologic classification (dry, average, wet), the years were analyzed for the amount of water available to be removed from the system. This constitutes a "worst-case scenario" where flows in excess of the HEFR-based flow prescription are removed.
3. Flows above overbank (31,800 ft^3/s) were removed by the following procedure. The hydrograph was analyzed for a full year from December 1st to November 30th, a 5-day window was set, and when a flow 5 days from the current day exceeded 31,800 ft^3/s, an

overbank flow event was started. Flows above 31,800 ft^3/s were removed until the desired flow volume and duration were reached. Until the flow volume and duration criteria were met, no flow was removed from system, even for flows less than 31,800 ft^3/s.

4. The hydrograph was analyzed for high-pulse flows in a matter similar to the overbank flow analysis. Seasonal high-pulse flow discharge values are based on dry, wet, and average hydrologic conditions. The hydrologic condition for each year was determined as discussed above. If the flows exceeded a high-pulse flow value for the season, they were removed from the system until pulse duration and volume were equaled or exceeded. One pulse per season was allowed; after one high pulse had passed, all flows above baseflow were removed from the system. See Figure 19 for how this was done in 1994 (December 1, 1993 to November 30, 1994).
5. Flows above baseflow and not part of an overbank or high-pulse flow event were removed from system. See Figure 19 for how this was done in 1994 (December 1, 1993 to November 30, 1994).
6. Flows less than baseflow were left untouched. Figure 19 shows an example for flows below the seasonal baseflow during an average flow year for few days in January and February of 1994.

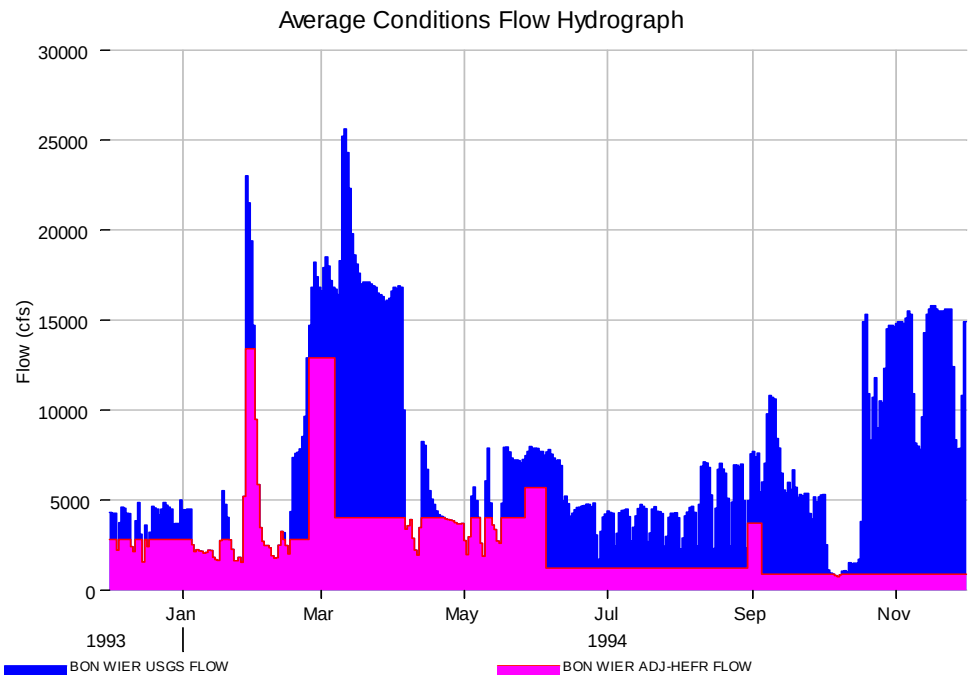

Figure 19. Daily flow hydrograph showing observed and HEFR-adjusted flows for December 1, 1993 to November 30, 1994, at USGS streamflow-gaging station 08028500, Sabine River near Bon Wier, Texas.

The daily flow records for all 36 hydrographs were adjusted, and a new flow-duration curve was computed (Figure 20).

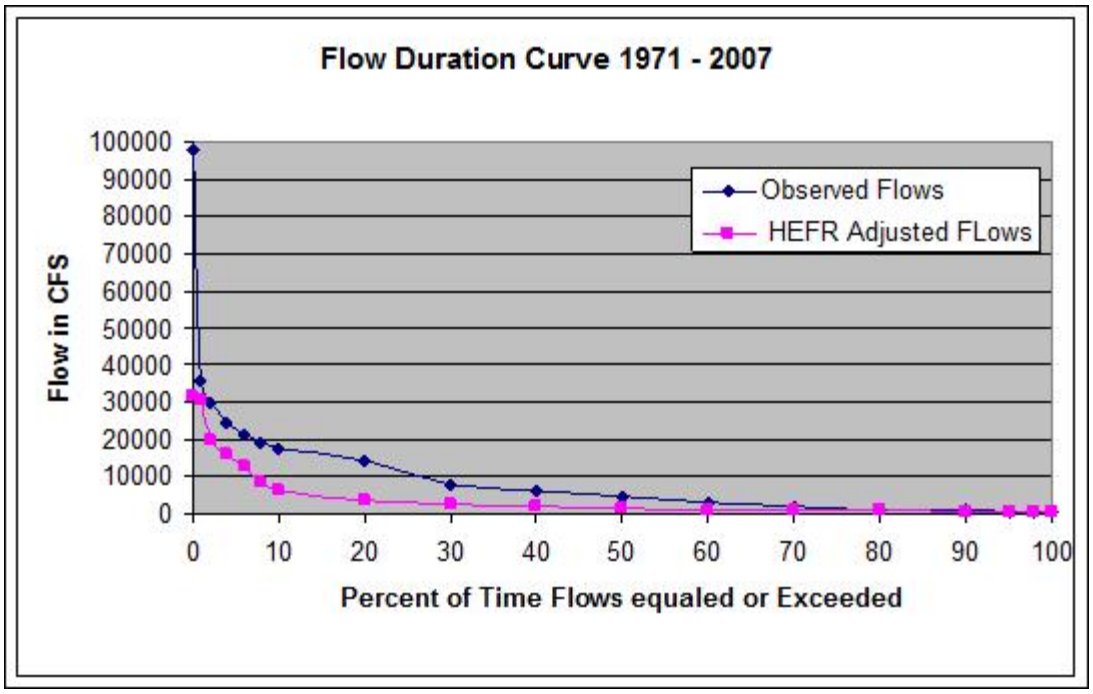

Figure 20. Flow-duration curves based on non-adjusted and HEFR-adjusted daily discharge values, at USGS streamflow-gaging station 08028500, Sabine River near Bon Wier, Texas.

7.5 STEP 5

The computation of sediment yield and the bed-material load histogram for HEFR-adjusted flow conditions requires the integration of the bed-material load rating curve with the flow-duration curve. The SAM Sediment Yield Module for the HEFR-adjusted hydraulic and hydrologic conditions shows that:

Average annual water yield is:	2,397,320 acre-feet
Average annual sediment yield is:	1,068,724 tons

Figure 21 shows the bed-material load histogram generated by the SAM Sediment Yield Module for the HEFR-adjusted hydrology. The histogram does not show a normal distribution, and the high-flow bins carry the greatest percentage of the bed-material load. This is because flows greater than 31,800 ft^3/s have been reduced to 31,800 ft^3/s, therefore compressing the flow-duration curve and increasing the percentage of time flows in this bin occur. Other observations from reviewing Figure 21 are that flows less than about 3,000 ft^3/s are carrying a high percentage of bed-material load, and a second peak in the bed-material histogram occurs at about 17,000 ft^3/s.

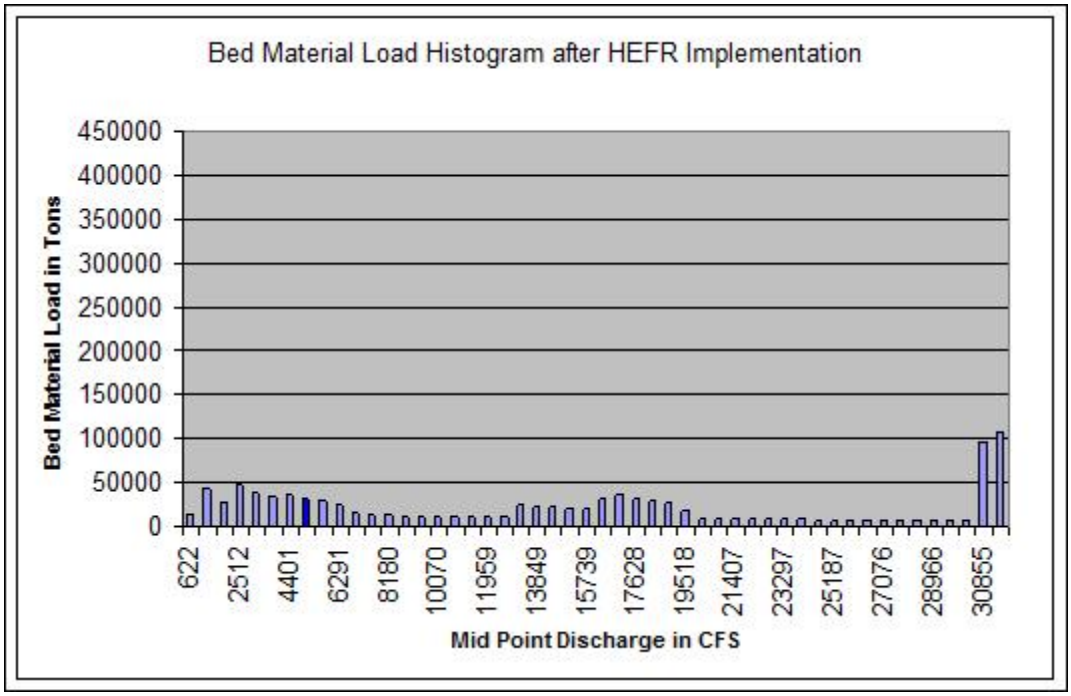

Figure 21. Bed-material load histogram for HEFR-adjusted conditions at USGS streamflow-gaging station 08028500, Sabine River near Bon Wier, Texas.

7.6 STEP 6

The SAM analysis of pre- and post-HEFR conditions at the Sabine River near Bon Wier, Texas shows a substantial difference for hydrologic and sediment-transport dynamics. Average annual water yield and average annual bed-material load are significantly reduced for the HEFR-adjusted flow regime (Table 5).

Table 5. Comparison of average annual water yield and average annual bed-material yield for observed and HEFR-adjusted flow regimes at USGS streamflow-gaging station 08028500, Sabine River near Bon Wier, Texas.

Condition	Average annual water yield (millions of acre feet)	Average annual bed-material yield (millions of tons)
Observed hydrology	5.5	3.3
HEFR-adjusted hydrology	2.4	1.1

The effective discharge computations for a pre- and post-HEFR hydrologic regime indicate a high probability for channel change and instability until steady-state equilibrium is achieved. The amount of channel instability could be determined by a long-term sediment-load monitoring program, which could be used to analyze how the timing of water and sediment withdrawals from the system affects channel adjustments. From the work of Schumm (1969), reducing both

the flow and sediment of a river channel can lead to a reduction in width, depth changes, a decrease in width-depth ratio, and an increase in sinuosity.

Despite the dramatic differences between observed and HEFR-adjusted water and sediment yields for the Sabine River near Bon Wier, Texas, it should be noted that (1) practitioners have alternatives in their assignment of HEFR results to create prescribed flow regimes, and (2) HEFR is an evolving software tool with updates that give practitioners more flexibility to statistically model hydrologic conditions at a given site. To summarize, the HEFR results could have been assigned differently, which would result to a change in annual sediment yield, or the HEFR model could have been parameterized differently, resulting in changes to annual water and sediment yield. Further, this example represents a "worst-case scenario" where the volume of water more than that protected by this particular HEFR-based flow prescription was removed to assess sediment transport. Such a scenario is only possible if a reservoir fully regulates flow, including floods, or if water diversions are sufficiently developed to withdraw all flows more than the HEFR-based prescription.

SECTION 8
CONCLUSIONS

An analysis of effective discharge of suspended-sediment load (SSL), bedload, bed-material load, and/or total load at streamflow-gaging stations could be used to modify HEFR-based flow prescriptions for establishing environmental flows. Specifically, a SAM (Hydraulic Design Package) analysis of effective discharge of bed-material load would be most informative for assessments of instream habitat conditions and dynamics. For the majority of locations, the high-pulse flow or overbank-flow categories are associated with the cumulative majority of sediment transport over time. Computations for suspended load should utilize historical measurements, if available, and bed-material load likely requires application of a model equation. Sediment transport, although relatively straightforward in its association with discharge, does not encompass the breadth of fluvial geomorphic processes. Furthermore, concepts of steady-state equilibrium challenge assumptions that a constant discharge value is responsible for the cumulative majority of sediment transport over time. Finally, practitioners utilizing effective discharge for rivers in Texas should be cognizant of the contemporary sediment-transport regime and historical channel adjustments at each location considered. Assignment of an effective discharge to altered or regulated rivers is problematic and implementation efforts could be harmful if a holistic perspective (e.g., sediment trapped behind reservoirs, non-representative cross section to estimate bedload transport, etc.) is not considered.

The SAM Hydraulic Design Package is a very useful desktop tool to assist practitioners in modeling sediment transport and determining effective discharge at streamflow-gaging stations. It conveniently facilitates the choice of a sediment-transport model equation based on user input, and can be used to compare annual sediment loads for existing and HEFR-based hydrologic conditions.

Although SAM is a useful tool to compare observed sediment-transport loads and effective discharge with HEFR-based conditions, little can be done using readily available desktop methods to prescribe a “sediment-load regime” that would adequately maintain instream ecology. The chief reason for this is the paucity of historically-observed geomorphic and sediment-transport data for rivers in Texas, contrasting with the availability of streamflow data for HEFR-based flow-regime analyses. Further, various fluvial processes (e.g., channel bar deposition and modification, channel migration, floodplain sedimentation) initiate and/or occur over a range of flows and, therefore, are dependent on sufficient rates of sediment transport during those flows. The unavailability of data for Texas rivers obfuscates the determination of optimized sediment concentrations or loads for these physically- and ecologically-relevant flows. At minimum, the practitioners responsible for environmental-flow prescriptions at a given site should be cautious if bed-material load is shown to be considerably reduced as a result of an implementable schedule of flows.

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SECTION 10
GLOSSARY

Bedload: a measure of the transport of fluvial sediment along or near the channel bed by traction or saltation mechanisms; either sand, gravel, or larger size; expressed as mass over time

Bed-material load: a measure of the transport of fluvial sediment as bedload or sand grains in suspension during turbulent flows; only comprised of particles derived from the channel bed; does not include silt or clay particles; expressed as mass over time

Effective discharge: the flow rate responsible for the majority of cumulative sediment transport over time; usually equated to a relatively frequent, moderate flow event; commonly accepted as bankfull discharge; association with bankfull discharge is less apparent for fluvial systems with a highly-variable flow regime

Saltation: a mechanism of bedload transport whereby particles skip along the channel bed

Sediment budget: a technique that accounts for sources (additions) and sinks (subtractions) of fluvial sediment in a defined system (e.g., watershed); accounts for sources from hillslopes, channel banks, tributaries, among others; accounts for removals by impoundments, floodplain storage, distributaries, among others

Steady-state equilibrium: concept that a river channel adjusts over graded time (decades to hundreds of years) to efficiently convey the amount of discharge and sediment load by maintaining a particular slope, pattern, and shape; suggests that the fluvial system will gradually recover from the effects of a disturbance to the system (e.g., 100-year flood); a fundamental, but controversial, fluvial geomorphic concept

Stream power: the product of average shear stress and average velocity; commonly used to predict sediment transport; expressed in SI units as watts/square meter

Suspended-sediment load: a measure of the transport of fluvial sediment continuously entrained in the water column; mostly clay and silt, with varying amounts of sand derived from the channel bed during turbulent flows; expressed as mass over time

Suspended-sediment concentration: the concentration of suspended sediment in the water column; computed as the ratio of suspended-sediment load to the streamflow; expressed as milligrams per liter

Traction: a mechanism of bedload transport whereby particles roll or slide along the channel bed

Wash load: a measure of the transport of fluvial sediment and other material continuously entrained in the water column (e.g., clay, silt, and organic matter); does not include the sand-sized fraction; expressed as mass over time

SECTION 11
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April 3, 2009

Transmittal to Basin and Bay Expert Science Teams (BBESTs)

Report # SAC-2009-02

Title: Geographic Scope of Instream Flow Recommendations.

The attached document constitutes another deliverable from the SB3 Science Advisory Committee (SAC) to assist the BBESTs in carrying out their responsibilities under SB3. This report addresses the geographic scope of environmental flow regime recommendations; that is, the number and spatial distribution of locations where specific flow recommendations will be developed in order to characterize an environmental flow regime for a particular basin.

The document presents various factors which should be considered by the BBEST in determining geographic scope. The importance of existing streamflow-gaging stations, primarily operated by the USGS, is identified. The report suggests using the USGS Core Network gages as a starting point, but strongly encourages the BBESTs to fully evaluate the adequacy of this network, and to increase or decrease the number of recommended streamflow-gaging stations as they deem appropriate to adequately define the environmental flow regime.

The SAC continues to offer this information as guidance and not prescription. The SAC is hopeful that the BBESTs will find this information useful in their deliberations, and we invite feedback as we all move forward with our respective responsibilities under SB3.

Robert J. Huston, Chairman, SB3 Science Advisory Committee

April 3, 2009

GEOGRAPHIC SCOPE OF INSTREAM FLOW RECOMMENDATIONS

Senate Bill 3 Science Advisory Committee for Environmental Flows

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April 3, 2009

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SECTION 1. INTRODUCTION

The purpose of this paper is to address the geographic scope of environmental flow regime recommendations for the Senate Bill 3 (SB 3) process. As defined by SB 3, an environmental flow regime means a schedule of flow quantities that reflect seasonal and yearly fluctuations that typically would vary geographically, by specific locations in a watershed, and that are shown to be adequate to support a sound ecological environment and to maintain the productivity, extent, and persistence of key aquatic habitats in and along the affected water bodies and receiving coastal bay system. The question of geographic scope for the SB 3 process is a matter of recommending the number and spatial distribution of locations where flow regime recommendations will be developed. This document does not address implementation of flow recommendations.

In contrast to the SB 3 process, environmental assessments of water rights applications are currently conducted on a case by case basis. Numerous sources are utilized to determine whether special conditions, including streamflow restrictions, are necessary to satisfy environmental concerns. If streamflow restrictions are recommended, an effort is made to tie the restrictions to a nearby active USGS gage. However, this is not always possible or practical.

For a diversion or project on an ungaged stream, an effort is made to locate an active gage with at least 20 years of flow data in the same watershed or an adjacent watershed. In addition to proximity, factors such as stream characteristics, ecological characteristics, hydrological characteristics (e.g. whether the gage and project location are influenced by wastewater discharges or reservoir releases), and drainage area size may be taken into consideration in selection of an appropriate gage. Once a gage has been selected and a historical period of record determined, streamflow restrictions for the gaged location are calculated based on median flow values for each month of the year. The resulting monthly restrictions are then prorated to the project location using a drainage area ratio. If streamflow restrictions are placed in the permit, the permittee is responsible for developing a method or installing a reference device to measure the appropriate flow value.

There are a number of issues that should be considered in determining the geographic scope of instream flow recommendations for the SB 3 process. For example, flow recommendation locations should consider, and be compatible with, the river segments identified by the Texas Instream Flow Program (TIFP) for Senate Bill 2 (SB 2) studies. In addition, biologic, hydrologic, and geomorphic information, water quality segments, basin management subdivisions and water availability could play a role in these location determinations. There are a broad range of aquatic ecosystems in Texas' rivers and the study methodology for instream flow recommendations may need to be customized for specific river systems (TCEQ et al., 2008). Thus for each river basin, the choices may be different.

The document includes general information that could be used to segment a river basin for purposes of determining the number of flow recommendation locations that might be

needed to characterize an environmental flow regime in a particular basin. Available information includes the spatial scale units adopted by the TIFP and other general information, such as hydrology, geomorphology, biology and water quality that are available for all river basins and should be considered in location determinations.

The document also describes basin specific information that could be added to the general information, or used to enhance this information, using the Trinity River Basin as an example application. The summary outlines a general process for determining geographic scope.

SECTION 2. GENERAL INFORMATION FOR DETERMINING GEOGRAPHIC SCOPE

This section begins with a brief discussion of the spatial scale units adopted by the TIFP, followed by general information that could be used to segment a river basin for the purpose of determining how many points are needed to adequately identify environmental flow needs consistent with SB 3. The data sets discussed in this section are readily available and could be used in any Texas river basin to facilitate the location selection process.

2.1 SPATIAL SCALE UNITS ADOPTED BY THE TEXAS INSTREAM FLOW PROGRAM

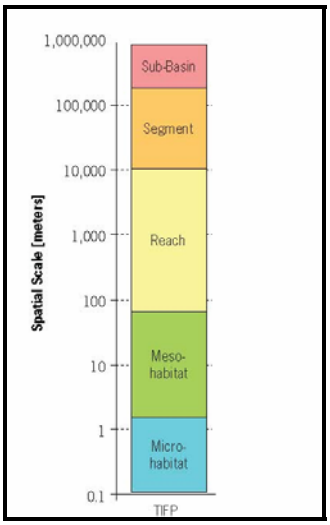

Figure 1. TIFP spatial scale units (adapted from TCEQ et al., 2008, p. 29. Figure 3.1 Nomenclatures describing the spatial scales of riverine ecosystems).

The TIFP adopted five specific definitions for the spatial scale of watershed components used in SB 2 studies (Figure 1.):

1. Sub-basin - *the full geographic extent of priority studies within major river basins in Texas, including the main channel, floodplain, tributaries, and contributing watershed area of all study segments.*
2. Segment - *subset of sub-basin study area. For priority studies, segments are equated to the corresponding river segments described in 30 Texas Administrative Code §307.1 through 307.10. The Agencies recognize that significant processes at this scale extend beyond the channel and include tributaries and contributing watershed area.*
3. Reach – *subdivision of a segment that exhibits relatively homogeneous channel and floodplain conditions…bounded by breaks such as the confluence of major tributaries and significant geomorphic features. The number of reaches within a segment depends on the degree of heterogeneity.*
4. Mesohabitats – *basic structural elements of a river or stream from an ecological perspective. For alluvial rivers, these elements include scour pools and submerged transverse bars…For smaller streams, mesohabitats are known by such names as pool, riffle, run and chute.*
5. Microhabitats – *zones of similar physical characteristics within a mesohabitat unit. Differentiated by aspects such as substrate type, water velocity, and water depth.*

These spatial scale units are intended to promote consistent nomenclature among the different disciplines for the multiple spatial scales of the SB 2 studies. The timeline for completion of studies for the priority river sub-basins is 2016.

Limited information is available for most of these scales for the priority basins.[1] At this time, the most readily accessible data is hydrologic data, which provides a "convenient, initial understanding of riverine systems (SAC, 2009, p. 6)." Hydrologic data is typically measured and reported at United States Geological Survey (USGS) gages. USGS gages represent discrete locations and do not necessarily coincide with the SB 2 study scales. In effect, gage locations provide point data at different scales and the user must determine the spatial extent over which the data can be used for hydrologic analysis. In addition to hydrologic data, any available data for any of these scales, biological, chemical, or geological, could be considered in determining and refining appropriate locations.

2.2 NATIONAL HYDROGRAPHY DATA SET (NHD)

The National Hydrography Dataset (NHD) is a geospatial data set representing surface water body features.[2] The NHD is basically analogous to state watercourses (30 TAC §297.1 (59)). The NHD is available in several resolutions (high, medium and local), originally based on 1:100,000 scale data. The high resolution NHD uses 1:24,000 or 1:12,000 scale data to add detail to the original NHD. NHDPlus is a geospatial data set, developed by the U.S. EPA and partners, which includes features from the NHD, NED (National Elevation Data Set), the NLCD (National Land Cover Data Set) and the WBD (Water Boundary Data Set). NHDPlus includes flow lines, flow directions and other attributes useful in geospatial applications.[3] The NHD is also presented in a new database design known as NHDinGEO.[4] NHDinGEO supports web-based access and data queries.

The NHD has a number of features that could be useful in the SB 3 context. For example, in NHDPlus, attributes such as average precipitation, average temperature, velocity, cumulative drainage area, and categorical data[5] are linked to the line coverage for streams. Other attributes that could be used for SB 3 streamflow analyses are elevation-derived catchments, Strahler stream order identifiers, links to water quality databases and USGS gaging stations that enable streams to be queried in upstream to downstream order. The utility of this additional data depends on the level of analysis undertaken for a particular river basin.

One main disadvantage of the NHD, regardless of format, is the sheer volume of data, i.e. the number of line segments. For example, the NHD for the Trinity River Basin includes over 155,000 individual line features (Figure 2). The number of stream features could overwhelm the computational methodologies (for example, the HEFR Methodology) currently being discussed for use in the SB 3 process. Measured hydrologic data is often only available for USGS gage locations and determining varying methods to apply the

[1] A list of completed and ongoing studies can be found at http://www.twdb.state.tx.us/instreamflows/studies.html
[2] United States Geological Survey. National Hydrography Data Set. Available at http://nhd.usgs.gov/index.html.
[3] Horizon Systems Corporation. NHDPlus. Available at http://www.horizon-systems.com/nhdplus/
[4] United States Geological Survey. NHD Data Availability. Available at http://nhd.usgs.gov/data.html.
[5] For example perennial vs. intermittent streams are identified and artificial flow paths such as canals are included.

computations at ungaged locations would be extremely time-consuming. Methods could be developed to aggregate data and reduce the number of line segments, however, time constraints for the SB 3 process may preclude development and validation of these methods.

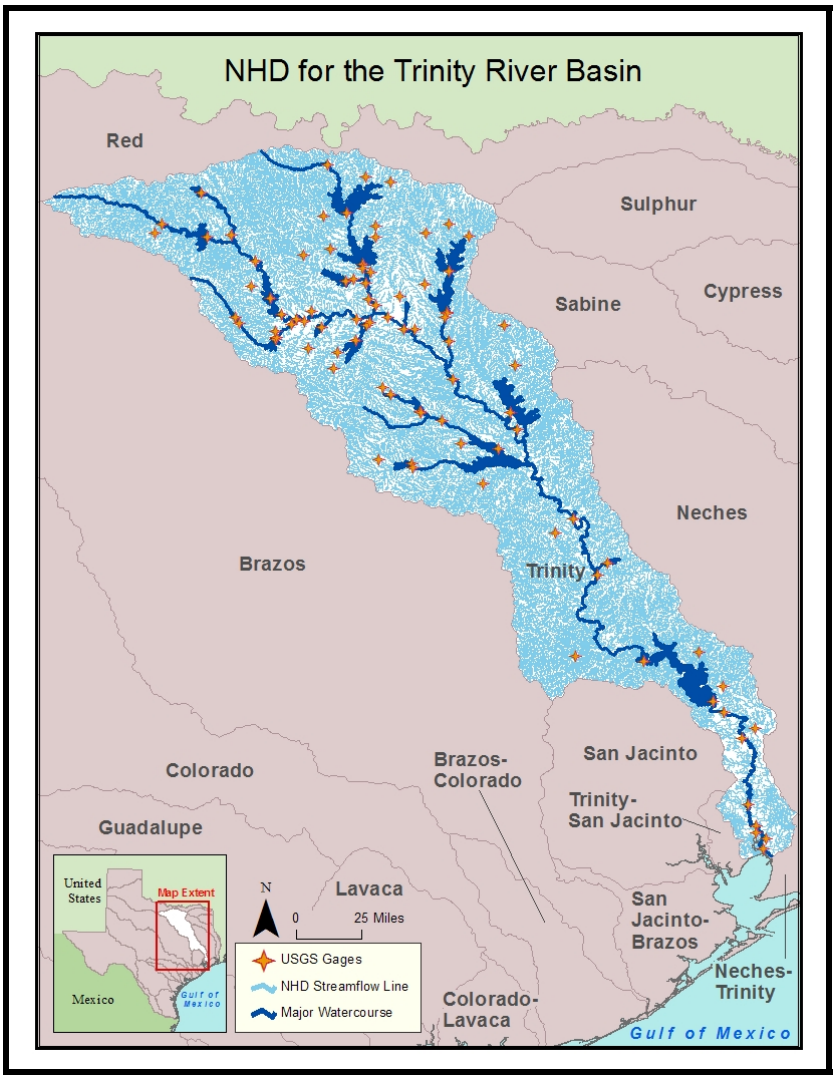

Figure 2. NHD for the Trinity River Basin.

2.3 TCEQ CLASSIFIED SEGMENTS

TCEQ applies water quality standards to designated water bodies in Texas (Figure 3). These water bodies are included in both river basins and coastal areas. The designated water bodies, referred to as segments, are based on regional hydrologic and geologic diversity (TCEQ, 2009). Although the classified segments, and data associated with them, are informative because of their use in water quality programs, relying solely on the classified segment network would not necessarily be useful. For example, classified segments include the impounded area of reservoirs. In addition, long classified segments may have many factors affecting their flow characteristics because of the segment length.

In this case, consideration should be given to breaking up long segments into smaller segments.

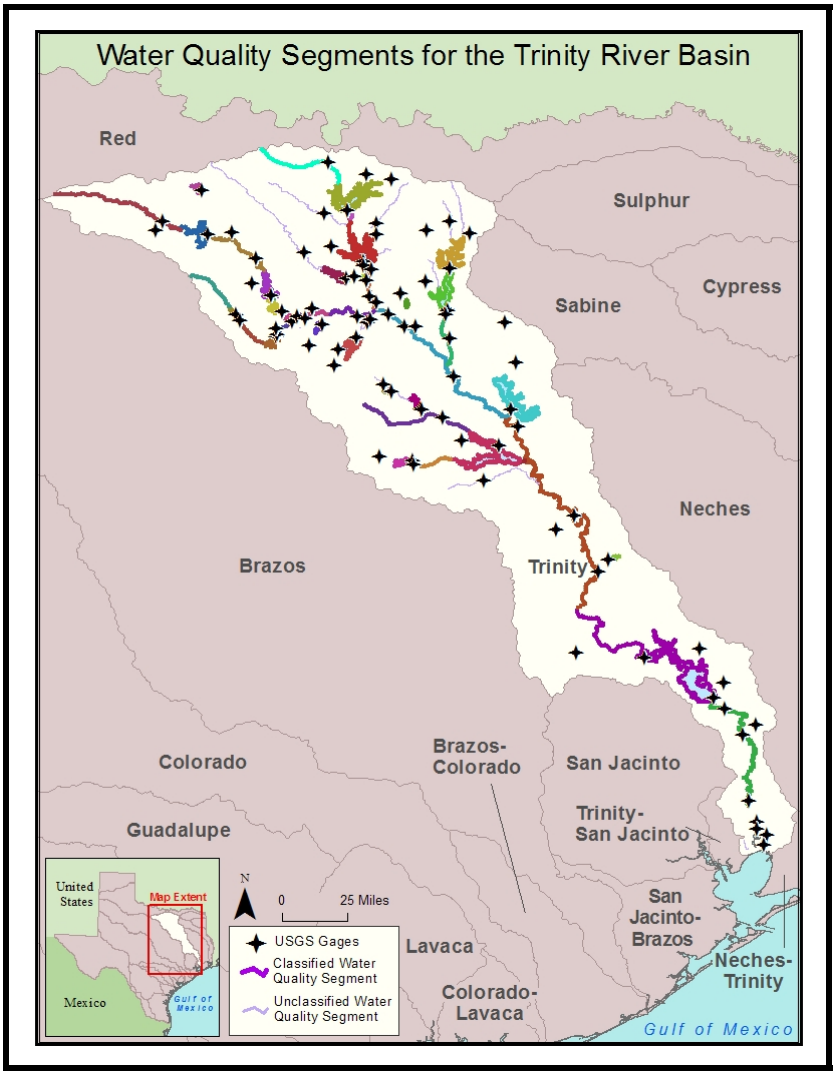

Figure 3. TCEQ Water Quality Segments for the Trinity River Basin.

2.4 GEOMORPHIC ZONATION

Geomorphic processes vary between and within river systems (TCEQ et al., 2008, p. 26). Large river basins can typically be separated into three geomorphic zones: the headwaters, transfer, and deposition zones, based on the dominant geomorphic processes in those zones (Figure 4). Basin characteristics such as channel slope, width, depth and discharge change from the upper to the lower sections of a river. For river systems with minimal site specific geomorphic data, this simple classification can be used to guide the location selection for instream flow recommendations. In some Texas basins (such as the middle and lower Trinity, lower Sabine, middle and lower Brazos and lower San Antonio), geomorphic classifications are provided as part of the SB 2 study process.[6] The geomorphic classifications may provide additional information to guide further

[6] A list of completed and ongoing studies can be found at http://www.twdb.state.tx.us/instreamflows/studies.html

segmentation of a particular river basin. However, using the detailed geomorphologic information to prioritize site selection for instream flow recommendations may have limited utility, because in those basins where geomorphic classification is completed, USGS gages will more than likely be used to represent the zones.

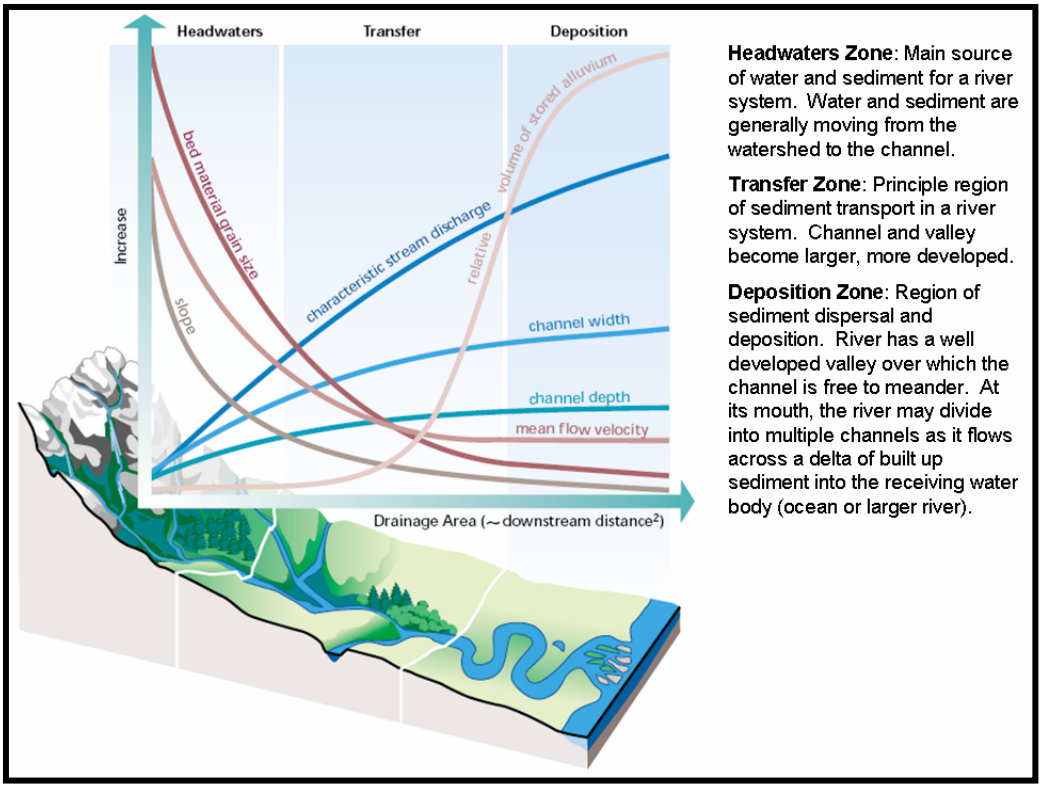

Figure 4. General geomorphic zones (adapted from FISWRG 2001).

2.5 ECOLOGIC ZONATION

An ecoregion is defined as:

> *A geographic area over which the macroclimate is sufficiently uniform to permit development of similar ecosystems on sites with similar geophysical properties. Ecoregions contain multiple landscapes with different spatial patterns of ecosystems.(TCEQ et al., 2008, p. 132)*

The spatial differences in landscape attributes such as geology, physiology, land use, climate, soils, and vegetation among defined ecoregions, may be useful for evaluating biological and ecological differences among watersheds in a river basin (Griffith et al. 2007). These distinctions may indicate either locations where there is a need for specific flow recommendations or provide an additional overlay to refine the calculation of flow components for individual instream flow recommendations. The ecoregions may be at

the segment or sub-basin scale (Figure 5). GIS data and descriptions of the ecoregions are available for ecoregions in all river basins in Texas at various scales. [7]

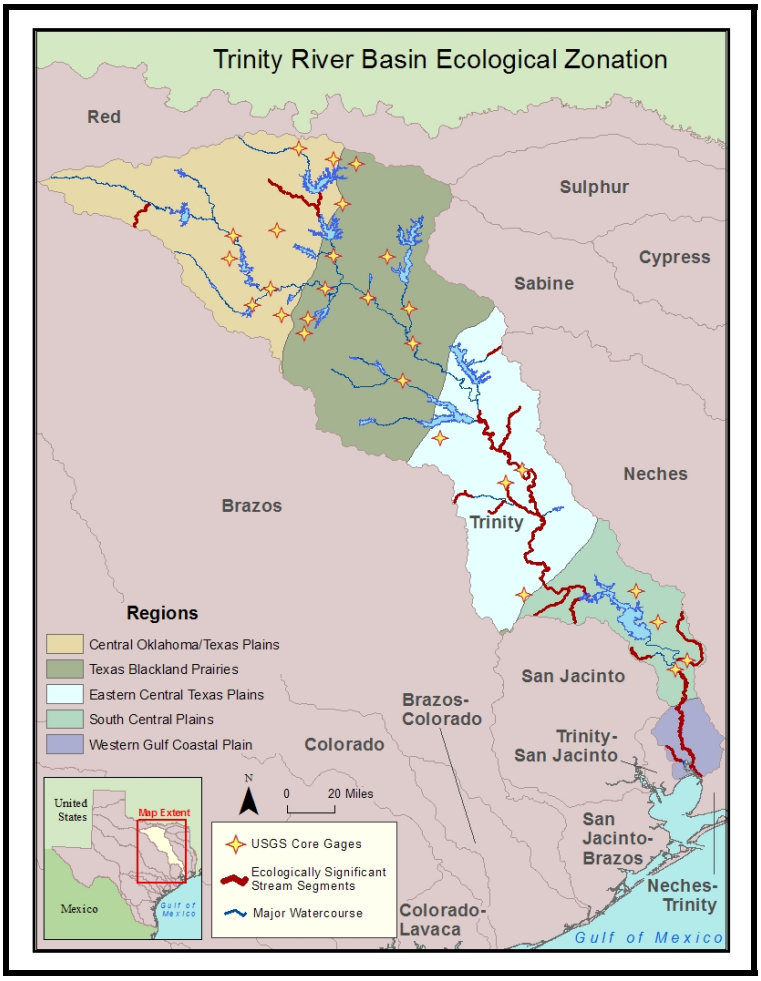

Figure 5. Trinity River Basin Ecoregions and Ecologically Significant Stream Segments.

In addition, the Texas Parks and Wildlife Department (TPWD) identifies ecologically significant stream segments for Texas river basins.[8] The segment designations take into account biological and hydrological function, riparian conservation areas, water quality, aquatic life and aesthetic value, threatened and endangered species, and unique communities. Ecologically significant stream segments for the Trinity River Basin are included in Figure 5.

For some SB 2 priority basins, additional information may be available to help guide the choice of locations. For example, documentation of species declines in the lower Brazos, lower Sabine and lower San Antonio Rivers (Bonner and Runyan, 2007) may indicate

[7] See http://www.tceq.state.tx.us/implementation/water/tmdl/atlas.html, http://www.epa.gov/wed/pages/ecoregions/tx_eco.htm and http://www.tpwd.state.tx.us/landwater/land/maps/gis/data_downloads/

[8] A list of ecologically significant stream segments for Texas River Basins can be found at http://www.tpwd.state.tx.us/landwater/water/environconcerns/water_quality/sigsegs/ This list is not exhaustive and additional segments may need to be considered.

that these areas require consideration of species-specific information with respect to selection of point locations for instream flow recommendations.

2.6 HYDROLOGIC ZONATION

The USGS maintains a network of 478 streamflow gaging stations in Texas.[9] Other entities also maintain streamflow gaging stations, for example the United States International Boundary and Water Commission (USIBWC) for the Rio Grande.[10] These gages are funded by federal, state and local governmental agencies (Slade et al., 2001). The USGS and the Texas Water Development Board (TWDB) evaluated existing gaging stations on the basis of four criteria: regionalization, major flows, outflow from the State, and streamflow conditions assessment. The USGS proposed a Core Network of gages that contribute to at least one of these four criteria (Figure 6).[11] Although these four criteria are certainly factors which contribute to understanding the hydrology of a river system, the Core Network was not specifically developed for purposes of computing environmental flows or to represent an environmental flow regime. Rather, gages that are not included in the Core Network for Texas provide redundant data or are maintained to meet objectives besides those outlined above (Slade et al., 2001, p. 7). These gages could, however be useful in developing flow recommendations by providing data to fill in gaps or to ensure adequate coverage for a particular river system.

Regionalization gages are selected because they provide flow data for regions with similar hydrological characteristics, i.e. these gages characterize a range of attributes within a hydrologically similar area (Slade et al., 2001, p.7). Regionalization stations provide data that can be used in the development of regional regression equations. Regional regression equations can be used to estimate flow characteristics at specific ungaged locations (Slade et al., 2001, p. 7). Major flow gages are selected so as to define spatial and temporal changes in streamflow along major streams (Slade et al., 2001, p.8). These gages are used to monitor and define streamflow rates and volumes in major streams across the state. Gages that provide data for the objective of streamflow conditions assessment measure flows in large natural watersheds and are geographically diverse (Slade et al., 2001, p. 9). Thus, the USGS Core Network can provide a framework to refine site selection for purposes of identifying measurement points for flows that are adequate to support a sound ecological environment.

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[9] http://waterdata.usgs.gov/tx/nwis/current/?type=flow

[10] http://www.ibwc.state.gov/Water_Data/rtdata.htm The BBEST members may also be aware of additional sources of streamflow gaging data in their basins. For example the Lower Colorado River Authority maintains 50 gages that are not part of the USGS network. (http://hydromet.lcra.org/repframe.html). Note that the BBESTs may consider whether any additional gaging information is publicly available on an instantaneous or near real time basis.

[11] The USGS Core Network does not include gages that measure springflow. A list of the Core Network Gages and their attributes, including drainage area, period of record, hydrologic region and objective for each gage's data can be found in Slade and others, Table 5. Core Network of Streamflow Gaging Stations in Texas, p. 32-40.

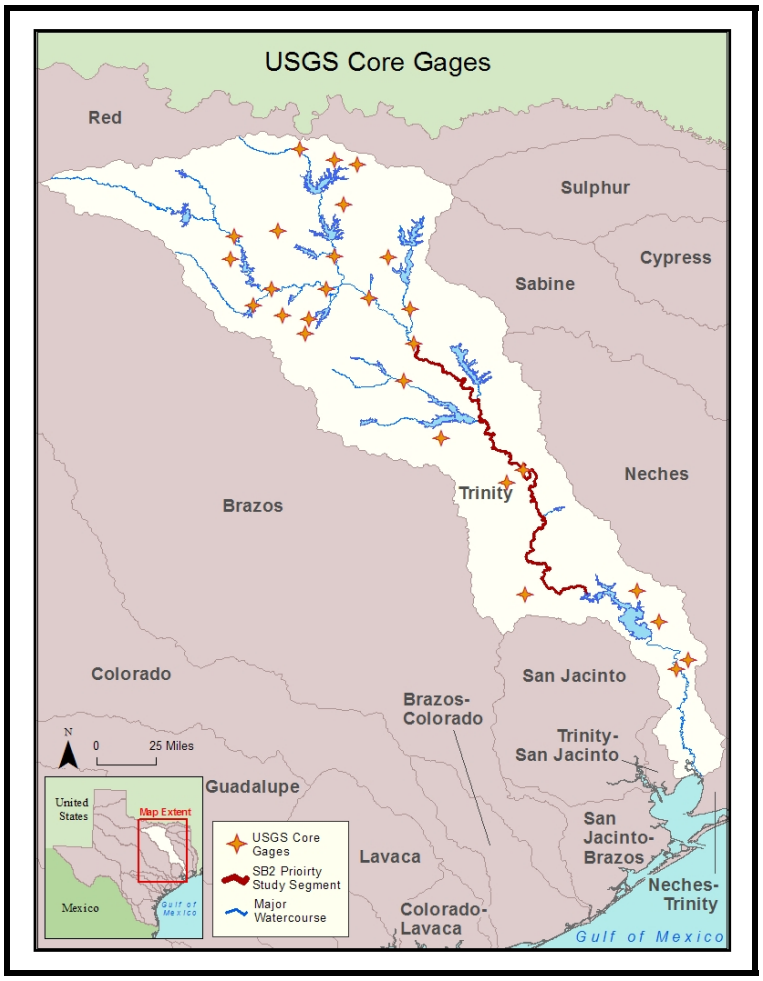

Figure 6. USGS Core Network Gages in the Trinity River Basin.

1	Basin Outflow/Bay Inflow 08066500 Trinity River at Romayor
3	Main Stem General Process Zones • Headwaters Zone of Trinity River • Transfer Zone of Trinity River • Deposition Zone of Trinity River
4	Main Stem Core Network Gages • 08057410 Trinity River below Dallas : : • 08066500 Trinity River at Romayer
12	Main Stem and Major Tributaries Core Gages • 08049500 West Fork Trinity River at Grand Prairie : : • 08066500 Trinity River at Romayer
27	Active Core Network Gages in Basin • 08044500 West Fork Trinity River near Boyd : : • 08066500 Trinity River at Romayer
60	Active USGS Gages in Basin • 08042800 West Fork Trinity River near Jacksboro : : • 08067000 Trinity River at Liberty

Figure 7. Hierarchy of Gage and Point Locations in the Trinity River Basin.

All USGS gages in a river basin can be arranged in a hierarchical structure with increasing numbers of gages at higher levels (Figure 7). For example, the number of gaging stations that might be needed to classify basin outflow is a single point at the coast. In contracts, all USGS gages in a river basin can be used to capture total flow in the basin.

SECTION 3. DETERMINING GEOGRAPHIC SCOPE AND EXAMPLE APPLICATION

The following example uses readily available data sources, including both general data sets discussed in Section 2 and additional basin specific information, as described below, to identify an adequate number of locations on a basin wide scale to characterize an environmental flow regime. The geographic scope of instream flow reference points for SB 3 in each river basin may be different because of the broad range of aquatic ecosystems in Texas' rivers. The following is an example of how a river basin could be segmented to determine an adequate number of locations for quantifying an environmental flow regime consistent with SB 3. This example is not intended to be an attempt to dictate to the Trinity and San Jacinto Rivers and Galveston Bay BBEST which points might be selected in those basins, but merely to illustrate a process that could be used in a river basin to quickly and efficiently determine locations where environmental flow regimes could be determined.

3.1 TRINITY RIVER BASIN DESCRIPTIVE INFORMATION

The Trinity River Authority (TRA) identifies four major types of streams in the basin. These are described by TRA as follows:

1. Effluent-dominated streams. In these streams, during dry periods, treated wastewater constitutes the majority of the flow. The major stream section in this class is the main stem of the Trinity from below the Dallas-Fort Worth Metroplex to Lake Livingston.
2. Reservoir release-dominated streams. In these streams, reservoir releases support baseflows. The TRA identifies five reaches where reservoir releases dominate the flow regime. (Figure 8)
3. Intermittent streams. These streams may stay dry for long periods.
4. Perennial streams. These streams, typically found in the eastern portion of the watershed from Cedar Creek Reservoir to Liberty, have baseflows supported by groundwater.

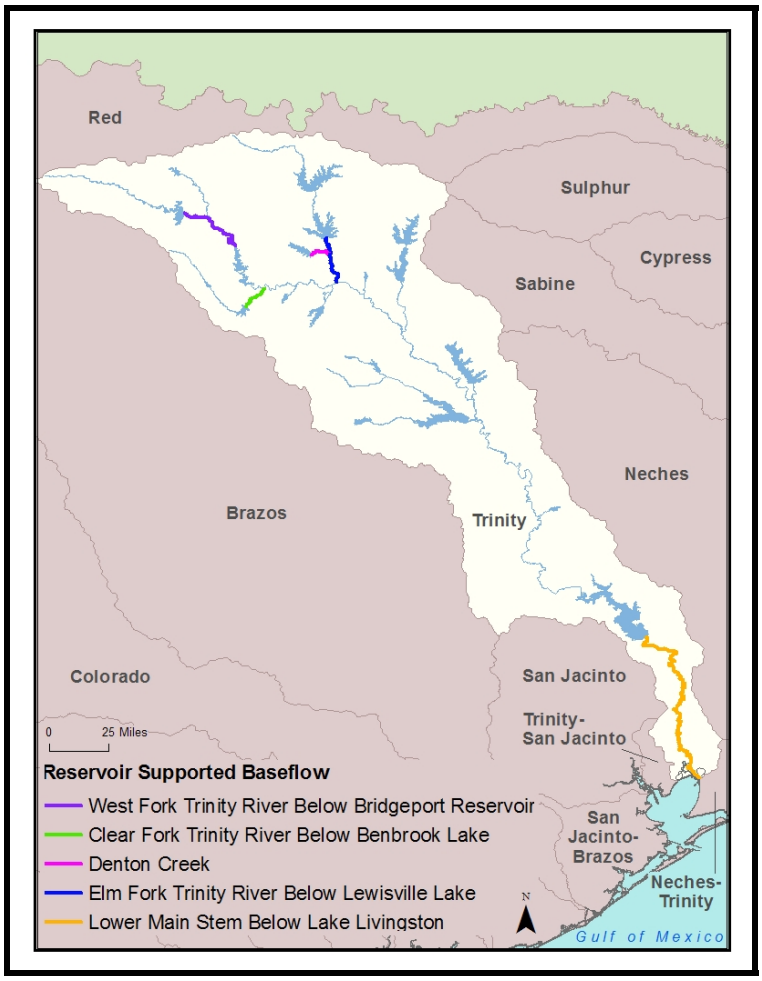

Figure 8. Reservoir supported baseflow in the Trinity (adapted from TRA, 2007, p. 21).

The TRA divides the basin into ten major sub-watersheds for water quality monitoring and management (Figure 9).

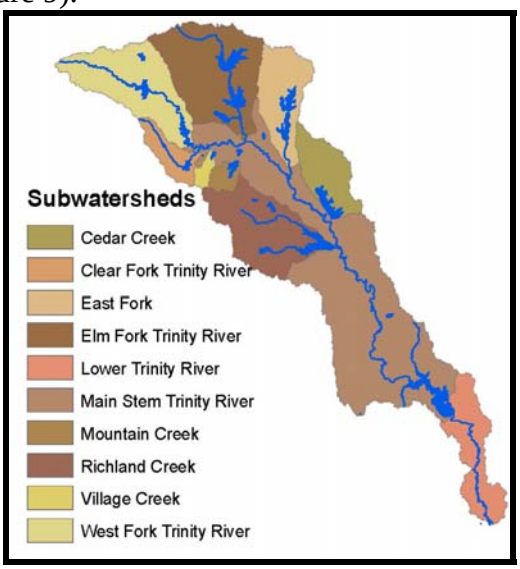

Figure 9. Subwatersheds in the Trinity River (from TRA, 2007, p. 22).

3.2 TRINITY RIVER BASIN GENERAL WATER AVAILABILITY

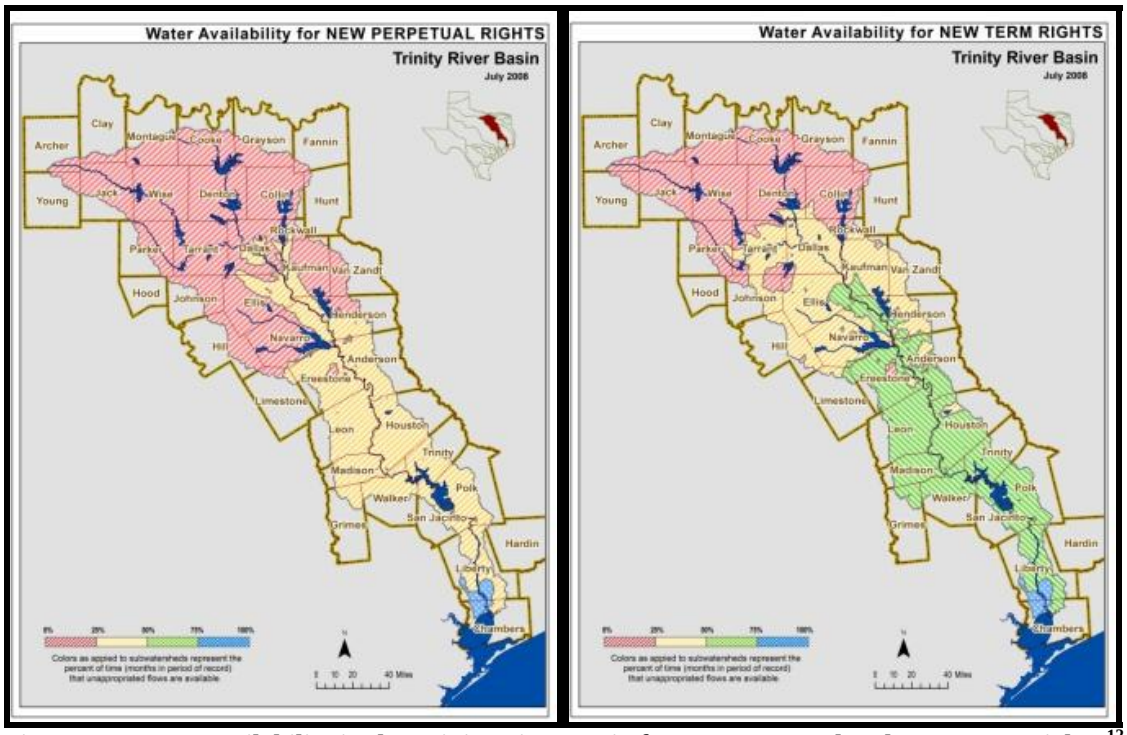

Figure 10. Water availability in the Trinity River Basin for new perpetual and term water rights.[12]

The TCEQ determines water availability for new appropriations using the TCEQ Water Availability Model (WAM). The Trinity WAM has a period of record from 1940-1996. This period is representative of hydrologic variability in the basin because it includes the drought of record, smaller droughts and both major and minor flood events. The hydrologic basis of the WAM is a data set of naturalized flows, representing an approximation of the flows in the river without human impacts such as reservoir storage, diversions and return flows. The WAM incorporates prior appropriation accounting. This means that senior rights divert or store their full authorized amounts before junior water rights can be exercised (Alexander Martin and Chenoweth, 2009). Instream flow requirements are treated like any other water right. For example, in water rights permitting, an instream flow requirement with a priority date of 2008 would constrain the diversion or storage of any upstream water right with a priority date junior to 2008. Water availability is extremely limited in the upper Trinity basin (Figure 10). Some water may be available in the middle and lower basin.

SB 3 does not limit the development of environmental flow regimes to areas where water is available for appropriation. SB 3 environmental flow standard development is independent of water availability. The goal is to develop flow targets wherever appropriate. There may be other ways to meet flow targets other than flow requirements in permits for new appropriations, for example, voluntary market transactions or dedicated return flows. The Science Advisory Committee (SAC) is only suggesting that

[12] These maps are available at http://www.tceq.state.tx.us/permitting/water_supply/water_rights/wam.html

water availability could be considered as a factor, along with other factors, in deciding how to segment a basin.

3.3 INCORPORATING THE SB 2 PRIORITY STUDY SEGMENT

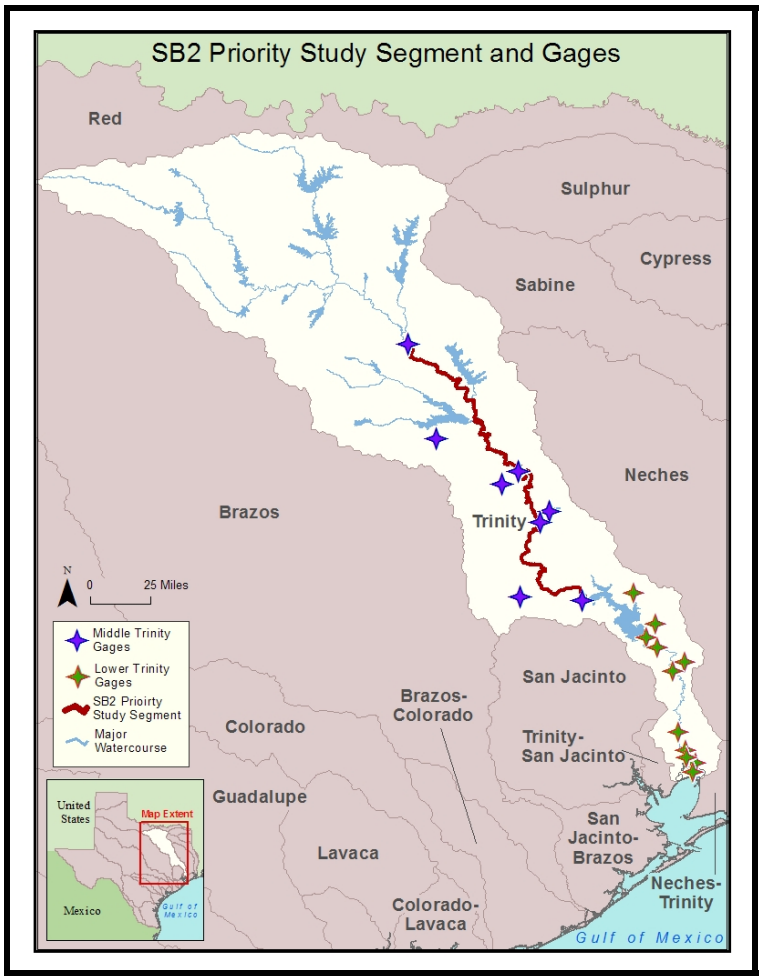

Figure 11. SB 2 study segment for the Trinity River Basin and all associated USGS Gages.

It is important to ensure that any ongoing studies for SB 2 are considered in the SB 3 process to determine an adequate number of environmental flow reference locations. SB 2 study results can inform the adaptive management process envisioned for SB 3. When completed, the SB 2 studies can be used to refine the SB 3 recommendations in the future. For example, the boundaries of the SB 2 study segment in the Trinity River Basin includes the main stem of the Trinity River from USGS gage 08062500, Trinity River near Rosser (located just downstream of the confluence with East Fork) to the headwaters of Lake Livingston (Figure 11). The sub-basin associated with the Trinity River priority segment includes the contributing watershed area for this portion of the river. This SB 2 study segment should be represented during determination of the number of point locations for a particular river basin.

Recommendations to protect freshwater inflows to bays and estuaries could be represented by a point at the mouth of the Trinity River, and the WAM includes a control

point at this location for purposes of water availability analyses. It is possible that instream flow requirements would not be sufficiently protective of flows needed to maintain the ecological health of bays and estuaries, and vice versa. If the recommendations for instream and freshwater inflows are sufficiently different, an additional point between Lake Livingston and Galveston Bay might be needed.

3.4 SEGMENTING A REACH USING BASIN SPECIFIC DATA SOURCES

Both general and basin specific data sources can be used to segment reaches of interest. As mandated by SB 2, studies are in progress to identify the biologic, geomorphic, and hydrologic processes in priority river systems. The SB2 studies will develop additional information on the interrelationship among these processes and their influence on attributes such as connectivity and water quality. The example provided below shows how the Trinity River, from downstream of Dallas to the coast, may be segmented to determine an adequate number of flow determination locations.

It is important to compare the spatial scales of biologic and geomorphic data, and hydrologic measurement points represented by all USGS gages and the smaller subset of gages comprising the USGS Core Network gages in this reach. In the Trinity River Basin, for example, there is not an exact correlation among classifications of this reach based on biology, hydrology or geomorphology (Figure 12).

All USGS gages could be used to segment the reach. However, as discussed in Section 2.6, the USGS Core Network gages were specifically identified based on regionalization, streamflow assessments and major flows. As such, these Core Network gages should adequately characterize processes within a segment and site specific data can be used to refine computations for instream flow recommendations at these points. Based on both generally available data and basin specific data, the USGS Core Network gages might provide adequate coverage for computation and application of environmental flow analysis methods. However, other gages not included in the Core Network may provide valuable information and should be considered when necessary to characterize important reaches or segments for which Core network gage data are not available.

In this case, the USGS Core Network Gages:

- provide flow determination locations within the reach designated for the SB 2 studies;
- account for TCEQ classified segments except for the reach located within the pool of Lake Livingston which, based on the method used to determine flow recommendations could be considered separately;
- account for ecoregions with the exception of the Western Gulf Coastal Plain, located in the lower basin, which could be taken into account based on the decision process for reconciling instream flow and bay and estuary inflow requirements for the basin; and
- are consistent with the water quality management divisions shown in Figure 9.

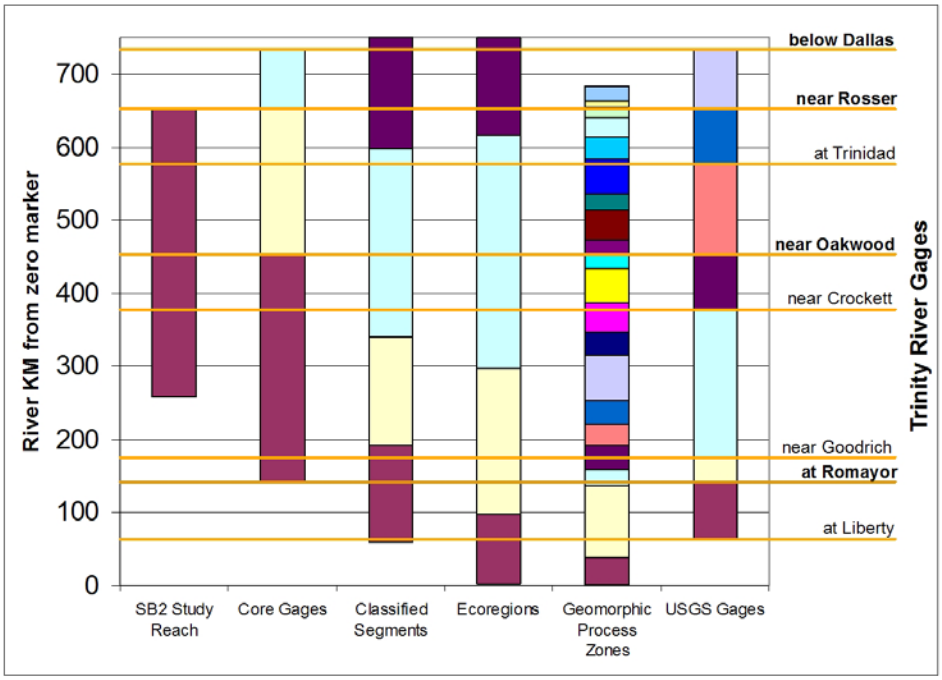

Figure 12. Comparison of spatial scales for hydrologic, biologic, and geomorphic data.[13]

The distribution and location of geomorphic process zones provide detailed information about some of the processes occurring within a segment (Figure 13). However, flows at USGS gages would likely be used to represent streamflows in those geomorphic areas. The geomorphic data set could be used as an overlay to refine hydrology-based computation of an environmental flow regime at gage locations.

[13] Points, such as USGS gages, are represented differently from segments. For USGS Gages, the beginning and end of the columns represent one gage. For water quality segments, geomorphic process zones, or ecoregions, one color represents the entire spatial segment. The bolded gage names are the USGS Core Network Gages.

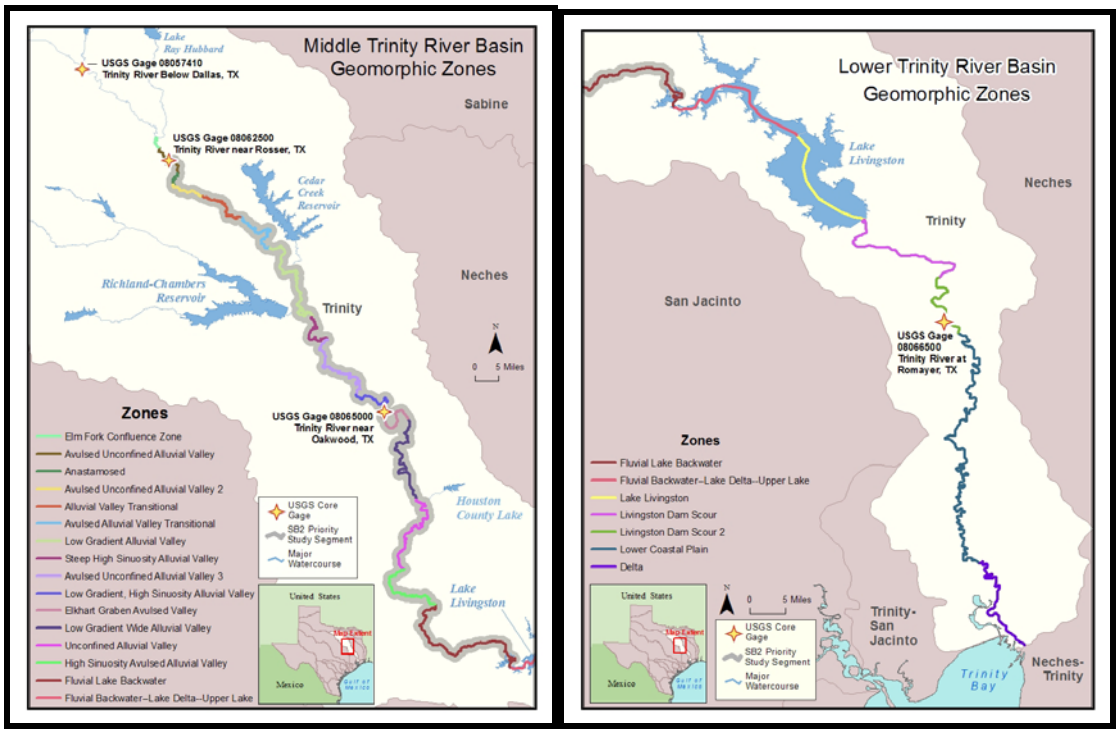

Figure 13. Geomorphic process zones in the Trinity River Basin and USGS Core Network Gages.

The SB 2 study segment for the Trinity River Basin includes three TCEQ classified segments, a portion of Segment 805, all of Segment 804 and a portion of Segment 803 which includes the pool of Lake Livingston. The 10 sub-watersheds delineated by TRA (Figure 9) generally represent the contributing watersheds of major reservoirs. The Main Stem Trinity River sub-watershed roughly coincides with the SB 2 study segment. It should be noted that for any future large water development projects, such as reservoirs, a site specific study may be required as part of the permitting process. If conducted, these site specific studies could possibly build on the SB 3 efforts.

USGS gages for the SB 2 study segment and tributaries are located below the upstream end of the reach (Figure 11). There are at least two major tributaries in the contributing watershed for the SB 2 reach, so it may be appropriate to include an additional point(s) farther downstream in this reach. The USGS Core Network includes a gage on the main stem of the Trinity River downstream of Richland Creek and Cedar Creek. There is an ecologically significant stream segment on Upper Keechi Creek that exhibits a high degree of biodiversity. There is a Core Network gage on Upper Keechi Creek and this location should be considered for inclusion as a flow determination location.

SECTION 4. SUMMARY

In the current document, potential sources for general (Figure 3 through 7) and basin specific (Figures 8 through 13) information are provided. These sources can be used to identify segments of a particular river basin for purposes of determining the geographic scope of instream flow recommendations. As stated previously, these locational decisions may be different for each basin. Following is a list of questions that should be asked and issues to be considered to refine the number of flow recommendation points that would be needed for a particular river basin. This list assumes that the starting point is the USGS Core Network:

4.1 HYDROLOGY

- Do the USGS Core Network Gages have a sufficient period of record for the type of flow recommendation analysis contemplated for the basin? Gages that do not have a sufficient period of record may need to be excluded from the hydrologic analysis. The adequacy of the period of record depends on the type of hydrologic analysis.
- Are there redundant gages in the Core Network? One representative gage could be adequate to characterize the environmental flow regime for multiple sub-watersheds. The Core Network may include redundant gages, particularly on major tributaries (Figure 6).
- Can the most downstream gage in the Core Network be used to represent both instream flows and freshwater inflows to the bays and estuaries? This may be highly dependant on the method used to determine freshwater inflows for a particular river basin and an additional point may be needed to represent the basin outlet.
- Are segments that include habitats or features that perform hydrologic functions such as flood attenuation, flow stabilization and groundwater recharge and discharge accounted for? In particular, segments that include spring resources with unique or critical habitats should be considered, whether or not these locations are gaged. In addition, because gage locations provide point data, the user of gaged data must determine the spatial extent over which they are comfortable extending the data or analysis. This may guide the decision on whether additional points are necessary to represent important hydrologic functions.
- If particular reaches of interest do not have Core Network gages, additional gages may need to be added for flow regime analysis.

4.2 BIOLOGY

- Is there a USGS Core Network gage for all ecoregions and/or biologically important streams in a basin? If not, additional gages may need to be added.
- Are ecologically significant stream segments accounted for? Note that the list provided by the TPWD (Section 2.5) is not exclusive and additional stream segment specific factors may need to be considered:
    - Biological function such as segments with significant habitat value, including both quality and quantity considering the degree of biodiversity,

age and uniqueness of habitats including terrestrial, wetland, aquatic or estuarine areas.

- Riparian conservation areas such as wildlife management areas, preserves, mitigation areas.
- Threatened and endangered species, including sites along river segments that are significant because of the presence of unique, exemplary, or unusually extensive natural communities.

4.3 WATER QUALITY

- Are TCEQ Water Quality Segments accounted for? Water quality considerations may be important in specific locations. Therefore, TCEQ Water Quality Segments and any additional water quality issues such as the 303(d) list may be considered.[14]
- Are there basin-specific water quality concerns? Stream segments with exceptional aquatic life uses dependant on or associated with high water quality should be considered in determining an adequate number of points in a basin. These considerations could also factor into decisions as to whether or not selected reaches should be segmented further.

4.4 GEOMORPHOLOGY

- At a minimum, are the dominant geomorphic process zones represented? If additional basin specific information is available, this information could be used to further segment reaches of interest.
- Are unique or problematic fluvial geomorphic features or process zones (e.g., avulsions, distributaries, erosion-dominant reaches, or rapids) accounted for in the basin? Fluvial geomorphic features and processes support the physical structure of instream and overbank habitats.

4.5 OTHER FACTORS

- Additional basin specific factors, determined by the BBEST groups could be used to further refine the flow determination locations created from the considerations outlined above.

[14] The 303(d) lists can be found at http://www.tceq.state.tx.us/compliance/monitoring/water/quality/data/wqm/305_303.html

SECTION 5. CONCLUSION

Determining an adequate number of points for environmental flow recommendations requires consideration of both general and site specific criteria as outlined in Section 4. Selection of an adequate number of locations for purposes of characterizing an environmental flow regime to support a sound ecological environment requires considerations of factors such as hydrology, biology, geomorphology, and water quality. In addition, the decision on how many points are adequate is basin specific in nature. Therefore, additional factors, as outlined for example in Section 3.1 may need to be included in the decision making process.

The considerations presented in Section 4 effectively represent decision points during a process of selection or elimination of streamflow-gaging stations and stream-channel reaches in a river basin. It is likely that particular reaches, tributaries, or distributaries could be subject to considerable debate prior to a decision. The BBEST groups should consider a careful documentation effort for both selected and non-selected gages and reaches, which might include a list of characteristics or reasons for their inclusion or exclusion. Documentation of the decisions made during this process may facilitate adaptive management strategies.

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June 5, 2009

Transmittal to Basin and Bay Expert Science Teams (BBESTs)

Report # SAC-2009-03

Title: Methodologies for Establishing a Freshwater Inflow Regime for Texas Estuaries, within the Context of the Senate Bill 3 Environmental Flows Process.

The attached document constitutes another deliverable from the Senate Bill 3 Science Advisory Committee (SAC) to assist the BBESTs in carrying out their responsibilities under the statute. This report addresses one of the principal mandates of the law, namely the establishment of an environmental flow regime to maintain a sound ecological environment in the estuarine systems on the Texas Coast. The complexity of this assignment is acknowledged at the outset, and the focus of the report is on applying existing available methodologies and data resources to successfully accomplish the task. The advice of the SAC is for you to recognize the need to simplify the approach as necessary, and to document the BBEST decision process along the way, realizing that the results will likely be imperfect.

The document presents a simplified conceptual model relating Inflow to "Biology", with Salinity as a keystone habitat attribute, as a likely approach that is reasonably achievable given the timeframe in which the current BBESTs must develop their recommendations. The document contains a concluding Section 6 which addresses realistic expectations and offers specific recommendations from the SAC at this point in the Senate Bill 3 process.

As in previous SAC deliverables, this document is characterized as a "Working Draft". Given the complexity of the estuarine environmental inflow regime determination, this characterization is particularly appropriate. We strongly encourage a healthy dialogue between the BBESTs and the SAC on the content of this document, which will surely result in improvements which will yield the best possible scientifically-based environmental flow recommendations. Finally, as always, the SAC offers this information as guidance and not prescription, and remains hopeful that the BBESTs will find this information useful in their deliberations. We look forward to your feedback as we undertake our respective responsibilities under Senate Bill 3.

Robert J. Huston, Chairman, SB3 Science Advisory Committee

WORKING DRAFT

Methodologies for Establishing a Freshwater Inflow Regime for Texas Estuaries Within the Context of the Senate Bill 3 Environmental Flows Process

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Senate Bill 3 Science Advisory Committee for Environmental Flows

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Document Version Date: June 5, 2009

Report # SAC-2009-03

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SECTION 1
INTRODUCTION

Environmental flows, which include flows in rivers and streams and freshwater inflows to bays and estuaries, have not been addressed uniformly in water development project planning and permitting in Texas. Senate Bill 3, passed by the Texas Legislature in 2007, set out a new regulatory approach to protect such flows through the use of environmental flow standards developed through Texas Commission on Environmental Quality (TCEQ) rulemaking. Senate Bill 3 directed the use of an environmental flow regime in developing flow standards and defined an environmental flow regime as a schedule of flow quantities that reflects seasonal and yearly fluctuations that typically would vary geographically, by specific location in a watershed, and that are shown to be adequate to support a sound ecological environment and to maintain the productivity, extent, and persistence of key aquatic habitats.

Each Basin and Bay Expert Science Team (BBEST) is charged with developing recommendations for both an instream flow regime and for a complete freshwater inflow regime to protect a "sound ecological environment" and to maintain the productivity, extent, and persistence of key aquatic habitats in bays and estuaries. Instream flow regime requirements have been addressed previously (SAC, 2009a),[1] by the Texas Environmental Flows Science Advisory Committee (SAC). The focus of this document is on bay and estuary inflows. This regime will have to be developed recognizing the inherent variability in weather and inflow conditions that have contributed to and sustained these productive estuarine ecosystems over time. Freshwater inflow serves a variety of important functions to coastal estuarine ecosystems by creating and preserving low-salinity nurseries, transporting sediments, nutrients, and organic matter downstream, and affecting estuarine species movements and reproductive timing (Longley 1994, Montagna et al. 2002; SAC, 2004).

This document provides background information and discussion of various methods that can be used to develop freshwater inflow recommendations for Texas bays and estuaries. While a few germane references to the literature are made, this document is not intended to be a tutorial on the physics and ecology of estuaries, nor on the range of modeling techniques of potential application. Rather, it attempts to present a succinct summary of methods that are presently sufficiently developed and suitable for application to Texas estuaries, for consideration by the Basin and Bay Expert Science Teams (BBESTs). For detailed background information on estuaries and the coastal environment, the 2004 Science Advisory Committee (formed under Senate Bill 1639) report (SAC, 2004) and citations therein should be consulted. Emphasis here is placed upon delineating the basic approaches of available methods, identifying the necessary supporting data and analyses, and stating their strengths and weaknesses. Section 2 reviews briefly the guidance offered by previous state scientific advisory committees regarding what constitutes a "sound ecological environment" and how that might apply in the bay and estuary context, particularly with regard to flow regimes as noted in Senate Bill 3. Section 3 identifies various sources of available hydrologic, abundance, habitat, salinity and water quality data for Texas bays and estuaries and discusses existing tools that constitute the "State Methodology", and how they have been used for evaluating these data in the context of establishing appropriate

[1] References are listed in Section 7 of this document.

freshwater inflow needs. Various methods for using the available data to develop freshwater inflow recommendations are described in Section 4, with key decision points involved in selecting and applying the various inflow methodologies briefly highlighted along with each method's strengths and weaknesses. Other considerations, including the role of nutrient and sediment delivery in sustaining the ecological environment of bays and estuaries and the issue of how instream flow recommendations might be integrated with freshwater inflow recommendations in a particular basin, are discussed in Section 5. Finally, SAC observations and recommendations regarding information presented in the document and how freshwater inflow recommendations for the bays and estuaries could be established within the scope and timeframe of Senate Bill 3 are summarized in Section 6. References cited in the text of the document are listed in Section 7, and a list of contributors is presented in Section 8.

SECTION 2
STRATEGIES FOR SPECIFYING INFLOW REQUIREMENTS

Senate Bill 3 provides that the BBESTs are to "develop environmental flow analyses and a recommended environmental flow regime for the river basin and bay system for which the team is established through a collaborative process designed to achieve a consensus. In developing the analyses and recommendations, the science team must consider all reasonably available science, without regard to the need for the water for other uses, and the science team's recommendations must be based solely on the best science available."

Senate Bill 3 defines "environmental flow analysis" as the "application of a scientifically derived process for predicting the response of an ecosystem to changes in instream flows or freshwater inflows." "Environmental flow regime" is defined by Senate Bill 3 as "a schedule of flow quantities that reflects seasonal and yearly fluctuations that typically would vary geographically, by specific location in a watershed, and that are shown to be adequate to support a sound ecological environment and to maintain the productivity, extent and persistence of key aquatic habitats in and along the affected water bodies." As applied to bay and estuary inflows, this includes, but is not limited to, addressing issues such as the required frequency of various flow amounts or inflow patterns needed during very dry periods, as well as the frequency of higher flows during wet years that help sustain a healthy bay and estuary ecosystem.

The legislation does not define "sound ecological environment." However, the recommendations from the SAC (2006) to the Governor's Environmental Flows Advisory Committee provided the following *guidance*, stating that a sound ecological environment is one that:

- sustains the full complement of native species in perpetuity;
- sustains key habitat features required by these species;
- retains key features of the natural flow regime required by these species to complete their life cycles; and
- sustains key ecosystem processes and services, such as elemental cycling and the productivity of important plant and animal populations.

Underlying each of these is the need to establish relationships between elements of the environment, including flows, and the native species and their functions.

2.1 THE ESTUARY ECOSYSTEM: COMPONENTS AND INTERACTIONS

Figure 2.1-1 is a highly simplified diagram of the major physico-chemical and biological variables of the estuarine ecosystem, in which the arrows represent causal connections. Despite the simplifications — e.g., suppression of variation in space and time of each of the components, omission of several components, such as temperature, known to exert important controls, compression of several or many variables into a single component, such as nutrients and non-

fishery organisms — this diagram demonstrates that the estuarine ecosystem is complex, comprised of many variables and their interactions.

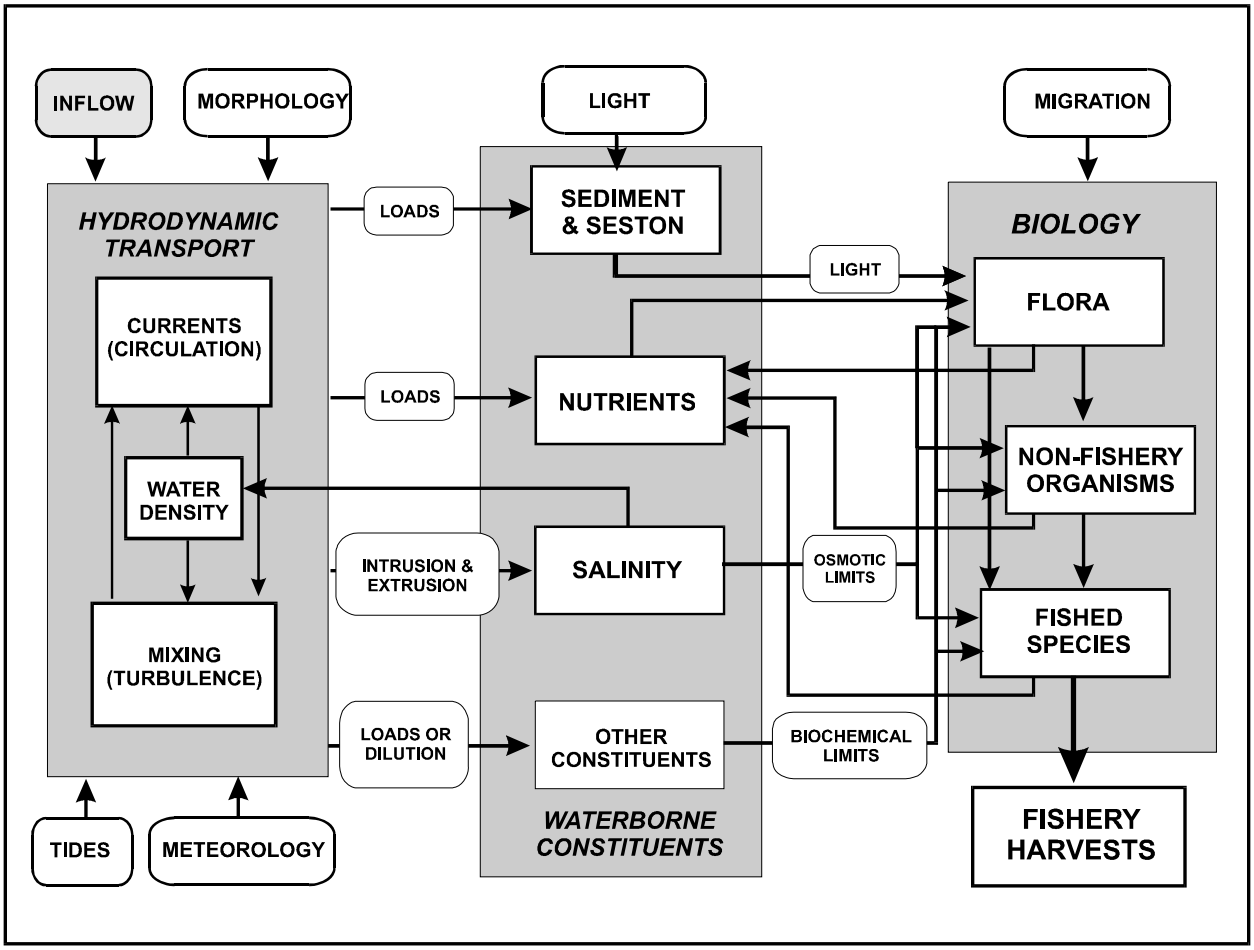

Figure 2.1-1 - Schematic Diagram of Estuarine Ecosystem

A few features of this system deserve special mention because they have important ecological function or relevance and because they depend directly on the inflow regime. Much of the complexity of estuaries derives from their nature as a transitional watercourse between freshwater and marine water. This is reflected in the multiple external forces controlling the estuary. The major Texas estuaries are coastal embayments, broad systems with complex morphology that develop internal circulations important in the distribution of waterborne constituents and biological populations. The exchange between estuary and sea is mainly effected by tides, gravity currents and meteorology (especially wind stress). Exchange between estuary and sea also manifests itself in the organisms, as indicated in Figure 2.1-1 by the external control of "migration". Many of the important estuarine animals, notably major fish and shellfish species, migrate between the sea and the estuary at various life-history stages. Most immigrate into the estuary from the sea as young, and mature in the estuary, taking advantage of sheltered, food-rich environments, then return to the sea as adults. Finally, the subdivision of the

biological components is on practical concerns rather than the usual compartments of flora (producers), herbivores (first-order consumers), and carnivores (higher-order consumers), because the animals are distinguished according to whether they represent a commercially or recreationally important species. This is an acknowledgment of the concerns of many stakeholders with the economic use of the estuary.

A direct measure of the physical exchange with the sea is the salinity distribution within the estuary. Salinity is the quintessential estuary parameter. It is the concentration by mass of dissolved salts in a water sample. Because the salinity of freshwater is essentially zero, and water in an estuary is a mixture of freshwater and seawater, the value of salinity is an indicator of the proportion of seawater in the mixture and is an excellent natural water tracer, which generally ranges from zero in and near the sources of freshwater inflow into the estuary to a maximum value in the mouth or inlets of the estuary, where it joins the ocean. (See Ward and Montague, 1996, for additional discussion of the function, utility, and modeling of salinity in estuaries.) Marine sea water in the Gulf of Mexico contains about 3.5 % salts (in conventional units 35 parts per thousand, ppt, ‰, practical salinity units, psu, or simply "salinity" without explicit units[2]). The waters of bays and estuaries generally exhibit a gradient in salinity from fresh water at the river mouth to full-strength sea water at the marine end.

The presence, or absence, of salts in water is a mediator in its biological function, as indicated in Figure 2.1-1. Most freshwater organisms cannot survive if salinity is too high, and most seawater organisms cannot survive if salinity is too low. An estuary is therefore an inhospitable environment for these "stenohaline" organisms. There are, however, "euryhaline" organisms that have a physiological capability to function—even thrive—in the intermediate and variable salinities of an estuary. The range and distribution of salinities can therefore be important demarcators of suitable habitat for estuarine species. The spatial estuarine gradient is fundamental for regulating differences in the functions, habitats, and integrity along the salinity gradient. Much is known about salinity gradients in estuaries and the average salinity over long time periods is an indicator of organisms' habitat. Areas where salinity variability is low (i.e., the coefficient of variation is <50%) tend to be more diverse and productive, and areas where salinity is highly variable (i.e., the coefficient of variation is nearly 100%) tend to resemble disturbed systems with lower diversity and many smaller organisms (Montagna and Kalke, 1995; Palmer et al. 2002; Montagna et al. 2008). On the other hand, some species, well-adapted to the high range of salinity in an estuary, tend to be relatively insensitive to its variation.

Inflow plays several roles in the estuary ecosystem, of which for the purposes of environmental flow evaluations, we emphasize three: (1) diluting seawater, thereby reducing the salinity of the mixture of fresh and salt water, and creating a gradient of salinity across the estuary; (2) providing an influx of nutrients derived from the land surface of the estuary's watershed; (3) providing an influx of suspended sediments, derived from the land surface, or eroded from the stream channels. It is through these intermediate effects that inflow exerts an influence on plant

[2] Salinity is typically measured by conductivity, which is in mV. A mathematical conversion is used to restate measurement in units as 3.5 g salt in 1 kg sea water, which is 35 parts per thousand, ppt, or ‰. A problem arises in that electrical current is converted to a proportion of the unit mass differences of the solid salt in water. This has been termed "practical salinity" by UNESCO (1981) and Millero and Poisson (1981). Today most oceanographers simply refer to "practical salinity" without explicit units (Millero et al. 2008).

and animal organisms in the estuary, i.e. its effect is indirect rather than direct. Moreover, it is not simply the magnitude of inflow that governs these effects, but its frequency, timing and duration are crucial considerations as well, especially the occurrence of higher episodic (pulse) flows and the establishment of sustained low inflows. The higher flow events are mainly responsible for influxes of nutrients and sediments into the estuary, and are effective in quickly replacing the salt water in the estuary with fresh water. It is the opinion of many estuary ecologists that the timing of organism immigration from the sea into the estuary has evolved to take advantage of seasonal inflow variation, and therefore the suitability of nursery habitats in the estuary and the successful growth of these species are dependent upon both the magnitude and timing of seasonal pulses of inflow. Even under drought conditions, inflows also appear to play a crucial role by providing zones of moderated salinities.

The above description of the role of inflows in the estuary, of providing variability upon which many organisms respond favorably, as well as the role of pulse "events" in supplying nutrients and sediment to the watercourse, is a clear parallel to the roles of streamflows in the stream environment (SAC, 2009a). There is, however, a central difference between the roles of flow in the river or stream, and in the estuary. In the riverine setting, flow is the dominating variable that controls almost all of the hydrographic and biological processes. In the estuarine setting, as depicted in Figure 2.1-1, inflow is one of several variables, such as exchanges with the sea driven by tides and winds, internal circulations driven by density differences, wind set-up, and channelization, all of which can influence biology and the interaction between marine and estuarine populations (both flora and fauna). In the estuary, there are multiple stressors and multiple physical drivers. For example, algal blooms, low oxygen events, pollution, thermal stress, physical stress, or combinations of these external variables can effect the biology or even be the dominate factor relative to the effects of inflow. Yet, the role of inflow is significant, and likely the dominant factor influencing estuarine biology in Texas, as evidenced by the change in character of the biota of Texas bays when progressing from the high inflow estuary of Sabine Lake down the coast to the often hyper-saline Laguna Madre.

The diagram of Figure 2.1-1 also serves as a schematic map of the variables and processes that would need to be represented in a *deterministic* model of the estuary. Such a model would be a coupled simultaneous calculation of each of the indicated variables carried out over a computational network that resolves the detailed spatial variation within the estuary and adjacent coastal zone, and employing a time increment to resolve time changes significantly shorter than a day. While such *deterministic* models have been under development for at least half a century, there remain some formulation and major operational difficulties in their application, as well as a requirement for data that are generally nonexistent. In any event, no such comprehensive model encompassing all the known estuarine processes presently exists for any of the Texas estuaries, and will not likely become available within the time frame of the BBESTs. Instead it will be necessary that the BBESTs rely upon sets of measurement from the estuary of concern and accompanying statistical evaluations, perhaps combined with limited deterministic models, to infer responses of the ecosystem to inflows.

Given the limited time available to the BBESTs, it will not be feasible to quantify each of the cause-and-effect relations diagrammed in Figure 2.1-1 by such an approach. Instead, the complexity of Figure 2.1-1 (simplified though it may be relative to reality) needs to be further

distilled to represent the most fundamental relations of inflow and ecosystem in a form that may be feasible for determining inflow requirements. This is diagrammed in Figure 2.1-2, and is presented as a "conceptual model" of the causal connection(s) between "biology" and "inflow". The "nutrients" and "suspended solids" components are shown in grey to reflect the present thinking of the SAC to address these as *overlays*, see Section 5. The primary determinants are the relation of salinity to inflow coupled with the relation of biology to salinity, and the direct relation of biology to inflow, though the data requirements and analytical methods will be more demanding to establish such a relation, which is why it is shown as a broken line in Figure 2.1-2. Though Figure 2.1-2 may represent the conceptual model upon which is based an analysis of flow requirements, the complexity of the problem that has been suppressed in order to achieve this illusion of simplicity needs to be borne in mind by comparison to Figure 2.1-1, along with the precept that *any variable or relationship not explicitly considered becomes a source of variance*.

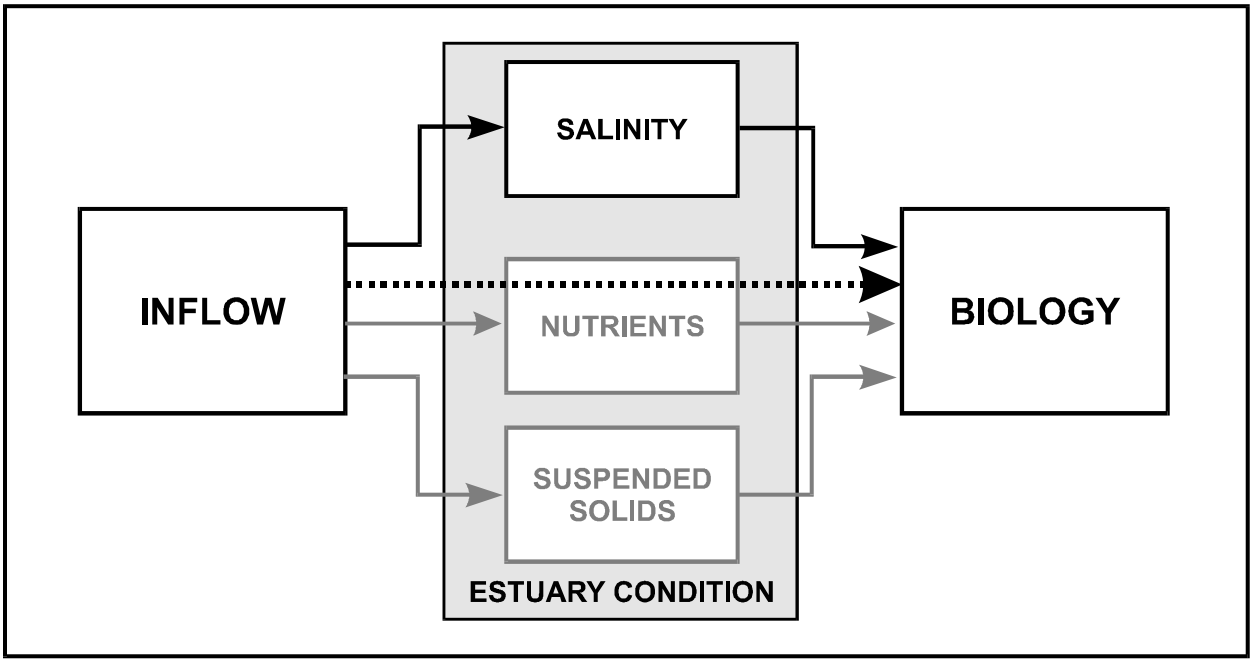

Figure 2.1-2 – Schematic of Relation of "Biology" to "Inflow" (Compressed from Figure 2.2-1)

The conceptual model of Figure 2.1-2 is consistent with the general scientific approach to the problem of delineating the effect of inflows on the estuarine ecosystem. Variations of this model can be traced back to Copeland (1966). In recent years, it has appeared in Sklar and Browder (1998, their Figure 1) and Alber (2002, her Figure 1).

Not only does Figure 2.1-2 encapsulate the cause-and-effect connection from inflow to other aspects of the estuarine ecosystem, it also summarizes the historical development of the subject, and depicts the requirement for data and sophistication of analysis. Historically, all freshwater inflow methodologies started from the perspective of hydrology (i.e., flow), later focusing on the distribution of water quality in the estuary, and more recently addressing the organisms in the estuary. This historical development is in part data-driven. Of the many sources of data relevant

to the estuary, the most extensive and reliable is that of freshwater inflows. Data on water properties and chemical constituents of water are generally much sparser, and fisheries harvest and fisheries-independent data are sparser yet. The data base for hydrology would support various analyses at a higher level of accuracy and sophistication than could be attained for waterborne constituents such as salinity or nutrients, much less for the biology. But this historical development was also driven by the relative ability of scientists to formulate the underlying cause-and-effect relations, which diminishes with distance to the right in Figure 2.1-2. The problem quickly encountered in the conceptual model of this diagram is that the relationships between biology and hydrology are complex and embedded in the food web and material flow dynamics of estuaries. One cannot grow fish by simply adding water to a fish tank.

In the end, biological resources in estuaries are influenced by the *effects* of inflow, notably on salinity, nutrients and sediments, not inflow *per se*. This is a different situation than that of a river or stream, where the actual velocity associated with river flow is an important ecological determinant. In order to determine these effects in an estuary, an even greater level of accuracy and sophistication is required of the analyses than that for inflows, with a concomitant demand for data. With distance to the right in Figure 2.1-2, the need for data from the estuary increases, but the base of available data diminishes. Also, with distance to the right the need for physical insight and mathematical complexity increases. These facts, early impediments to progress, are still with us and must be addressed by the BBESTs. Typically, the information base for an estuary will support the quantification of one or two of the cause-and-effect linkages of Figure 2.1-2, and usually at a rudimentary level.

2.2 HYDROLOGICAL CHARACTERIZATION

"Inflow" is in fact a complex function of time and space. The first step in quantifying the relationship(s) implicit in the conceptual model of Figure 2.1-2 is characterizing this variable, i.e. processing the inflow data to isolate and expose those features considered to be important in determining the ecological response of the estuary to various inflow situations. Essentially this process is a characterization of patterns of inflow, driven by climate, that reoccur fairly regularly and with some degree of predictability. Such a characterization then becomes the basis for constructing a sort of hydroclimatology for the estuary.

In applying inflow data to the analysis of an estuary, the analyst must also specify the period of record over which the analysis is to be performed. Generally, the longer the period of record the better, to ensure representation in the record of the full range of inflow hydroclimatologies. But the analyst must carefully define the purpose of the analysis, and how that purpose may be affected by watershed alterations during the record. For example, in a study of the association between resource data, such as salinity or organism abundance, and inflow, the historical record (for the same period as the resource data record) would be indicated. For estimation of inflows under some planning or management scenario, however, it may be necessary to employ a subset of the record during which some watershed condition was sustained, e.g. use of an early portion of the historic record to estimate pre-development conditions, or selection of a time interval to depict drought, or to employ a modeled or synthesized inflow record such as that used in the

TCEQ's Water Availability Model (WAM), e.g., for a present or projected level of human development in a particular river basin.

In this regard it is also important to be cognizant of the continuing evolution of the bay systems in response to many independent processes. Most of the data and studies available for Texas bays were obtained in the last several decades after and during major changes in the pattern of inflows, sediment and nutrient inputs, the degree of interaction with the Gulf, and fishery harvests. In effect, such data are snapshots of evolving systems—valuable to build understanding. But as time passes and the bays continue a gradual evolution, such data will need to be renewed.

A prominent feature of inflow into an estuary is its extreme variability in time. It is tempting to average out this variation to expose larger-scale temporal signals of inflow, which then may have explanatory value in interpreting historical water quality or ecology of the estuary. An implicit example of this was given above, where was noted the change in character of the estuaries along the Texas coast from Sabine Lake to Laguna Madre, and interpreted as a response to the decrease in long-term mean inflow from east to west (see also Orlando et al. 1991). Another example is the employment of annual flows in explaining year-to-year variation in water quality, production, or species abundance, but this is generally more successful in watercourses like lakes and large rivers than in estuaries.

The variation within the year, notably the occurrence of pulses of flow and of sustained, usually low flows over a substantial period, is thought by many ecologists to be a prime control on the ecological health of the water body. Moreover, though the annual flows may vary from year to year, there is often a general consistency in the relative seasonal variation within the year. The problem is how to best characterize this variation to identify those features of potential ecological importance. There are two broad time-depiction strategies summarized in the following sections: the cyclical strategy, which seeks an essentially repeatable pattern of flow variation from year to year, and an inflow "event" strategy in which various time signals are defined and the inflow time series analyzed for their occurrence. This dichotomy of strategy obtains in any watercourse, but it is a source of peculiar difficulty in an estuary because (1) the transit of streamflows through the watershed to their mouths in the estuary acts as an integrator of the signal, so that the storm pulses and interstorm low flows are "smeared" out; (2) multiple sources of inflow with varying watershed sizes, ranging from peripheral coastal drainages to major basins, with different hydroclimatologies, create a complex time signal; (3) these multiple inflow sources can obfuscate the role of specific inflow sources on critical habitat regions; (4) these multiple inflow sources may exhibit different water quality, thereby obfuscating the roles of inflow as nutrient and sediment suppliers; (5) the multiplicity of organisms in the estuary ecosystem, from freshwater to marine, and both temporary and permanent residents, entails potentially different responses to the inflow time signal.

2.2.1 Cyclical Analysis

Because the intra-annual variation in streamflow is keyed to precipitation on the watershed, which in turn is driven by seasonal atmospheric circulation patterns, it is frequently hypothesized that there is a predictable seasonal "pattern" of inflows characteristic of the hydroclimatology of

the watershed, which further exerts a control on the organisms whose success is "tuned" to this pattern. Such patterns are manifest in Texas hydroclimatology, evidenced most clearly by the season(s) of maximum precipitation (e.g., Ward, 2005). This is the genesis of the analysis of inflow for an annual cycle (i.e., tracking the annual revolution of the earth about the sun). The role of a "cycle" in temporal fluctuation was identified by Colwell (1974) as supporting "predictability" in an ecosystem, and this was analyzed in rainfall and streamflow time series by Gan et al. (1991), who evaluated the effects of binning on the Colwell indexes. In practice, this has become a "calendar period" strategy based upon a hypothetical variation of averages over some convenient subdivision of the year.

Probably the simplest calendar-period approach that attempts to characterize the annual pattern of inflow is to determine statistics of the flows after being subdivided by months, of which the most basic statistic is the monthly mean flow. A plotting of the monthly-mean inflows to the Texas bays certainly suggests a pattern, with winter inflow maximum in the extreme east of the state, shifting to a spring maximum and the appearance of a separate fall maximum further west, see Figure 2.2-1. (This figure plots the relative seasonal variation as a ratio to the period-of-record mean, with error bars indicated the coefficient of variation. What this figure does not show is a decline in mean inflow from Sabine Lake to Corpus Christi Bay of nearly two orders of magnitude. The standard deviation also declines down the coast, but not as much as the mean flow, hence the increase in coefficient of variation.)

The essential hypothesis of the cyclical or calendar-period analysis is that the flows averaged (or accumulated) over a subdivision of the calendar represent a physically meaningful quantity by dint of that calendar period. For example, the March-May period might be asserted to represent runoff due to spring frontal systems. Therefore, the array of March-May aggregated flows exactly quantifies year-to-year variation in this element of the hydroclimatology. Further, this aggregated flow can be identified as an independent variable in response analyses, because that period represents a well-defined component of the annual hydrograph cycle to which other variables, such as water quality or abundance of an organism, respond. The size of the period relative to the time scales of variation in flow determines whether the aggregation in time is merely a computational convenience, to reduce the size of a data file while maintaining the attributes essential to depicting flow variation, or attaches a separate physical significance to the flows over that calendar period. A prime example of the latter is the annual flow computed over the period of a water year, defined (hypothetically) so as to begin in the driest month of the year, thereby capturing the full range of hydrological activity for the annual period.

2.2.2 Event-Based Analysis

Two major branches of hydrology address storm hydrographs and periods of drought, respectively. Both of these types of temporal behavior of streamflows are considered "events," by which is meant a sequence of flows that exhibit some sort of coherent, autonomous behavior in time. The event-based approach seeks to identify these in the hydrological record, usually by mathematical specification, and subject them to analysis as identifiable occurrences, typically determining their statistics of magnitude, probability, and time trends. Their occurrence in the hydrological record is generally approached without regard to calendar, but once identified, these events may be analyzed for seasonal clustering.

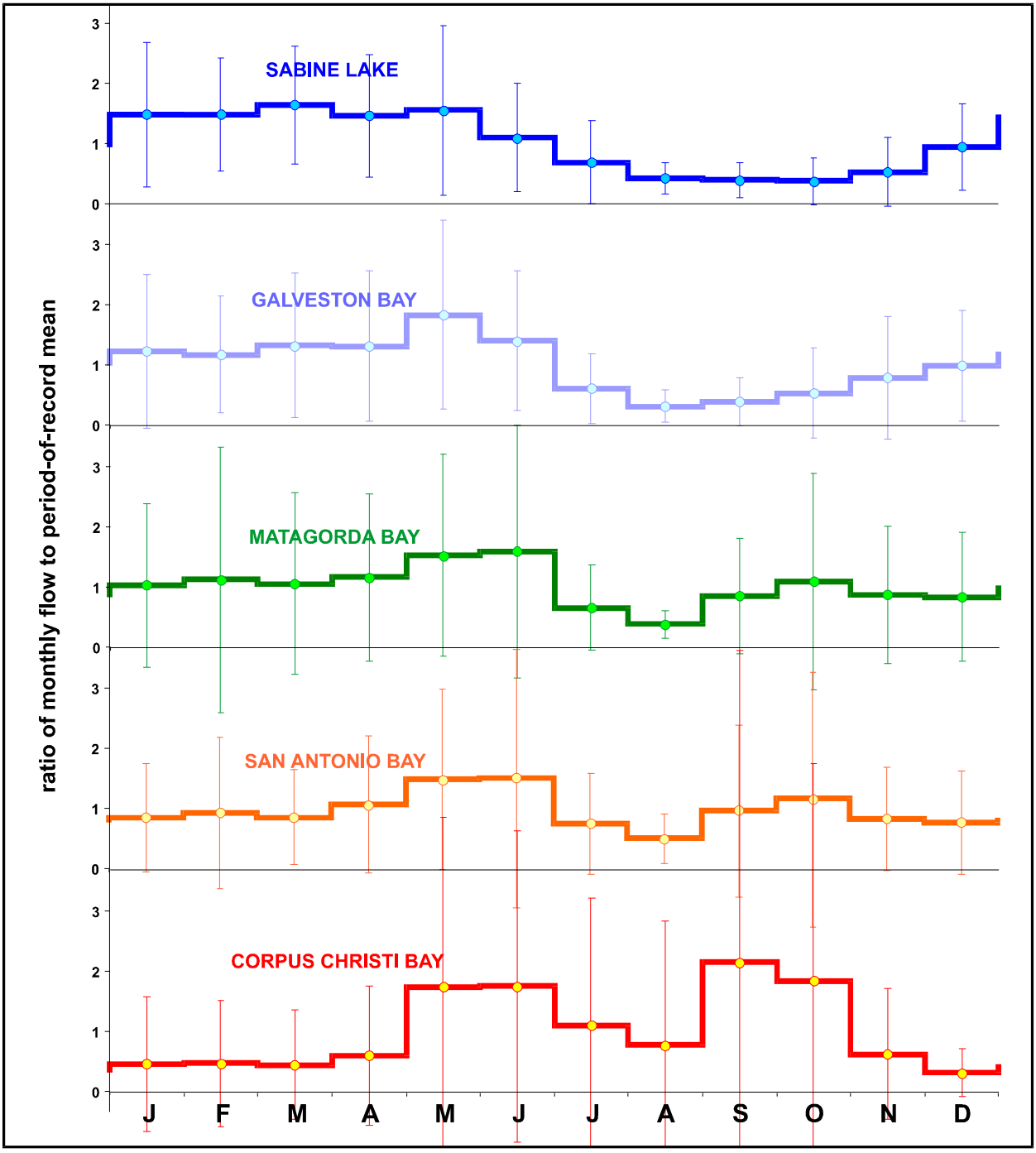

Figure 2.2-1 – Annual Patterns of Monthly Gauged Inflows into Texas Bays As Averages Over 1941-2000 Period With Error Bars for Coefficients of Variation
(based on TWDB data)

Examples of hydrological events are shown in the time trace of 1964 flows in the Trinity River at Romayor, Figure 2.2-2. One advantage that storm hydrograph identification enjoys in Texas derives from the fact that precipitation in the state is almost entirely due to deep convection, so rainfall tends to occur in relatively short, intense bursts, which produces a well-defined rise and recession in runoff (see SAC, 2004). These hydrographs are clearly evidenced in the time plot of daily streamflow, e.g. Figure 2.2-2, even though a mathematical algorithm to identify these in the streamflow time series may prove problematic. Another event identified in Figure 2.2-2 is the summer low flow, sometimes referred to as the "summer drought", which is a regular occurrence in many, but not all, years.

Methods for identifying storm hydrographs in the daily flow time series are well-documented and will not be reviewed here. Convenient summaries may be found in Gray (1970) and Pilgrim and Cordery (1993), among others. The initiation of a storm hydrograph is typically abrupt, and algorithms for detecting these events are straightforward and generally successful, challenged mainly when confronted with a complex hydrograph in which multiple storm events are superposed. The termination of a flood hydrograph is more ambiguous, however, because the recession limb tends to be extended and confused by the discharge of water stored in the stream bank and adjacent soil layers (interflow).

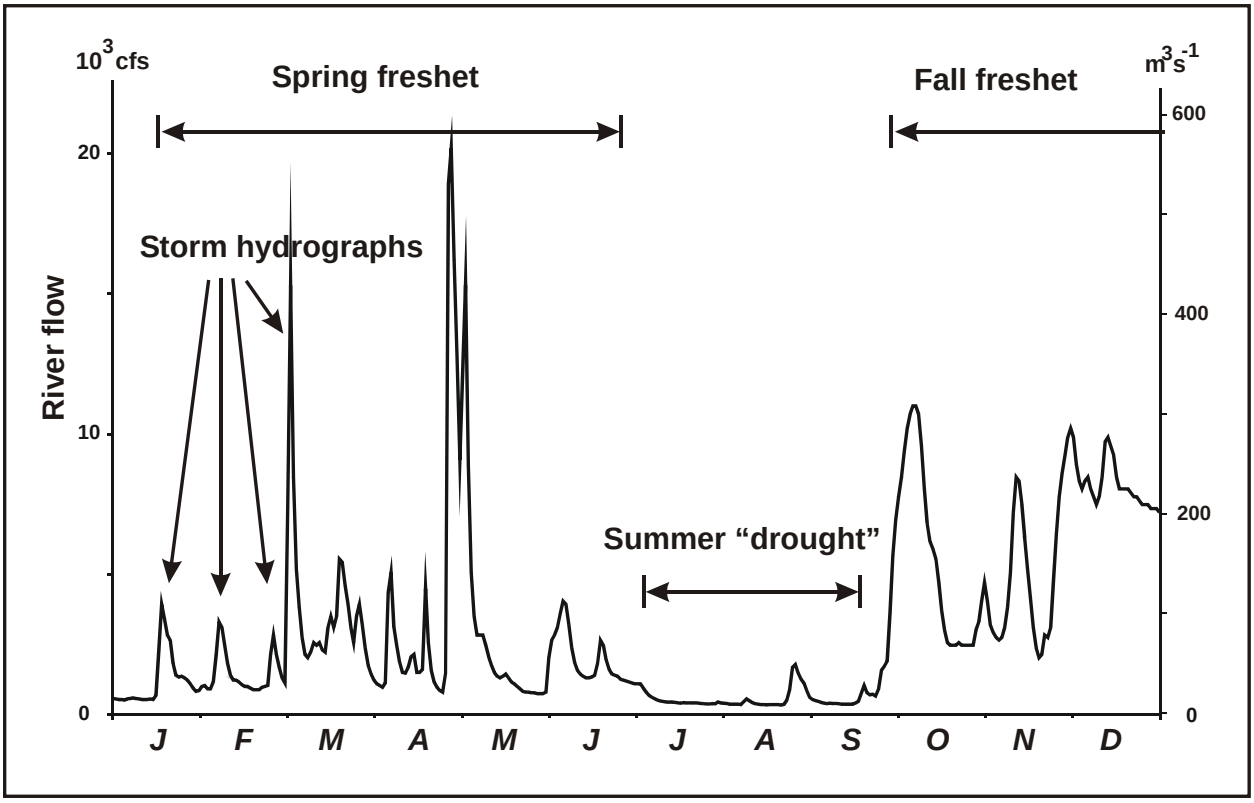

Figure 2.2-2 - 1964 Daily Flows in Trinity River at Romayor Showing Various Hydrological "Events"

Another type of event that has received study in recent years is the "freshet" concept. This is a large-scale influx of river flow, generally made up of a series of storm pulses closely spaced within a relatively short period of time (a few months, say). Examples are identified in Figure 2.2-2. The hypothesis underlying the definition of this event is that the estuary is not sensitive to the details of time fluctuation during the period of freshet delivery, because the responses of the salinity structure and biota act as a time integrator. The key parameters of a freshet are its volume, date of onset, and duration, and any of these may vary from year to year. Although these freshets can occur any time during a year, they tend to favor certain seasons in which meteorological activity is concentrated, and therefore they are the primary determinants of seasonality of river flow.

Freshets were used in the Water Quality Status and Trends projects of the National Estuary Programs (NEP) for Galveston Bay and Corpus Christi Bay to characterize hydrology. The analysis was based upon monthly inflow data, in which a freshet was defined to be the three-month period of maximum inflow for a given year or half-year. The pre-specified freshet length simplifies the analysis, and the use of monthly data reduces the file sizes to a more convenient length. (Use of monthly data would also make the NEP method potentially useable with the Water Availability Model (WAM) results.) More recent work has generalized this so that daily (rather than monthly) streamflow data are used in delineating freshet events, which is performed by a mathematical process. An example of the results of a freshet analysis, for the Colorado River, is shown in Figure 2.2-3 (see MBHE, 2006). The *y*-axis marks time, increasing upward but folded back to the *x*-axis at the beginning of each year, plotted along the *x*-axis. Freshets are shown as rectangles whose lower boundary corresponds to the beginning of the event, upper boundary corresponds to the end, and whose area is proportional to the volume of the event. Thus, the tendency for freshets to occur in a given season can be inferred by eye. As a standard of comparison and a unit of measure, the area of the red square represents the volume of Matagorda Bay.

The freshet analysis may prove a better characterization of inflows for purposes of assessing the response of biology. Preliminary statistical analyses in Matagorda Bay (MBHE, 2006) using seasonal freshets as an independent variable yield greater explanatory power for the variation of annual-mean abundance for several major species than can be achieved using calendar-period flows.

2.3 ESTUARY CONDITION AND HABITAT CHARACTERIZATION

By "estuary condition" is meant the suite of physical and chemical variables potentially important, either directly or indirectly, to the functioning of the estuary ecosystem. Among the physical variables are included tides and tidal currents, wind-driven circulations, surface waves, water temperature, light within key spectral bands, and suspended solids in the water column. Among the chemical variables are included salinity, species of inorganic nitrogen and phosphorus, dissolved oxygen, silicates, various organic compounds, and both inorganic and organic toxins. Habitat refers to the complex of physical and chemical conditions necessary to support an organism or community of organisms. More broadly, it includes other organisms that may act as prey or predator, provide substrate (e.g., reefs or marshes), or process nutrients and organics into assimilable forms. The network of relations diagrammed in Figure 2.1-1 implicitly

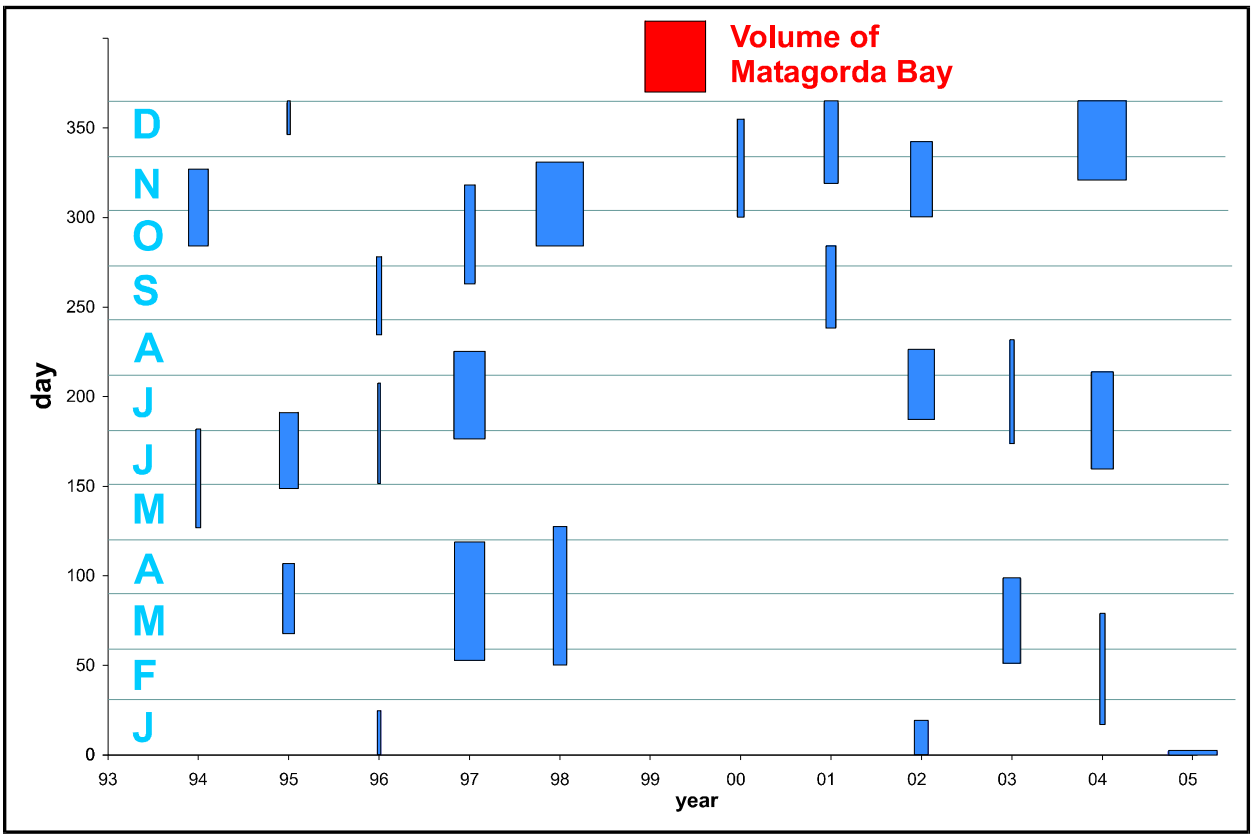

Figure 2.2-3 Occurrence of Freshets in Colorado River 1993-2005

includes habitats. Habitat characterization consists foremost in selecting, among the myriad variables and relations comprising habitat, which habitat variable(s) will be explicitly considered. Clearly, estuary condition is an important aspect of habitat. In the stripped-down relationships of Figure 2.1-2, only three parameters of estuary condition are shown, and the only habitat variable remaining is the salinity zone (although the nutrient/sediment overlays may be relevant to some habitats, and some specific organisms may be included in the biology component that provide a habitat function).

The relation of salinity at a region of an estuary to inflow is a complex dynamic response. While salinity is affected by inflow, there are complications because of the interactions between tides and geomorphology. In addition, the intrusion of salinity from the sea into an estuary is governed by several processes, notably gravity currents, tides and mixing (see Figure 2.1-1), none of which is directly affected by inflow. In a simple statistical relation of salinity on inflow, even when inflow is characterized properly, the relations are noisy, because these other processes affecting the time variation of salinity are neglected in such an analysis and therefore increase the variance about the relation.

An example is shown in Figure 2.3-1 showing the relation between point measurements of salinity in a region of Galveston Bay (combined over a number of data collection programs) and inflow, where the scatter is considerable (standard error about 5 ppt) despite the proximity of the

data region to the source of inflow. Nor is this scatter a consequence of the (typically) sparse point measurements in this data set. Figure 2.3-2 displays the daily mean salinity measurements from the TWDB Trinity Bay sonde, whose regression is almost identical (with a standard error of about 4 ppt). This scatter in fact underlies all of the relationships sketched in Figure 2.1-2, and entails considerable uncertainty about the salinity (or nutrients, or sediment) predicted from a level of inflow (which is further compounded if the inflow characterization is errant).

However, this is not to suggest that relating salinity to inflow is subject to so much variance that no inference can be made. Because of the pivotal role that salinity will likely play in the work of the BBESTs, alternative formulations of the independent inflow variable, separated geographically or temporally, should be explored.

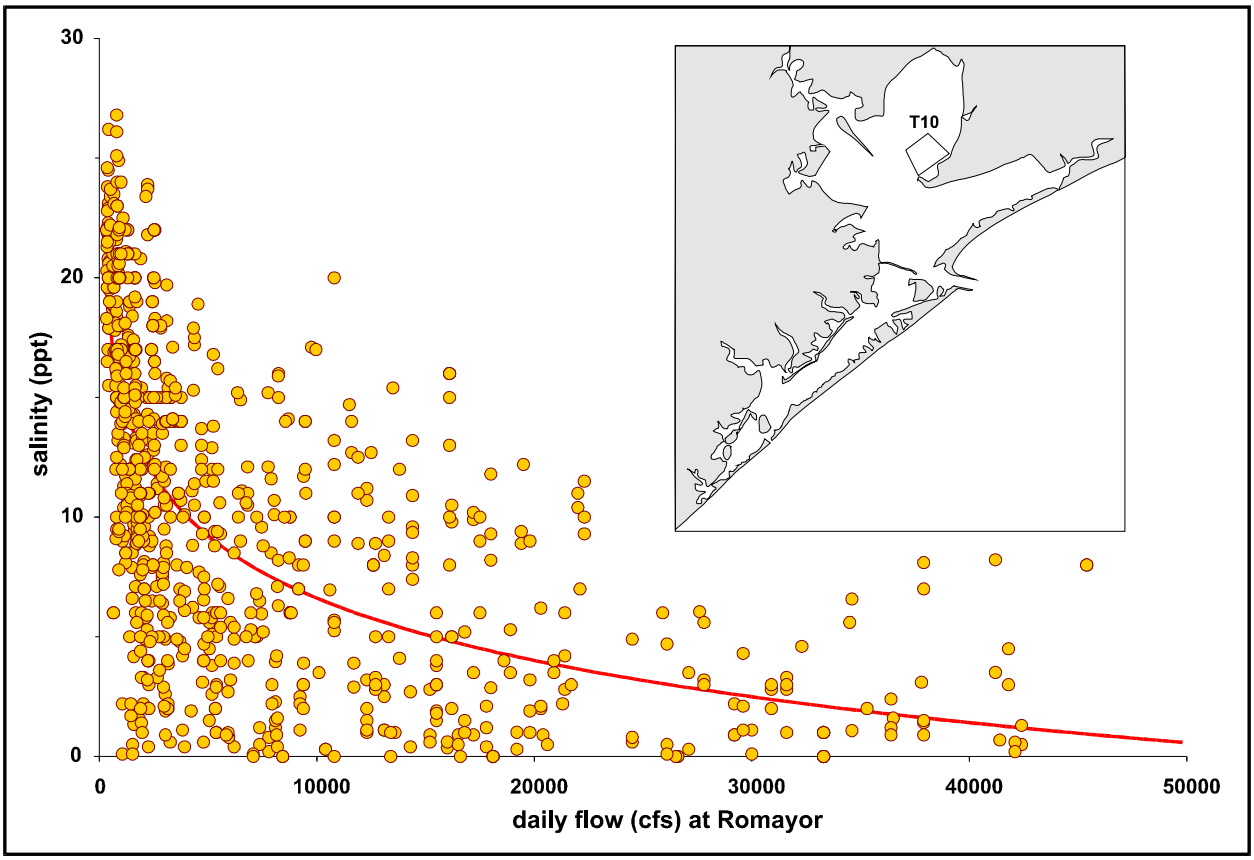

Figure 2.3-1 Surface Salinity in Segment T10 Versus Trinity River Flow at Romayor with 30-Day Lag of Salinity Behind Flow for 1958-1991
(from database compiled by Galveston Bay National Estuary Program)

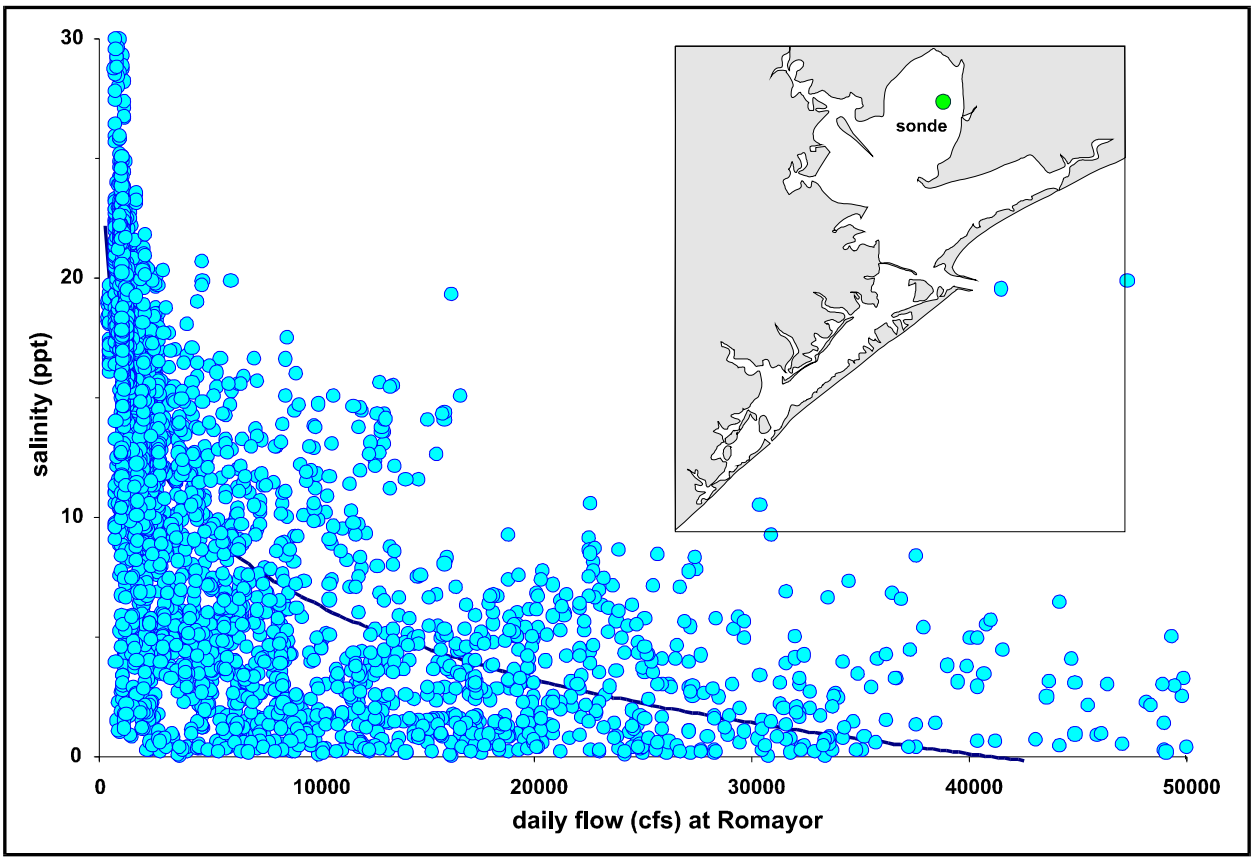

Figure 2.3-2 Surface Daily-Mean Salinity at Trinity Bay Sonde Versus Trinity River Flow at Romayor with 30-Day Lag of Salinity Behind Flow for 1986-2007
(from data files of Texas Water Development Board)

The definition of habitat includes the notion of a distribution in space, which might be a value of area (or volume), an overlay of geomorphic region with biochemical properties (the nearshore environment being a prominent example), or a specific region of an estuary historically associated with a complex of biochemical properties (e.g., a prominent oyster reef). In order to quantify this aspect of habitat, the characterization may include any of these spatial attributes. In particular, the salinity-zone specification attaches a measure of the spatial area (or volume) included within a range of salinity values that is not tied to a specific region of the estuary. Examples of this approach to habitat characterization are given in Section 4.2.

2.4 BIOLOGICAL CHARACTERIZATION

Biological characterization consists of selection of which biological components are to be addressed and what spatial and temporal formulas are to be used in quantifying the data. The biological components can be individual species or can be complexes of species, perhaps parameterized by some ecological structural measure such as diversity. These possibilities are discussed further below. The strategy of Figure 2.1-2 requires that, once the biological components are identified, either the habitat requirements are delineated, which may be confined to salinity, or that a direct relationship on inflow be developed.

2.4.1 Key Species Approach

The key species approach to characterizing the biology of a watercourse for purposes of impact assessment has been employed for at least half a century. It entails the focus on one or several so-called key species. Basis for selection of a key species is either (1) that the species enjoys some prominence, typically as a favored recreational target, as a commercial fishery hence having economic significance, or as a charismatic species commanding widespread public interest, or (2) that the species typifies in some way a key element of the ecosystem. (In contrast, a "keystone" species is one that has an impact on the structuring of a community that is disproportionate to its population size, Paine, 1966.) In Texas, shrimp and crab are examples of key species supporting important commercial fisheries, and black drum, flounder, red fish, and seatrout are examples of species favored by recreational fishers. The whooping crane is an example of an endangered species, which is also iconic to bird watchers. Oysters, seagrasses, and cordgrass (*Spartina* sp.) are examples of individual species that ecologists consider to be representative of important ecosystem engineers, or foundation species, that create habitats and provide important functions that sustain ecosystem services. The utility of key species is enhanced if they exhibit sensitivity to inflow-controlled parameters such as salinity or nutrient concentrations.

The oyster is an unusual candidate in that (1) it supports a major commercial fishery, (2) it is an important element of the ecosystem, providing a substrate for an entire, unique community, and (3) because it is a sessile filter feeder, it can function as a sentinel, (4) it is considered to be responsive to inflows.

The limiting factor in the application of the key species approach is basic data on the species. Ideal data would result from a monitoring program in the estuary maintained over many years, and employing uniform sampling gear and protocols. From such a program, the abundance, by life stage, of the species can be estimated over time, and this data used to assess the response of that species to inflows. Typical data sources of this type are academic research programs and agency monitoring projects. The Coastal Fisheries Division Resource Monitoring Program of the Texas Parks and Wildlife Department (TPWD) is an example and a a valuable resource to the state. Since the 1950's, TPWD has monitored the abundance of higher organisms in the bays of Texas, and since the mid-1970's the results of the program have been archived in digital format. TPWD biologists perform regular collections using a variety of standard gear types on nearly a daily basis, and count and report everything caught. The value of this program for monitoring and analysis of the ecosystems of the Texas bays cannot be overstated.

The principal application of abundance data for a key species is to determine whether there is an apparent association of the abundance of that species with inflow, as represented by the broken arrow of Figure 2.1-2. An example is shown in Figure 2.4-1, of white shrimp abundance in Matagorda Bay as a linear function of the volume of the fall freshet (see Section 2.2.2, above). Although, the TPWD data files in their original forms are enormous and not easily manipulated for analysis, several tools have recently been developed by TWDB, TPWD, and the Houston Advanced Research Center to facilitate use of these data (see Section 3.3). However, unless work is already underway (or has been undertaken by others) to apply this data resource in a bay

system, it is unlikely that a BBEST will have the time or resources to explore relations of abundance of a key species to inflow. If information does exist on the habitat requirements of that species, then the analysis can be carried out as indicated in Figure 2.1-2, except that the direct relation of species abundance to inflow cannot be addressed.

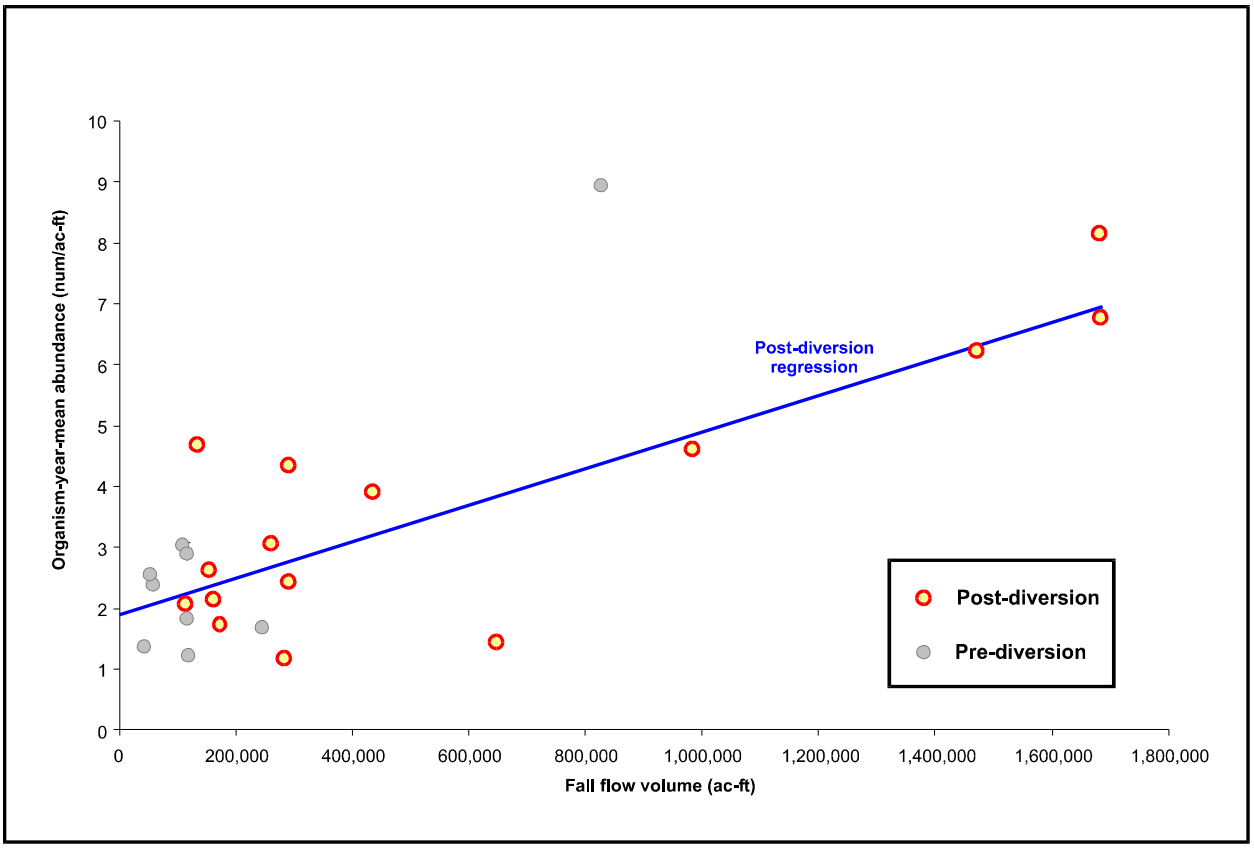

Figure 2.4-1 – Abundance of White Shrimp in Matagorda Bay Versus Freshet Volume in Colorado River
(Diversion refers to the USCE Diversion Project of the Colorado River channel)

A slight modification of this approach is to substitute salinity for flow volumes to determine the realized salinity range of a species. This approach was developed for Texas (Montagna et al. 2002) but more recently used for the central western coast of Florida (Montagna et al. 2008). The approach is based on a non-linear model, which assumes there is an preferred range for salinity and values decline prior to and after meeting this maximum value. That is, the relationship resembles a bell-shaped curve. The shape of this curve can be predicted with a three-parameter, log normal model:

$$Y = a \times \exp(-0.5 \times (\ln(X / c) / b)2)$$

The model is used to characterize the nonlinear relationship between a biological characteristic (Y, e.g., abundance or diversity) and salinity (X). The three parameters characterize different attributes of the curve, where a is the peak abundance value, b is the skewness or rate of change of the response as a function of salinity, and c the location of the peak response value on the

salinity axis (Montagna et al. 2002a). For example, it was determined that the small clam *Rangia cuneata* in the tidal river estuaries of southwest Florida has a salinity range between 1 and 10 psu, with a realized preferred range of 4 psu (Figure 2.4-2).

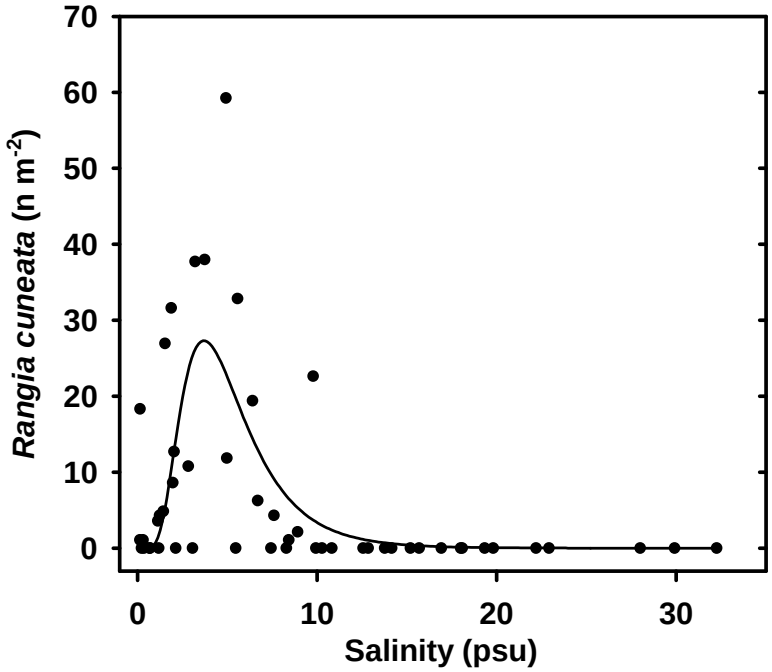

Figure 2.4-2 – Relationship Between Salinity and Species Abundance in Southwest Florida Estuaries
Adapted from Montagna et al. 2008

2.4.2 Ecological Component Approach

In contrast to the key-species approach, which focuses on single species and their dependency upon habitat and/or inflow, the ecological-component approach identifies a community of species for analysis as an entity. This approach derives from interpreting a "sound ecological environment" in Senate Bill 3 in terms of ecosystem integrity and sustainability. Integrity is the state of the community structure and is acceptable when biological diversity and species composition are comparable to some standard, typically that of natural habitats in the same region. The community is recognized as an important functional unit of the system, or as one that is sensitive to the external factor under evaluation, in this case inflow. This type of community specification may also be important in refining the requirements of nutrients and sediments delivered by inflow.

An example of the ecological-component approach is the use of benthos data in Matagorda Bay to develop a model for the benthic macrofauna component (Kinsey and Montagna, 2005; Montagna et al., 2006; see also MBHE, 2008). Benthic macrofauna are good indicators of environmental condition because they are relatively long-lived, sessile, live in the bay sediments,

and respond to food from above; thus, they integrate effects caused by changes in the overlying water over long time periods. The benthic macrofaunal community structure was studied from 1988 through 2007 in two geographic regions of Matagorda Bay, *viz*. Lavaca Bay and the Eastern Arm of Matagorda Bay. Six stations were sampled along freshwater inflow gradients emanating from the Lavaca and Colorado Rivers. The analysis of long-term benthic community structure data revealed strong year-to-year variability in benthic biomass and freshwater inflow, and indicated a general decline in long-term biomass. More importantly, these data also show strong spatial gradients of benthic biomass, productivity, community structure, and diversity related to three identifiable salinity zones within the estuary (Figure 2.4-3).

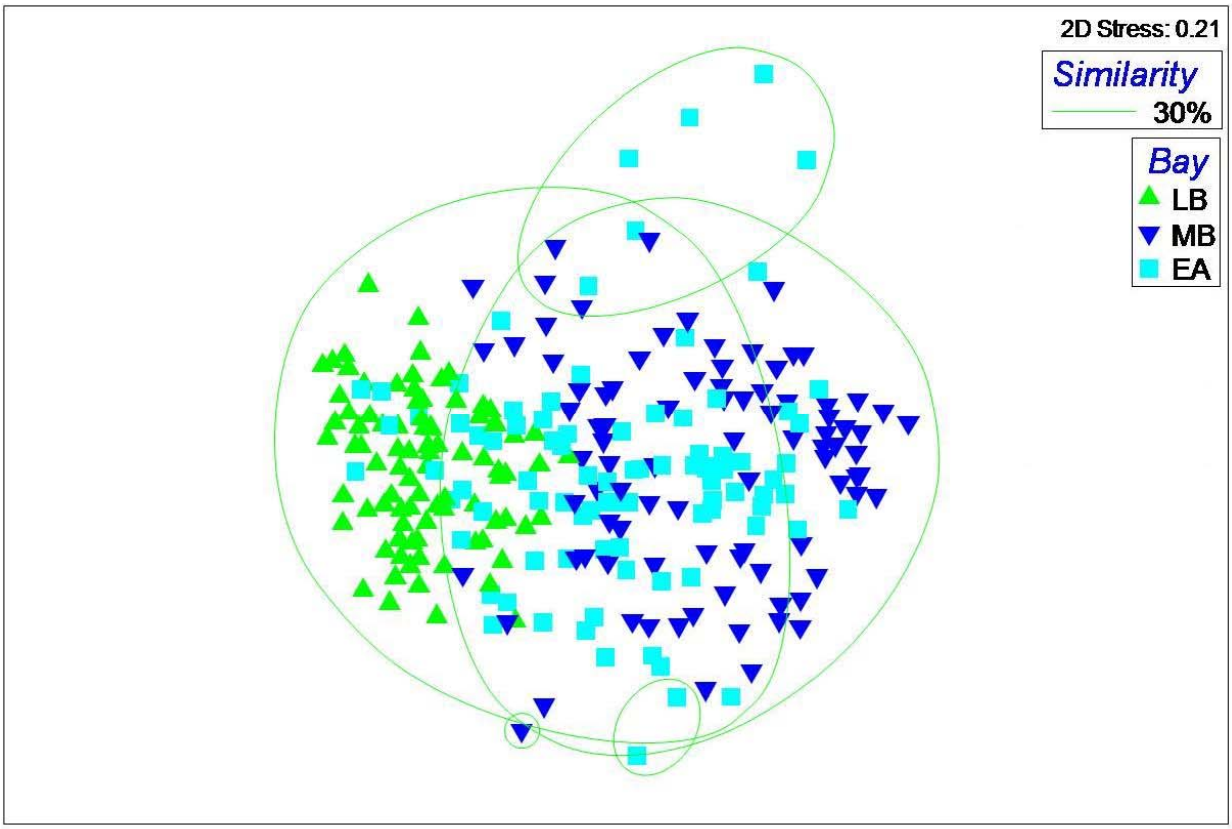

Figure 2.4-3 – Salinity Habitat Zones in the Lavaca-Colorado Estuary Defined by Benthic Community Structure Using Non-Metric Multi-Dimensional Scaling (LB=Lavaca Bay, MB=Matagorda Bay, EA=Eastern Arm)
See Clarke and Gorley (2001); Adapted from MBHE (2008)

Using an ecological component approach is simple if there is sufficient data at the species level over the scale of the estuaries and over long periods of time. Much of this kind of data exists for nearly all bays in Texas, but benthic data resides mostly in academic units. In contrast, the TPWD data is publicly available at the species level. If the benthic data can be identified, this approach will be very useful to the BBESTs.

Using the component approach also requires information about salinity in order to use the information to determine inflow requirements to protect ecological health. For example,

consider Table 2.4-1, and note that the average salinity in each zone (LB < EA < MB) correlates to the dispersion of the samples from left to right in Figure 2.4-3. Thus, if the average inflow in Lavaca Bay (LB) is reduced so that its average salinity resembles the average salinity in the Eastern Arm of Matagorda Bay (EA), then the dispersion among the ecological components would disappear and the ecosystem would be reduced to just two zones. Should this occur, then the unique Lavaca Bay (LB) community depicted in Figure 2.4-3 would disappear and become similar to the Eastern Arm (EA) community. The loss of diversity of habitat zones could be considered a degradation of the ecological environment.

Table 2.4-1 Long-Term Average Salinity and Mean Psu ± 1 Standard Deviation for Benthic Samples in Figure 2.4-3
Adapted from MBHE 2008

Bay	Salinity (ppt)	± 1 Std. Dev.
LB	14.0	9.2
MB	24.3	7.9
EA	21.3	8.4

2.4.3 Ecological Function Approach

An alternative method of biological characterization is to identify key functions, e.g., production, trophic links, reproduction, etc, along with acceptable ranges of indicators of ecosystem function necessary to ensure sustainability. Like the ecological component approach, the functional approach derives from interpreting a "sound ecological environment" in Senate Bill 3 in terms of ecosystem integrity and sustainability. In this case, integrity is the state of the ecosystem processes and is acceptable when structural redundancy and functional processes are comparable to some standard, typically that of natural habitats in the same region. Sustainability is acceptable when an ecosystem maintains a desired state of ecological balance (e.g., the ecosystem provision of ecosystem services from habitats). Typically inflow studies focus on benthos, epibenthos, or nekton community structure and diversity (as indicators of integrity); and oyster reef, seagrass, or marsh plant vegetation cover (as indicators of sustainability).

The functional approach was also used in concert with the component approach in the Matagorda Bay Health benthic studies (MBHE 2008). In addition to time series analysis of the benthic data, a bio-energetic model of macrobenthic biomass was developed to relate biomass to salinity in the two geographic regions (Figure 2.4-4). The model simulates biomass of two macrobenthic groups—suspension feeders and deposit feeders. The former include bivalves and other organisms that filter phytoplankton or graze on benthic diatoms, and the latter include burrowing worms and other organisms that consume organic matter that has settled into the sediment. The model represents the biomass of each benthic group over time as a balance between growth and limitation by the environment and predators. The model was used to calculate the sensitivity of the benthic community to changes in salinity. In general, the model predicts that higher salinity will produce large increases in deposit feeder biomass in Matagorda Bay, but no change in Lavaca Bay, and substantial decreases in suspension feeder biomass in both bays (Figure 2.4-4). Thus, reduced freshwater inflow changes the functional diversity and productivity of both bays.

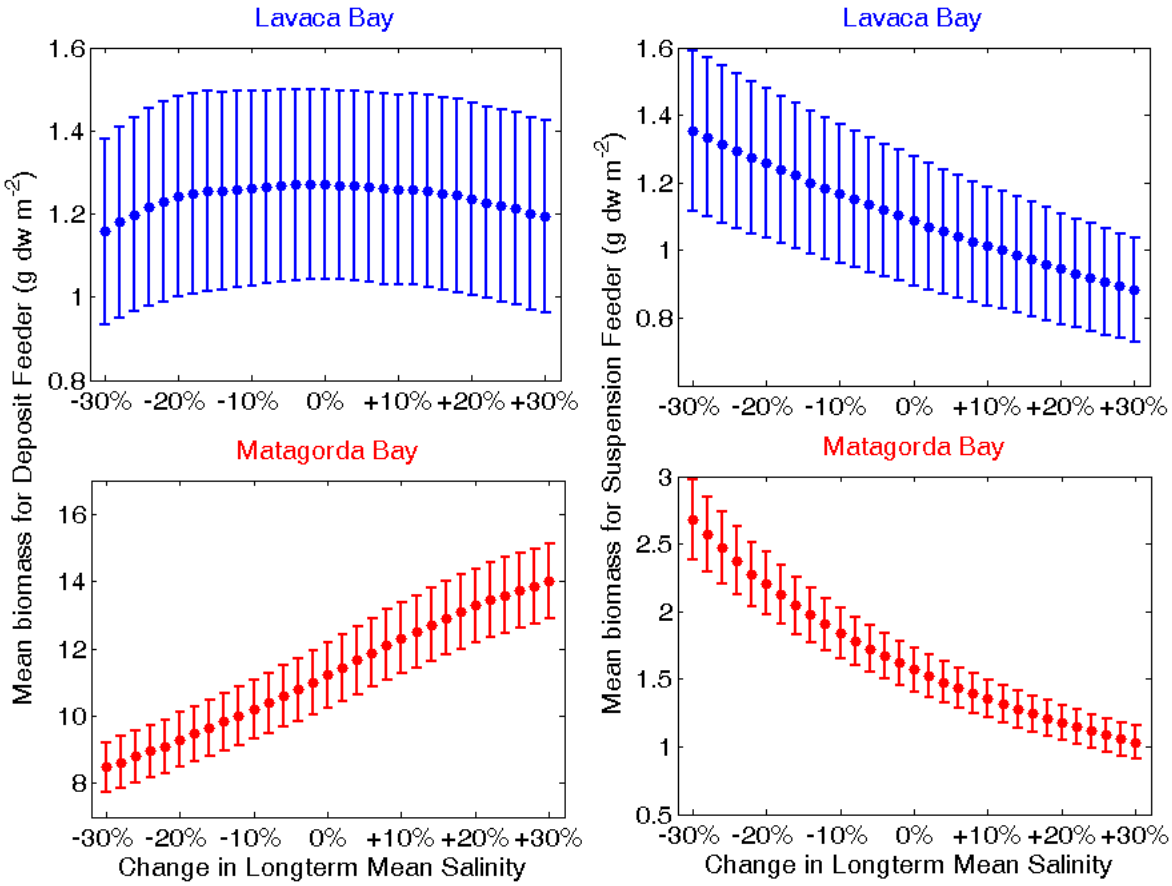

Figure 2.4-4 – Predicted Change in Productivity of Two Trophic Groups Resulting from Change in Long-Term Average Salinity
Source MBHE (2008)

Clearly, the viability of this approach to the BBESTs will require access to a considerable base of scientific study of the estuary ecosystem. When such work has been carried out and is available, it will be advantageous for the BBESTs to exploit it. Otherwise, this approach will not be practical within the limited time presently available to the BBESTs. While this approach is likely not practical for the BBESTs to complete within the time frames available, a report on three additional Texas estuaries (Guadalupe, Nueces, and Laguna Madre) will be available in 2010 (Kim and Montagna, 2010).

2.5 SUMMARY

The simplified functional diagram of inflow giving rise to estuary conditions that then affect biological components (Figure 2.1-2) affords an approach to inflow determination for an estuary that exploits the existing scientific information base and is at least potentially responsive to the guidance from the August 2006 SAC presented at the beginning of this chapter. Mathematical relationships would be formulated that describe the response of salinity habitat zones to inflow,

and the species selected would dictate both necessary habitat properties and the direct relationship, if any, of that species' abundance upon inflow.

The diagram of Figure 2.1-2 is a suggested conceptual model of how changes in inflow will influence habitat, thence biology, in which the arrows depict causal connections. With these relationships quantified from data, the conceptual model would indicate how the effects of a change in inflow would manifest themselves in changes in the selected components of biology. Inflow specification requires two additional procedures by the BBESTs:

(1) Formulation of specific ecosystem management goals, e.g. the desired presence/ absence and range of abundance of the key species, and/or the desired range of attributes of the estuary condition, notably salinity

(2) Quantification of the range of inflows that correspond to the conditions desired in (1)

There may be a need to conform the format and articulation of the goals to the extent to which the causal relationships from inflows to habitat parameters to key-species abundance, depicted in Figure 2.1-1, can be reliably and quantitatively established for the estuary. At minimum, some insight into the possible effects of inflow can be gained from an analysis of the inflow record itself, together with conceptual interpretations of how the ecosystem responds to inflow. This should be viewed as the default option of Figure 2.1-2, to be elected only when there is no information on the other elements of the estuarine ecosystem.

This situation is analogous to that of the stream or river condition addressed in SAC (2009a). The Hydrology-based Environmental Flow Regime (HEFR) approach is proposed, in which a "regime" of flow is established as a statistical occurrence by month for several categories of streamflow considered to have ecosystem or hydraulic functions, as specified in the Texas Instream Flow Program (TIFP) (TCEQ, 2008)). An analogous approach to the estuary has been suggested, addressed further in Section 4.3.1. Several flow categories and their qualitative justification are as follows. During drought periods, "subsistence" low flows are necessary to provide salinity refuge conditions near the mouths of inflow sources. For low flow conditions not as extreme as drought, the area of lower salinities is somewhat larger, allowing for tolerable conditions for sessile organisms like oysters. Under normal conditions, the main salinity gradient encompasses more of the estuary, and inflow pulses provide inflow variability, conditions thought to be needed to sustain oyster reef health, improve benthic conditions and provide suitable marsh, shellfish and finfish habitat. Very high, infrequent inflows provide episodic loads of sediments, nutrients and organic matter. These relations of the estuary environment to inflow, while plausible, depend on observation, quantification, and analysis.

The responsibilities of the BBESTs are (1) to quantify as many relations depicted in Figure 2.1-2 as feasible from the available information base, which includes the proper characterization of the variables involved, (2) to indicate the associated uncertainties in the relation, which includes statistical measures of variance, and qualitative judgments about the extent of scientific support within the estuarine system being addressed for each of these relations, (3) to assist in the quantitative formulation of goals for each of the elements of the ecosystem depicted in Figure 2.1-1 that are included in the analysis, which may include statistics of achievement, both historically and as a standard of performance. It is important that the BBESTs clearly identify when hypotheses (i.e., assumptions), however plausible, are being invoked as scientific support.

SECTION 3
BAY AND ESTUARY DATA RESOURCES AND "STATE METHODOLOGY" TOOLS AVAILABLE TO EVALUATE DATA

Senate Bill 3 provides that the BBESTs in developing flow recommendations must take into consideration all reasonably available science, without regard to the need for the water for other uses, and the BBESTs' recommendations must be based solely on the best science available. As noted in the 2004 SAC report (SAC, 2004), the twin pillars of the scientific method are observation and explication: put another way, data and models. "Models" in this context includes statistical inferences, mechanistic models, and qualitative judgments ("conceptual models"). The BBESTs should, in principle, array all of these sources of information in developing flow recommendations. The purpose of this chapter is to provide a convenient summary of data and models derived from or applied to the estuaries of Texas and which are readily available to the BBESTs. Emphasis is given to the information resources of the Texas Water Development Board (TWDB), because of the breadth and accessibility of its holdings. But it should be emphasized that for a specific estuary there may be additional resources of data or models available from state or federal agencies, from private consultants and engineering companies, and from academic research projects, of which the BBESTs should avail themselves.

Because the TWDB has long recognized the need to include estuary inflow requirements in the State water planning process, the TWDB and the TPWD have been engaged in studies of the estuaries of Texas for nearly half a century, seeking to establish a scientific basis for determining the effects of inflows. Many of the results of this program of study have become elements of the State Methodology, as summarized in Longley (1994), and may be of value to the BBESTs. Table 3-1 identifies the main "tools" available from the State Methodology according to the major category and type of tool. The "tools" are distinguished as being "Data", "Analysis", or a "Model". "Data" refers to raw or processed data sets, many of which are employed in multiple-variable analyses or models. They are only listed once where they first occur. The "Analysis" type refers to an analysis of data (specified in the "Data" column) that generates a mathematical relation, and may arise from, e.g., a mass-budgeting, a statistical regression, formulation of a constraint, or informed judgment. The "Model" type refers to a mechanistic, i.e. deterministic, mathematical formulation of some property (or properties) of the estuarine environment, typically implemented for numerical solution on a computer. These models may also rely upon the data listed in the "Data" column and the results of "Analysis" for complete specification of model inputs. (An "Analysis" in the sense used here is a *statistical* model, which is fitted to measurements. For clarity, the statistical and mechanistic models are differentiated. In practice, any mechanistic model of an estuary includes statistical models within its formulation, so these are hybrid models.) Most of these data sets and models are described more fully in the following sections.

3.1 HYDROLOGY

The historical timing and quantity of inflows to Texas estuaries is essential to virtually all subsequent analyses (cf. Figure 2.1-2). Total inflow to an estuary is found by summing the flows measured at streamflow gages, flows below these gages and in ungaged watersheds, diversions

Table 3.1-1 State Methodology Component Data, Analysis, and Models

Category	Data	Analysis	Model
Hydrology	Precipitation, monthly gaged and ungaged inflows	Historical inflow exceedance frequencies	TxRR
Salinity	Historical TWDB, TPWD, TDH salinity data	Species/inflow regression equations	
Biology	TPWD Coastal Fisheries abundance data, historical harvest data	Harvest/inflow, Harvest/abundance regression equations	
Hydrodynamics/ Salinity Transport	Synoptic flow, elevation, salinity data		TxBLEND
Nutrients	USGS and TCEQ water quality data, NOAA atmospheric deposition data	Estimated nutrient loads, nutrient budgets for some estuaries	
Sediment	USGS, TWDB sediment data	Estimated sediment loads	
Optimization		MinQSal, MinQ, MaxH inflows	TxEMP

removed from the ungaged streams and watersheds, and return flows returned to ungaged streams and watersheds or directly into the estuary. Inflows entering the stream below the downstream-most gage and in ungaged watersheds are referred to as "ungaged" inflows. The estuary's freshwater balance is further affected by the net of precipitation and evaporation at the surface. TWDB has developed and compiled records of these component inflows for all the major estuaries in Texas. The Texas Rainfall-Runoff (TxRR) model has been applied to all ungaged coastal watersheds that contribute runoff to major estuaries in Texas. Combined surface inflows (sum of gaged, ungaged, and return inflows, minus diversions) and freshwater balances (surface inflow plus precipitation minus evaporation from bay) have also been computed. Data on total inflows that occurred prior to 1978 were obtained from earlier TWDB studies in which only monthly data were stored, and thus are available only as monthly values. For periods after 1978, inflows are available with daily resolution.

Data - USGS streamflow, TCEQ diversions and return flows, NWS raingage and NEXRAD rainfall, TWDB evaporation, NRCS land use.

Analysis - Various aggregated or integrated measures of inflow, identification of hydrological events, statistical distributions over time

Models - Texas Rainfall Runoff (TXRR), based upon the SCS curve-number method, is available for ungaged watersheds contributing to all major estuaries.

3.2 SALINITY

Salinity is a useful ecological indicator of habitat condition that has been widely collected and analyzed in Texas estuaries. As noted in Section 2.3, salinity is a fundamental estuary parameter representing chemical habitat condition. Its magnitude, which ranges from zero to seawater (unless net evaporation is high, which can result in hyper-saline conditions), is an indicator of the proportion of seawater in the water of the estuary. Because of its properties as a tracer, salinity is essential for calibration of hydrodynamic and salinity transport models.

Data - Salinity can be measured by several methods, which vary in accuracy and convenience. Fortunately, the extreme variability in salinity in an estuary obviates the need for precision in measurement, and several alternative techniques yield approximate values of salinity sufficiently accurate for estuary application. These include chemical analysis of water samples for salts or dissolved solids, conductivity of water sample, and refractive index. An important innovation is field-hardened automated data collection technology employing a small conductivity probe and data logger (or, perhaps, telemetry), which enables the operation of a robot measurement system anchored in the estuary, referred to as a "sonde". Several agencies have deployed sondes in the estuaries of Texas, some for as long as the last twenty years, to obtain a virtually continuous time series of salinity, including the TWDB, Texas Coastal Ocean Observation Network (TCOON) of Texas A&M—Corpus Christi, the U.S. Geological Survey, and the National Ocean Service, as well as river authorities and academic researchers.

As a component of the State Methodology, TWDB has compiled salinity time-series data from its Datasonde Program, and point measurements primarily from TDH, and TPWD. Sonde records are also available from other agencies or entities such as TCOON, river authorities, and navigational data operations.

Analyses - Desirable salinity regimes for different species, multivariate flow-salinity regressions as a function of inflow for multiple sites in the Texas estuaries.

Models - Numerical solutions to the salt-transport equation. In the State Methodology, this is coupled into the hydrodynamic model TxBLEND, described in more detail below. The Corps of Engineers has applied its RMA series of models to several of the Texas estuaries, and limited application has been made of the EPA EFDC model.

3.3 BIOLOGY

Biology includes identification of the key flora and fauna of the estuary, as well as direct measurements of their abundance (e.g., as number of organisms per unit area or per unit volume) as a function of space and time. For vegetational species and sessile animals such as reef builders, their specific distribution within the estuary boundaries over time can be an important index to habitats. Though rarely recognized as key species, the plankton, i.e., minute or microscopic organisms (including bacteria) suspended in the water column, and the benthos, i.e the micro-and macrofauna living in the sediments on the bed of the estuary, are major components of the ecosystem. All of these species have been studied by researchers in

universities, and federal and state agencies over the years. Quantitative data on their abundance in time and space are highly variable in completeness, accuracy, period of record, and accessibility. The Coastal Fisheries Division Resource Monitoring Program of the Texas Parks and Wildlife Department (TPWD) is designed to monitor the abundance of higher organisms (primarily nektonic macrofauna) of the estuaries, and is a valuable resource to the state. Since the 1950's, TPWD (or its predecessor agencies) has routinely conducted such sampling in the bays of Texas, and since the mid-1970's the results of the program have been archived in digital format. TPWD biologists perform regular collections using a variety of standard gear types on nearly a daily basis, and count and report everything caught. .This sustained data collection program has provided a virtually continuous record of the larger organisms on the Texas coast for nearly four decades. In addition, TPWD has conducted numerous special studies of more limited observation in space and time to address particular biological issues, and it and its predecessor agencies have made routine collections in several of the Texas bays dating back to the 1950's. Although, the TPWD data files in their original forms are enormous and not easily manipulated for analysis, several tools have recently been developed by TWDB, TPWD, and the Houston Advanced Research Center (HARC) to facilitate use of these data[3].

TWDB has developed species abundance-inflow regression equations for selected animal species found in Texas estuaries. Equations originally were developed using commercial fisheries harvest data, assumed to be a measure of organism abundance in the estuary, thus yielding biomass-inflow equations. Later, abundance-inflow equations were developed. Abundance was based on TPWD's Coastal Fisheries effort-independent monitoring data. Inflows in these regressions were based on hydrology data accumulated over bimonthly periods.

Data - TWDB combined inflows, historical annual fisheries harvest and TPWD-based abundances.

Analyses – Multivariate linear regression equations developed for several selected species for each major estuary in Texas.

3.4 HYDRODYNAMIC AND SALINITY MODELS

Numerical hydrodynamic and mass transport models, also known as circulation models, are used to simulate the variation of salinity, flow, and water levels throughout a bay, and have been applied to investigate different inflow scenarios. Only a brief overview of the nature and characteristics of circulation models can be given here. The term "model" strictly refers to the mathematical formulation of a physical relationship. The jargon that has evolved applies the term to a computational scheme implemented on a digital computer, frequently even a specific computer code, e.g., TxBLEND, DYNHYD, POM, and EFDC. Any model is a simplification. The point of departure in modeling is to decide what real-world features should be modeled, and which others will be discounted as irrelevant, or deemed to be beyond the capacity of a particular model formulation. The differences between models lie in how this simplification is achieved,

[3] See following web sites for information on TPWD data analysis tools:
For major bays: http://midgewater.twdb.state.tx.us/TPWD/tpwd.html;
For minor bays: http://www.tpwd.state.tx.us/landwater/land/maps/gis/ris/catch_rate/index.phtml;
For Galveston Bay: http://www.galvbaydata.org/LivingResources/FisheriesDataPortal/tabid/203 /Default.aspx

i.e. what features are retained and what are sacrificed, and what aspects of the real world the simplified model depicts.

Simplification can be applied at three different levels of formulation: conceptual, mathematical and computational. Generally, the conceptual simplifications are the most transparent and easiest to evaluate because they explicitly state what kinds of features the simplified model will retain. Examples are whether tides are explicitly treated or suppressed by averaging over several tidal cycles, whether the estuary geometry is represented as one-, two- or three-dimensional, and whether density-driven circulations are explicitly treated or implicitly specified by some external parameter. Mathematical simplifications have the objective of expediting the mathematical solution of the problem, while maintaining fidelity to the conceptual model. This level of formulation includes the incorporation of specific mathematical expressions for different processes (which can include some conceptual simplification). Evaluation of a mathematical simplification is obviously more subtle than a simplification at the conceptual level, and may require some sophisticated analysis. Simplification at the third level, the computational, involves approximation of the mathematical expressions to achieve a numerical solution. Theory is uneven, providing only guidance at best, and evaluation is usually empirical, hence case-specific.

Model application requires the specification of boundary conditions. Estuary waters are in contact with the rest of the world, at their surface, at the bottom, around their shoreline, at the entrances to the sea, and at the upstream points of inflow, and various exchange processes operate at each of these boundaries. These must be specified to "close" the solution. Though often treated as an afterthought, the correct specification of boundary conditions is easily half the problem of correctly applying a complex circulation model. Depending upon their characteristics, these boundary conditions may be developed from field data, from statistical relations or from other models. At a minimum the inflows to the estuary, friction at the bottom, stresses at the surface, and tides and salinity at the ocean boundary of the computational area must be specified. Generally these are functions of time, which is a further complication. The complexity of specifying boundary conditions at the estuary inlet(s) to the sea is often obviated by moving the boundary out into the ocean, thereby allowing the hydrodynamics to dictate the exchange at the inlet(s).

The development and application of hydrodynamic/salinity models rely upon an extensive base of field data from the estuary itself. Despite the imposing theory upon which such models are based, there remain "free parameters" in the equations, i.e., variables employed to quantify key processes but whose values must be supplied, such as bed friction coefficients, mixing coefficients (including diffusivities and dispersivities), and wind-stress coefficients. Values of these parameters must be established by a process of trial and error, in which model predictions are compared to field observations, and the parameters adjusted to force agreement. Clearly, the more parameters that must be treated, the more independent sets of data must be available. Moreover, these free parameters are typically site-specific and cannot be transferred from another estuary. This general process of adjusting the free parameters to replicate observed data is referred to as "calibration". Ideally, a model would be further subjected to "verification", in which the model outputs are compared to additional (and independent) sets of data to assess the quality of the model prediction.

TWDB has developed, calibrated, and applied two-dimensional (horizontal) models (circulation and salinity distribution of vertical-mean parameters in the horizontal plane) for all the major estuaries in Texas using the TxBLEND model program (TPWD and TWDB 1998, 2001, 2002, 2004, 2005). Reports describing calibration results are available for the Corpus Christi Bay model (CCBNEP 1997) and for the Galveston Bay model (TWDB 2005). The Lower Colorado River Authority (LCRA) has also calibrated and applied TxBLEND in support of freshwater inflows studies for Matagorda Bay (LCRA 2006). Calibration results quantifying model performance and plots of model versus measurement comparisons for the remaining major estuaries are available from the Bays and Estuaries Team at TWDB. In all cases, model water level and velocity were typically calibrated over shorter periods of a few days, while salinity was calibrated with data over several years. This is a reflection of the lower availability of velocity data and the greater availability of salinity data.

Multi-bay models have also been developed in which adjacent connected bays are incorporated into a single model grid, and output files have been generated in some studies for multi-year simulations. TWDB is also now evaluating three newer generation models (SELFE, FVCOM, and UTBEST) for potential future use. Other agencies have also employed advanced numerical hydrodynamic/salinity models for some of the Texas bays, including in a few cases, three-dimensional models. The U.S. Army Corps of Engineers has made extensive application of its RMA series of models (which includes both two-dimensional and three-dimensional versions) to Sabine Lake, Galveston Bay, Matagorda Bay, Corpus Christi Bay and the Laguna Madre. Research-level models for a few of the estuaries have been developed at several Texas universities.

Data - NOAA bathymetry, NOAA/TCOON tides, NWS rainfall, TWDB evaporation, TWDB inflows, TWDB salinity, water levels and flow.

Models - A TxBLEND model is available for all major estuaries in Texas from the TWDB.

3.5 NUTRIENTS

Nutrients can be considered the "food" that drives the estuarine ecosystem and are essential for overall production. Nutrients are measured by standard chemical analyses, almost always on samples of water retrieved from the estuary. For the Texas estuaries, compounds of nitrogen and phosphorus are the nutrients of greatest concern, because they are greatly affected by human activities. Chemical sampling of these compounds has been carried out by a number of federal, state and River Authority/Water District monitoring programs, as well as by academic researchers. Both National Estuary Programs in Texas (Galveston Bay and Corpus Christi Bay) acquired and compiled a combined data base of historical measurements from the various agencies and programs.

The load of a nutrient is its mass transfer into the watercourse. Estimates of long-term average nitrogen loads have been completed by the TWDB for all major estuaries, and phosphorus loads have been completed for most. More complete nitrogen budgets that describe important nitrogen sources (inflows, wastewater loads, atmospheric deposition, release from sediments, tidal influx, etc.) and sinks (denitrification, ammonification, export to Gulf, burial, etc.) were developed for

some estuaries, as noted below. Because the data required for developing loads and budgets are limited, they should be considered starting points for further investigation.

Historically, researchers at academic institutions and consulting firms have also assembled nutrient budgets. The two National Estuary Programs in Texas included work tasks that performed nutrient budgeting.

Data - USGS streamflow, TCEQ and USGS water quality, NOAA Atmospheric Deposition Program. water chemistry data collection by various agencies.

Analyses - Estimated nitrogen and phosphorus loads can be provided by the TWDB, including basic nitrogen budgets for some major estuaries (Trinity-San Jacinto, Nueces, Lavaca-Colorado).

3.6 SEDIMENT

Sediment, which includes fine-grained solids suspended in the water column, sand-size (and larger) particles and organic debris (seston), play important roles in the estuarine ecosystem. Because some nutrient compounds sorb readily to fine particulates, sediment loads can represent an associated load of nutrients. As physical particles, sediment, when deposited, can support physical habitat. In particular, sediment transported into a delta or marsh by inflows can be important compensation for erosion of the delta surface at high waters and for the effects of subsidence. Sediments can also affect production in the estuary by limiting the vertical penetration of sunlight. Various measures of suspended sediment are routinely monitored, including turbidity, water density, and TSS, and, though they can be interconverted, the conversions are empirical and noisy.

The mass transfer rate of sediment is the sediment load. Estimates of long-term average sediment loads from suspended solids data combined with the appropriate flow have been developed for all major estuaries by the TWDB, as well as by academic and consulting research workers. As with nutrients, data for this purpose is limited, and the estimated loads should be viewed as starting points for further analyses.

Data - USGS streamflow, USGS and TWDB sediment concentration data. Shoreline erosion studies by the Bureau of Economic Geology, of the University of Texas. Data on littoral sediment interception, deposition and dredging from the Galveston District Corps of Engineers. Historical measurements of turbidity by TCEQ, TPWD, and academic researchers.

Analyses - Estimated sediment loads can be provided by the TWDB for Guadalupe Estuary and Laguna Madre. A sediment budget study was conducted for Laguna Madre.

3.7 OPTIMIZATION

In the early years (i.e., the 1960's and 1970's), the TWDB Bays and Estuaries Program pursued the idea of defining inflow "needs" of an estuary as the levels of inflows that resulted in a maximum of productivity (as measured by the commercial harvest of key species). The first round of estuary inflow reports, the LP-series dating from the early 1980's, relied upon linear

programming to determine this optimum (Martin, 1987), in which the seasonal effects of freshwater inflow variation was captured by defining six independent variables of inflow to be the bimonthly totals (January+February, March+April, etc.). Since then, a provision for optimization has remained in the State Methodology as a major tool. The original Simplex-based linear-programming code has been replaced by a far more sophisticated program, TxEMP, which is an extension of the fully nonlinear optimization program GRG2 (Lasdon and Waren, 1986) to accommodate constraints on all of the input and output variables, as well as levels of probability ("chance-constraints", see Tung et al., 1990). The management-target inflow patterns of MinQ and MaxH (or MaxC) detailed in Longley (1994), are determined by application of TxEMP. The TxEMP optimization model is one means of combining information on inflow, salinity, harvest or productivity (measured as harvest biomass or as abundance), nutrients, and sediments to achieve specific objectives related to flow, salinity, and harvest or productivity.

Analyses - TWDB salinity-inflow regression equations, TWDB species-inflow regression equations, TWDB inflow hydrology, species- and location-based salinity constraints, nutrient and sediment constraints, all employed as inputs to TxEMP.

Model - TxEMP optimization solutions for all major estuaries in Texas for the problem statements *minQ*, *maxH* (or *maxC*) and *minQ-sal*. See Longley (1994) for the technical definition of these problem statements.

SECTION 4
METHODOLOGIES FOR DEVELOPING BAY AND ESTUARY FRESHWATER INFLOW RECOMMENDATIONS

There is a variety of methodologies that could be used to develop freshwater inflow recommendations, as surveyed in two recent reviews of approaches to the problem (Alber 2002, Esteves 2002). These and several other methods were summarized in the 2004 SAC report (SAC, 2004). In this chapter we focus on only those methods that have been historically applied in Texas estuaries, or in principle could be applied with modest effort because the information resources required are generally available.

The conceptual model for the recommended approach is diagrammed in Figure 2.1-2. To summarize Section 2 of this report, a methodology is determined by: (1) the variables in this diagram, proceeding from left to right, that are explicitly addressed; (2) how these variables are characterized, i.e. how they are measured and how the measures are processed in space and time; and (3) what goal(s) are sought to be achieved in the ecosystem by dictating the inflow "regime". While the causal effects of flow are directed: inflow → salinity → biology, the specification of a necessary inflow requires addressing the converse problem. First, the biological resource to be protected is identified. Second, the habitat requirements of that resource, including but not limited to a salinity range, are identified in both space and time. Third, the flow regime needed to support these requirements, e.g. a required distribution of salinity, is determined, based upon either statistical analysis of field data or mechanistic salinity-transport models. When information is absent on biological resources, or their biochemical requirements, this process may have to be truncated.

Because of the complexity of the relationship between flow and biology of a watercourse, and the difficulty of establishing it, approaches have been developed that rely solely on protecting the inflow hydrological regime, assuming that if the flow were maintained in some historical fashion, then the biology would be taken care of. This is the basic foundation that underlies the IHA (The Nature Conservancy, 2007, Richter et al., 2006, see Section 4.4.1 below), HEFR (see Section 4.3.1 below), NWF Inflow Pattern (see Section 4.3.2 below), and Percent of Flow (see Section 4.4.3) approaches. Historical hydrological patterns, particularly seasonal, also play an important role in applications of the State Methodology (Section 4.1, below), the Salinity Zone (Section 4.2), and the LCRA-SAWS Inflow Criteria (Section 4.4.2 below) methods, but, to varying degrees and levels of sophistication, other factors and relationships pertaining to salinity, species abundance or productivity, nutrients, water quality, and/or sediment loadings also are incorporated into the decision process for determining freshwater inflow requirements.

In presenting candidate methodologies in this section, we summarize the methodological approach including the information resources exploited, and indicate how the method corresponds to a specific implementation of the simplified relationships depicted in Figure 2.1-2.

4.1 STATE METHODOLOGY

4.1.1 General Procedure

The Texas Water Development Board (TWDB) and the Texas Parks and Wildlife Department (TPWD) are responsible for determining the total inflow to each bay necessary "...for the maintenance of productivity of economically important and ecologically characteristic sport or commercial fish and shellfish species and estuarine life upon which such fish and shellfish are dependent," referred to as "beneficial inflows" [Texas Water Code §11.147]. This determination involves a two-step process. The first step, conducted by the TWDB, is the application of a quantitative methodology to determine optimal inflows to the bay under consideration that will achieve specified management "goals". The second step, conducted by the TPWD, is to select that inflow solution, among the several determined by TWDB, considered to best achieve the purpose of maintenance of ecological health and productivity. The method employed in the first step (by the TWDB) is referred to as the State Methodology, and that of the second step (by the TPWD) is referred to as "verification analysis." This is the terminology employed in the 2004 SAC report (SAC, 2004), and the terminology observed here. However, it should be noted that sometimes "State Methodology" is applied to the combined two-step procedure. In the present section the TWDB State Methodology is described. The TPWD Verification Analysis is addressed in Section 4.2.

The State Methodology is documented in an extensive report (Longley 1994), consisting of many components of study, data compilations and analyses, and modeling (see SAC, 2004, and Section 3 above). The final answer is a sequence of monthly flows to the estuary that will achieve a specified "goal". Central to the inflow determination are two sets of relationships: salinity at selected locations in the estuary as a function of inflow, and abundances of several key species as a function of inflow. Both of these are determined by a statistical fit to data. For the salinity relation, a multivariate linear regression is used on two independent inflow variables, the monthly-mean flows corresponding to, and preceding, the date of salinity measurement.

More important is the relation of abundance of a key species on inflow. In Figure 2.1-2, this represents the direct relation between "inflow" and "biology" depicted by the bold broken arrow. Abundance is measured in two ways in the work of the TWDB. In the early analyses of major estuaries, when commercial harvest was the only long-term species information available, commercial harvest was used as a surrogate for abundance. This assumes in effect that harvest is primarily dependent upon the population density of the organisms in the bay. With the increasing data base of directly measured abundance data from TPWD, this assumption could be tested. This dependence has proven to be weak because other variables affect, and even dictate, the commercial catch, not the least of which is economics. In later estuary analyses, abundance based upon the TPWD Coastal Fisheries database has been used. The key species vary with the estuary; they are summarized in Table B-1 of Appendix A for the major bays.

The regression equations intended to reflect dependence of species abundance on seasonal variation in inflow, therefore the characterization in inflow must exhibit seasonality. Inflows were aggregated into bimonthly periods, as follows:

Q_{JF} -	January + February	Q_{JA} -	July + August
Q_{MA} -	March + April	Q_{SO} -	September + October
Q_{MJ} -	May + June	Q_{ND} -	November + December

This is an example of cyclical (or calendar period) inflow characterization, described in Section 2.2.1 above, because the inflow aggregation is locked into the calendar. The statistical models used are multivariate linear regressions in which each of these bimonthly flows is a separate independent variable.

The last substantial step of the State Methodology process is to employ the salinity and key species regressions in a sophisticated nonlinear multivariate optimization model called TxEMP, described in Section 3.7, to determine the distribution of monthly inflows that either maximizes or minimizes some variable, defined by a specific management "goal". The most important of such goals are:

maxH/maxC total annual harvest/abundance is maximized, subject to constraints on inflows

minQ total annual inflow is minimized, subject to the constraint that total annual harvest be no lower than 70% of its period-of-record average, and subject only to constraints on salinity

In addition, solutions are sometimes provided for *maxQ* and *minQ-sal*, and additional potential goal formulations are given in Longley (1994). Both *maxH* and *minQ* monthly flows are shown in Figure 4.1-1 for Galveston Bay. The TxEMP solutions for all of the major bays are summarized in Table A-4 in Appendix A.

The "constraints on inflow" in the above definitions of *maxH* and *minQ* are an important feature of the TxEMP solution. Because the functions being optimized, *viz*. the abundance-versus-inflow regression equations, are monotonic they do not exhibit a local optimum. In order to achieve such an optimum, bounds must be imposed. These bounds are input into the TxEMP solution as "constraints" on the answer. The inflow constraints for all of these solution goals are that each of the bimonthly and monthly inflows must lie between the lowest decile and the median for that month/bimonth. Additional constraints related to salinity, ratios of species abundances, and other factors are also applied. These constraints represent a combination of both policy and science decisions, and can be modified as information related to policy or science changes.

In terms of the conceptual model of the inflow determination process, Figure 2.1-2, the State Methodology employs *both* a salinity relation, with salinity viability limits that represent the aggregated salinity bounds for key species selected for the estuary, and a *direct relation* of species abundance to inflow. In principle, the State Methodology also includes requirements for nutrient transport and sediment loading (see Appendix A). However, in practice, the requirement is to maintain average historical loads, and satisfaction of the biological "productivity" and

salinity "viability limits" goals of the method have been found to provide at least the annual historical loads of sediment and nutrients, so these conditions have no effect on the final answer.

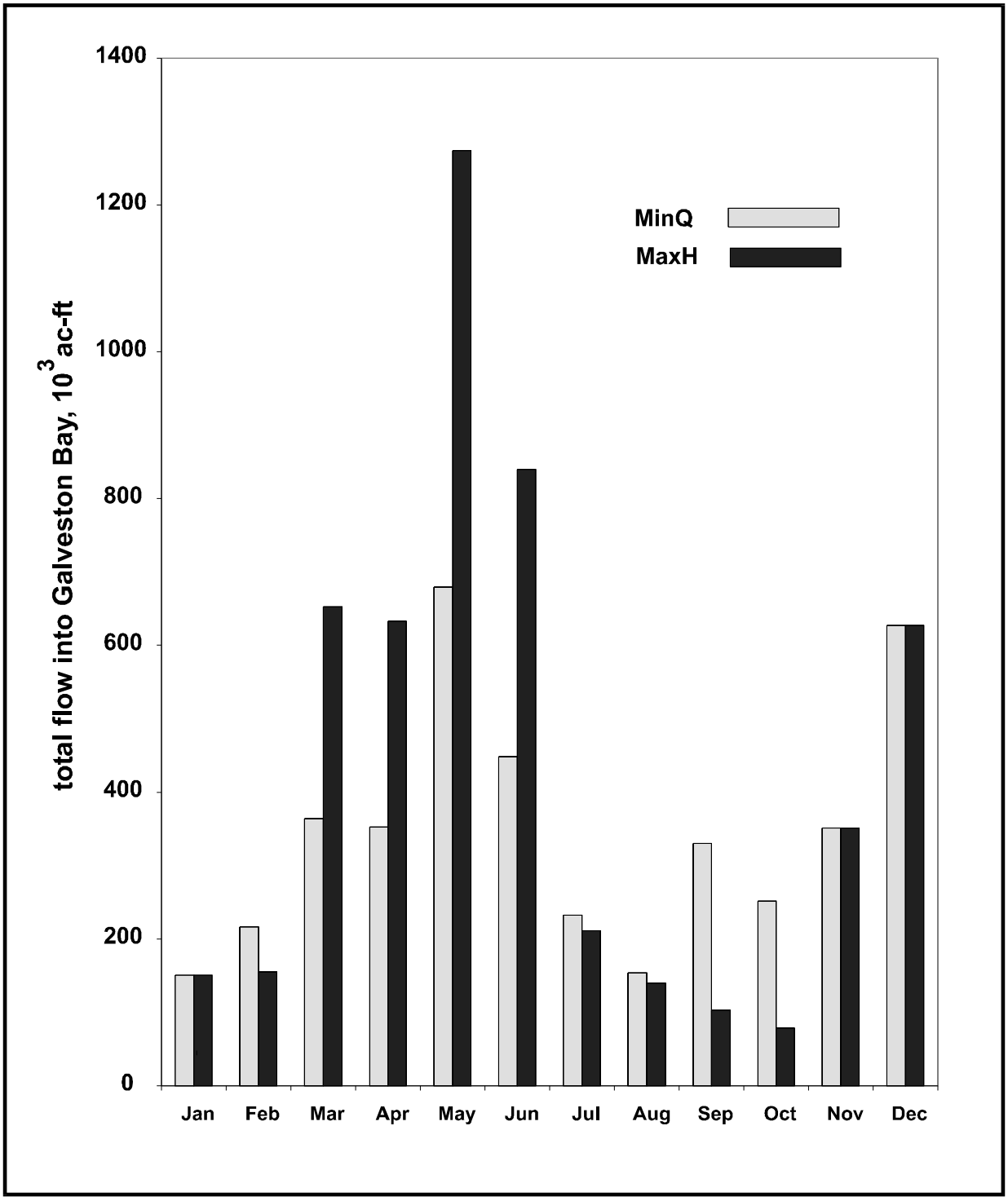

Figure 4.1-1 - TxEMP Inflow Solutions for Galveston Bay

4.1.2 Strengths and Weaknesses

Strengths of the State Methodology include:

- *Easily understood objectives* - The harvest/abundance goal of maintaining a minimum abundance/harvest as a fraction of the historical mean of "economically important and ecologically characteristic sport or commercial fish and shellfish" is clearly understood.
- *Sensible way to integrate disparate information* - TxEMP integrates management goals with hydrological and biological goals and constraints.
- *Attempts to make best use of flow resource* - TxEMP computes the minimum flows that meet goals and constraints.
- *Constraints keep solution "reasonable"* - Hydrological and biological constraints keep the solution "reasonable". Salinity zones are evaluated for important habitat areas as a final check. Although the optimization may be weak due to nature of harvest equations, reasonableness of the solution is enforced by constraints.
- *Optimization model is objective* - Solution found after goals and constraints are set is objective.
- Solutions have been obtained for each of the major estuaries of the State and are available in an appendix to the TPWD verification reports.

Weaknesses of the State Methodology include:

- *Commercial harvest data subject to numerous sources of error and are affected by factors having no relation to abundance* - Fishing effort, reporting of catch, and other issues affect accuracy of reported harvest can undermine the use of harvest as a representation of abundance. Moreover, harvest may not have occurred in the system where it was sold at dockside.
- *Low predictive ability of harvest/abundance equations* - Predictive ability of harvest/abundance equations is low, although this is not surprising due to the complexity of the ecological relationships between flow and harvest/abundance.
- *Species may not fully represent estuarine ecology* - Initial applications of the State Methodology focused exclusively on commercial species (mainly because harvest data records provided the only sufficient record of species information). As extended periods of TPWD fisheries independent data became available, more recent applications have included one or two species of ecological, but not commercial, significance.
- *Solution implies that flows must always be met* - While the goal of determining flows to meet targets is met by the State Methodology, the solution calls for the flows to always to be met. That is, there is no attainment strategy, such as a statistical frequency of occurrence. Moreover, the *maxH* and *minQ* patterns do not occur, even approximately, in the historical inflow record to the estuary.

- *Does not address low flow needs explicitly*. This is because low flows do not arise as optimum solutions as long as there is a biological constraint, or biology is the objective function.
- *Does not provide an inflow regime consistent with the requirements of Senate Bill 3* that reflects seasonal and yearly fluctuations, including the required frequency of various inflow amounts or inflow patterns needed during very dry periods, as well as the frequency of higher inflows during wet years that help sustain a healthy bay and estuarine ecosystem
- *The optimized solution is dominated by the constraints*, e.g. that each monthly or bimonthly flow must lie between the decile and median values, which are specified without scientific defense. While constraints are a necessary and important aspect of the optimization problem specification because they ensure that the solution is realistic, when the majority of the resulting monthly flows are the constraint values, these constraints are, in effect, the answer, and therefore the basis for their specification becomes central.

4.2 SALINITY ZONE APPROACH

4.2.1 General Procedure

The salinity-zone approach assesses the suitability of the distribution of salinity within an estuary for a specific organism. By "within an estuary" is meant some measure of the geographical extent of various ranges of salinity, or even their specific geographical location(s). It therefore is a combination of salinity-preference/tolerance limits and salinity mapping, and requires data depicting both classes of information. As noted elsewhere, salinity can be important to the biological functioning of estuarine organisms, though almost by definition such estuarine organisms are also able to withstand, and even thrive in, a wide range of salinities. Nonetheless, much effort has been invested in determining the ranges of salinities for individual species that are "preferred", some of which is summarized in Longley (1994). If such an "optimum" range of salinity can be defined for an organism, then the next task is to determine the geometrical configuration of those salinities in the estuary. Typically, this is based upon field data that are displayed in a geographical format, e.g., as a distribution of isopleths of equal salinity ("isohalines"), on which the water enclosed by the isohalines corresponding to the bounds of the optimum zone is identified. This salinity-optimum region can be quantified by the area or volume enclosed between the isohalines. A more sophisticated approach is to determine how this optimum salinity zone overlays other habitat features considered to be important to the organism in question, such as water depths, bed characteristics, vegetation, or marsh habitat.

Because this approach is based upon the display and analysis of two combined sources of information, viz. salinity preference zones for the organism, and empirical patterns of salinity in the estuary, it may be considered a derivative of other analytical approaches. Its novelty is in the geographical display of the salinity information within the estuary in a form that is relevant to the organism of concern, a procedure that is greatly facilitated by the use of Geographical Information Systems (GIS) methods. This method thereby affords a means of (perhaps)

interpreting the observed abundance density of that organism in view of the salinity regime obtaining when the abundance observations were made.

The link to freshwater inflow is through its control on salinity distribution. With empirical isohaline patterns, the corresponding measurements of total inflow to the bay must be determined from hydrological and climatological data (see Section 3.1). Only those flow regimes for which salinity data exist will be represented in this analysis. A separate issue is how to extend the analysis to inflow levels for which data may not be available. If there are data-based salinity depictions for a wide range of inflows, it may be possible to infer the salinity patterns for other inflows by interpolation, extrapolation or more sophisticated regressions.

An alternative is to employ the predictions of salinity from a hydrodynamic/salinity-transport model at a specified inflow regime. This, of course, assumes that a suitably formulated and adequately validated model is available to the analyst.

A prominent example of the salinity zone approach is the "verification analysis" carried out by TPWD in which the results of the TWDB-application of the State Methodology (Section 4.1) are compared to field observations of the occurrence of representative species in the estuary. The TPWD undertakes a separate evaluation to select among the flows obtained from the State Methodology for different management goals, principally the *maxH/MaxC* and *minQ*. The TPWD "verification" procedure generally consists of:

1. Use of the simulated time series of salinity in key areas of the bay, produced by the hydrodynamic circulation model TXBLEND to choose the flow regime that produces the most favorable salinity range.

2. Application of the TPWD Coastal Fisheries data for selected species to determine the spatial distribution of abundance in the bay, and its association with salinity distribution.

3. Application of the simulated salinity distributions from TXBLEND to examine the areas enclosed with the preferential salinity range for an organism, those flow regimes with maximal areas being considered preferable.

Other conditions specific to the individual estuaries, such as instances of oyster disease, increased predation by marine organisms, and marsh inundation, may be invoked as further ecological and scientific lines of evidence in support of the selection of inflow regime options.

TPWD performs a GIS-based analysis to evaluate the association of average abundance of various species with average field measurements of salinity, then uses TxBLEND-modeled salinity distributions under *minQ* and *maxH*/*maxC* inflow scenarios to determine how the acceptable salinity zones from the abundance analysis compare to model projections. An example of the GIS-based analysis of abundance-salinity association for two species in Galveston Bay is shown in Figure 4.2-1. Though the period of years over which the average abundances and salinities are computed is the same (1982-93), the ranges of months differ, so the isohaline distributions are different. Figure 4.2-2 shows the GIS-determined observed salinity

distribution and TxBLEND model results for Sabine Lake, on which is superimposed the distribution of various marsh habitat types.

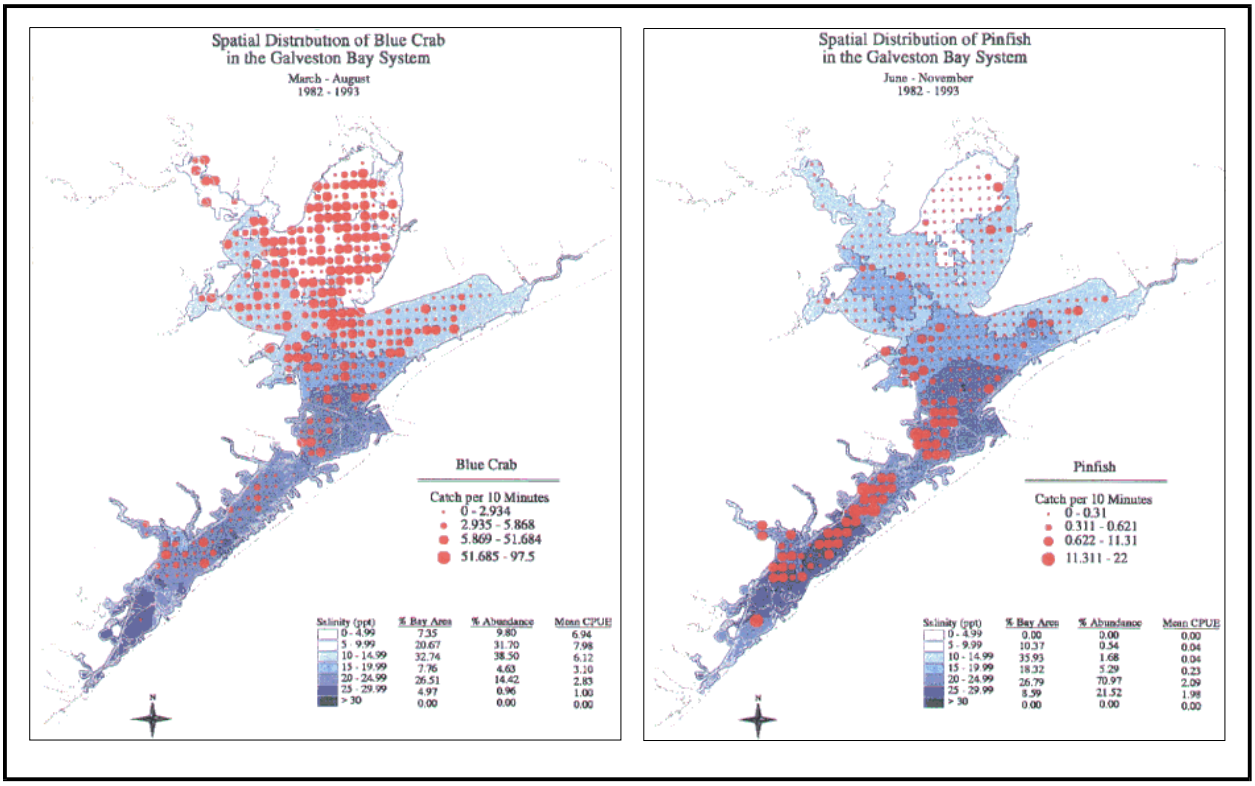

Figure 4.2-1 Abundance of Blue Crab and Pinfish in Galveston Bay Superposed on Averaged Salinity Distribution

With respect to the diagram in Figure 2.1-2, the salinity-zone approach is based entirely upon the relation inflow → salinity → biology, in which a desirable salinity zone is based upon the occurrence (or preference or tolerance) range of a key species, and this salinity zone is characterized by its area of occurrence within the estuary. The management goal is derived from the identification of the target species, and literature and/or experimental determination of the salinity range occupied by that species. In the case of the TPWD verification analysis, only the optimum solutions *maxH/maxC* and *minQ* of the State Methodology are addressed (which, as noted in Section 4.1, are presented without recommended statistics of attainment). Because these optimum flow patterns do not occur in the historical hydrology, it is not clear how an attainment statistic can be prescribed.

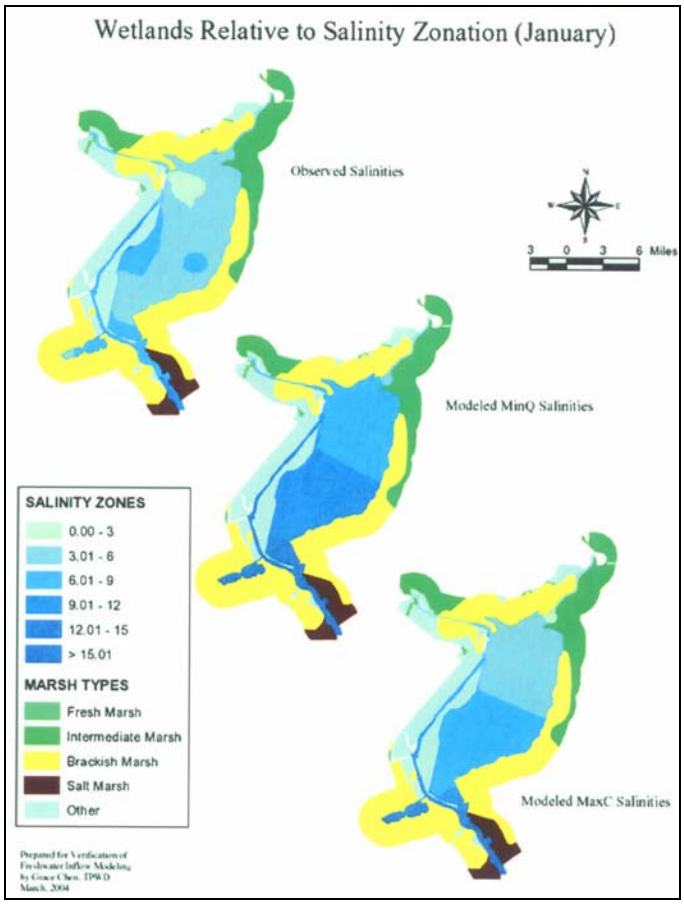

Figure 4.2-2 Observed Mean Salinity and TxBLEND-Predicted Salinity Zones Compared to Locations of Marsh Habitat Areas
(from Sabine Lake TPWD Verification Analysis)

4.2.2 Strengths and weaknesses

Strengths of the salinity zone approach:

- Provides quantitative measure of the extent of the desirable salinity range within the estuary.
- Is not as sensitive to minor variations in inflow and associated isohaline locations
- Allows capability to combine salinity zone with other geographical features of the estuary, e.g. shallow-water zones, marshes, etc.
- Affords graphic display capability to easily communicate results

Weaknesses of the salinity zone approach:

- Extremes of flow may not be well represented in either the data or model results to supply meaningful statistical evaluations.

- Is dependent upon the accuracy with which isohaline patterns may be delineated.
- In the case of the TPWD verification analysis, is based upon TxBLEND-generated isohalines, which is not yet a well-validated model. (Note that the calibration results support the use of TxBLEND for this purpose, validation of the model is in progress, and that other models could equally well be used.)

4.3 HYDROLOGY-BASED APPROACHES

4.3.1 Hydrology-Based Environmental Flow Regime (HEFR) Method

The Hydrology-Based Environmental Flow Regime (HEFR) method is a new, relatively flexible computational approach for developing a flow regime matrix that is consistent with the Texas Instream Flow Program in the sense that it identifies multiple flow regime components and hydrologic conditions across different months, seasons, or years. Presented herein is a brief summary of HEFR. Additional details can be found in SAC (2009a).

The primary goal of HEFR is to identify a reasonable schedule of flow components that are adequate to protect a sound ecological environment. For instream applications, this is largely predicated on identifying important flow components (e.g., subsistence flows, baseflows, high flow pulses, and overbank events), understanding the ecological roles provided by those components (e.g., high flow pulses may provide spawning cues; see also §2.2 of SAC (2009a) and Table 1 of Richter et al. (2006)), and quantifying reasonable facsimiles of those historically-observed components for inclusion in an environmental flow matrix recommendation. For an application of HEFR to bays and estuaries, analogous flow components, with associated ecological roles, have to be identified. Depending on those components and roles, it is possible that a careful selection of HEFR parameters could generate meaningful results[4]. It is also possible that additional flexibility would have to be coded into HEFR to provide the appropriate flow components and characteristics.

With respect to the diagram in Figure 2.1-2, only the inflow component is considered in HEFR. This therefore represents the "default" state of the process to be employed only when there is no base of information on either the habitat features of the ecosystem, or its biology (see Section 2.5).

4.3.1.1 General Procedure

HEFR is based solely upon hydrologic data and computes simple summary statistics of individual flow regime components. HEFR begins with the selection of a flow gage and a period of record. The next step in HEFR is to separate the hydrograph into appropriate flow components (based on identified ecological roles of the components). HEFR offers two options to separate the daily hydrograph, the IHA and MBFIT, discussed in detail in SAC (2009a). This parsing results in each day of the hydrograph being classified as one of up to five flow regime

[4] Recent modifications to HEFR, including increased seasonal flexibility, alternative calculation methodologies for hydrographic separation and episodic events, and flexible percentile assignments, have greatly increased the flexibility of HEFR. These recent enhancements to the HEFR program are described in the Instream Flow SAC report (2009a) dated April 20, 2009.

components that correspond generally to the TIFP regime protocols (TCEQ et al., 2008), an example of which is shown in Figure 4.3-1. We note that in the instream environment the individual storm hydrographs are considered to be important, whereas in the estuary environment there is considerable integration, both in the inflow signal and in the response of estuary condition (e.g., salinity) and biology. Therefore, it is not clear that the specific storm events have an ecological significance in the estuary comparable to their role in the stream.

While HEFR was originally conceived as a tool to develop instream flow recommendations, it could also be appropriate for freshwater inflows to estuaries. For application to an estuary, a daily flow record is required for inflows to the estuary. Such a record can be created from the daily data at the lowest USGS gages on each of the principal inflowing rivers, which can be further augmented by TxRR output for ungaged areas. As summarized in Section 3.1, TxRR results are available from TWDB at a daily resolution for recent simulation periods, and monthly back to around 1941 (in some cases earlier). (Diversion and return flow data generally are monthly only, but typically these do not vary appreciably from day to day, so they could be added as a daily rate computed from the monthly values.)

As an example of this kind of application, a provisional HEFR application was made to the total inflow record for San Antonio Bay, in which the sum of the daily gaged flows of the San Antonio (Goliad) and Guadalupe (Victoria), the summed TxRR daily runoff simulations for ungaged areas, and the net return flows – diversions (converted to a daily rate from monthly data) for the period 1977-2005. For this case study, the HEFR algorithms were run with the IHA hydrograph separation program, using the default values listed in Appendix A of SAC (2009a), except that the winter season was specified to start in January. This change allowed the wet spring months of April, May, and June to be grouped together into one season. Also for this case study, no attempt was made to identify estuary-specific flow components or ecological roles, as would be necessary in a more formal HEFR simulation in an estuarine context. The resulting HEFR matrix is shown in Figure 4.3-2.

While the San Antonio Bay case study presents some graphical comparisons of results from the State Methodology and from the HEFR-based approach for developing instream flow recommendations, it is not considered to be a comprehensive presentation of this subject nor a full demonstration of how HEFR might be applied to assess freshwater inflow requirements for an estuary. Still, there is information that may prove to be useful not only with regard to reconciling differences in riverine instream flow recommendations and estuarine freshwater inflow recommendations, but also possibly with establishing a common approach for developing estimates for both types of aquatic systems within the timeframe of Senate Bill 3.

4.3.1.2 Strengths and Weaknesses

Strengths of HEFR include:

- Hydrologic data are relatively robust and consistent at multiple locations, compared to other potential datasets. HEFR shares this strength with other hydrologic methods.

- Hydrology has been considered the master variable in regards to environmental instream flows and may also be considered a very important variable with regards to estuarine inflows. HEFR shares this strength with other hydrologic methods.
- HEFR is computationally efficient, allowing for repeated tests and exploratory analyses.
- There is significant flexibility in setting parameters to parse the hydrograph as well as summary statistics of the flow regime components.
- HEFR outputs have the same format as expected results from the TIFP studies.
- HEFR provides an initial set of recommendations that reflect key aspects of the natural flow regime including multiple flow components and hydrologic conditions (Poff et al., 1997).

Weaknesses of HEFR include:

- HEFR is largely designed to mirror some fraction of historical hydrology and is not based on a defined flow alteration - ecological response relationship. In a similar vein, HEFR has not been validated against biological, geomorphological, and water quality data. HEFR shares this weakness with other hydrologic methods.
- HEFR is not suitable where hydrologic data are lacking and cannot be synthesized. HEFR shares this weakness with other hydrologic methods.
- There is no track record of application of HEFR, especially in an estuary setting, and there are few precedents for some of the decisions that must be made.
- HEFR would not provide useful results in minor bays or lagoons with little inflow.

Overbank Flows	Return Period (R) : 2.7 (years)		Duration (D) : 49 (days)	
	Volume (V) : 1743452 (ac-ft)		Peak Flow (Q) : 30000 (cfs)	
High Flow Pulses	F: 0	F: 0	F: 0	F: 0
	D: 18	D: 22	D: 17	D: 12
	Q: 14125	Q: 15550	Q: 11825	Q: 8570
	V: 352171	V: 433473	V: 278202	V: 90605
	F: 1	F: 1	F: 1	F: 1
	D: 11	D: 14	D: 9	D: 9
	Q: 10500	Q: 10500	Q: 8850	Q: 3700
	V: 148305	V: 233782	V: 89449	V: 52621
	F: 2	F: 1	F: 1	F: 1
	D: 7	D: 7	D: 6	D: 6
	Q: 4903	Q: 8735	Q: 3630	Q: 2373
	V: 57962	V: 93710	V: 36786	V: 22191
Base Flows (cfs)	4910	5700	2110	1839
	2350	3670	1839	1839
	1839	2258	1839	1839
Subsistence Flows (cfs)	1839	1839	1839	1839
	Dec | Jan | Feb	Mar | Apr | May	Jun | Jul | Aug	Sep | Oct | Nov
	Winter	Spring	Summer	Fall

Hydrologic Conditions	
	Wet (75th %ile)
	Average (50th %ile)
	Dry (25th %ile)
	Subsistence

High Flow Pulse Characteristics	
	F = Frequency (per season)
	D = Duration (days)
	Q = Peak Flows (cfs)
	V = Volume (ac-ft)

Figure 4.3-1 Example Flow Regime Matrix for the Neches River at Evadale

Overbank Flows	Return Period (R) : 2.3 (years)		Duration (D) : 23 (days)	
	Volume (V) : 489751 (ac-ft)		Peak Flow (Q) : 40790 (cfs)	
High Flow Pulses	F: 1	F: 1	F: 1	F: 1
	D: 8	D: 8	D: 7	D: 7
	Q: 8207	Q: 8071	Q: 6641	Q: 7314
	V: 70612	V: 59571	V: 54290	V: 53442
	F: 2	F: 2	F: 2	F: 2
	D: 6	D: 5	D: 5	D: 5
	Q: 4747	Q: 4009	Q: 3840	Q: 4709
	V: 35030	V: 30924	V: 30742	V: 31776
	F: 3	F: 3	F: 3	F: 4
	D: 4	D: 4	D: 3	D: 3
	Q: 3296	Q: 3280	Q: 2207	Q: 3205
	V: 18124	V: 18058	V: 13000	V: 13893
Base Flows (cfs)	1964	1953	1816	1756
	1477	1353	1170	1257
	1080	1056	858	873
Subsistence Flows (cfs)	827	827	827	827
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Hydrologic Conditions	
	Wet (75th %ile)
	Average (50th %ile)
	Dry (25th %ile)
	Subsistence

High Flow Pulse Characteristics	
	F = Frequency (per season)
	D = Duration (days)
	Q = Peak Flows (cfs)
	V = Volume (ac-ft)

Figure 4.3-2 Example Flow Regime Matrix for Total Inflows to San Antonio Bay

4.3.2 NWF Inflow Pattern Approach

The National Wildlife Federation has developed a method called an "inflow pattern" approach for establishing some portions of an estuarine inflow regime. While it is generally acknowledged that freshwater inflows to an estuary play the important roles of governing salinity and delivery of sediments and nutrients (e.g. Ward and Montague 1996), the NWF approach focuses on specific naturally-occurring inflow patterns that appear to be important for the estuary. This concept is not unique to the NWF inflow pattern approach, as it also provides the framework for the "freshet" definitions that are utilized in the LCRA-SAWS Inflow Criteria Method (see Section 4.4.2).

Although the inflow pattern approach is primarily hydrologic, utilizing the historic or "natural" inflow record[5], it also relies on physical, biologic, and chemical (salinity or nutrient) lines of evidence, to the extent such information is available, to identify key inflow events which support key ecosystem functions. An explicit goal of the inflow pattern approach is to maintain the timing, magnitude, duration, and frequency of these key inflow events within some reasonable range of departure from their historical or natural occurrence levels.

[5] The historic record can be used unless there is evidence that watershed alterations have been large enough such that the timing, magnitude, duration, or frequency of certain key inflow events has been seriously modified. In such a case, either a pre-development portion of the historic record, if of sufficient duration, or synthesized inflow record such as the naturalized flows associated with the Texas water availability models can be used as the starting point for the analysis.

The inflow pattern approach is an estuarine application of the "natural flow paradigm" originally developed for stream and river settings (Poff et al. 1997). This paradigm is focused on maintaining reproductive and other biologic processes for fish, invertebrates, and other organisms that are heavily influenced by naturally-occurring seasonal patterns of flow[6]. Although the derivation and application of the natural flow paradigm is rooted in river and stream settings, with limited application to estuaries (e.g. Mattson 2002), there are also strong indications of the ecological importance of certain reoccurring inflow patterns for Texas estuaries. For instance, several studies have found positive correlations between the abundance of several shellfish and fish species and higher inflows in the spring to early summer (LCRA et al. 2006, TPWD and TWDB 2002). Another common Texas freshwater inflow pattern is a low flow period in the summer to early fall which can have deleterious effects on oysters. Oyster predators and diseases are amplified due to the coincidence of these high salinity periods with higher summer water temperature (see Cake 1983 for a summary). Thus, the underpinning of this approach is that there are important, identifiable features of the natural flow regime, including intra-annual and year to year variability, which are essential for ecosystem processes.

Also noteworthy, the term "natural" as used in this connotation does not imply that maintaining fully natural flows is the goal. Rather, it indicates that natural patterns, with regard to the timing, frequency, duration, and magnitude of key events should be maintained within some reasonable degree of departure.

As illustrated in Figure 4.3-3, the inflow pattern approach involves three-steps to identify certain key seasonal patterns of inflow to Texas estuaries that may comprise some portion of an overall estuarine inflow regime.

First, key inflow patterns (or events) which hold particular ecological relevance are identified through a combination of hydrological, biological, and/or chemical lines of evidence. Second, after these key patterns are identified at a general level, it is necessary to detail a specific criterion through a combination of some or all of the following attributes: inflow timing, inflow volume, event frequency, event duration. Not all of these attributes will be necessarily appropriate for the various criteria that may comprise an overall estuary inflow regime. For example, a very low inflow, analogous to the subsistence flow value in the SAC's Instream Flow document (SAC, 2009a), may be focused on maintaining salinity at some tolerable level in a limited area to serve as a refuge for key species. Thus, it will have a volume and frequency of occurrence specified, and perhaps a maximum duration, but likely will not have specific seasonal attributes. Similarly, an extremely high inflow, which could be important for sediment transport and marsh and delta maintenance, may be a short-duration, low-frequency event focused on flow rate that can occur at anytime of the year. Other portions of the inflow pattern may have more constrained timing (season) and volume attributes, such as a spring inflow pulse as discussed below.

[6] This was termed "biological relevance" by Richter et al. (1996) and "ecologically relevant" by Richter et al. (1997) with regard to the natural flow paradigm for river and stream settings.

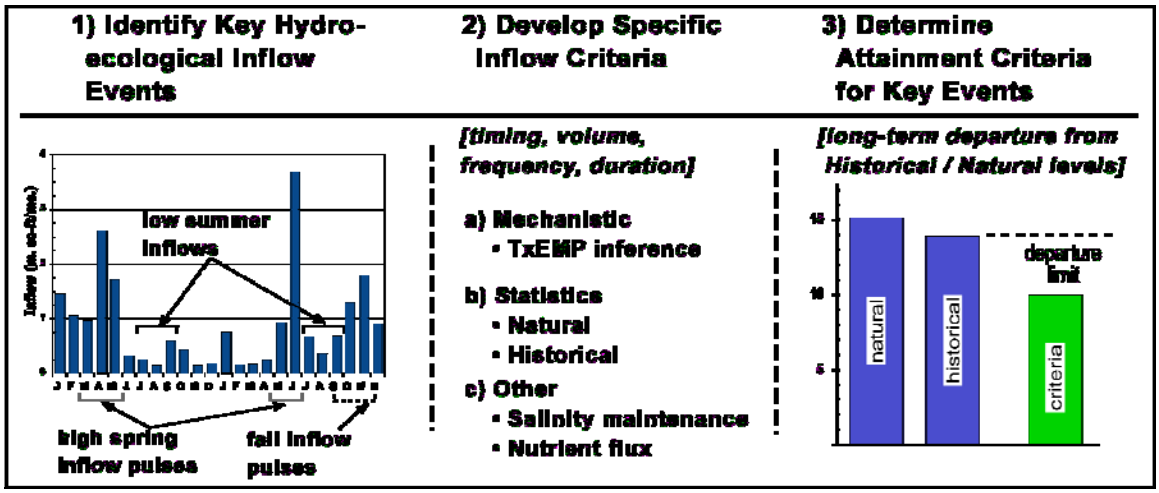

Figure 4.3-3 NWF's Method for Assessing Freshwater Inflows to Texas Estuaries

(Note: The inflow sequence shown in the left panel represents a possible pattern of inflow to Texas' estuaries.)

Choosing the specific values of these attributes may rely upon several types of information as shown in the middle panel of Figure 4.3-3. For instance, a criterion aimed at addressing the needs of a low or low-base level inflow, analogous to the dry period base flow in the SAC's Instream Flow document (SAC, 2009a), could utilize purely statistical values, such as the 25th percentile of historic or natural inflow for some or all of the months. By comparison, a criterion aimed at addressing higher seasonal inflow pulses which have apparent ecological significance may be ascribed a timing and volume based on other more "mechanistic" information such as productivity-inflow relations or peak abundance characteristics of key species.

In the third step of the inflow pattern approach, the target for future occurrence for each criterion must be chosen. A typical approach would be to determine the attributes, such as volume, frequency and duration, under historical or natural conditions and then, using a combination of scientific evidence and professional judgment, determine an allowable departure that will still maintain the intended ecosystem function.

4.3.2.2 Strengths and Weaknesses

Strengths of inflow pattern approach include:

- Method focuses on maintaining characteristics of the estuary natural inflow regime.
- Can accommodate several criteria, each based on an ecologically-relevant inflow pattern.
- Criteria can be based on variety of inflow metrics. Examples include: inflow percentiles from historical or natural record, inflows to maintain a target salinity; inflows linked to productivity levels of select species or communities.

Weaknesses of inflow pattern approach include:

- Requires specification of inflow patterns with apparent important roles in the estuary. May be hindered by lack of data or inability to link ecosystem functions to inflow.
- Requires specification of an acceptable change in key inflow events as measured by one or more of the attributes: volume, timing, frequency, duration.

4.3.3 Percent of Flow Approach

The percent of flow approach was developed in Florida. Florida defines the need for inflows broadly as "the limit at which further withdrawals would be significantly harmful to the water resources or ecology of the area." Florida is divided into five Water Management Districts, which were established in 1972. The result is that freshwater inflow studies and rules are unique to each estuary, and the different Florida water management districts have adopted different strategies for regulating freshwater flows in response to different intensities of human engineering and societal expectations of water management (e.g. flood control versus water supply). For example, for the rivers and streams draining into Tampa Bay, the withdrawal is limited to a percent of streamflow at the time of withdrawal (Flannery et al. 2002).

The percent of flow approach is similar to the hydrological approach. In Florida, the approach is based on the assumption that the natural flow regime is considered the baseline for assessing effects of withdrawal. Because the biological response to altered flow is often nonlinear, the environment is protected during low inflow periods by taking a small percent of the volume. Although the rule is based on percent of flow, identifying the value follows a familiar course of action: first key species are identified, then regressions are performed between species abundance and flow rates to determine the natural range, then a percent reduction value is chosen. The choice depends on expert opinion and can be arbitrary.

There is no reason to think that there is one magic number or that any given methodology would lead to similar percent flow values in different ecosystems. For example, the TxEMP solutions using the State Methodology (Table A-4) yield a variety of different percent flow solutions (Figure 4.3-4). The flow recommendations range from 10% of annual flow for *MinQSal* in Aransas Bay to 90% for *MaxH* in Galveston Bay.

4.3.3.1 Strengths and Weaknesses

Strengths of percent of flow approach include:

- It is quick and simple because the flow data are readily available on the TWDB website and the statistical summary calculations are routine.
- It is intuitive that the change in the environment is proportional to inflow reductions.
- Choosing a percent number is a democratic governance process that relies on best expert opinion, collaboration, cooperation, and negotiation among stakeholders.

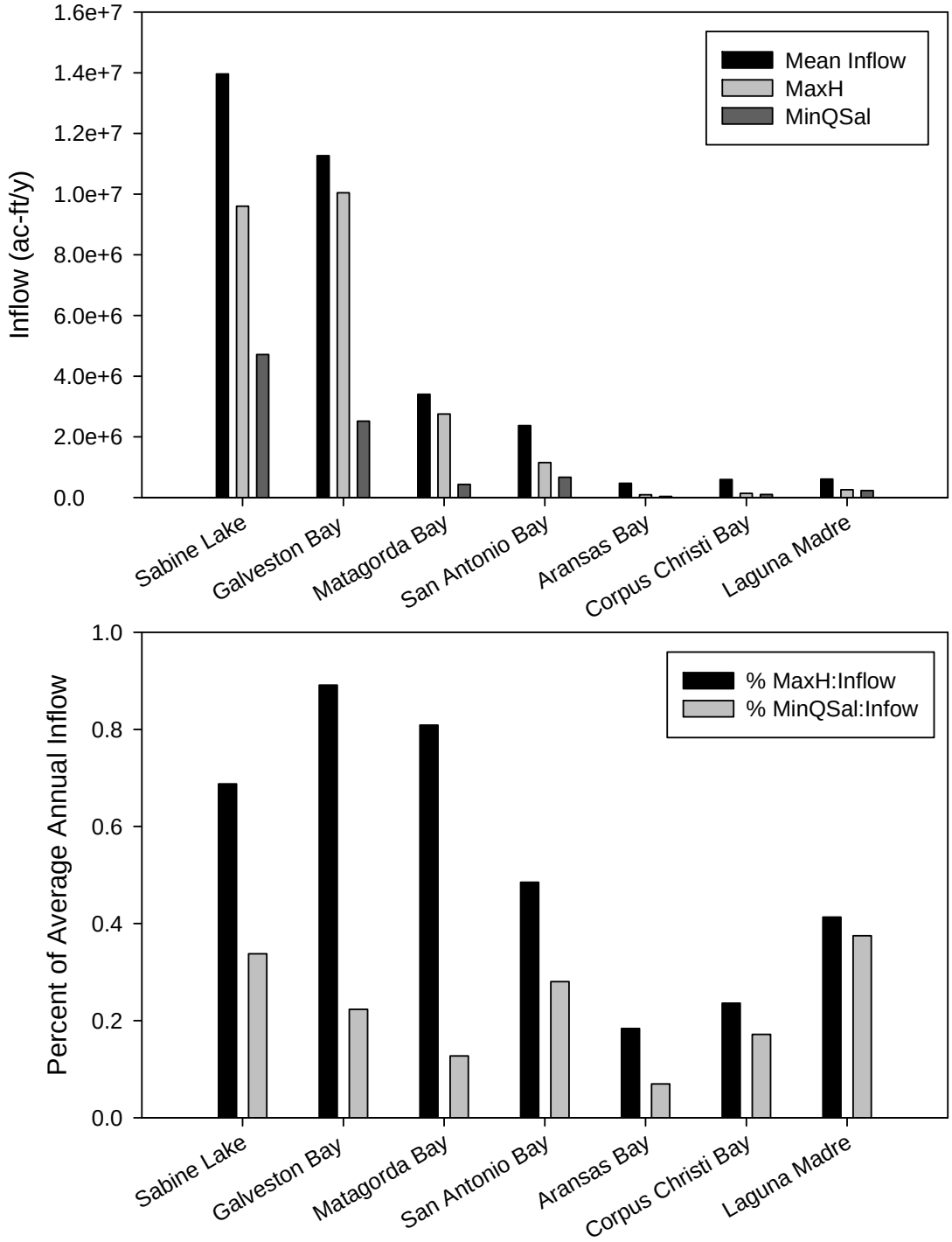

Figure 4.3-4 Inflow Solutions Using TxEMP (Table A-4) Relative to Average Annual Inflow Volumes (top) and as a Percent of Flow (bottom)

- It shares characteristics of the hydrology-based approach, but the human decisions are more transparent in the outcome, because the number comes through stakeholder deliberation, not a model.
- It is easy to create a metric (e.g., salinity or a population abundance) to monitor and use in an adaptive management process.
- Outcome provides a regime in that natural conditions are simply proportionally reduced.
- Allows more water to be diverted during floods if the percent values vary with flow rates.

Weaknesses of the percent of flow approach include:

- It is easy to pick a percent number that is arbitrary.
- The relationships between flow, environmental condition, and biotic responses are not linear. Yet, the assumption of linearity is fundamental to the percent of flow approach. Since the reduction of flow is arbitrary, it may in fact have an excessive impact on the estuary, or it may limit diversions from the rivers when such diversions might be ecologically acceptable.
- It is an empirical approach based on hydrological data (but some argue this is actually a strength).
- It completely avoids the question of the quantitative impact of flow reduction on biology. Moreover, even though the effect of such a reduction may be "monitored", it's not apparent what actions might be taken if these impacts prove excessive.

4.4 OTHER CANDIDATE METHODS

While the emphasis in this section is on methods that have some record of application or relevance to the bays and estuaries of Texas, there are several recent approaches that warrant mention, and are briefly summarized here.

4.4.1 Nature Conservancy (IHA/EFC) Method

The Index of Hydrologic Alteration (IHA) method was proposed by Richter et al. (1996), staff members of The Nature Conservancy (TNC) and its contractors, and is the basis for a software product, the IHA Program. The purpose of the IHA method is to quantify the alterations in the stream regime, generally but not necessarily resulting from human activities, especially for use in appraising predicted modifications due to proposed projects. Changes in the numerical values of the indices are proposed as a metric for evaluating the resulting impact to the hydrological regime, hence to the stream ecosystem. The IHA indices are more useful as an impact evaluator than a means for estimating environmental flows.

In its latest version (TNC, 2007), the IHA software product includes an evaluation of "Environmental Flows Components (EFC)". The evolution of this capability of the IHA is summarized by Mathews and Richter (2007). The fundamental tenet of the method is that the stream ecosystem is dependent upon a "regime," by which is meant a suite of statistics that

quantify components of variability in streamflow, the occurrence of many of which is seasonal. The EFC part of the program works with a record of daily flows and first sorts these data into categories, which we refer to here as "pulse" and "non-pulse" (to avoid the confusing terminology of TNC). The sorted data record is then used to compute statistics of five categories of flow or flow event, listed below. :

Large floods (event)	Large, rare pulse events (return interval greater than 10 years)
Small floods (event)	Infrequent, moderate pulse events
High-flow pulses (event)	Frequent pulse events (return interval < 2 years)
Low flows	monthly central value of flows exceeding the lowest decile non-pulse flows
Extreme low-flow (event)	time series of flows that never exceed the lowest decile non-pulse flows

The procedure for "parsing" the daily flow time series into these five classifications is depicted in Figure 4.4-1. In both the figure and the listing above, it is emphasized that four categories of hydrological "events" are separated in the daily-flow time series, *viz*. three "flood" events, and the "extreme low-flow" event. The remainder of the daily-flow data is categorized as "low flow" and monthly central measures (i.e., means or medians) are computed to characterize the annual pattern of flows. The events are parameterized by intensity, duration and date of initiation, and, in the case of the flood events, probability of occurrence (as measured by a return interval).

The IHA Program has become increasingly popular as a means of quantifying environmental flow components, especially when stream condition and biological data are lacking. In particular, it is one of the options available in the HEFR method (see Section 4.3.1 above, and citations therein).

While no instance could be found in which this EFC method has been applied to a large lagoonal estuary typical of the Texas bays, in principle this could be carried out (cf. Appendix B). The only requirement is that the total inflow to the estuary has to be specified as a daily time series. Certainly, the gauged components of the inflowing rivers are compiled as daily time series (see Section 3.1), and for many of the estuaries daily TxRR output is available back to the late 1970's. The advantages attending such an application would be that it is straightforward, exploits software that is freely distributed, well-supported and has modest platform requirements, and would represent a generalization of a procedure that has already engendered considerable employment in the riverine environment. The chief disadvantages are (1) the mechanisms invoked to justify the ecological significance of the environmental flow components in a riverine setting do not readily translate into the estuarine environment, (2) because of the long integration of the inflow signal in the responses of the estuary, it is not at all clear that the same process of identification of the flow events is meaningful, and (3) even if one can argue that the EFC "events" are ecologically significant to the estuary, the method does not quantify a relation between these events and some measure of ecological productivity.

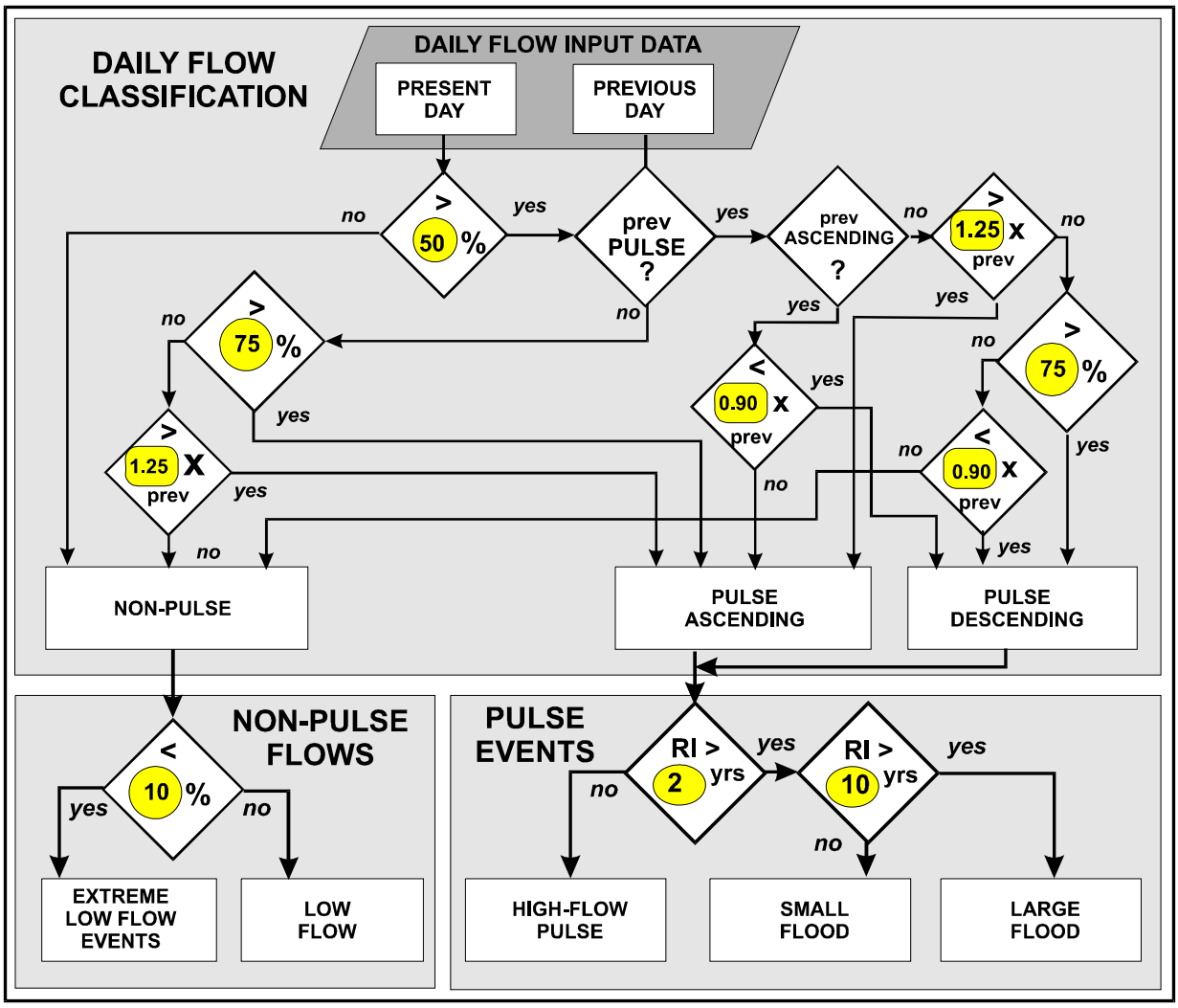

Figure 4.4-1 Flow Diagram Illustrating the Processing Strategy for Separating Flow Record into Environmental Flow Components

4.4.2 LCRA-SAWS Inflow Criteria Method

To support the proposed LCRA-SAWS Water Project (LSWP), studies of Matagorda Bay (often referred to as the Matagorda Bay Health Evaluation (MBHE)) entailed development of substantial modeling and data analysis, which was employed to assess the relationship between causative factors and resulting bay condition. Several measures of bay condition were investigated, including salinity, habitat condition, species abundance, nutrient supply, and benthic condition. These various models and data analyses were used to establish a suite of recommended Matagorda Bay Inflow Criteria for the Colorado River, which, if achieved in the future, should be protective of bay health and productivity. The full development of the inflow criteria is reported in MBHE 2008.

The principle MBHE models employed to develop the criteria are the salinity, habitat, oyster, and benthic modeling for most inflow levels, and the nutrient modeling and data analyses for the long-term flow component. While extensive biostatistical analyses relating species abundance to freshwater inflow was conducted as part of the MBHE, these results were not used directly in the development of inflow criteria. These analyses were useful in testing the inflow recommendations against historical biological data, and confirmed that the recommendations fell within the bounds of previously observed data.

An initial objective was that the inflow criteria needed to be comprehensive and cover the full flow spectrum from very low flows (near drought-of-record conditions), in which species refuge becomes of primary importance, to higher flow events sufficient to provide adequate nutrient supply to the bay system. The MBHE freshwater inflow categories and specific criteria, as summarized in Table 4.4-1, include a wide range of inflow conditions with the goal of providing the essential components to maintain the health and productivity of Matagorda Bay.

The techniques to develop specific components of the inflow criteria suite focused on appropriate "Design Areas" where different MBHE modeling and data analysis tools were applied (see Figure 4.4-2). These areas ranged from the substantial and important Delta area being formed at the mouth of the Colorado diversion channel, which was used to assess very low flow conditions, to the upper half of the Eastern Arm of Matagorda Bay (EAMB) for the inflow regime portion, and finally, to the entire EAMB for higher flow conditions. In essence, these design areas represent appropriate geographic areas in the bay in which desired conditions (often expressed as salinity ranges) can be related to inflow from the Colorado River using the MBHE models.

Table 4.4-1 MBHE Freshwater Inflow Categories and Specific Criteria

Inflow Category	Inflow Criteria	Description
LONG-TERM	Long-term Average Volume and Variability	provide adequate bay food supply to maintain the essential food supply and existing primary productivity of the bay system
MBHE INFLOW REGIME	MBHE 4	provide inflow variability and support high levels of primarily productivity, and high quality oyster reef health, benthic condition, low estuarine marsh, and shellfish and forage fish habitat.
	MBHE 3	provide inflow variability and support quality oyster reef health, benthic condition, low estuarine marsh, and shellfish and forage fish habitat.
	MBHE 2	provide inflow variability and sustain oyster reef health, benthic condition, low estuarine marsh, and shellfish and forage fish habitat
	MBHE 1	maintain tolerable oyster reef health, benthic character, and habitat conditions
MINIMUM	Threshold	refuge conditions for all species and habitats

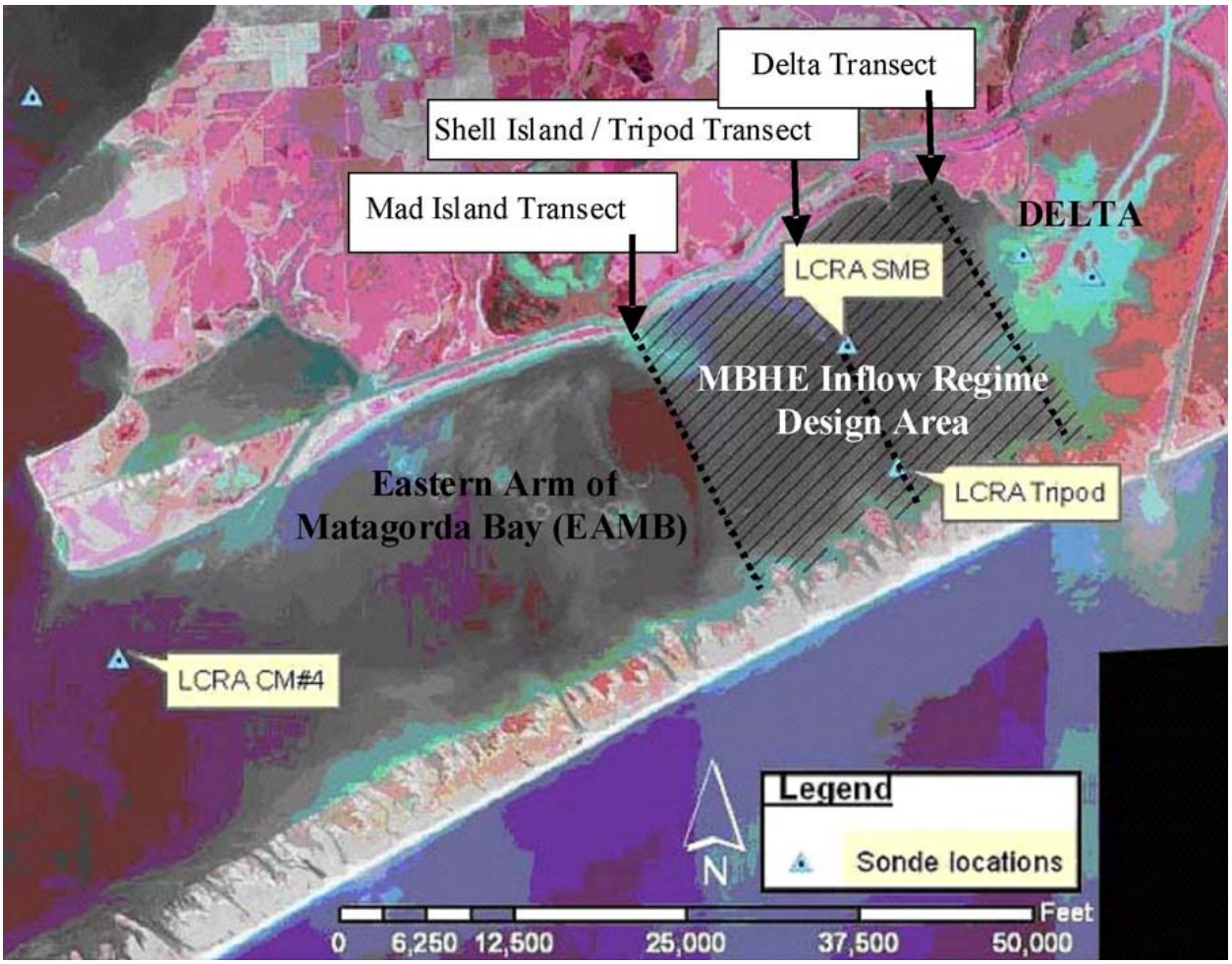

Figure 4.4-2 Design Areas Used in LSWP Matagorda Bay Health Evaluation

Habitat modeling was utilized to provide relationships between the Weighted Useable Area for several key species and salinity as reported in MBHE 2007. Oyster and Dermo modeling, also described in this report, was utilized particularly in the development of low flow recommendations. Nutrient modeling was also performed using the EPA WASP model to determine the relationship between freshwater inflow, nutrient loading, and primary productivity, as measured by chlorophyll-*a*. Finally, salinity condition related to benthic populations was also investigated to set salinity targets for each of the inflow criteria level. The levels in the inflow criteria suite can be described as follows:

Long-term Average Volume and Variability Criteria. An essential element of the criteria is the need to maintain the flow amounts and patterns that provide a major source of food to support the health and productivity of the estuary and maintain phytoplankton primary production. An important and widely used measure of this primary production is the concentration of phytoplankton chlorophyll-*a* in the water column. Both field data and modeling have confirmed a functional relation between the concentration of chlorophyll-*a* in the EAMB and the amount of inorganic N carried by river inflows. Inflows carrying inorganic N as well as organic matter are important drivers of the ambient level of

chlorophyll-*a* and primary productivity in the EAMB, particularly under higher flow conditions, since a large portion of the nitrogen and organic matter loads are conveyed to the EAMB during higher flow events. Maintaining these flow pulses, an important part of the variability, is thus essential to meeting the historical long-term average level of primary productivity.

MBHE Inflow Regime Criteria. The MBHE 1-4 criteria involve an inflow regime aimed at maintaining the health and productivity of Matagorda Bay.

MBHE 4 criteria are recommended to bridge the gap between long-term volume and variability and MBHE 3. MBHE 4 criteria allow for a high level of primary productivity and when implemented in concert with the other MBHE criteria, enhance the intra-annual variability so valuable to estuarine systems. MBHE 4 criteria would likely take place during average climatic conditions. The reference to climatic conditions just represents conditions that would likely cause salinity ranges associated with these criteria, not operational triggers. The goal for the MBHE 4 criteria is to maintain high quality conditions for oyster health, benthic habitat, low estuarine marsh, and shellfish and forage fish habitat throughout the entire upper EAMB Design Area. This in turn will provide near optimal conditions for all trophic levels within the delta. This spatial expansion of high quality habitat and added inflow variability to the system will assist in maintaining the health and productivity of Matagorda Bay.

MBHE 3 is recommended to support intra-annual variation in the inflow regime. MBHE 3 criteria would likely take place during somewhat below average climatic conditions with the reference to climatic conditions representing conditions that would likely cause salinity ranges associated with these criteria, not operational triggers. The goal for MBHE 3 is to maintain higher quality conditions for oyster health, benthic habitat, low estuarine marsh, and shellfish and forage fish habitat than the lower two MBHE criteria. This spatial expansion of higher quality habitat and added inflow variability to the system will strengthen the MBHE inflow regime.

MBHE 2 is also recommended to provide intra-annual variation and would likely take place during dry but not extreme climate conditions. Again, this just represents conditions that would likely cause salinity ranges associated with this criteria, not operational triggers. The goal for MBHE 2 is to sustain conditions of oyster health, benthic condition, marsh productivity, and shellfish and forage fish habitat. During these relatively dry conditions, the mid-bay region would experience lower quality ecological conditions for each trophic level. Depending on inflows from the Lavaca Basin, it is also likely that during these conditions the reefs, benthic habitat, low estuarine marsh, and shellfish and forage fish habitat would be largely reduced further west into the Matagorda Bay system. These low inflow and higher salinity conditions have been experienced in the past and will no doubt be experienced in the future, and, as previously noted, play an important ecological role in an estuary.

MBHE 1 embodies salinity conditions that would naturally be experienced during fairly extended dry conditions, though less extreme than those experienced at the Minimum

inflow category. These climatic conditions are descriptive of what it would likely take to cause the salinity ranges associated with this criteria, but do not imply operational triggers. Although the role of low flows may not always appear as beneficial based on modeling results, they do support the long-term variability to which native species have evolved. Important roles include marsh die-off, promoting native species, and promoting genetic strengthening. Marsh die-off provides organic matter input not only for nourishment of the soils for continued marsh development but also as a source of bay food. Higher salinities and other water quality parameters are extreme conditions that are observed naturally. Experiencing these natural extremes puts stress on non-native species and promotes the survival of the fittest concept within the native flora and faunal community. As discussed for the Threshold criteria below, extended low-flow periods also have negative effects that may alter the character of the bay if experienced outside the realm of historical conditions.

Threshold Criteria. Extremely low freshwater inflow conditions (i.e., at or near drought of record) do occur in natural systems. An estuary is different than a river in that a bay will not go dry with no inflow. This condition allows some level of habitat to remain, but it worsens as the bay gets saltier, warmer, has less food supply, etc. Short periods of such extreme conditions can provide benefits that include marsh die-off (source of organic matter input to the bay) and genetic strengthening (survival of the fittest). However, continued conditions can lead to excessive marsh die-off which can destabilize marsh sediments leading to erosion and overall marsh loss. Positives and negatives relative to an estuarine inflow regime are the foundation for ecological variability and the long-term health of an estuary. It is the frequency and duration of these extremely low to no inflow periods that, if extended beyond the natural tendency of the bay, can shift the ecological community to a more saline tolerant assemblage (e.g., Laguna Madre). While the Laguna Madre is considered a healthy and productive system, its condition would likely not meet the test of "maintaining the health and productivity of Matagorda Bay."

The MBHE Regime and Threshold criteria largely utilize salinity ranges as the surrogate for determining if desired habitat conditions are being achieved. Hence salinity becomes the link between freshwater inflow and biological result. In the LCRA-SAWS studies, relating bay salinity conditions to freshwater inflow was accomplished using a hydrodynamic/salinity transport model based on the U. S. Army Corps of Engineers RMA-2 and RMA-4 code. To provide a long-term simulation of bay hydrodynamics and salinity, the required input data was assembled to model the period from July 1995 through December 2003. This span of time included two extended low flow periods of 20 and 22 months, respectively, as well as a 22-month period of high flow. These results provided the underlying hydrodynamics and salinities for the habitat and nutrient modeling, as well as flow/salinity relationships. Using the long-term model output, regression equations were developed (see Figure 4.4-3) relating salinity conditions at various transects within the upper EAMB design area with flow in the lower Colorado River. In this manner, flow levels resulting in desired salinity conditions can be estimated.

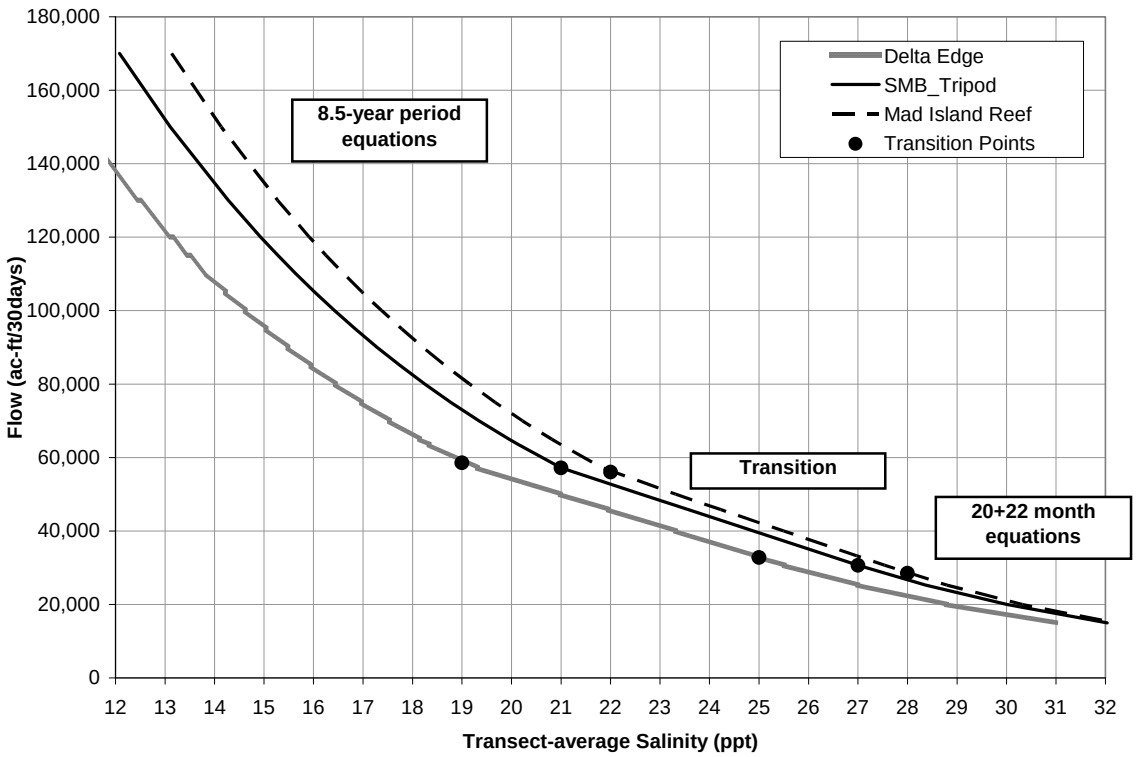

Figure 4.4-3 Salinity-Colorado River Inflow Regressions

The timing of freshwater inflow to a bay has long been acknowledged as being extremely important in maintaining the ecological productivity of the system. For ease of planning and perceived operational constraints, flow recommendation methods often adhered to a fixed calendar (e.g. monthly, quarterly, etc.). However, estuarine organisms react less to specific calendar months, but rather are considered to be responsive to pulses of nutrients, alterations in salinity, and the suitability of habitat conditions, along with many other factors, throughout their respective life cycles. In the MBHE studies, this motivated the formalization of a hydrological seasonal pulse or "freshet" and its incorporation into the inflow criteria developed for Matagorda Bay. The freshet methodology employed is more fully described in MBHE 2006. The results of the seasonal analysis was to establish a three-month "spring" pulse volume which could occur any time during the January through July period, a three-month "fall" volume between August and December, and an "intervening" volume to occur over the remaining six months, wherever they occurred. Hence, the actual numerical criteria for each of the MBHE Inflow Regime level are a set of three volumes distributed seasonally.

The final aspect of the MBHE proposed criteria is a set of achievement guidelines, expressed as desired occurrence frequencies, for each of the inflow criteria levels. For the recommended Threshold criteria, and the Long-term Volume and Variability criteria, the MBHE studies recommended a 100% achievement guideline. For the four MBHE Regime criteria, recommended frequency of occurrence were based on statistical analyses of both historical flow and salinity data, as more fully described in MBHE 2008.

Because the proposed criteria embody recommended achievement guidelines, which suggest that certain flow conditions should be maintained or exceeded a certain percentage of the time, it is necessary to utilize a forecast of future inflow conditions to determine if the criteria will be satisfied. In the LCRA-SAWS studies this was accomplished using a WAM-type model developed for the Colorado Basin. In the case of the lower Colorado, operationalizing the proposed criteria requires establishment of an operating protocol for the Colorado River system that, when superimposed on historical hydrology, yields results satisfying the full suite of inflow criteria. The MBHE team also suggested that the operations process could provide an opportunity to adjust the operating protocol when unusual conditions in the coastal inflows (substantially higher or lower than normal) exist. Adopting this type of adaptive management would provide an opportunity to both protect bay health and productivity and meet long-term water supply needs.

SECTION 5
OTHER CONSIDERATIONS

In previous sections, the focus has been on identifying the hydrology of inflow as it alters salinity habitat conditions, and how those conditions might affect biological resources. However, there are other important considerations such as: 1) estuary conditions today are a function of historical and ongoing changes, 2) inflows provide the bulk of the sediment needed to maintain shoreline habitats, and 3) inflows provide much of the nutrient supplies to the estuaries.

A sound ecological environment typically includes having inflows maintained at appropriate levels and with general temporal patterns that are supportive of existing habitats. However, it also requires that the key constituents of water quality and productivity be supplied with reasonable continuity as well. Some of the key constituents include sediments, organic matter, and nitrogen, which is the nutrient most likely to be limiting to primary productivity in Gulf Coast estuaries. The biological responses to nutrients, organic matter and sediment flowing into the bays and estuaries occur in the context of the historical changes that have taken place along the coast as human populations have increased.

As noted in Section 2, while the ideal model of the estuarine ecosystem would encompass simultaneous solutions to all the applicable relations delineating all the key variables, the fact is that this may not be feasible because: 1) the relevant variables may exert different levels of control over the ecosystem, and, therefore, vary in relative importance in different places, 2) the scientific basis for causal relationships expressed via a mathematical model may be unequal, and therefore the associated uncertainty will vary, and 3) the connections to freshwater inflow may diverge among the controlling variables. Given this complex situation, it is useful to focus a large portion of the quantitative efforts on inflow (and that is the approach taken by Senate Bill 3), specifically the effects of inflow on organism abundance, as manifested either by a direct relationship or through the intermediate variable of salinity. Nevertheless, other variables can exert a real effect on the relation between inflow and the estuarine ecosystem and should not be ignored. This modifying role of additional variables is referred to as an "overlay" for purposes of this report. In the case of Figure 2.1-2, the relationship between inflow → salinity → biology, salinity is considered the primary variable because it is related to inflow (albeit with uncertainty), and most estuarine organisms are affected by salinity, a key measure of the chemical habitat. A direct relationship between inflow and biology could supplant an indirect relation through salinity, if the data are adequate and the relation well established. The variables of nutrients and sediment, in the context of historical changes, have important but complex roles in coastal ecosystems, but the existing data base is frequently inadequate for developing statistically valid quantitative relationships that can be effectively applied in a predictive fashion. Therefore, they are addressed here as "overlays," to be employed to modify or supplement the inflow regime specifications.

5.1 HISTORICAL CHANGES

It should be recognized that all Texas bays that we know today have been modified substantially from their historical, natural condition due to agricultural practices, fishery harvests, navigation

channels, inflow pattern modifications, waste discharges, and other factors. Approximately 80% of marine pollution stems from land-based sources, so estuaries are the most susceptible to pollution effects, especially those adjacent to urban areas (Kennish 1998). Considering the length and large size of the Texas coast, there are relatively low human population sizes near the coast. Houston (about 2.2 million people in the city and 5.6 million in the metropolitan area) is the only very large city in Texas within 50 miles of the Gulf of Mexico, and Corpus Christi (about 286,000 people in the city and 414,000 in the area) and Beaumont-Port Arthur-Orange (with a combined population of about 400,000) are the only medium size cities directly on a bay. Consequently, when national assessments are performed, Texas estuaries are judged as being in relatively good condition, except for a few localized industrialized sites. For example, Texas mollusks and fish had among the lowest tissue contaminant values found during the NOAA Mussel Watch and Status and Trends national programs (Mearns et al. 1988, NOAA 1995, O'Connor 1994). Also, the recent NOAA national eutrophication survey found that the overall eutrophication condition along the Texas coast was low-moderate to moderate (Bricker et al. 2007).

Specifying an inflow regime which maintains a sound ecological environment is the key requirement for environmental flow recommendations under Senate Bill 3. A reasonable management goal is to maintain the modified, but still sound ecological environment that has evolved for each bay system, and this requires consideration of multiple sources and processes. These include:

- Changes in water exchange with the Gulf, as affected by deeper navigation channels, inlet modifications, and relative sea level rise,
- Changes in the level of commercial and recreational fishing pressure,
- Changes in the supply of sediment and nutrients resulting from water supply and flood control projects in each watershed,
- Changes in inputs from rain and wastewater discharges that can affect the magnitude and composition of nutrient inputs, and
- Changes in the amount and quality of tributary inflows resulting from land use changes and agricultural practices.

All of these changes to the watersheds and bays have been important over the last century, and these aspects are continuing to change, in some cases at an accelerating rate.

The bays and estuaries of Texas are changing still. Certainly population growth and consequent urbanization will continue. Climate change is increasingly of concern and could be especially important on the Texas coast because its flat terrain makes it susceptible to sea level rise (Montagna, et al, 2007; Montagna, et al, 2009). Sea-surface temperature change and changes in weather patterns will also affect the Texas coast. While it is likely that climate change is mainly a concern for the future, the basis for a recommended inflow regime should include cognizance that historical patterns may change, or already may be changing.

5.2 SEDIMENT AND NUTRIENT LOADINGS

With future regulatory analyses of both inflows and constituent inputs, decisions will be required on how much of a change from current conditions is acceptable. Those decisions will be informed by knowledge of both the current condition and the longer-term pattern of evolving changes. For this reason the recommended approach to addressing sediment inputs and nutrient loadings is to perform both:

- A present-conditions quantification in the form of a sediment, nutrient, and organic matter budget, and
- Development of a long-term analysis of the changes or trends in key parts of the budget.

The present sediment, nutrient and organic matter budget should reflect current conditions in an average year as well as representative wet and dry years. The long-term budget should address the changes that have occurred over the last century in direct inputs, land use in the watershed, and bay physical and water exchange conditions, to the extent practical. Ideally this would include considering the effects of changes in the chemical form and ratios between the key nutrients.

5.2.1 Sediment Delivery to Bays and Estuaries

Bays and estuaries are dynamic transitional systems that absorb inputs and disturbances from both rivers and oceans, including inland floods and coastal storms. Over the course of hundreds to thousands of years, their physical dimensions adjust with sea-level fluctuation, ground-surface subsidence, sediment delivery rates, and organic production rates (e.g., oyster beds). In historical times, especially in the case of the Texas bays, they have been greatly modified by channelization, among other direct and indirect anthropogenic actions. It is imperative, therefore, that in evaluating ecological conditions one recognize that significant anthropogenic changes have been made, and that it may not be possible to revert to previous unaltered conditions. Notwithstanding, sediment delivery is one of the natural processes that should be considered for maintaining the ecological integrity of bays and estuaries.

The transport of sediment from watersheds draining to bays and estuaries is a vital process that maintains deltaic and coastal marsh environments, minimizes shoreline erosion, contributes to benthic habitat composition, and affects turbidity in open-water environments (Ward and Montague, 1996). As much as bays and estuaries represent a transition from fresh- to saline-aquatic conditions, they also represent a shift from fluvial- to coastal-dominated sediment transport processes. During normal hydrologic and tidal conditions, suspended sediment can remain in the water column, be deposited in low-elevation coastal margins, or settle to the bottom in low-energy estuarine settings. In addition to these processes, floods or abnormally-high tides can result in the deposition of suspended sediment in deltaic marsh environments or relatively high-elevation coastal wetlands. Coarser sand-sized sediment supplied by bedload-transport processes contributes to deltaic progradation, forms a considerable portion of benthic substrate, and comprises the majority of sediment reworked by coastal processes along shorelines and beaches. Various characteristics and processes associated with estuarine sediment are described in Ward and Montague (1996).

Healthy and sustainable bays, estuaries, and coastal environments require a sufficient sediment supply from rivers and streams. Threats to sediment supply include upstream reservoir impoundments, sand and gravel extraction activities, certain flood mitigation efforts, and various land-use practices. Upstream threats to sediment supply are compounded by various coastal processes that counteract sediment inputs, including sea-level rise, ground-surface subsidence, and storm erosion. Approaches that account for sediment delivery into bays and estuaries should consider the volume for a given timeframe, thereby informing an assessment of the sediment budget (Figure 5.1-1). Sediment budget assessments are difficult for estuaries because of the complex exchanges between rivers and open-water environments (Wright and Schoellhamer 2005), and commonly rely on historical bathymetry and substrate composition (e.g., Hobbs et al. 1992). The most straightforward approach is using historical sediment-load data or sediment-load model equations at the downstream-most streamflow-gaging station of coastal-draining rivers and streams (e.g., Solis et al. 1994). This approach does not consider ungaged watersheds and, if measured or estimated for a degraded river, might not represent the natural conditions responsible for ecological integrity of the bay or estuary. For smaller, ungaged watersheds draining to bays or estuaries, a relatively simple approach to estimate sediment load could be application of a rainfall-runoff model coupled with a soil-loss equation (e.g., Revised Universal Soil-Loss Equation). Soil-loss equations, however, only predict the earth material removed by erosion and do not account for subsequent storage within the watershed, which would result in overestimates of loads delivered to estuarine systems.

An alternative approach to estimate the sediment required to sustain the physical dimensions of bays and estuaries is a static volumetric assessment of the sediment necessary to offset shoreline erosion and relative sea-level rise (i.e., sea-level rise and ground-surface subsidence). For a known rate of relative sea-level rise, the rate of sediment delivery required for preservation of bathymetry in open-water environments and elevation of all marsh and deltaic areas could be computed. The target volume could be based on estimates of contemporary (or desired) bathymetry, the extent of subaerial coastal/deltaic wetland environments, biological contributions (e.g., shell fragments), and flux of sediment exchanged to oceanic areas through tidal channels (see Ward and Montague, 1996) of a given bay or estuary. A clear disadvantage of this approach is its disregard for natural trajectories of regressive (i.e., shoreline retreat) or transgressive (i.e., shoreline extension) behavior through time in estuarine systems. Further, the practical application of this approach is questionable when considering the uncertainty associated with estimates of sediment volume and flux. Despite the disadvantages of this approach, it offers a conceptual framework to assess the balance of oppositional processes that contribute to change in the physical dimensions of bays, estuaries, and coastal wetland environments.

One example that could be categorized as a volumetric approach is discussed in Hobbs et al. (1992) for Chesapeake Bay (Figure 5.1-2). The authors primarily utilized historical bathymetric surveys to estimate volumetric change of sediment. The conversion to sediment mass was done using measurements of sediment type (i.e., particle size), assumptions of sediment density, and computations of porosity. Further, the volumes of sediment delivered by shoreline erosion, mass of suspended sediment, and mass of biogenic sediment were included from previously published works. In summary, the investigation of the sediment budget for Chesapeake Bay utilized

desktop methods to evaluate and synthesize previously published data, and serves as an example to guide similar endeavors in other estuaries.

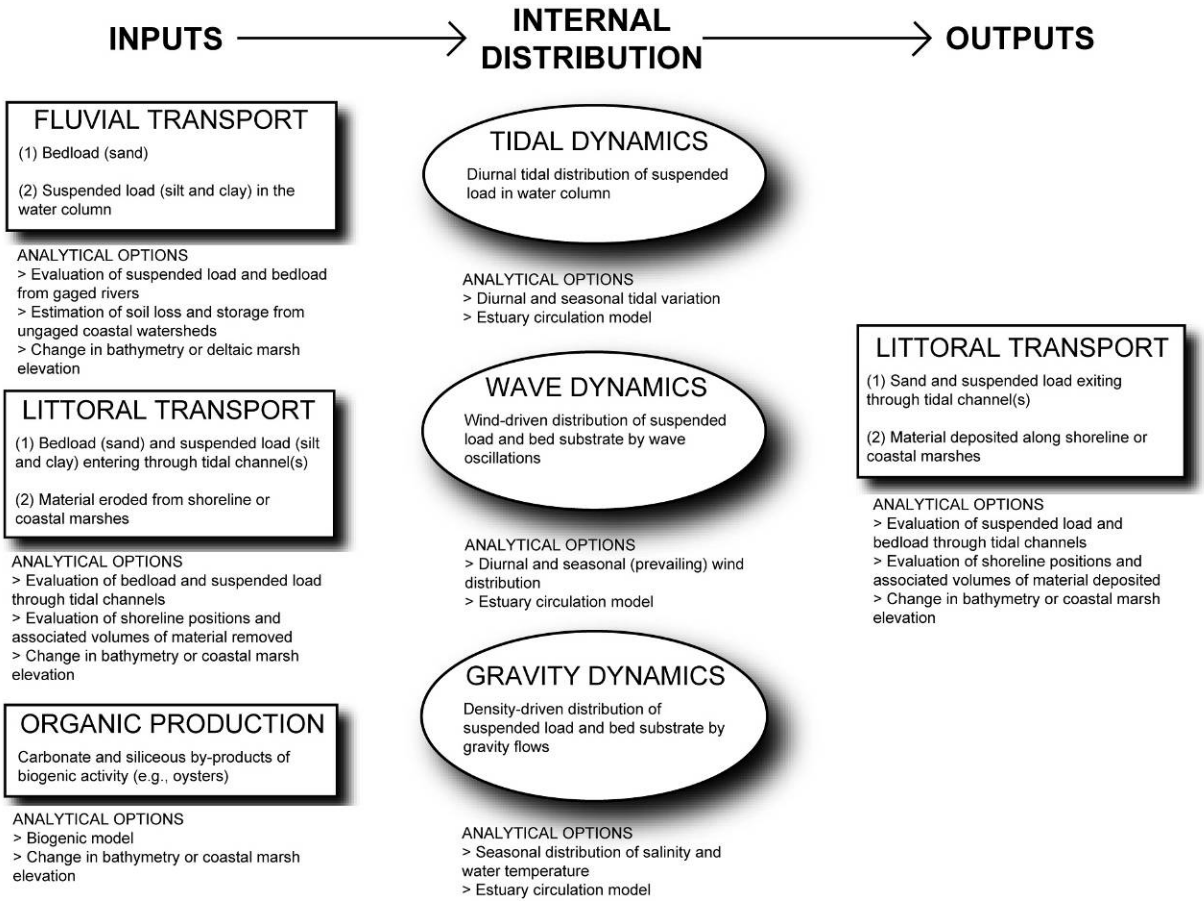

Figure 5.2-1 Conceptual Approach to Assess the Sediment Budget of a Bay or Estuary

(Inputs include fluvial sediment, sediment delivered from offshore sources, and organically-derived material. Internal mechanisms distribute sediment throughout the estuarine system. Finally, sediment can exit the estuarine system through tidal channels or by depositional mechanisms.)

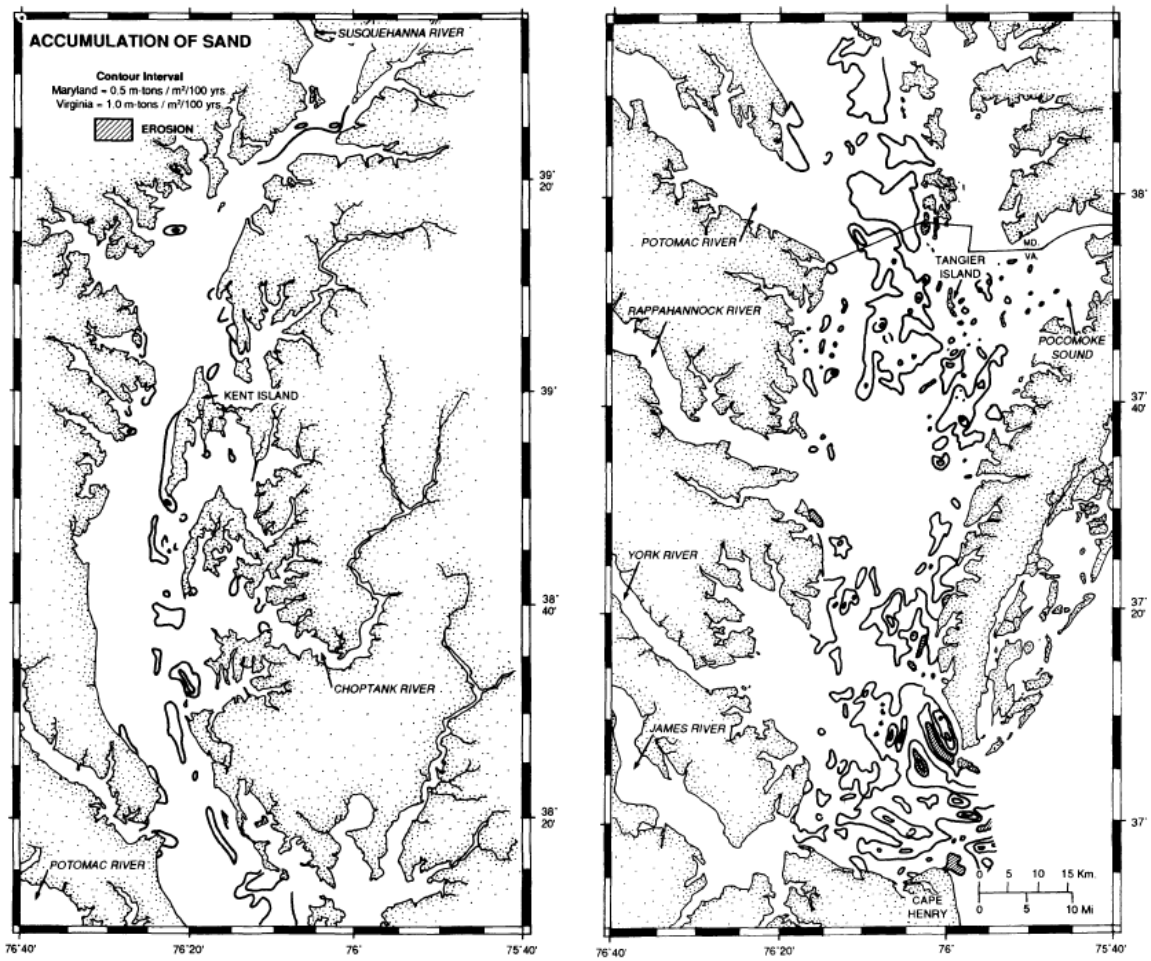

Figure 5.2-2 Map of Sand Deposition Rates in Chesapeake Bay, USA
(The data largely were derived from historical bathymetric surveys and previously published sources.)
Source: Hobbs et al. 1992

Although limited in ability to prescribe environmental flows, an estuary-circulation model (e.g., TxBLEND) adapted for sediment distribution could be informative in determining the fate of sediment in estuarine systems. A model that includes wind patterns, bathymetry, gravity currents, tidal fluctuations, and sediment loads and sizes might be able to predict locations and rates of sediment deposition in benthic zones, along the shoreline, and in tidally-influenced wetland environments. Although current models developed for Texas estuaries, including TxBLEND, are not specifically designed to address sediment dynamics, they could offer some information useful in predicting directions of sediment transport and locations of erosion or deposition. Development of new models or extensions of existing estuary-circulation models to include sediment dynamics would be a favorable research effort to inform inflow regime development programs in the future.

In summary, readily-available tools to assess the transport and distribution of sediment in bays and estuaries are limited. An elementary approach is consideration of sediment transport at the downstream-most gaging stations along coastal-draining rivers (e.g., SAC, 2009b). A more

robust approach is an evaluation of the sediment budget, which estimates the inputs and outputs of sediment to an estuary. Sediment budgets commonly include historical bathymetric surveys, shoreline positions through time, and sediment transport estimates for rivers and tidal channels. A more advanced analysis of sediment distribution within an estuary would include circulation models of tidal-, wave-, and gravity-driven dynamics.

5.2.2 Nutrient and Organic Matter Delivery to Bays and Estuaries

Nutrient and organic matter delivery to the coast occurs nearly instantaneously when fresh water flows into bays (Shank et al. 2009). The rate of nutrient delivery is a function of inflow, which is pulsed during flood events. Nutrient delivery is coupled with sediment supply because nutrients are dissolved ions, and for some of them, their behavior is mediated by direct adsorption to silt. This is especially important for highly charged anions such as phosphate (Day et al. 1989). Both flocculation and adsorption are a function of salinity, and thus drive the concentrations of dissolved ions along the salinity gradient. Suspended silt, clay, and humic acids are negatively charged ions, thus ionic repulsion in fresh water dominates and stable suspensions are formed. This is destabilized as salinity changes in the estuarine gradient. Dissolved inorganic nitrogen is highly bioreactive. Typically, freshwater inflow introduces nitrates and nitrites, which are very quickly taken up by plants and microalgae as the water moves down the estuarine gradient. Thus, estuaries are sinks for these oxidized forms of inorganic nitrogen. In contrast, metabolism by all micro- and macro- organisms generates reduced forms of inorganic nitrogen such as ammonia. Because ammonification primarily occurs downstream in the more saline parts of the estuarine gradient, estuaries can be sources of nitrogen. Thus, the chemistry of an estuary resembles a mixing bowl where the mixing drivers that control concentration are the salinity gradient, suspended sediments, and biological metabolic processes.

The changes in water quality that are related to inflow are easily visualized using multivariate analysis. For Lavaca and Matagorda Bays, principal components analysis was used on a long-term water quality data set (Figure 5.1-3, top, Pollack et al. 2009). The first axis clearly represents an inflow effect, where a decrease in salinity (or increase in freshwater inflow) is associated with an increase in nutrients. The second axis represents a seasonal effect, with high temperatures correlated with low dissolved oxygen. Although freshwater inflow was highest in spring and fall, the variability was high enough such that inflow effects and seasonal effects were independent of one another. The importance of salinity zones defining habitat is described in Section 2.3. Station scores for each sample of the data matrix can be visualized on the same axes, and this indicates the salinity zones in the ecosystem (Figure 5.1-3, bottom). Thus multivariate analysis of existing datasets allows for distinguishing freshwater inflow effects from seasonal effects. In addition, salinity effects zones can be identified.

To assess environmental flow recommendations it is necessary to understand both current nutrient conditions and recent historical changes of nutrient supplies to bays and estuaries. Both will require some level of analytical effort.

Examples of present condition budgets for nitrogen (N) and organic matter are shown in the Tables 5.1-1 and 5.1-2 respectively, which are taken from work on the Matagorda Bay for the LCRA-SAWS Water Project (MBHE, 2005). These show the distribution of inputs by tributary

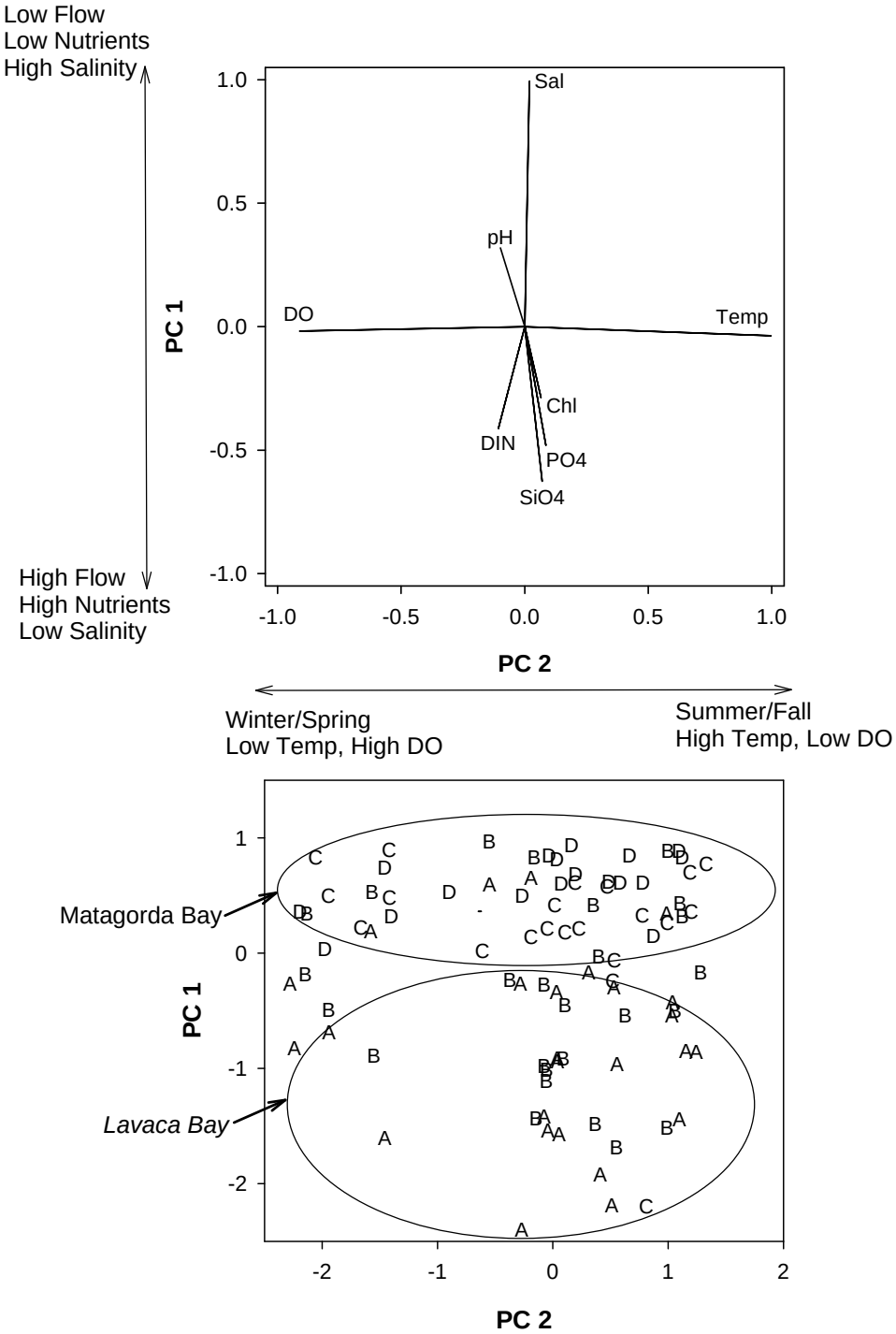

Figure 5.2-3 Multivariate Analysis of Water Quality Variables in Lavaca Bay and Matagorda Bay

Top: Variable loads showing contribution to PC scores. Abbreviations: Sal = salinity, pH = pH, DO = dissolved oxygen, Temp = temperature, SiO4 = silicate, PO4 = phosphate, DIN = dissolved inorganic nitrogen, Chl = chlorophyll a.

Bottom: Station scores showing salinity habitat zones.

Source: Pollack et al. 2009.

Table 5.2-1 Matagorda Bay Nitrogen Budget (metric tons/year)
Source: MBHE. 2005.

	1984		1987		2001	
	Pre-Diversion	Post-Diversion	Pre-Diversion	Post-Diversion	Pre-Diversion	Post-Diversion
Matagorda Bay						
Direct Inputs						
Colorado River	666	1,241	2,261	7,474	1,549	3,526
Navidad River	353	353	770	770	804	804
Lavaca River	165	165	947	947	932	932
Tres Palacios River	262	262	185	185	286	286
Garcitas/Placedo Creeks	96	96	209	209	194	194
Ungaged Flows	1,454	1,454	1,788	1,788	2,739	2,739
Wastewater	111	111	111	111	111	111
Precipitation	95	95	351	351	297	297
Dry deposition	330	330	596	596	596	596
Subtotal In	3,532	4,107	7,218	12,431	7,506	9,484
Bio-geochemical Losses						
Denitrification	1,355	1,355	1,355	1,355	1,355	1,355
Burial in Sediments	60	60	410	410	323	323
Fisheries Harvest	82	82	97	97	93	93
Escapement	104	104	208	208	182	182
Subtotal Loss	1,601	1,601	2,070	2,070	1,953	1,953
East Matagorda Bay						
Direct Inputs						
Colorado River via GIWW	350	326	786	738	650	606
Ungaged Flows	1,708	1,708	982	982	2,359	2,359
Precipitation	20	20	72	72	61	61
Dry deposition	68	68	123	123	123	123
Subtotal Inputs	2,145	2,122	1,964	1,916	3,193	3,149
Bio-geochemical Losses						
Denitrification	279	279	279	279	279	279
Burial in Sediments	12	12	84	84	66	66
Fisheries Harvest	17	17	20	20	19	19
Escapement	21	21	43	43	37	37
Subtotal Loss	330	330	426	426	402	402
Export to Gulf by Difference	3,746	4,298	6,685	11,851	8,344	10,278
Direct Export to Gulf	636	85	5,447	282	2,141	208
Total Export to Gulf	4,382	4,382	12,132	12,132	10,485	10,485

Note: 1984 considered relatively dry, 1987 relatively wet and 2001 employed as an average year.

Table 5.2-2 Matagorda Bay Organic Matter Budget (metric tons/year)
Source: MBHE. 2005

	1984		1987		2001	
	Pre-Diversion	Post-Diversion	Pre-Diversion	Post-Diversion	Pre-Diversion	Post-Diversion
Matagorda Bay						
Direct Inputs						
Colorado River	12,990	31,849	57,729	241,071	34,550	88,888
Navidad River	8,177	8,177	17,820	17,820	18,601	18,601
Lavaca River	4,121	4,121	54,249	54,249	50,556	50,556
Tres Palacios River	17,876	17,876	9,985	9,985	18,702	18,702
Garcitas/Placedo Creeks	4,872	4,872	14,810	14,810	13,596	13,596
Ungaged Flows	79,183	79,183	88,901	88,901	172,899	172,899
Wastewater	56	56	56	56	56	56
Subtotal In	127,274	146,134	243,549	426,892	308,959	363,298
Bio-geochemical Losses						
Burial in Sediments	951	951	6,499	6,499	5,112	5,112
Fisheries Harvest	1,300	1,300	1,537	1,537	1,478	1,478
Escapement	1,648	1,648	3,297	3,297	2,885	2,885
Subtotal Loss	3,899	3,899	11,333	11,333	9,474	9,474
East Matagorda Bay						
Direct Inputs						
Colorado River via GIWW	5,586	5,286	16,305	15,547	13,038	12,292
Ungaged Flows	134,306	134,306	52,228	52,228	191,164	191,164
Subtotal Inputs	139,892	139,592	68,533	67,775	204,202	203,457
Bio-geochemical Losses						
Burial in Sediments	196	196	1,339	1,339	1,053	1,053
Fisheries Harvest	268	268	317	317	304	304
Escapement	340	340	679	679	594	594
Subtotal Loss	803	803	2,335	2,335	1,952	1,952
Export to Gulf by Difference	262,464	281,023	298,415	481,000	501,736	555,328
Direct Export to Gulf	20,276	1,717	189,387	6,802	58,287	4,694
Total Export to Gulf	282,740	282,740	487,802	487,802	560,022	560,022

Note: 1984 considered relatively dry, 1987 relatively wet and 2001 employed as an average year.

for a relative dry (1984), wet (1987) and average year (2001) and effect of the river diversion constructed between 1988 and 1992. The bulk of the wastewater N load is incorporated in the Colorado River flows so the explicit wastewater contribution is relatively small. The inputs include particulate forms of N that become part of the sediment, which provides a valuable buffer to bay nutrient concentrations. Some of this N in the sediment is released in dissolved inorganic forms and some is lost to denitrification. The denitrification rate shown in the table was developed from available measurements and not scaled for different levels of inflow. The organic matter budget is similar except that some terms such as precipitation do not apply. The organic matter budget involves an attempt to represent the contribution of macro-detritus (branches and other organic matter too large for normal sample bottles) by doubling the volatile suspended solids (VSS) loads concentration. Similar budgets have been produced over the years by TWDB and TPWD for all of the bay systems (see Appendix A). These budgets would need updating, but with the availability of data today, updating the input data would be a relatively modest undertaking, and various programs do exist to calculate such loads, e.g., SPARROW and LOADEST[7]. However, developing information on processes such as sediment interactions and transfers to the Gulf would be more complex.

Examples of the long-term trend in key bay processes are more limited. A long-term trend analysis was not performed for the LCRA/SAWS Water Project because the main focus was on maintaining the conditions after the most recent major modification, the Colorado River diversion. A limited long-term trend example is available for N inputs to Galveston Bay as affected by population growth in the watershed, reservoir development, and improvements in wastewater treatment (Figure 5.1-4). These processes caused major changes in the N inputs to the Galveston Bay system. In addition, there were major changes in Gulf water exchange and bay volume during the period due in part to significant navigation channel development. Since the long-term trend analysis was performed in 1990, it is somewhat dated. But with those limitations, it makes the point that changes in what is carried by inflows can be significant and potentially important. A similar kind of analysis can be produced using population and other changes in the watershed with relatively modest effort.

5.3 INTEGRATION OF ESTUARINE INFLOW AND RIVERINE FLOW RECOMMENDATIONS

Under Senate Bill 3, BBESTs are required to develop environmental flow recommendations for protecting both riverine instream uses and estuarine aquatic resources. Considered separately, this twofold directive has the potential to generate inconsistent flow recommendations near the mouths of major rivers because of the different methodologies that may be used for analyzing these different types of aquatic ecosystems. There is also the distinct possibility that the environmental flow recommendations for either one of these two aquatic systems could be adequate to provide the necessary flows for the other.

Because of the distinct differences between riverine and estuarine ecosystems, requirements for environmental flows also are distinctively different. While a single approach or methodology potentially could be applied to estimate environmental flow requirements for these different

[7] http://water.usgs.gov/nawqa/sparrow/
http://water.usgs.gov/software/loadest/

systems (such as the HEFR hydrology-based method), different input parameters would have to be established for each system in order to appropriately describe important components of the flow regimes considered necessary to protect the different ecosystem features.

Regardless of the approach or approaches applied to estimate the environmental flow requirements for protecting the instream uses in the lower reach of a river and for providing the necessary freshwater inflows to its associated estuary or bay, it would seem that the logical process for resolving inconsistencies in the flow requirements operationally would be to err on the conservative side by always implementing the more restrictive of the two. This would ensure that both types of flow regimes would always be satisfied. However, there still may be site-specific circumstances or conditions that may warrant some modification of the individual environmental flow requirement, and this would have to be addressed on a case-by-case basis.

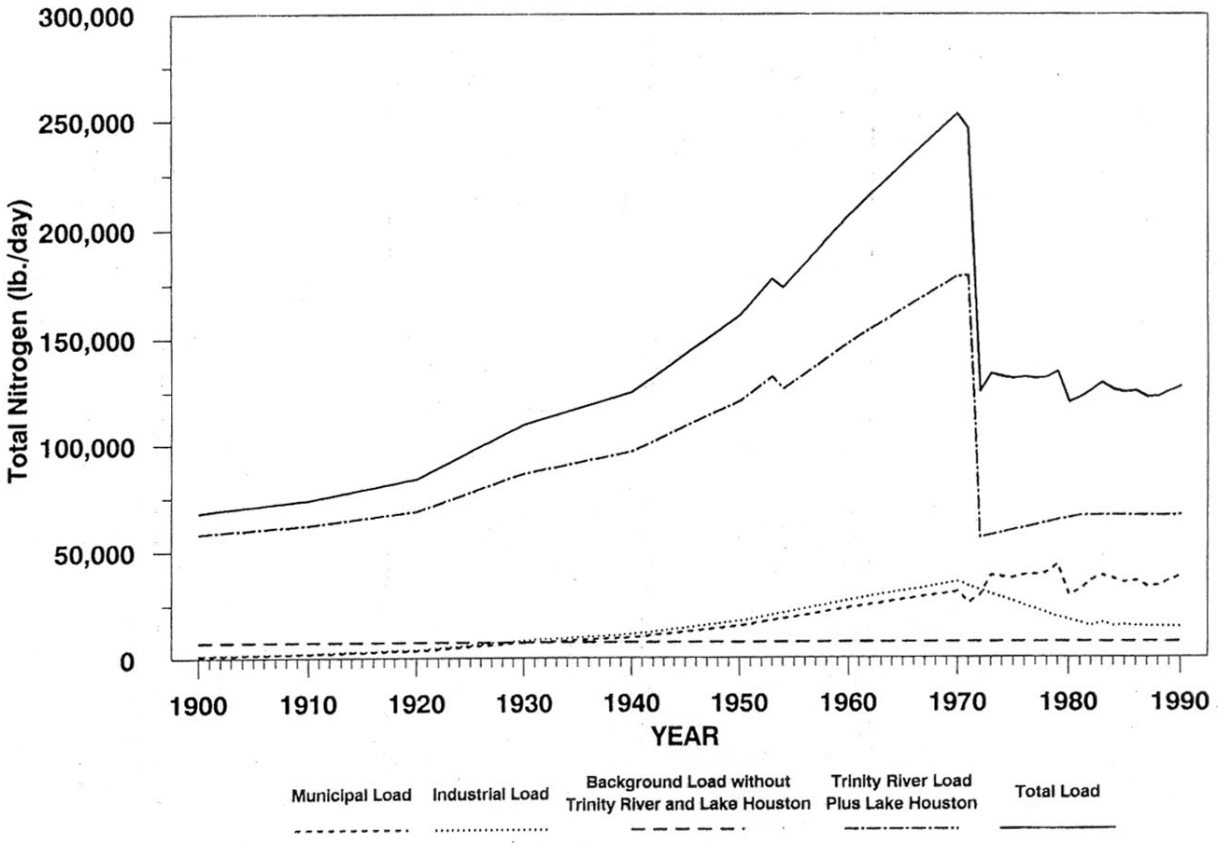

Figure 5.2-4 Total Nitrogen Load to Galveston Bay
Source: Jensen et al. 1991

SECTION 6
SUMMARY AND RECOMMENDATIONS

The focus of this document is on the importance of freshwater inflows for protecting aquatic resources in bays and estuaries along the Texas coast and on methodologies that might be considered by the BBESTs for developing freshwater inflow regimes pursuant to the requirements of Senate Bill 3.

Senate Bill 3 provides that the BBESTs must develop an environmental flow analysis and "a recommended flow regime for the . . .bay system". The legislation defines an environmental flow regime as a "schedule of flow quantities that reflects seasonal and yearly fluctuations that typically would vary geographically, by specific location in a watershed, and that are shown to be adequate to support the sound ecological environment and to maintain the productivity, extent, and persistence of key aquatic habitats in and along the affected water bodies. Such inflow regimes will have to be developed by BBESTs recognizing the inherent variability in hydrometeorological conditions that contributed to and have sustained these productive estuarine ecosystems over time.

The foregoing sections have provided information on the estuarine characteristics considered vital to understanding how freshwater inflow regimes affect the ecological health of Texas bays and estuaries (Section 2); a guide to the data, information and tools that are currently available from the State Methodology to help develop freshwater flow recommendations (Section 3); and a description and analysis of available methodologies for developing inflow regime recommendations (Section 4). Section 5 presents other considerations that the BBEST should review when formulating its flow regime recommendations. The SAC provides the following summary and recommendations from the information presented herein:

The Estuarine Ecosystem

- **An estuary is a waterbody on the boundary of the oceanic and terrestrial environments, and is transitional between freshwater and marine.**

  The major Texas estuaries are coastal embayments, broad systems with complex morphology that develop internal circulations important in the distribution of waterborne constituents and biological populations. The functional components of the estuary ecosystem may be usefully classified as hydrodynamic (the currents and circulations within the system), waterborne constituents (the materials and chemical compounds carried in solution or suspension within the estuary waters, whose levels determine suitability of the water for use by organisms), and biology (the various organisms ranging from microscopic to macroscopic, that inhabit the estuary).

- **Of central importance to the estuarine environment is the exchange with the ocean.**

  The exchange between estuary and sea is controlled by tides, seasonal water-level excursions, gravity currents and meteorology (especially wind stress) as well as the

morphology and dimensions of the inlet(s) connecting the estuary to the sea. A direct measure of the physical exchange with the sea is the salinity distribution within an estuary. Salinity is the quintessential estuary parameter. The range and distribution of salinities can therefore be important demarcators of suitable habitat for estuarine species. The spatial estuarine gradient is fundamental for regulating differences in the ecological functions, habitats, and integrity of the estuary along the salinity gradient.

Exchange between estuary and sea also manifests itself in the organisms. Many of the important Gulf of Mexico animals, notably major fish and shellfish species, are "estuarine dependent" meaning that they migrate between the sea and the estuary at various life-history stages.

- **Freshwater inflow affects the estuary through multiple mechanisms**

  Freshwater inflow serves a variety of important functions to coastal estuarine ecosystems by creating and preserving low-salinity nurseries, transporting sediments, nutrients, and allochthonous organic matter downstream, and affecting estuarine species movements and reproductive timing.

- **The estuary is influenced by multiple factors, one of which is freshwater inflow**

  There is a central difference between the roles of flow in the river or stream, and in the estuary, with regard to protecting environmental resources. In the riverine setting, flow is the dominating variable that controls almost all of the hydrographic and biological processes. In the estuarine setting, inflow is one of several variables, such as exchanges with the sea driven by tides and winds, internal circulations driven by density differences, wind set-up, and channelization, all of which can influence biology, in addition to the interaction of marine and estuarine populations (both flora and fauna). There are many processes acting within the estuary, which respond to these multiple external factors, that determine the levels and distributions of waterborne substances and the locations and viability of organisms. While freshwater inflow is only one variable in this complexity, it is a very significant variable in terms of overall health of the estuary and is the focus of Senate Bill 3 requirements.

Setting Realistic Expectations

- **To infer the relation between inflow and the ecosystem, some type of model(s) will be needed.**

  While *deterministic* models of complex estuarine ecosystem processes have been under development for at least half a century, there remain major theoretical and operational difficulties in their application, as well as a requirement for data that may not exist. No comprehensive model encompassing all estuarine processes presently exists for any of the Texas estuaries, and will not likely become available within the time frame of the BBESTs' activities. Instead it will be necessary that the BBESTs rely upon sets of measurement

from the estuary of concern and accompanying statistical evaluations, perhaps combined with limited deterministic models, to infer responses of the ecosystem to inflows.

- **Without a model representing the full complexity of the estuary ecosystem, inflow effects will have to be treated with an abridged conceptual model retaining only the most salient inflow effects.**

  Given the limited time available to the BBESTs, it is not likely to be feasible to quantify each of the cause-and-effect relations known to be important in estuarine ecosystems. In some systems that have been studied in more detail (e.g. Galveston Bay and Matagorda Bay), more information will exist to help define these relationships, at least in terms of trends and/or basic interactions. In other systems, however, only the most fundamental relations of salinity and some biotic population abundance with inflow and the ecosystem may be feasible for use in determining inflow requirements

  A "conceptual model" of the indirect causal connection between "biology" and "inflow", as diagrammed in Figure 6-1, is suggested to serve as a basis for a technical approach. The "nutrients" and "suspended solids" components are shown in grey to reflect the present thinking of the SAC to address these as *overlays* (see Section 5). The primary determinants are the relation of salinity to inflow coupled with the relation of biology to salinity. It may be possible to establish a direct relation of biology on inflow, as indicated by the broken line of Figure 6-1, though the data requirements and analytical methods will be more demanding.

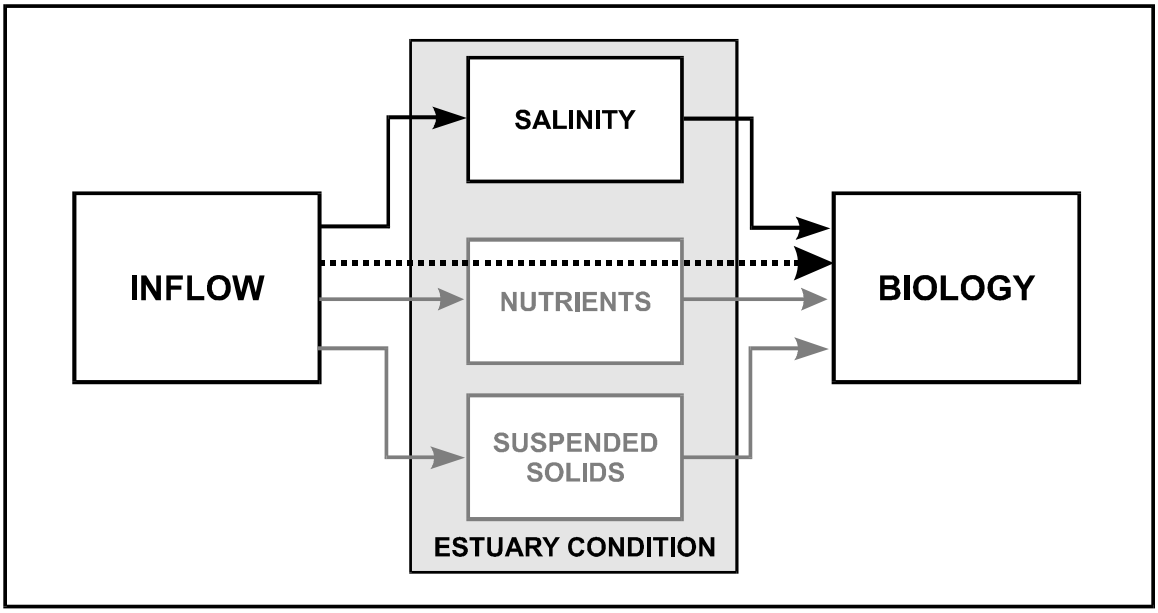

Figure 6-1 – Schematic of "Conceptual" Relation of "Biology" to "Inflow"

Biological characterization consists of selection of which biological components are to be addressed and what spatial and temporal formulas are to be used in quantifying the data.

The biological components can be individual species or can be complexes of species, perhaps parameterized by some univariate ecological structural measure such as diversity, or through multivariate analysis. The strategy of Figure 6-1 requires that, once the biological components are identified, either the habitat requirements are delineated, which may be confined to salinity, or that a direct relationship to inflow be developed.

The complexity of the problem that has been simplified in the depiction of Figure 6-1 needs to be borne in mind. The uncertainty implicit in these relationships should be quantified and made part of the analysis.

- **The characterization of inflow data, i.e. how its time/space variation is depicted, is important in identifying major "regime" components and in exposing relations of salinity and/or biology on inflows.**

  Standard depictions can be either cyclic (based upon regularly repeating behavior, such as a seasonal "pattern") or event-based (in which droughts, floods, etc. are separated and quantified), or a combination of the two. Methods employed in the State Methodology are based upon cyclical depiction of monthly inflows. If available, a freshet analysis may prove a useful characterization of estuarine inflows for purposes of assessing the response of biology. Preliminary statistical analyses using seasonal influx events ("freshets") as an independent variable yield better explanations for the variation of annual-mean abundance for several major species than can be achieved using calendar-period flows.

- **Even though salinity dilution is thought to be a direct function of inflow, when the relation between salinity and inflow is depicted as a simple function it proves to be noisy.**

  A simple statistical relation between salinity and inflow is noisy, because other processes affecting the time variation of salinity are neglected in such an analysis and therefore appear as increased variance. However, this is not to suggest that relating salinity to inflow is subject to so much variance that no inference can be made. Because of the pivotal role that salinity will likely play in the work of the BBESTs, alternative formulations of the independent inflow variable, separated geographically or temporally, should be explored.

Recommendations

The SAC believes that there exists a combination of methodologies that can be used by the BBESTs to develop scientifically-sound freshwater inflow regime recommendations for the purposes of Senate Bill 3. The recommended regime should be designed to cover the full flow spectrum, from very low flows (near drought-of-record conditions), in which species refuge becomes of primary importance, to higher flow events sufficient to provide adequate nutrient and sediment supply to the bay system for longer-term ecological health. One or more inflow levels between very low and high flows, and their expected frequency of occurrence, should complete, as appropriate, the inflow regime recommendation. These are the essential components of an inflow regime to protect the health and productivity of Texas bays and estuaries while respecting their natural variability.

Specific recommendations are as follows:

- **The scientific objective of the BBESTs should be to quantify as far as possible the cause-and-effect relations diagrammed in Figure 6-1.**

  The diagram of Figure 6-1 is a conceptual model of how changes in inflow will influence habitat, thence biology. The arrows depict causal connections. With these relationships quantified from data, Figure 6-1 would indicate how the effects of a change in inflow would manifest themselves in changes in the selected components of biology. In determining inflow regime recommendations, the BBESTs can in so far as possible: use biological information to define salinity ranges and necessary habitats within the estuary system; analyze field data and/or appropriate hydrodynamic/salinity relationships to define critical salinity refugia at extremely low (near drought-of-record) flows; carry out hydrological evaluations, in combination with salinity and/or biological analyses to characterize suitable mid-to-upper level flows; and apply sediment transport and nutrient input overlay analysis, especially for defining periodic high flow events. The depth and range of each of these determinations will depend upon the availability of information for the particular bay/estuary system.

- **The BBESTs should be cognizant of the extent to which the causal connections of Figure 6-1 can in fact be established from available data and known relationships. Absent this information, the default option is to rely upon inflow data alone, which provides no information on the response of estuary condition or species abundance.**

  Under the circumstance when habitat or key species data are limited (or, perhaps, incapable of being evaluated within the available time frame) or do not yield informative relations, **the evaluation of historical inflow data may be the only means of quantifying an inflow requirement**. This is the default option of Figure 6-1, to be elected only when there is no information on the other elements of the estuarine ecosystem. Even at this, it is still necessary to characterize the inflow, which may involve conceptual models (i.e., hypotheses) of how the biology might respond to inflow, and to formulate specific inflow goals to attain, such as achieving certain statistics of flow variation. This is the basic foundation that underlies the Nature Conservancy/IHA (Section 4.4.1), HEFR (Section 4.3.1), Percent of Flow (Section 4.4.3) and NWF Inflow Pattern (Section 4.3.2), approaches, though the latter does also rely on biological inferences to some degree.

- **When existing data and known relationships exist, the approach to extend the analysis to include estuary condition is sounder than reliance upon inflow data alone**

  Historical hydrological patterns, particularly seasonal, also play an important role in applications of the State Methodology (Section 4.1), the Salinity Zone (Section 4.2), and the LCRA-SAWS Inflow Criteria (Section 4.4.2) methods, but, to varying degrees and levels of sophistication, other factors and relationships pertaining to salinity, species abundance or productivity, nutrients, water quality, and/or sediment loadings also are incorporated into the decision process for determining freshwater inflow requirements.

- **While recognizing the availability of freshwater inflow needs analyses performed by the State agencies for the principal bays of Texas, based on application of the full State Methodology, caution is recommended in interpreting the results as an appropriate basis for Senate Bill 3 environmental flows.**

  Freshwater inflow recommendations have been made for each of the major bay systems by the TPWD and TWDB based upon application of the full State Methodology. The recommended monthly flow patterns (typically the *maxH* flows) are intended to optimize the productivity for a set of key species. However, constraints set in the optimization model tend to dictate the monthly flows, and the resulting pattern of monthly flows does not occur in the historical inflow data record. Moreover, the State Metholology flow recommendations were designed to determine "beneficial inflows", and do not provide an inflow regime consistent with the requirements of Senate Bill 3. Hence, these flow recommendations are not endorsed as satisfactory for the Senate Bill 3 objective of maintaining a sound ecological environment. There are, however, many elements of the State Methodology (see Section 3) and the Verification Methodology, stemming from the comprehensive and valuable studies performed by the TWDB and the TPWD over the years, that are of potential utility to the BBESTs in determining the flow regimes needed to meet Senate Bill 3 objectives.

- **In delineating the ecological state, the maintenance of which is the inflow specification goal, consideration must be given to the present (or relatively recent) nature of the estuary.**

  Whatever method is selected in a particular bay system to produce environmental flow recommendations, it must be recognized that all the bays that we know today have been modified substantially from their historical, natural condition. Maintenance of a sound ecological environment, as required by Senate Bill 3, should consider the evolved bay system, as it is highly unlikely that the bay system will return to some historical natural state. However, understanding the evolution process by which the bay system achieved its current state also is an important aspect of effectively managing and protecting estuarine resources.

- **While it is unlikely that the flow recommendations for the riverine environment and the estuarine environment will be exactly consistent, substantial differences should be closely examined.**

  Under Senate Bill 3, BBESTs are required to develop environmental flow recommendations for protecting both riverine instream uses and estuarine aquatic resources. Considered separately, this twofold directive has the potential to generate inconsistent flow recommendations near the mouths of major rivers because of the different methodologies that may be used for analyzing these different types of aquatic ecosystems. Because the river and bay system in a particular basin evolved under largely the same conditions, a *significant* misalignment between instream and freshwater inflow recommendations should signal the need for a thorough cross-check of the methods. Regardless of the approach or approaches applied to estimate the environmental flow

requirements for protecting the instream uses in the lower reach of a river and for providing the necessary freshwater inflows to its associated estuary or bay, it would seem that the logical process for resolving inconsistencies in the flow requirements operationally would be to err on the conservative side by always implementing the more restrictive of the two. This would assure that both types of flow regimes would always be satisfied. However, there still may be site-specific circumstances or conditions that may warrant some modification of the individual environmental flow recommendations, and this should be addressed on a case by case basis.

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SECTION 8
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APPENDIX A
SUMMARY OF RESULTS OF THE STATE METHODOLOGY FOR THE PRINCIPAL ESTUARIES OF TEXAS

The State Methodology, described in detail in Longley (1994) has two basic management goals based on earlier legislative directives. These are:

1. Ensure the maintenance and productivity of economically important and ecologically characteristic sport or commercial fish and shellfish, and
2. Ensure the maintenance of estuarine life upon which such fish and shellfish are dependent.

The State Methodology addresses the first goal, "maintenance of ... fish and shellfish", by setting a management goal to achieve more than 70% of historical average harvests or abundances of important fish and shellfish. This requirement is set in the Texas Estuarine Mathematical Programming Model (TxEMP) optimization model as a lower constraint, ensuring that flows determined by TxEMP to be valid solutions must meet this requirement. Multiple solutions, where each exceeds the target harvest or abundance, are possible. For each target above the minimum, TxEMP computes the minimum amount of water that meets that target while also meeting other prescribed constraints. Operationally, and equivalently, it determines for a particular annualized volume of water the monthly distribution of that volume required to maximize harvest or abundance while meeting the constraints. TxEMP is the component of the State Methodology that provides viable flow options to be considered for a flow recommendation (Figure A-1).

The State Methodology addresses the second goal, "maintenance ... of estuarine life upon which such fish and shellfish are dependent", in two ways. First, constraints applied in TxEMP recognize the biotic requirements for particular salinity regimes, sediment, nutrients, and habitat. Second, and less explicitly, in the final check of needs salinity levels resulting from the inflow solutions provided by TxEMP are examined at important locations within the estuary (Figure 4-3). This step ensures that the recommended inflows will provide conditions favorable to maintaining the fish, shellfish, and estuarine life upon which they are dependent, *i.e.,* an ecologically healthy system.

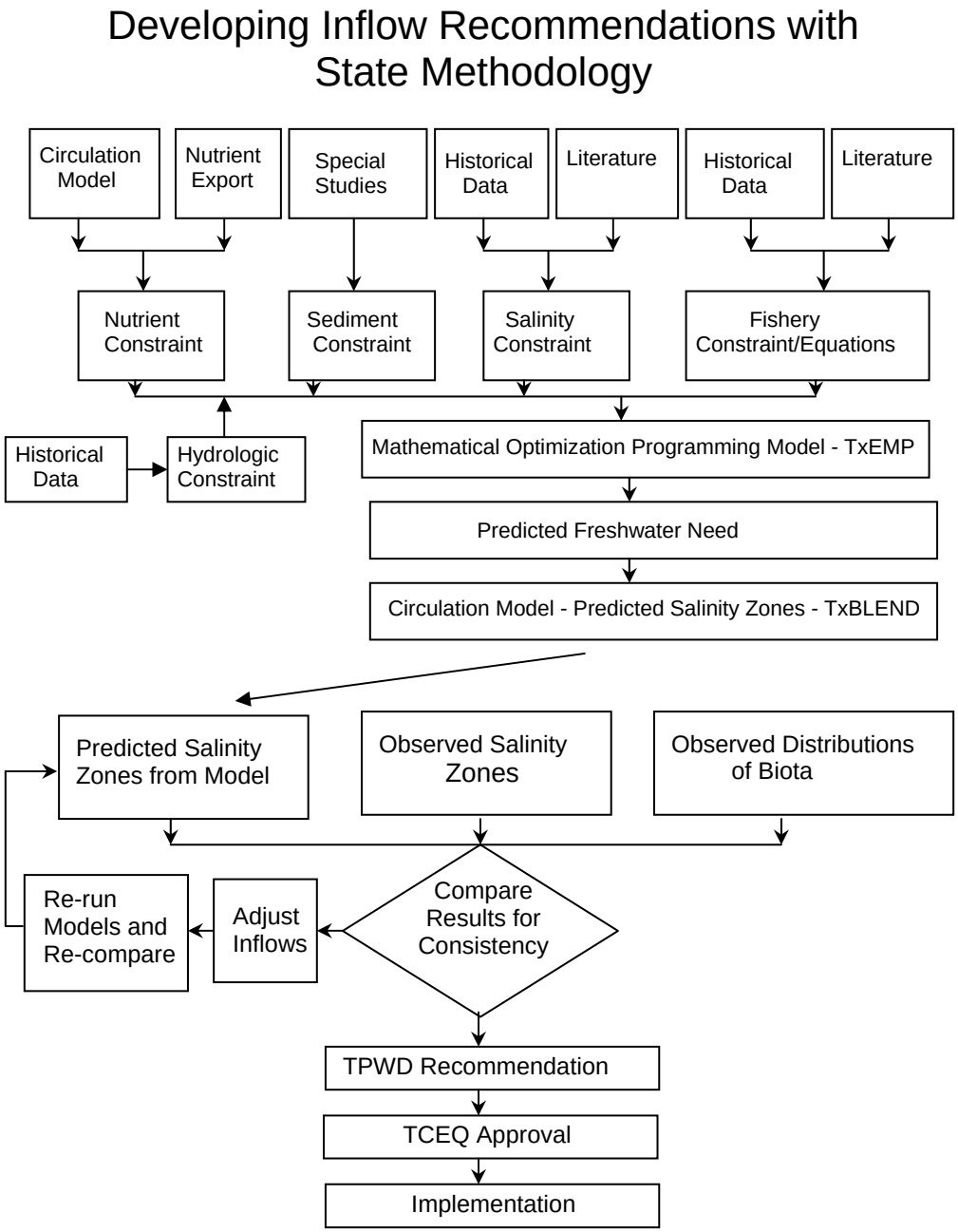

Figure A-1 State Methodology for Developing Inflow Recommendations

Management objectives, and management and scientific constraints are input to TxEMP, which provides viable flow solutions. These are then analyzed and considered for the final flow recommendation.

A-1 Management Objectives

TxEMP can be used to determine flows that achieve different management objectives. These objectives include a subsistence goal (MinQSal) which is the minimum set of inflows that meet

only salinity constraints, a maintenance goal (MinQ) which is the minimum set of monthly flows that meet harvest/abundance goals and all hydrological and biological constraints, and an enhancement goal (MaxH or MaxC) which is the set of flows that maximizes harvest/abundance while meeting all hydrological and biological constraints. The final flow recommendations for the major estuaries in Texas as derived using the State Methodology have typically been between MinQ and MaxH.

A-2 TxEMP Constraints

Constraints are needed to keep TxEMP from producing physically unreachable or ecologically undesirable solutions. Also on a practical level, the model deals only with inflows that are in the range of management options. In water-use permitting, water volumes pertinent to establishing the permit are related to the availability and frequency of particular inflows. Likewise, planning for future inflows to the estuary may require acknowledging the historical range of inflow. Harvest or abundance constraints similarly reflect a management goal for the system that is based on historical data. For example, we may choose to set a constraint which will maintain at least 70% of historical abundance and according to the historical proportions of the target species in the estuary while limiting inflows to less than the historical monthly median.

Salinity Constraints - Salinity constraints define one set of upper and lower limits on the TxEMP solution. They are based on the statistical characteristics of salinity within the estuary combined with known salinity preferences and tolerance limits of the target species. Salinity constraints help to ensure that the TxEMP solutions are reasonable and that the management goals are achieved.

Inflow Constraints – Inflow constraints are specified as monthly upper and lower bounds and/or seasonal (bimonthly) upper and lower bounds. Upper bounds on monthly inflows generally are set at the median historical monthly flow, while lower bounds are set at the 10th percentile flows.

Harvest/Abundance Target – The harvest/abundance constraint is set so that harvest or abundance as calculated by the model is at least some percentage of the historical average (70% and 80% have been used).

Biomass Ratio (or Relative Abundance) – This constraint is set to produce solutions which include harvest/catch for a set of species that reflect the historically observed proportions. This is necessary to prevent a solution dominated by a particular species.

Salinity and Harvest Probability) – Constraints can be set on the probability that the solution produced meets the salinity or harvest criteria. When probabilities are defined to be high, the model may be very limited in the range of solutions which can be explored.

Nutrient and Sediment Constraints) – These constraints are expressed in terms of inflows. To ensure a minimum supply of beneficial nutrients and sediments, constraints can be set on the inflows.

A-3 Outputs

TxEMP outputs monthly flows that meet the management objectives for harvest or abundance and that meet all the management and biological constraints (Figure A-2). Several solutions meeting different management objectives and points in between are commonly assembled to create a response curve. On that curve, an "annualized" flow represents the sum of the monthly flows obtained by TxEMP as a solution.

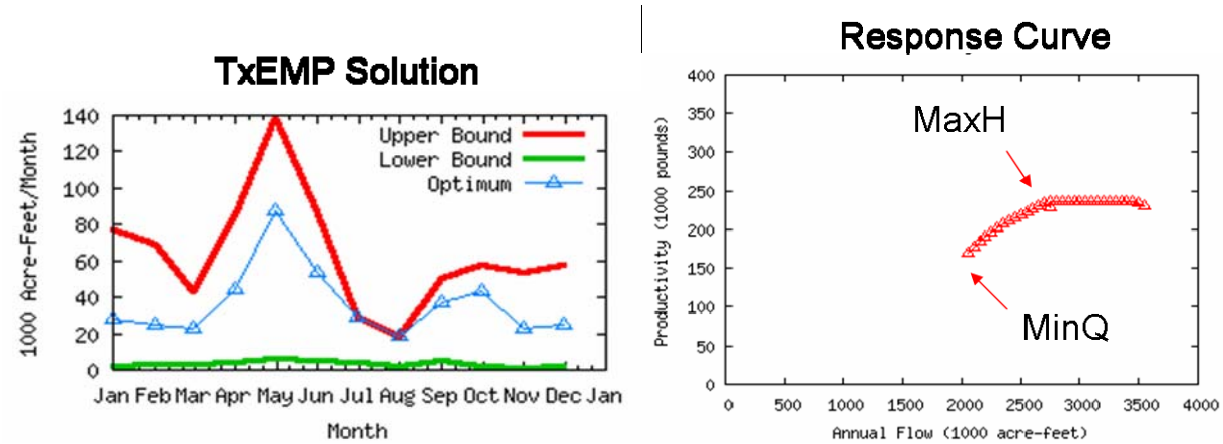

Figure A-2 Example of Monthly Flow Solution Computed by TxEMP.

Upper constraint on flow is shown by the red line, lower constraint is shown by the green line. Monthly flow solutions are shown with blue symbols on the left graph. Annualized (sum of monthly flows) flow in the left figure represents a single "annualized" flow volume on the horizontal axis of the Respons Curve in the right graph.

Results from application of the State Methodology to bays and estuaries along the Texas coast are summarized in the following tables. The significant species that have been selected and used to develop freshwater inflow recommendations for different estuarine systems are indicated in Table A-1). Estimated required nitrogen loadings and associated total annual inflows for the different estuarine systems are summarized in Table A-2. Table A-3 presents similar information with regard to sediment loadings. Finally, solutions from the TxEMP analysis in terms of freshwater inflow needs for different management objectives are presented in Table A-4 for each of the major estuaries in Texas.

The State Methodology in effect assumes that it would be possible to manage inflows to the bay/estuarine system such that the “optimized” monthly pattern of inflow would prevail and, thereby, result in maximum, or some other target, species abundance. In reality, due to the wide range of naturally occurring hydrologic and climatic conditions and other factors, that is not likely to be the case. While the State Methodology itself has shortcomings that limit the utility of its results for establishing freshwater inflow recommendations, particularly in the context of a flow regime consistent with Senate Bill 3 directives, the process of developing and applying the State Methodology to individual bay and estuary systems along the Texas coast has produced a wealth of useful data and information that could assist with the development of environmental flow requirements for bays and estuaries pursuant to Senate Bill 3.

A-4 Decision Points

As described in Longley (1994), decisions about objectives and some constraints applied in TxEMP may be considered to be more in the realm of stakeholder input rather than science; although, it most likely will be a combination of the two that ultimately determines how the State Methodology may be applied to a particular bay and estuary system. Significant decision points that must be addressed in applying TxEMP include the following:

- *Species* to be included and relative *Weighting of Species* - In earlier studies that relied on commercial harvest data, the species included in the analysis consisted of only those where this information was available. More recent studies that rely on TPWD Coastal Fisheries data have included many of the same commercial species, but could include a wider variety of species less weighted towards commercial species. The choice of species used in the analysis is a mix of policy and science.
- *Inflow Constraints* - TxEMP solutions are bound by upper constraints (typically median or mean monthly inflows) to keep the solution reasonable from a management perspective. This constraint could be loosened to explore other viable solutions. The lower flow constraint, typically set as the 10th-percentile monthly flow, could also be varied.
- *Area-Specific Salinity Limits* - Salinity constraints are set and viable solutions are evaluated for areas considered to be important habitat. Decisions on what is considered important habitat is a mix of policy and science.
- *Harvest/Abundance Targets* - Minimum harvest/abundance targets have been set between 70% and 80% of combined historical averages. The target limit is also a mix of policy and science.

Table A-1 Species Used in Freshwater Inflow Analyses for Major Estuaries

Species	Sabine-Neches	Trinity-San Jacinto	Lavaca-Colorado	Guadalupe	Mission-Aransas	Nueces	Laguna Madre
Brown Shrimp	X	X	X	X	X	X	X
White Shrimp	X	X	X	X	X	X	X
Blue Crab	X	X	X	X	X	X	X
Red Drum	X	X	X	X	X	X	X
Atlantic Croaker	X						
Gulf Menhaden	X		X				
Spot	X						
Spotted Seatrout	X	X		X		X	X
Eastern Oyster		X	X	X	X		
Black Drum		X		X	X	X	X
Southern Flounder		X			X	X	X
Striped Mullet			X				
Speckled Trout					X		
Pink Shrimp							X

Table A-2 Nitrogen Loads to Major Estuaries and Their Use for Freshwater Inflow Recommendations

Estuarine System	Required Total N Load 10^6 kg N/yr	Basis for Required Loading	Resulting Annual Inflow 10^6 acre-feet*	Purpose for Which Loading/Inflow Values Were Used
Sabine-Neches	11.4090	Based on land-use estimated pre-modern average concentration of 0.6 mg TN/l (Omernik, 1976) and historic flows	10.28	Reference Value
Trinity-San Jacinto**	15.2680	Based on land-use estimated pre-modern average concentration of 1.2 mg TN/l (Jensen et al., 1991) and historic flows	4.27	Reference Value
Lavaca-Colorado**	13.3600	Based on requirement to maintain productivity at least 101 g C/m^2/yr; Matagorda bay FINS (1997)	1.71	Lower Bound on Inflow in TxEMP
Guadalupe	2.4720	Based on land-use estimated pre-modern average concentration of 0.9 mg TN/l and historic flows	0.86	Lower Bound on Inflow in TxEMP
Mission-Aransas	1.6000	Based on 1977 to 1987 data from TNRCC and USGS	Not Provided	Not Used
Nueces**	0.52	Based on land-use estimated pre-modern average concentration of 1.35 mg TN/l (Baird et al., 1996; Twidwell and Davis, 1989; Omernik, 1976) and historic flows	0.12	Reference Value
Laguna Madre	0.3610	Based on land-use estimated pre-modern average concentration of 1.0 mg TN/l (Baird et al., 1996; Twidwell and Davis, 1989; Omernik, 1976) and historic flows	0.07	Reference Value

* Assuming no changes in stream concentrations and relative importance of various flows compared to recent (past 20 years) historical data.

** Part of a comprehensive nitrogen budget

Table A-3 Sediment Loads to Major Estuaries and Their Use for Freshwater Inflow Recommendations

Estuarine System	Required Total Sediment Load 10^6 kg/yr	Basis for Required Loading	Resulting Annual Inflow 10^3 acre-feet*	Purpose for Which Loading/Inflow Values Were Used
Sabine-Neches	Not Determined	n/a	n/a	Not Used
Trinity-San Jacinto	Not Determined	n/a	n/a	Not Used
Lavaca-Colorado	Not Determined	n/a	n/a	Not Used
Guadalupe	225.6215	Based on offsetting sea-level rise in Mission Lake (Longley and Malstaff, 1994)	439.38	Lower Bound onInflow in TxEMP
Mission-Aransas	NotDetermined	n/a	n/a	Not Used
Nueces	Not Determined	n/a	n/a	Not Used
Laguna Madre**	Sediment load with freshwater inflows is insignificant	Based on Morton et al. (1998)	n/a	Not Used

* Assuming no changes in stream concentrations and relative importance of various flows compared to recent (past 20 years) historical data.

** Part of a comprehensive sediment budget

Table A-4 Summary of TxEMP Solutions for Major Estuaries

Month	Sabine-Neches Estuary Sabine Lake			Trinity-San Jacinto Estuary Galveston Bay			Lavaca-Colorado Estuary Matagorda Bay			Guadalupe Estuary San Antonio Bay		
	MinQSal	MinQ	MaxC	MinQSal	MinQ	MaxH	CriticalQ*	MinQ	Target Q	MinQSal	MinQ	MaxH
January	438,940	624,000	1,246,400	150,490	150,500	150,500	40,300	n/a	319,800	52,420	111,200	111,200
February	354,300	832,500	1,539,200	216,700	216,700	155,200	40,300	n/a	307,900	52,420	124,200	124,200
March	482,000	998,000	1,565,780	363,900	363,900	652,800	40,300	n/a	121,100	52,420	52,420	52,420
April	416,200	778,600	1,136,640	267,270	352,600	632,500	40,300	n/a	141,800	52,420	52,420	52,420
May	379,800	691,900	691,900	309,970	679,700	1,273,700	40,300	n/a	480,100	61,000	186,050	222,600
June	427,460	478,700	478,700	413,560	448,100	839,700	40,300	n/a	376,700	60,860	135,980	162,700
July	377,550	424,470	547,300	211,500	232,700	211,500	40,300	n/a	204,000	60,860	60,860	88,610
August	427,810	361,810	466,500	140,000	154,000	140,000	40,300	n/a	111,700	60,860	60,850	88,330
September	172,550	574,600	574,600	102,960	332,200	103,000	40,300	n/a	206,500	52,420	52,420	52,420
October	429,090	537,900	537,900	78,600	251,900	78,600	40,300	n/a	214,900	52,420	52,420	52,420
November	378,100	237,510	237,550	164,390	351,500	351,500	40,300	n/a	136,900	52,420	73,830	73,830
December	426,660	574,020	574,130	93,870	626,800	626,800	40,300	n/a	128,700	52,420	66,200	66,200
Annual	**4,710,460**	**7,114,200**	**9,596,600**	**2,513,210**	**4,158,600**	**5,215,800**	**432,000**	**n/a**	**2,750,000**	**662,920**	**1,028,850**	**1,147,350**

Month	Mission-Aransas Estuary Aransas & Copano Bay			Nueces Estuary Corpus Christi Bay			Upper Laguna Madre & Baffin Bay			Lower Laguna Madre & South Bay		
	MinQSal	MinQ	MaxH	MinQSal	MinQ	MaxH	MinQSal	MinQ	MaxC	MinQSal	MinQ	MaxC
January	2,940	2,940	2,940	2,230	2,230	2,230	2,080	2,080	2,080	16,950	16,230	16,230
February	4,100	5,010	5,010	2,780	2,780	2,780	1,550	1,550	1,550	16,020	16,020	16,020
March	3,040	3,050	3,050	4,410	4,410	4,920	1,280	1,260	1,360	16,690	16,690	19,720
April	2,950	2,430	2,430	5,180	5,180	5,180	1,210	1,200	1,290	19,170	19,170	22,650
May	3,850	12,860	19,120	32,130	32,140	37,770	1,460	1,520	1,740	22,230	26,250	27,830
June	2,340	10,660	15,830	9,280	19,990	36,430	940	2,010	2,300	22,090	22,090	23,000
July	1,910	1,410	1,410	9,820	6,980	9,820	1,240	1,750	1,750	18,100	18,100	18,100
August	1,880	2,200	1,880	9,750	9,750	9,750	1,280	1,730	1,820	15,030	15,030	15,030
September	2,750	7,360	17,650	9,600	11,040	9,600	1,490	1,490	1,490	15,510	15,900	16,720
October	1,830	4,290	10,310	4,380	8,690	7,560	1,970	3,480	3,480	16,750	17,170	18,050
November	2,180	3,760	3,760	6,410	7,780	7,780	1,700	1,720	2,140	16,430	16,930	18,330
December	2,780	2,780	2,780	4,670	4,670	4,670	1,770	1,770	1,770	14,920	15,370	16,650
Annual	**32,550**	**58,750**	**86,170**	**100,640**	**115,640**	**138,490**	**17,970**	**21,560**	**22,770**	**209,890**	**214,950**	**228,330**

* Critical flow is divided between the Lavaca River (4,300 acre-feet/month) and the Colorado River (36,000 acre-feet/month). Target flow is also divided between the two river basins.

APPENDIX B

CASE STUDY
PRELIMINARY COMPARISON OF HEFR FLOW REGIME TO FRESHWATER INFLOWS NEEDS FOR THE GUADALUPE ESTUARY BASED ON THE STATE METHODOLOGY

Senate Bill 3 requires that environmental flow recommendations be developed for both protecting riverine instream uses and providing adequate freshwater inflows to bays and estuaries. This twofold directive has the potential to generate inconsistent flow recommendations near the mouths of major rivers if differing methodologies are used for these two systems. There is also the distinct possibility that the environmental flow recommendations for either one of these two aquatic systems could be adequate to provide the necessary flows for the other, which suggests that a single methodology might be adapted and used for establishing flow recommendations for both riverine and estuarine systems within a given river basin.

This section describes a comparison between HEFR, a potential candidate for establishing instream flow recommendations, and the Texas State Methodology, which has been applied and relied on by the state agencies for estimating freshwater inflow requirements for Texas bays and estuaries, as a proof of concept to determine if, and how, these methodologies could be compared. It should be noted that the values in this report are not final values, they have not been approved by any BBEST or BBASC, and are simply presented here as a proof of concept to facilitate more rigorous comparisons in the future.

The Guadalupe Estuary was selected as the location for this example comparison because of the multitude of studies that have been performed in the basin.

1.0 BACKGROUND

Instream flow recommendations and freshwater inflow recommendations can differ in fundamental respects. Instream flow recommendations are typically specified using a daily unit of time with required flow rates expressed in terms of daily average cubic feet per second (cfs). Objectives frequently include maintenance of water quality, provision of adequate habitat for biota, satisfactory movement of sediment, and inundation of riparian habitats. In contrast, freshwater inflow recommendations are typically specified using monthly or longer units of time, with required inflow volumes expressed in acre-feet (ac-ft). Objectives include the establishment of suitable salinity zones for different biota, seasonal patterns of freshets to encourage spawning and migration, influx of nutrients and sediment during high flow periods, and desirable productivity and/or harvest of key estuarine species.

In this case study, instream flow recommendations from HEFR are compared to freshwater inflow recommendations from the State Methodology at a common location to determine if the two can be reconciled.

2.0 HEFR APPLICATION TO TOTAL INFLOWS TO GUADALUPE ESTUARY

For this case study, HEFR-based instream flow recommendations were developed that could easily be compared to the State Methodology freshwater inflow recommendations for the Guadalupe Estuary. Because the previous application of the State Methodology to the Guadalupe estuary (including San Antonio Bay) quantified total inflows to the system (excepting direct precipitation and evaporation), the HEFR analysis was performed using the best available estimate of historical total inflows to the system.

Daily flow records are available for the San Antonio River at Goliad since 1924, with continuous recordings since 1939. Daily flow records are available for Coleto Creek near Victoria since 1939, with continuous recordings since 1978. Continuous daily flow records are available for the Guadalupe River at Victoria since 1934. However, runoff downstream of these gages, as well as runoff from coastal basins, is ungaged. These have been estimated using the TxRR Rainfall-Runoff model. The gaged and modeled datasets have been combined with diversion and return flow data in the ungaged areas to develop a water balance for total inflows entering the Guadalupe estuary, as follows:

Total Inflows	=	Measured Flow in San Antonio River at Goliad
	+	Measured Flow in Guadalupe River at Victoria
	+	Measured Flow in Coleto Creek near Victoria (when gaged)
	+	Modeled Flows (TxRR) from Ungaged Areas
	+	All Return Flows in Ungaged Areas
	–	All Diversions in Ungaged Areas

Additional details on these calculations are provided in the TWDB-authored appendix of Pulich et al. (1998).

Daily estimates of such TxRR flows are only available from January 1, 1977 through October 31, 2005. Monthly flow estimates are available prior to 1977, but disaggregating these to appropriate daily values was not deemed necessary for this proof of concept case study. Thus, based on the available data and the fact that HEFR needs to use entire calendar years, the HEFR analysis was run from 1/1/1977 through 12/31/2004.

For this case study, the IHA hydrograph separation and HEFR algorithms were run with the default values listed in Appendix A of SAC (2009a), except that the winter season was specified to start in January. This was chosen to allow the wet spring months of April, May, and June to be grouped together into one season.

The HEFR-input 7Q2 value was set to the sum of the published San Antonio River at Goliad 7Q2 value plus the published Guadalupe River at Victoria 7Q2 value. This resulted in a value of 827 cfs and essentially ignores the other flow contributions in the calculation of 7Q2. The results indicate that the monthly medians of the IHA identified extreme low flows were always

less than 827 cfs and thus this summed 7Q2 was specified as the subsistence flow recommendation for each month.

The resulting HEFR matrix is shown in Figure B-1.

Overbank Flows	Return Period (R) : 2.3 (years)		Duration (D) : 23 (days)	
	Volume (V) : 489751 (ac-ft)		Peak Flow (Q) : 40790 (cfs)	
High Flow Pulses	F: 1	F: 1	F: 1	F: 1
	D: 8	D: 8	D: 7	D: 7
	Q: 8207	Q: 8071	Q: 6641	Q: 7314
	V: 70612	V: 59571	V: 54290	V: 53442
	F: 2	F: 2	F: 2	F: 2
	D: 6	D: 5	D: 5	D: 5
	Q: 4747	Q: 4009	Q: 3840	Q: 4709
	V: 35030	V: 30924	V: 30742	V: 31776
	F: 3	F: 3	F: 3	F: 4
	D: 4	D: 4	D: 3	D: 3
	Q: 3296	Q: 3280	Q: 2207	Q: 3205
	V: 18124	V: 18058	V: 13000	V: 13893
Base Flows (cfs)	1964	1953	1816	1756
	1477	1353	1170	1257
	1080	1056	858	873
Subsistence Flows (cfs)	827	827	827	827
	Jan, Feb, Mar	Apr, May, Jun	Jul, Aug, Sep	Oct, Nov, Dec
	Winter	Spring	Summer	Fall

Hydrologic Conditions	
	Wet (75th %ile)
	Average (50th %ile)
	Dry (25th %ile)
	Subsistence

High Flow Pulse Characteristics	
	F = Frequency (per season)
	D = Duration (days)
	Q = Peak Flows (cfs)
	V = Volume (ac-ft)

Figure B-1 HEFR Results for Total Inflows to Guadalupe Estuary

3.0 STATE METHODOLOGY AS APPLIED TO GUADALUPE ESTUARY

The application of the State Methodology for estimating freshwater inflow needs for the Guadalupe estuary is documented in Longley et al. (1994) and Pulich et al. (1998). The resulting inflow recommendations are shown in Table B-1.

MinQSal is conceptualized as a subsistence goal that only meets salinity constraints. MinQ is conceptualized as a maintenance goal that meets harvest/abundance goals and all hydrological and biological constraints. MaxH is conceptualized an enhancement goal that maximizes harvest/abundance and also meets all several biological and hydrological constraints.

Table B-1 Freshwater Inflow Recommendations for the Guadalupe Estuary and San Antonio Bay Based on the State Methodology

Month	MinQSal (ac-ft)	MinQ (ac-ft)	MaxH (ac-ft)
January	52,420	111,200	111,200
February	52,420	124,200	124,200
March	52,420	52,420	52,420
April	52,420	52,420	52,420
May	61,000	186,050	222,600
June	60,860	135,980	162,700
July	60,860	60,860	88,610
August	60,860	60,850	88,330
September	52,420	52,420	52,420
October	52,420	52,420	52,420
November	52,420	73,830	73,830
December	52,420	66,200	66,200
Annual	662,920	1,028,850	1,147,350

4.0 COMPARISON OF HEFR AND STATE METHODOLOGY FLOW RECOMMENDATIONS

HEFR has four flow components (subsistence flow, base flow, high flow pulses, and overbank flows) and four hydrologic conditions (subsistence – subsistence is conceptualized as both a flow component and a hydrologic condition, dry, average, and wet). Two of these components (subsistence and base flows) are relatively steady and lend themselves to comparisons with the monthly State Methodology volumes. However, the other two instream flow components (high flow pulses and overbank flows) are episodic and do not directly compare to the monthly volumes from the State Methodology. Annual volumes of the different flow components produced by the two methods are presented in Table B-2.

To facilitate a useful comparison using these flow components, decisions must be made regarding which month(s) to assign to the high flow pulse and overbank flow components. In the following discussion, comparisons are attempted between flow characteristics under reasonably consistent conditions, e.g., the lowest instream flow recommendation (subsistence) is compared to the lowest freshwater inflow recommendation (MinQSal). High flow pulses and overbank flows are added, as appropriate.

4.1 Subsistence Instream Flows Versus MinQSal Freshwater Inflows

The first comparison, shown in Figure B-2, is between flow recommendations under drought or near drought conditions and contrasts subsistence instream flows against the MinQSal inflow recommendations using common units of acre-feet per month (ac-ft/month).

Table B-2 Annual Volumes of Flow Components for the Guadalupe Estuary and San Antonio Bay Based on the State Methodology and HEFR

Method, Condition and Components	Annual Volume (ac-ft)
HEFR	
Subsistence Only	598,988
Dry Condition	
Base Flows Only	701,923
Base Flows plus High Flow Pulses	817,549
Base Flows plus High Flow Pulses and Overbank Flows	1,260,547
Average Condition	
Base Flows Only	953,495
Base Flows plus High Flow Pulses	1,100,708
Base Flows plus High Flow Pulses and Overbank Flows	1,531,661
Wet Condition	
Base Flows Only	1,357,596
Base Flows plus High Flow Pulses	1,488,046
Base Flows plus High Flow Pulses and Overbank Flows	1,892,649
STATE METHODOLOGY	
MinQSal	662,920
MinQ	1,028,850
MaxH	1,147,350

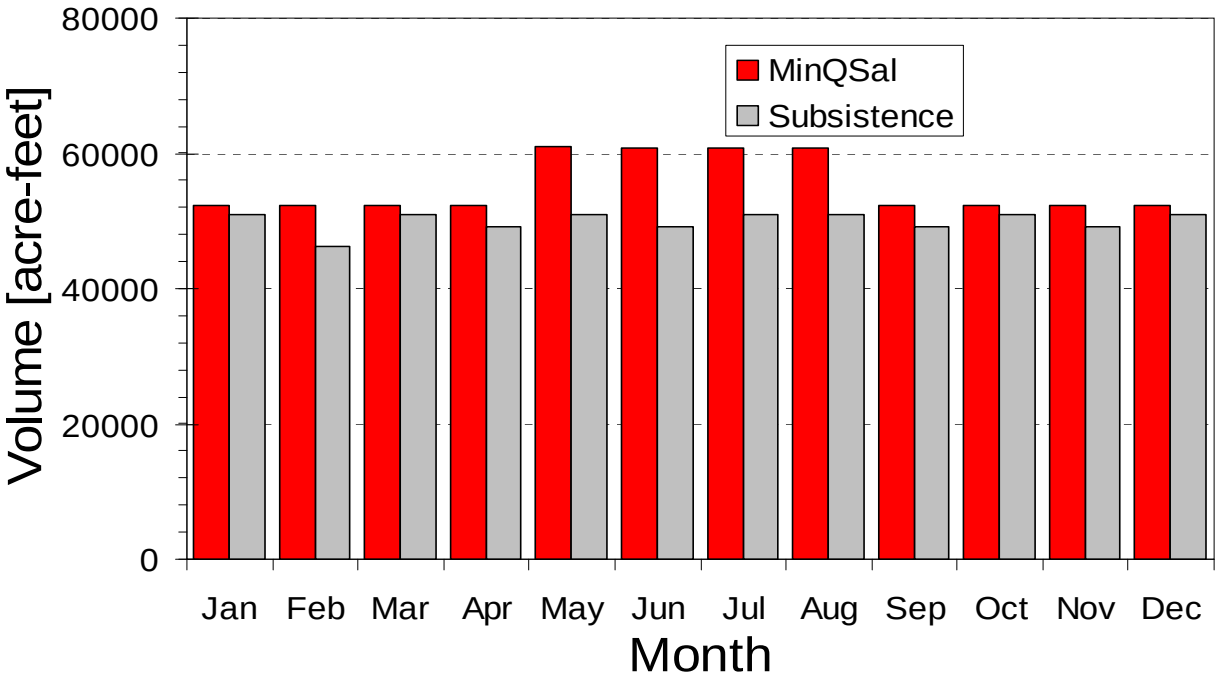

Figure B-2. Comparison of MinQSal Inflows Versus Subsistence Flow Recommendations

As shown in Figure B-2, the values are reasonably similar, with the MinQSal values exhibiting some seasonal pattern and always being a little higher than the subsistence flow values. The slight variations in subsistence flow values in Figure B-2 are solely based on the variation in number of days per month, because all of the monthly subsistence flow recommendations were set to the combined 7Q2 value of 827 cfs (see discussion above). In the subsistence hydrologic condition, there are no recommendations for high flow pulses or overbank flows, so none are presented in this figure.

The annualized flow volumes for MinQSal and subsistence flows are 662,920 and 598,988 ac-ft, respectively, which results in about a 10% relative percentage difference.

4.2 Dry and Average Instream Flows Versus MinQ Freshwater Inflows

The second comparison, shown in Figure B-3, is between flow recommendations during fairly dry or average, but not drought, conditions. In this figure, the MinQ freshwater inflow recommendation is contrasted with the HEFR estimated base flows under dry and average hydrologic conditions.

The MinQ inflows exhibit greater monthly variation than either of the instream flow recommendations (e.g., Jan/Feb and May/Jun are relatively high whereas Mar/Apr is relatively low). The dry and average base flow recommendations exhibit modest seasonal variations.

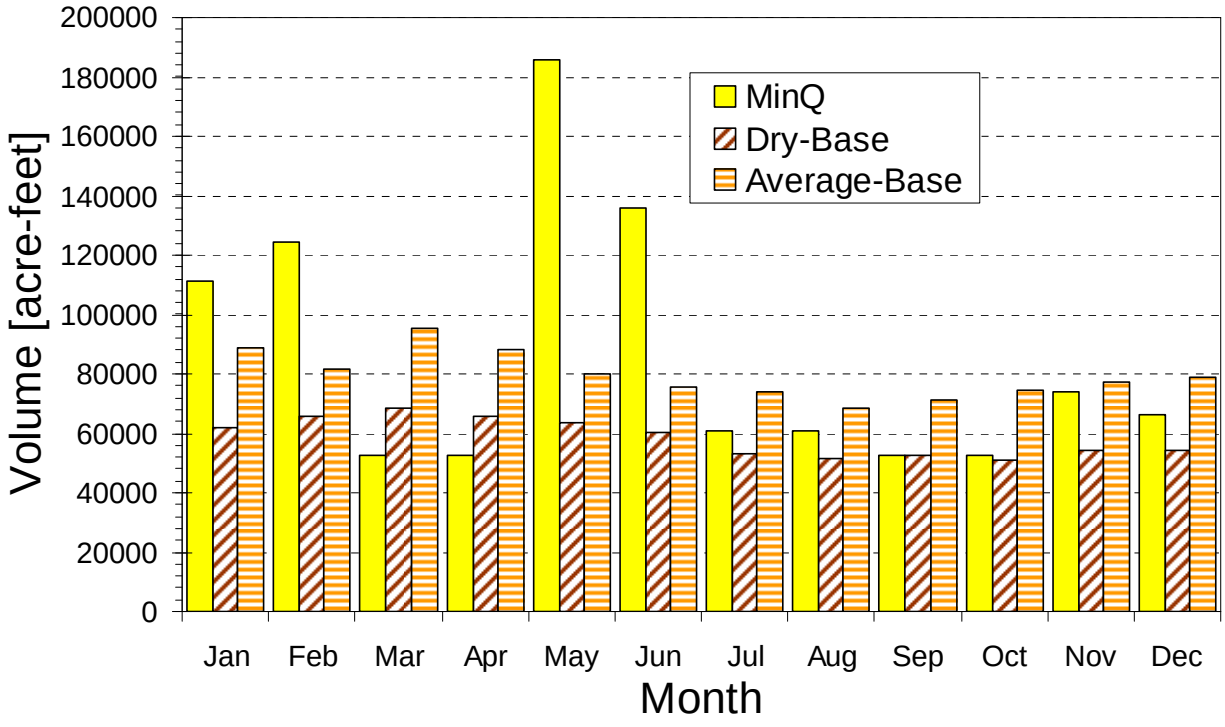

Figure B-3 Comparison of MinQ Inflows Versus Dry and Average Base Flow Recommendations

The annualized flow volume for MinQ is 1,028,850 ac-ft. The annualized flow volume for dry base flows is 701,923 ac-ft and the annualized flow volume for average base flows is 953,495 ac-ft. Again, the instream flow recommendations in this comparison are somewhat lower than the freshwater inflow recommendation. The relative percentage difference between the annualized MinQ flow volume and the annualized average base flow volume is about 8%.

Figure B-4 is an extension of Figure B-3 where the high flow pulses have been added. In this figure, dry condition high flow pulses have been added as one to each month, with two in November. The average condition high flow pulses have been added as one to the latter two months of each three month season.

In this instance, the high flow pulses add a modest volume to the instream flow recommendations. In a few months, the addition of the high flow pulse volume caused an instream flow recommendation to go from below MinQ to above MinQ (compare months where the instream flow recommendations exceeded MinQ in Figure B-3 versus Figure B-4. The total annualized flow volume of average base flows plus average high flow pulses is 1,100,708 ac-ft, which now exceeds the MinQ annualized flow volume. The relative percentage difference between these is 7%.

Note that the high flow pulses offset base flow days. In Figure B-3, the June dry base flow is about 60,000 ac-ft. In Figure B-4, the same June dry base flow is just over 50,000 ac-ft, because the four-day long high flow pulse offsets four days of dry base flow (at 1,014 cfs), so the June dry base flow in Figure B-4 is 4×1014×1.98 = 8,030 ac-ft less than the June dry base flow shown in Figure B-3.

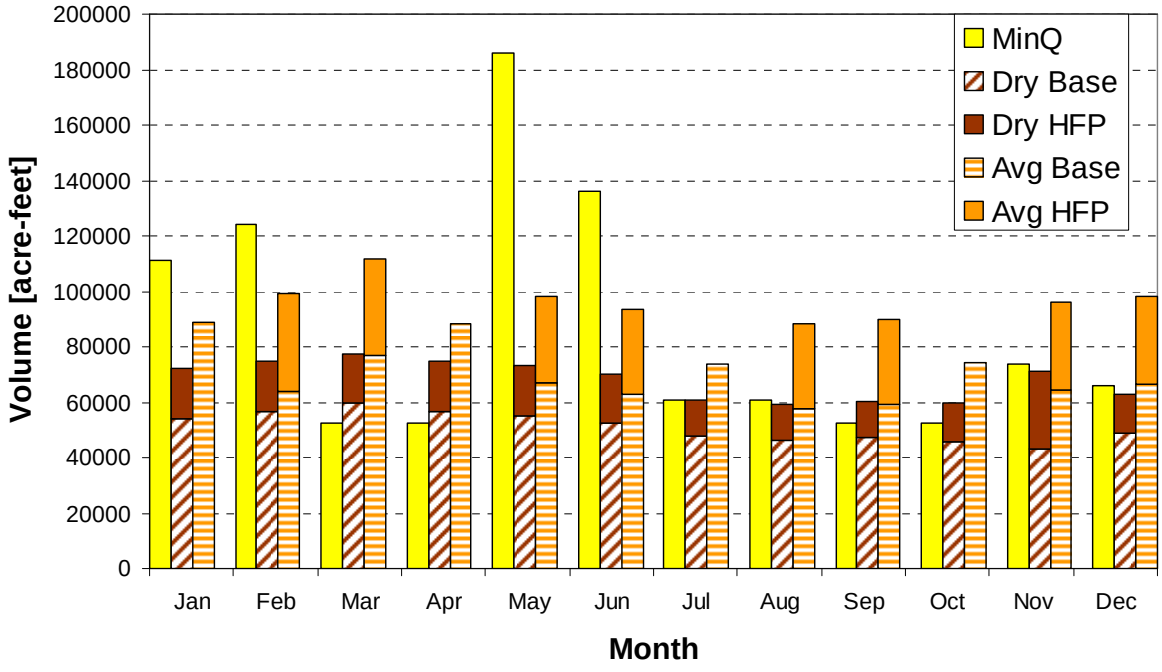

Figure B-4 Comparison of MinQ Inflows Versus Dry and Average Base Flow Recommendations Plus High Flow Pulse Recommendations.

Figure B-5 expands this comparison one step further by adding the overbank flow across the months of May and June (assuming an overbank event happens that year). In the total inflows dataset, May had the most overbank flow events (16% of the total) followed by June (with 14% of the total). The overbank flow recommendation has a duration of 23 days. For display purposes, fifteen of those days (and 15/23 of the total overbank volume recommendation) were assigned to May. Eight of those days (and 8/23 of the total overbank volume recommendation) were assigned to June.

In this example, the overbank flows cause both the dry and average conditions to exceed MinQ in the months of May and June.

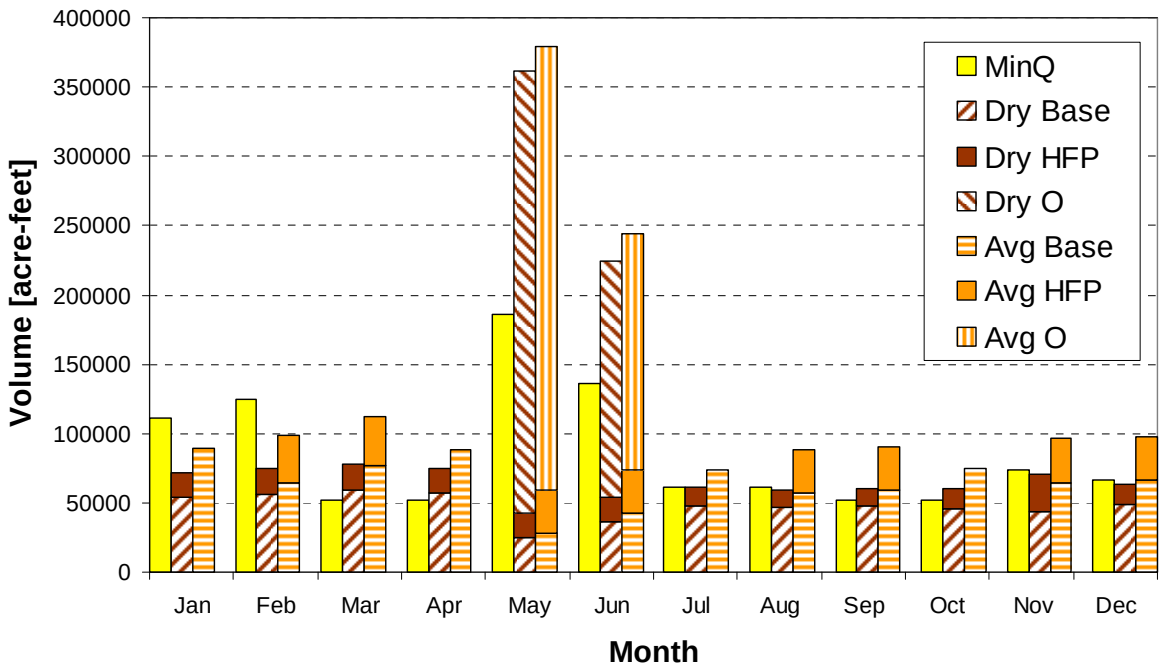

Figure B-5 Comparison of MinQ Inflows Versus Dry and Average Base Flow Recommendations Plus High Flow Pulse and Overbank Flow Recommendations

4.3 Wet Instream Flows versus MaxH Freshwater Inflows

The third comparison, shown in Figure B-6, is between flow recommendations during somewhat wetter periods. This comparison is between the MaxH freshwater inflow recommendation and the wet condition base flows from HEFR. It is important to remember that MaxH is a constrained optimum value. One of the constraints is that the MaxH inflow cannot exceed the monthly median inflow from the 1941-1987 period of record. Thus MaxH is not particularly representative of "wet" conditions, but it is the highest inflow recommendation from the State Methodology and thus is compared against wet base flows here.

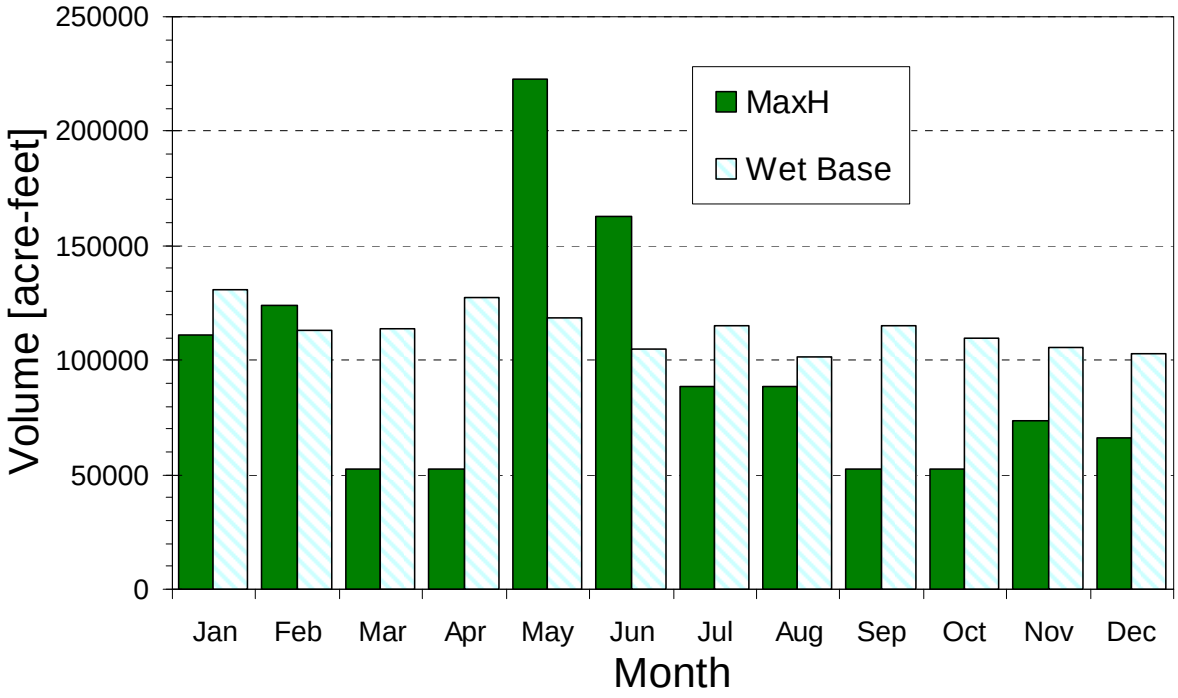

Figure B-6 Comparison of MaxH Inflows Versus Wet Base Flow Recommendations

Again, while the HEFR wet base flow results exhibit some seasonal pattern, there is a more pronounced pattern in the MaxH inflow recommendations. In 9 of 12 months, the wet base flow recommendation exceeds the MaxH inflow recommendation. The annualized flow volume for MaxH is 1,147,350 ac-ft. The annualized flow volume for wet base flows is 1,357,596 ac-ft.

Figure B-7 adds high flow pulses and overbank flows to Figure B-6 to provide another comparison to the MaxH freshwater inflows. In this instance, the high flow pulse assigned to February causes the instream flow recommendation to exceed the MaxH inflow in that month. Similarly, the overbank flows assigned to May and June cause the instream flow recommendations to exceed the MaxH inflows in those months.

4.4 Salinity Implications of HEFR Flow Recommendations

Salinity has been identified as a key water quality characteristic affecting estuarine productivity (Longley et al., 1994). Log-linear relationships between salinity at three locations and the antecedent monthly total inflows to the Guadalupe estuary were developed in Pulich et al. (1998, pg 60). Salinities computed using these relationships and HEFR-generated flows are provided for two of these sites (Upper San Antonio Bay and Lower San Antonio Bay).

It is important to note that flow recommendations developed through the Senate Bill 3 process will only apply to water right permits that are issued on or after September 1, 2007 (even though many existing water rights already have restrictions that require streamflows to be passed up to

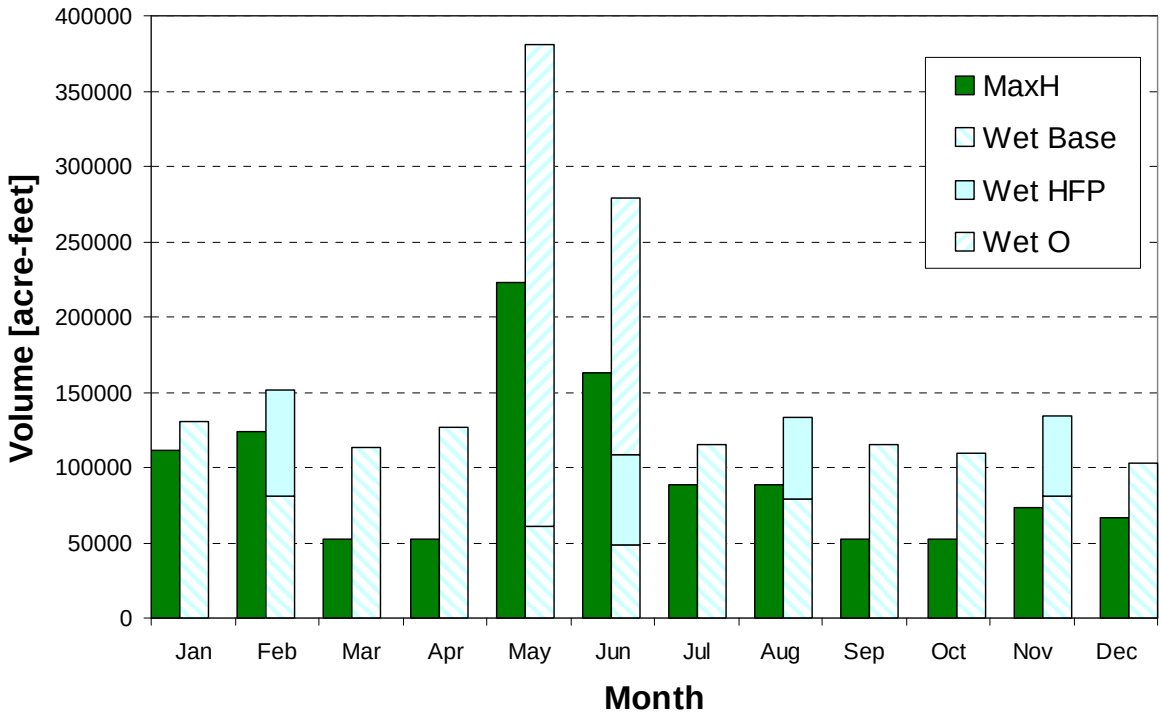

Figure B-7 Comparison of MaxH Inflows Versus Wet Base Flow Recommendations Plus High Flow Pulse and Overbank Flow Recommendations

specified environmental flow values). Furthermore, water rights typically do not require the compulsory release of stored water from a reservoir if natural inflows are below the downstream environmental flow recommendations. Thus, this salinity exercise is a hypothetical evaluation of what salinities might look like in future months if flow recommendations were to be met exactly, but should not be interpreted as a realistic prediction of actual future salinity patterns. Actual future salinities, like actual future freshwater inflows, are dependent on a multitude of factors besides just the flow recommendations, including future weather and climate conditions, actual water usage and return flows, groundwater extraction, and watershed development.

Figure B-8 illustrates the various salinity predictions at the Upper San Antonio Bay site (near Seadrift), along with historical monthly medians from two separate datasets (Hist Median TWDB and Hist Median TPWD) and an historical annual median from a third dataset (Longley Annual Median). The data "Hist Median TWDB" were calculated by querying the TWDB datasonde database for the San Antonio Bay site (near Seadrift) and excluding data that have not been QA/QC'd. This process resulted in only data from the late 1980s through the early 2000s, depending on the month, remaining for the analysis. Data were not further processed, thus the presented historical median values represent a partial description of the past behavior of the system. The data "Hist Median TPWD" were calculated by querying the TPWD Coastal Fisheries database in the vicinity of Seadrift, including data from 1991 through 2008. Also shown in Figure B-8 is the annual median salinity value at Seadrift as reported in Longley et al. (1994, pg 29, 3.25 ppt)

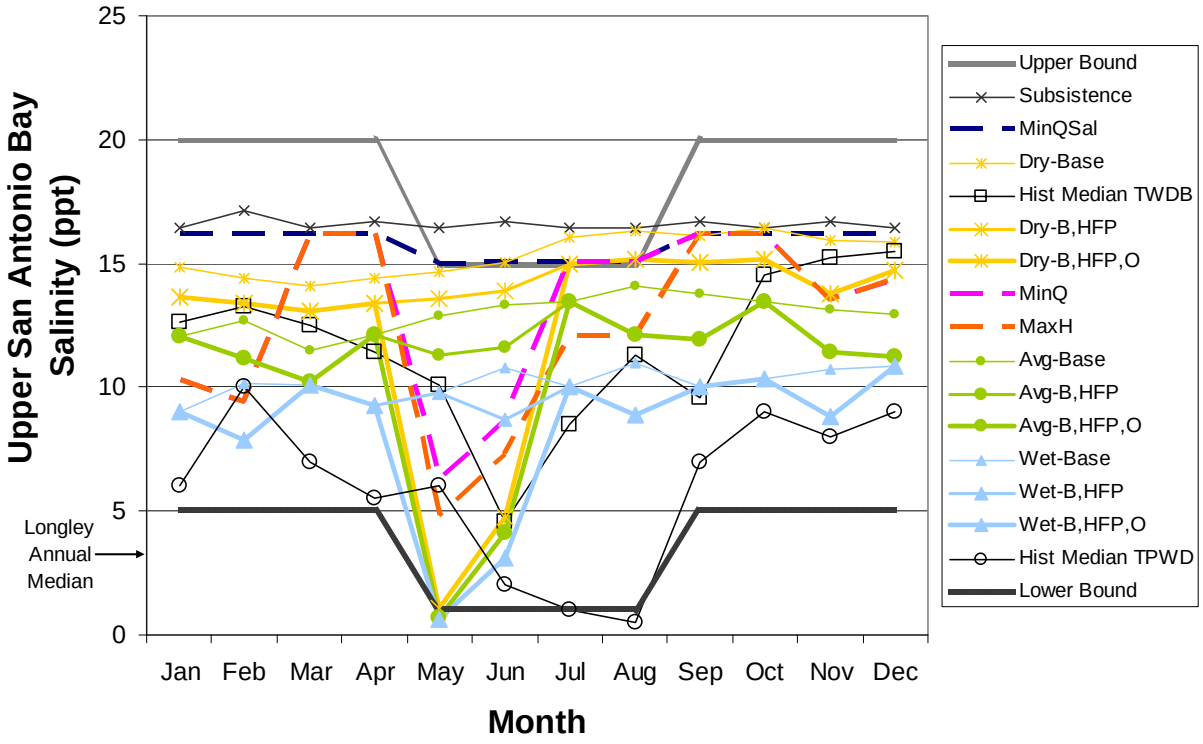

Figure B-8 Salinity Predictions and Historical Median Salinity Values in Upper San Antonio Bay

Several observations can be made from this figure:

- Some of the subsistence and dry baseflow recommendations result in salinities that exceed the State Methodology upper salinity bounds in the summer (most notably in July and August), as occurs naturally as well.
- The subsistence flow recommendation results in salinities that equal or slightly exceed the MinQSal predicted salinities.
- MinQ and MinQSal inflows produce salinities that are constrained by and therefore equal to the upper salinity bounds in July and August, whereas all of the dry base instream flow recommendations result in slightly higher salinities for these months (again, which also occurs naturally).
- With overbank flow volumes distributed across May and June, the dry, average, and wet instream flow recommendations result in dramatically lower salinity predictions in these months, as compared to the same categories without overbank flows. In May, these predicted salinities fall slightly below the State Methodology lower salinity bounds.

Figure B-9 illustrates a similar analysis for the Lower San Antonio Bay site. Again, the Longley et al. annual median salinity value (1994, pg 29, 18.46 ppt) is indicated.

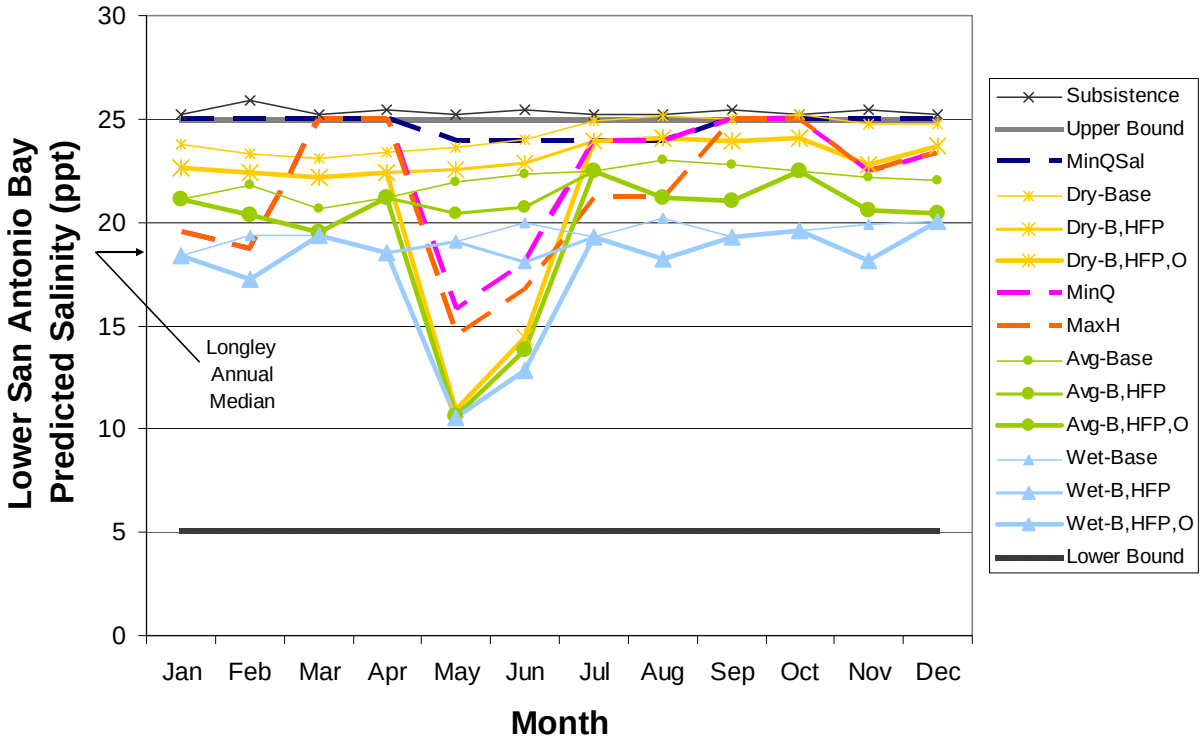

Figure B-9 Salinity Predictions in Lower San Antonio Bay

Observations similar to those above can be made from this figure, with some subtle differences. Plus, there are a couple of additional observations:

- All of the subsistence and the July-October dry baseflow recommendations result in salinities that equal or slightly exceed the State Methodology upper salinity bounds.
- All of the subsistence flow recommendations result in salinities that equal or slightly exceed the MinQSal predicted salinities.
- MinQSal inflows produce salinities that are constrained by and therefore equal to the upper salinity bounds from September through April, whereas the MinQ and MaxH inflows produce salinities that are constrained by and therefore equal to the upper salinity bounds in March and April and in September and October.
- With overbank flow volumes distributed across May and June, the dry, average, and wet instream flow recommendations result in dramatically lower salinity predictions in these months, as compared to the same categories without overbank flows.
- None of the predicted salinities from either the State Methodology inflows or the HEFR flow values fall below the State Methodology lower salinity bounds.

4.5 Summary and Conclusions

In general, the State Methodology inflow recommendations exhibit more pronounced seasonal patterns than the HEFR results. When graphically displaying the results, the seasonal pattern in HEFR is partly dependent on the month(s) to which the high flow pulses and overbank flows are assigned. Because these recommendations are calculated seasonally (or annually in the case of overbank flows) and the events themselves are episodic, a decision must be made with regards to which month(s) to assign these flow components. The selection makes no difference regarding the annualized flow volume, but does affect the graphical displays of monthly patterns.

The HEFR-generated instream flow recommendations appear to fall within reasonable bounds of conceptually-similar flow recommendations from the State Methodology. Thus, if determined to be necessary or desirable, it appears that these two methods could be reconciled, although the comparison of their individual flow values is confounded by several issues, including:

- Different time scales
- Different objectives
- Absence of frequency recommendations associated with the various State Methodology freshwater inflow levels
- Upper flow constraint (historical median monthly flows) on MaxH inflow values results in MaxH not truly representing wet conditions, as the wet condition instream flow is intended to do

The HEFR-generated salinity values require additional thought. While the calculated values generally stayed between the upper and lower salinity bounds, these bounds alone do not necessarily define estuarine health and productivity. In addition, at the Upper San Antonio Bay site, without overbank events, the instream flow recommendations do not produce the lower salinities in May and June that are identified with the State Methodology. This may or may not be a shortcoming of the HEFR methodology with regard to freshwater inflow requirements.

This case study has presented some graphical comparisons of results for the Guadalupe estuary from the State Methodology and from the HEFR-based approach for developing instream flow recommendations, but is not considered to be a comprehensive presentation of this subject. Still, there is information here that may prove to be useful not only with regard to reconciling differences in riverine instream flow recommendations and estuarine freshwater inflow recommendations, but also possibly with establishing a common approach for developing recommendations for both types of aquatic systems within the timeframe of Senate Bill 3.

November 3, 2009

Transmittal to Basin and Bay Expert Science Teams (BBESTs)

Report # SAC-2009-06

Title: Nutrient and Water Quality Overlay for Hydrology-Based Instream Flow Recommendations.

This working draft report completes a series of guidance documents offered by the Science Advisory Committee (SAC) to assist the BBESTs in carrying out their responsibilities to develop instream environmental flow regime recommendations. This document deals with the important issue of taking water quality into account in the flow regime development process. It presents sources and methods for the BBESTs to utilize water quality data and information to refine a hydrology-based flow matrix. It should be used in concert with the previous SAC report on Biological Overlay recommendations (SAC-2009-05) which identified numerous connections between biology and water quality.

The document provides an overview of established Texas water quality programs, with particular emphasis on those programs that involve data collection and analyses. It discusses various aspects of the relationship between water quality and subsistence flows, base flows, and higher flow conditions. It concludes with steps that the BBEST can take to consider water quality in their flow regime recommendations.

This report, as is the case with previous SAC documents, is published as a "working draft." We anticipate that these guidance documents will likely be updated and improved as the SB3 process matures. We acknowledge the helpful participation of the state resource agencies in preparing this and the other SAC reports. Finally, the SAC is hopeful that existing and future BBESTs will find this information useful in their deliberations, and we invite feedback as we all move forward with our respective responsibilities under SB3.

Robert J. Huston, Chairman, SB3 Science Advisory Committee

WORKING DRAFT

Nutrient and Water Quality Overlay for Hydrology-Based Instream Flow Recommendations

Senate Bill 3 Science Advisory Committee for Environmental Flows

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Draft Document Version Date: November 3, 2009

Report # SAC-2009-06

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SECTION 1. INTRODUCTION AND BACKGROUND

SB 3 directed the development of environmental flow recommendations for Texas waters through a science-based determination and stakeholder process, followed by Texas Commission on Environmental Quality (TCEQ) rulemaking. Environmental flow regimes are defined as schedules of flow quantities that reflect seasonal and yearly fluctuations for specific areas of watersheds, support a sound ecological environment, and maintain the productivity, extent, and persistence of key aquatic habitats. The Science Advisory Committee (SAC) provides an overview of how hydrologic data might be used to develop hydrology-based flow regime recommendations (SAC 2009a) and describes one piece of the collaborative process envisioned by SB 3 for the identification of flows to maintain a sound ecological environment in rivers and streams. The document notes that other disciplines such as biology, geomorphology, and water quality also warrant specific attention to ensure that instream flow recommendations are based on the broadest set of information available. The approach taken by the SAC is to have these disciplines addressed as separate assessments or overlays on the hydrology-based analyses.

Water quality is the focus of this overlay document. Numeric and narrative criteria developed by the state address matter carried in suspension and solution, such as dissolved and suspended solids, as well as nutrients, toxics, indicator bacteria, temperature, pH, dissolved oxygen, and other parameters. Under some circumstances all might play a role in the determination of an environmental flow regime. Changes in a flow regime can be expected to produce changes in water quality conditions. The challenge is to ensure that the recommended flow regime protects water quality, particularly during low or subsistence flow conditions, and also considers water quality needs during higher flow conditions.

It is often assumed that under natural conditions, which may have existed prior to human impacts, the quality of the water supports the desired sound ecological environment. While this may be true it should be recognized that it may be impossible to return to the naturalized flow condition due to land use changes, point and nonpoint source discharges, water supply needs and operational constraints. In addition, ecological changes may have already occurred in response to altered land use patterns and flow regimes. It must also be recognized that natural conditions encompass a substantial range in all of the dimensions of water quality in response to hydrologic, seasonal and weather variations and include a full range of outcomes.

The Water Quality Overlay provides an overview of Texas water quality programs along with the programs that collect and make water quality data available. It then discusses various aspects of the relationship between water quality and subsistence flows and water quality and base and higher flow conditions. The document includes a specific example of the relationship between flow and various water quality parameters and provides steps the BBESTs can take to consider water quality issues in their recommended flow regimes.

SECTION 2. WATER QUALITY PROGRAMS IN THE TEXAS REGULATORY FRAMEWORK

Management and protection of water quality has been a primary mission of the TCEQ and predecessor agencies in Texas since well before the federal Clean Water Act in 1972. The TCEQ has established a set of Surface Water Quality Standards (TCEQ 2000) that includes uses, narrative and numeric criteria and an antidegradation policy. There are general requirements and those that are specific to water quality segments specified in each major river basin, including the Gulf of Mexico. As such, the standards attempt to account for the climatic and hydrologic variation of state waters. The evolution of water quality efforts has historically centered on control of wastewater discharges, partly through developing wastewater discharge permits. In cases where the Texas standards are not attained through normal wastewater permitting, special studies such as Waste Load Evaluations, Total Maximum Daily Load projects, or Watershed Protection Plans are required. In recent years, attention has also been focused on storm water quality and permitting that includes the control of runoff quality associated with construction, industrial activities, and municipal separate storm sewer systems (MS4). The standards are also periodically updated as data and knowledge are improved, and a revision process is underway at this time.

The Clean Water Act framework, implemented by the TCEQ, has five major components laid out in the following sequence: establish the uses of water that will be protected, determine the criteria necessary to protect those uses, base decisions on meeting those criteria, conduct ambient monitoring to ensure criteria are met and uses are maintained, and require corrective action when it is determined that uses are impaired. In order to protect the physical, chemical, and biological integrity of rivers and streams, relevant parameters must be defined and measured, the types and sources of pollution must be identified, and plans to protect and restore water quality must be implemented. Texas uses a varying cycle of activities to manage water quality based on statutorily determined time frames. These activities are coordinated through several programs within the TCEQ.

2.1 Clean Rivers Program

The Texas Clean Rivers Program (CRP) is a state fee–funded program for water quality monitoring, assessment, and public outreach. The program is a collaboration of 15 partner agencies (ex. San Antonio River Authority, Brazos River Authority, Houston-Galveston Area Council, etc.) and the TCEQ. The program provides the opportunity to approach water quality issues within a watershed or river basin locally and regionally through coordinated efforts among diverse organizations. The program has also helped to increase the amount of available water quality data. The CRP works as a hub for participating collaborators to provide data as well as coordinated watershed protection. For detailed information, visit: http://www.tceq.state.tx.us/compliance/monitoring/crp/.

2.2 Surface Water Quality Monitoring Program

The Surface Water Quality Monitoring (SWQM) Program monitors and assesses the quality of surface water to evaluate physical, chemical, and biological characteristics of aquatic systems with reference to human health concerns, ecological condition, and designated uses. In addition to periodic data collection, the SWQM program continuously monitors water quality parameters in real-time in selected watersheds throughout Texas. All water quality data obtained may be used for identifying impairments or concerns, water quality issues, setting water quality standards for water bodies, providing baseline data to support Total Maximum Daily Load (TMDL) studies, or TMDLs and Watershed Protection Plans. The data are also used to improve the science behind Texas Pollutant Discharge Elimination System (TPDES) wastewater permitting. More information can be found at: http://www.tceq.state.tx.us/compliance/monitoring/water/quality/data/wqm/mtr/index.html

2.3 Water Quality Standards Development

The Texas Surface Water Quality Standards can be found in Title 30, Chapter 307 of the Texas Administrative Code. The state and federal requirements for standards development are to establish uses, set criteria to maintain those established uses, and establish an antidegradation policy. The antidegradation policy protects existing uses and establishes extra protection for water bodies that exceed fishable/swimmable quality. Specific numerical criteria for 39 toxic pollutants, expressed as maximum instream concentrations, protect aquatic life. Human consumption of fish and drinking water are protected by numerical criteria for 65 toxic pollutants. Water Quality Standards also specify provisions for controlling total toxicity of permitted discharges, which involves exposing selected aquatic organisms to samples of a discharge effluent. The general criteria are narrative, and apply to all waters in the state. These standards address pollutants for which there are no specific established numerical criteria and also specify procedures for developing site-specific standards for small unclassified water bodies. The Texas Surface Water Quality Standards are available on the TCEQ website: http://www.tceq.state.tx.us/nav/eq/eq_swqs.html

2.4 Water Quality Standards Implementation

Water quality standards are used in assessing water bodies and in restoration and remediation efforts, and are implemented through state certification of US Army Corps of Engineers permits and through effluent limits established in TPDES permits that authorize discharges of wastewater into surface waters of the state. Technical guidance for the latter process is available in the regulatory guidance document *Procedures to Implement the Texas Surface Water Quality Standards*, RG-194 (Revised), January 2003. The document can be accessed from the following website: http://www.tceq.state.tx.us/comm_exec/forms_pubs/pubs/rg/rg-194.html

2.5 Total Maximum Daily Load

The Total Maximum Daily Load Program works to improve water quality in impaired or threatened water bodies in Texas. The program is authorized by and created to fulfill the requirements of Section 303(d) of the Federal Clean Water Act. The goal of a TMDL is to restore the full use of a water body that has limited attainment in relation to one or more of its uses. The TMDL defines an environmental target, and based on that target, the state develops an implementation plan to mitigate anthropogenic sources of pollution within the watershed and restore full use of the water body.

An implementation plan usually puts the TMDL into action by outlining the steps necessary to reduce pollutant loads through regulatory and voluntary activities. Implementation could include adjustment of an effluent limitation in a wastewater permit, a schedule for the elimination of a certain pollutant source, identification of any nonpoint source discharge that would be regulated as a point source, a limitation or prohibition for authorizing a point source under a general permit, or a required modification to a storm water management program and pollution prevention plan. Voluntary measures may also be included to address agriculture, forestry and other nonpoint pollution sources. In some instances, TMDLs are implemented through a plan that protects the entire watershed.

2.6 Assessment

The Texas Water Quality Inventory and 303(d) List describe the status of Texas waters based on historical data and identify water bodies that are not meeting standards set for their use. The Inventory also describes ground water monitoring and assessment activities and identifies constituents of concern in Texas aquifers. The reports satisfy the requirements of the Federal Clean Water Act for both Section 305(b) water-quality reports and Section 303(d) lists. The Inventory and List are produced every two years in even-numbered years, as required by law. A List must be approved by the EPA before it is considered final. A list of approved inventories can be found on the TCEQ website: http://www.tceq.state.tx.us/compliance/monitoring/water/quality/data/wqm/305_303.html

SECTION 3. WATER QUALITY DATA SOURCES

The collection of water quality data was uncommon prior to the 1960s and did not become widespread until the early 1970s. Initially, most water quality monitoring was performed by state agencies and the United States Geological Survey (USGS). Later, the number of organizations collecting data and the provisions for sharing these data have expanded and improved. In addition, the quality and level of quantification has improved for many parameters and there is a continued program of improvement in these areas. The following sections describe some of the key developments in the process of making water quality data available.

3.1 Surface Water Quality Monitoring

The SWQM Information System (SWQMIS) serves as a repository for quality assured surface water quality data and is maintained by the TCEQ. These data are collected by SWQM, contributing river authorities, cities, and other local, state, and federal agencies. TCEQ, CRP and other acquired data go through a quality assurance review prior to inclusion in the TCEQ Surface Water Quality Monitoring Information System (SWQMIS) database. SWQMIS also provides validation and reporting tools, a mapping interface, and modules for tracking information about analytical laboratories, quality assurance documents, and monitoring equipment. Water quality data is used by TCEQ to monitor the impact of anthropogenic and natural influences on Texas surface waters. TCEQ has received and maintained data since 1967, allowing for the assessment of short and long term trends. Existing water quality data can be compared to established water quality standards for stream, reservoir, and coastal segments. The public interface for SWQMIS can be found on the following website: http://www8.tceq.state.tx.us/SwqmisWeb/public/index.faces or http://www.tceq.state.tx.us/compliance/monitoring/crp/data/samplequery.html.

3.2 Clean Rivers Program

The Clean Rivers Program (CRP), established in 1991, provides a mechanism by which river authorities and other entities cooperate and partner with TCEQ in the collection, quality assurance, and sharing of water quality data. The CRP partners collect data and work with cities or other entities in their area to obtain and make data available.

In addition to data collection efforts, CRP partners perform analyses of data in their areas, conduct special studies to address particular issues and issue basin reports. Basin Summary Reports provide an extensive overview of the CRP activities and water quality trends over a five year period. A Basin Highlights Report is an annual update of events affecting water quality and projects performed by CRP partners.

To assure that water quality monitoring resources are used effectively, a statewide database is hosted by the Lower Colorado River Authority (LCRA) to coordinate water quality monitoring activities among CRP partners and the TCEQ. The Coordinated Monitoring Schedule (CMS) manages the monitoring activities of over 50 agencies

statewide across 25 basins, and allows these agencies to administer and share their schedules. The CMS can be found on the following website: http://cms.lcra.org/.

3.3 USGS Data Sources

The USGS maintains a network of approximately 1,000 stream gages in Texas that measure and record a wide variety of hydrologic, climatologic and water quality based parameters. The types of data collected are varied, but generally fit into the broad categories of surface water and groundwater. Surface water data, such as gage height (stage), streamflow (discharge), temperature, rainfall, conductivity, dissolved oxygen, humidity, evaporation, etc, are collected from major rivers, lakes, and reservoirs. Groundwater data, such as water level, are collected at wells and springs. These data are made available electronically on a near real-time basis via the National Water Information System (NWIS), developed and hosted by the USGS. Information for a specific stream gage(s) can be downloaded directly from the website: http://waterdata.usgs.gov/nwis/sw

3.4 Water Quality Management Programs

In addition to the routine monitoring programs above, water quality data are also obtained from special studies or planning efforts. Typically, water quality data produced from these studies and efforts are housed within SWQMIS. Data that are not stored in SWQMIS can be obtained by contacting the respective TCEQ program areas that conduct or oversee the special studies or planning activities.

3.4.1 Watershed Protection Plans

TCEQ and the Texas State Soil and Water Conservation Board (TSSWCB) support the development and implementation of Watershed Protection Plans as a means to prevent or manage nonpoint source pollution. These plans are developed through local stakeholder groups with funding and technical assistance from the TCEQ or the TSSWCB, and the U.S. Environmental Protection Agency. The TCEQ is the State's lead agency for preventing and abating nonpoint source pollution from urban and other nonagricultural sources. The TSSWCB fulfills those responsibilities for agricultural and forestry lands. Both agencies administer grant funds that may be used to prevent or reduce nonpoint source pollution. Data collection efforts are focused on the constituent of interest (e.g. nutrients or bacteria) in an effort to determine pollutant loadings from nonpoint sources. More information can be found at the TCEQ website: http://www.tceq.state.tx.us/compliance/monitoring/nps/mgmt-plan/index.html

3.4.2 Use Attainability Analysis

Use Attainability Analyses (UAAs) are assessments of the physical, chemical, and biological, and economic factors affecting attainment of a water body use (40 Code of Federal Regulations §131.10(g)).[1] UAAs are used to identify and assign attainable uses and criteria to individual water bodies. In general, UAAs are performed on impaired

[1] Although economic factors may be considered, economic hardship has rarely or ever been employed in Texas UAA assessments.

water bodies as indicated in the Texas 303(d) List. UAAs that involve data collection typically involve a wide range of data types including biological (macroinvertebrates and fish), physicochemical (DO, temp, pH, specific conductivity, nutrients, TSS, BOD, etc.), and physical habitat parameters collected over multiple sampling events. 24 hr data for parameters such as DO, temp, pH, and specific conductivity is often collected. The TCEQ Water Quality Standards Development Program is responsible for the oversight of all UAAs.

3.4.3 Receiving Water Assessments

Smaller water bodies do not have specific uses or criteria established in the Texas Surface Water Quality Standards. Receiving Water Assessments (RWAs) may be conducted in order to establish appropriate uses and criteria for these smaller water bodies. RWAs are site-specific assessments of physical, chemical, and biological factors and are usually conducted when a regulatory action has been taken or is anticipated to be taken by TCEQ or because sufficient concern exists to provide an aquatic life use designation. Data collection for RWAs can include the same data types as for UAAs; however the sampling frequency is generally more limited. All RWAs are coordinated by the TCEQ Water Quality Standards Implementation Program.

3.4.4 Total Maximum Daily Load

The TMDL program is tasked with improving water quality in impaired or threatened water bodies in Texas. The TMDL program collects various types of data to further characterize water body problems such as impaired biological communities, depressed dissolved oxygen, and high levels of bacteria, metals, nutrients, dissolved solids, pH, temperature, organic chemicals, and sediment toxicity, although the specific data collected depends on the pollutant of concern. This program frequently conducts more intensive water quality data collection in support of modeling activities. More about TMDL projects currently under way or completed can be found at the TCEQ website: http://www.tceq.state.tx.us/implementation/water/tmdl/nav/tmdlprogramprojects.html

SECTION 4. RELATIONSHIPS BETWEEN WATER QUALITY AND FLOW

During initial development of a flow regime recommendation, a hydrology-based approach will probably be used (SAC 2009a) as a starting point. Water quality information can then be used as an overlay to make adjustments to the initial flow regime matrix. The flow components recommended through the hydrology-based approach will be similar to the Texas Instream Flow Program (TIFP) framework includes subsistence, base, high flow pulse, and overbank flows, seasonally adjusted as appropriate (TCEQ et al. 2008). Streamflow and water quality parameters are sometimes functionally related; therefore, it is necessary to consider water quality concerns during development and refinement of the flow regime.

In this section, water quality concerns are addressed from two directions. First, the BBESTs should consider whether the recommended flow components are adequate to support water quality standards and support ecological functions related to water quality. Second, while improving water quality is not a specified goal of the SB 3 process, it is an appropriate consideration where a particular water quality problem or concern has been identified (e.g. through the State's 303(d) or 305(b) programs).

Water quality concerns associated with inflows are currently addressed on a case-by-case basis. For example, aeration of water releases may be required in situations where flows released from a reservoir during the summer may have relatively low dissolved oxygen (DO) content. Another example is TCEQ's use of a modified version of the Lyons Method (SAC 2009a) as the basis for establishing environmental flow restrictions for new water right permits and amendments when existing site-specific information is not available. A Lyons Method restriction requires minimum flows, calculated as 40% of the monthly median flow from October to February and 60% of the monthly median flow from March to September. TCEQ typically imposes a lower flow limit equal to the 7Q2 if the Lyons derived value is less than the 7Q2.

4.1 Water Quality Standards in Relationship to Flow

Water quality standards were developed largely in the context of addressing pollution due to human activity, such as wastewater discharges, and thus tend to be oriented toward providing protection under critical low flow conditions. Aspects such as providing pulses of higher flow or modifying the low flow distribution for ecological reasons have not been a focus of water quality standards up to now. Another limitation that must be recognized is that water quality records are available for a short period of time relative to the periods that flow measurements are available. Further limiting the duration of usable water-quality data is the fact that measurement techniques for some parameters are still evolving. Where that evolution is still in progress, we must live with censored data (values replaced by "nondetect" flags when below designated reporting levels).

4.2 Water Quality Considerations for Subsistence Flows

As noted in the Technical Overview document (TCEQ et al. 2008), subsistence flows are infrequent low flows that occur during times of drought or under very dry conditions. The primary objectives of subsistence flows are to maintain water quality criteria and prevent loss of aquatic organisms due to, for example, lethal high temperatures or low dissolved oxygen levels. Secondary objectives may include providing life cycle cues based on naturally occurring periods of low flow or providing refuge habitat to ensure a population is able to re-colonize the river system once more normal, base flow conditions return. Assuming that native fauna are adapted to survive brief periods of subsistence flows; these low flow levels can help to purge invasive species from a stream system. Subsistence flows can also sustain a minimum level of connectivity between pools during dry times.

This description suggests that variability in the flow regime is important and that subsistence flows should be considered in any flow regime analysis. HEFR incorporates a default hydrologic condition where subsistence conditions occur at approximately the 2.5th percentile of the flow record (SAC 2009a).[2] HEFR also allows the user to select other values for subsistence flows, such as the 7Q2. Consideration of the applicability of the default or other values is an important part of the overlay process. Note that having the subsistence flow at the low end of the flow spectrum and overbank flows at the high end assures a high degree of flow variability.

The 7Q2 was established several decades ago to be the practical minimum stream flow for the evaluation and permitting of wastewater discharges in Texas and was defined as a design dilution flow. Although the 7Q2 has not been explicitly evaluated for ecological relevance, its use recognizes that occasional low flow stressors occur naturally over time. As established in the Texas Surface Water Quality Standards, many of the numerical water quality standards for non-tidal streams and rivers do not apply when stream flow conditions are less than "critical low flow conditions", as determined by the 7Q2. The 7Q2 is used in modeling by the TCEQ to determine the allowable discharge load to a stream in Waste Load Evaluations, TMDLs and wastewater discharge permits. To be issued a wastewater discharge permit, an applicant must ensure that the level of treatment at the maximum allowed discharge flow value is sufficient to maintain the dissolved oxygen criterion at the 7Q2 streamflow. In some cases the 7Q2 plays a similar role for other parameters besides oxygen–demanding constituents.[3]

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[2] For example, the IHA method uses a default of the 10th percentile of the Group 1 flows defined as those flows below the 25th percentile, although other flows could be classified in this category. In effect, this is approximately the 2.5th percentile flow.

[3] As stated in TAC §307.8(2) (a) (3) the 7Q2 flows are not intended to serve as minimum flow requirements. “Low-flow criteria in Appendix B of §307.10 of this title are solely for the purpose of defining the flow conditions under which water quality standards apply to a given waterbody. Low-flow criteria listed in Appendix B of §307.10 of this title are not for the purpose of regulating flows in waterbodies in any manner or requiring that minimum flows be maintained in classified segments.”

7Q2 flows are periodically reevaluated by the TCEQ using the most recent available streamflow records; hence, 7Q2 values are sensitive to activities that might affect streamflows, such as wastewater discharges or hydroelectric releases that can sustain low flow conditions that would not exist naturally. Thus 7Q2 flows may be either flows that reflect natural conditions or artifacts of man-made conditions. Because the 7Q2 is calculated using the most recent flow data, it will tend to reflect the most recent streamflow alterations.

Another water quality factor in setting subsistence flows is the evolving nature of wastewater discharges. To some extent the 7Q2 is a legacy of a day when available dilution was an important part of wastewater discharge permitting. For example, the level of treatment required by the Clean Water Act in 1972 was secondary, defined as 30 mg/L of biological oxygen demand and total suspended solids, with no nitrification. Since that time there have been major changes. Most Texas wastewater permits have for many years required much better treatment, such as a BOD concentration of 20 mg/L or lower and essentially complete nitrification, irrespective of streamflow conditions. The effect of these much higher levels of wastewater treatment is that in dry weather conditions there frequently is very little oxygen demand contributed by wastewater discharges, and the traditional assumption that low flows produce low DO levels is often not supported with data. As a consequence relationships between water quality parameters and flow should be quantified with data to the extent that information is available. If data are not available, a valid alternative would be to employ existing water quality models. However, if this is done it is important that modeling employ representative dry weather effluent characteristics.

Depending on the information used in their development, subsistence flows developed based on pre-impact streamflow records may overemphasize the pre-development condition. The SAC (2009c) recommends that in the preliminary development of the flow regime matrix, the 7Q2 value not be used. A subsistence flow based on a more natural flow regime may be less than the 7Q2 at a given point. In some river systems, particularly when pre-impact flows are used in the analysis, the 7Q2 value can exceed not only the subsistence threshold value (e.g. 10th percentile) but also the values generated for base flow conditions. In this situation, the BBESTs should consider the difference between the current 7Q2 and more natural subsistence flows and determine an appropriate subsistence flow for current conditions.

In addition, subsistence flow values should be evaluated and adjusted to ensure water quality parameters such as dissolved oxygen and temperature are maintained in a suitable range to ensure aquatic life persists/endures (SAC 2009c). Relationships between water quality parameters and flow should be quantified to the extent that information is available.

4.3 Water Quality Considerations for Base and Higher Flow Conditions

Embedded in the use of a hydrology-based approach to develop environmental flow recommendations is the assumption that the flow components provide and support

various ecological functions, several of which are related to water quality. As part of the water quality overlay process, it may prove worthwhile to further investigate the relationship between various ecological processes and other flow components such as base and higher flow conditions. It is important to recognize that other flow regime components are important for maintaining the assimilative capacity of the stream and its long term water quality.

Doyle et al. (2005) provides an overview of work on how different flow ranges affect different ecological aspects, drawing on the relation with sediment transport, where moderate flow pulses (1 to 5 year recurrence interval) tend to be the most effective in sediment transport. Doyle et al. investigated four ecological processes: sediment and nutrient transport, habitat regulator, process modulator and ecological disturbance, and found varying types of relations with flow. For example, with sediment and nutrient transport, there would be a difference in the effective flow range depending on the functional relation. With particulate matter (sediment and part of the nutrient pool), there is often an increase in concentration with flow so that the most effective flow for transport will be in the moderate pulse range. But in streams such as the Trinity River shown on Figure 11, where the total N concentrations are highest at the lower flows, which also tend to have the highest frequency of occurrence, the most effective discharge for total N will tend to be shaded more towards the base flows.

From the perspective of habitat regulation, Doyle et al. (2005) found that flow was often a key factor in determining the amount of habitat in a river but that relations could be very different for different species. In relation to process modulation and disturbance, the most effective flow range can be defined for a specific ecological response function. The problem is that there are many different processes and disturbance mechanisms to consider. Developing the target or most ecologically important flow range to emphasize depends on defining the desired ecological response. Related information can be found in previous SAC documents on fluvial sediment transport (SAC 2009b) and biology (SAC 2009c).

Evaluating higher flow recommendations may be more difficult than the evaluation for subsistence flows described above, especially since implementation aspects are undetermined at this time. Because the method of implementation may not be known when the environmental flow regime is developed, the following section only addresses a simple method of assessing the relation between flow and water quality. In general, the level and detail of analysis should be geared to the knowledge of and immediacy of potential actions.

4.4 Developing Flow-Water Quality Relationships

Assuming that the environmental flow regime recommendations involve a change in the distribution and timing of flows that could lead to changes in quality characteristics, a first step is to understand the existing relationship between flow and quality parameters. A simple technique to assess this correlation is to examine plots of flow and water quality parameters. If anomalies in the relationship of flow to water quality are found using simple analyses, the use of more sophisticated statistics and/or modeling could be

productive. For instance, considerable literature discusses using Spearman Rank Correlation tests or other statistics to examine flow versus water quality parameters. Routine analyses used by the USGS to examine relationships between flow and water quality can be found at: http://pubs.usgs.gov/circ/circ1173/Methods.htm.

As an example application of the simple overlay approach, we employ the same station used as an example station in SAC (2009a), the Neches River at Evadale, USGS gage 08041000. Figure 1 shows the location of the station and upstream reservoirs. B. A. Steinhagen Lake began impoundment in April 1951 and impoundment of the Sam Rayburn Reservoir began in March 1965. This station was selected because it had a long period of record (1922–present) that included a substantial period (January 1, 1922 to December 31, 1964 used in the HEFR example) when there was relatively little upstream reservoir development and thus could be taken to approximate natural conditions.

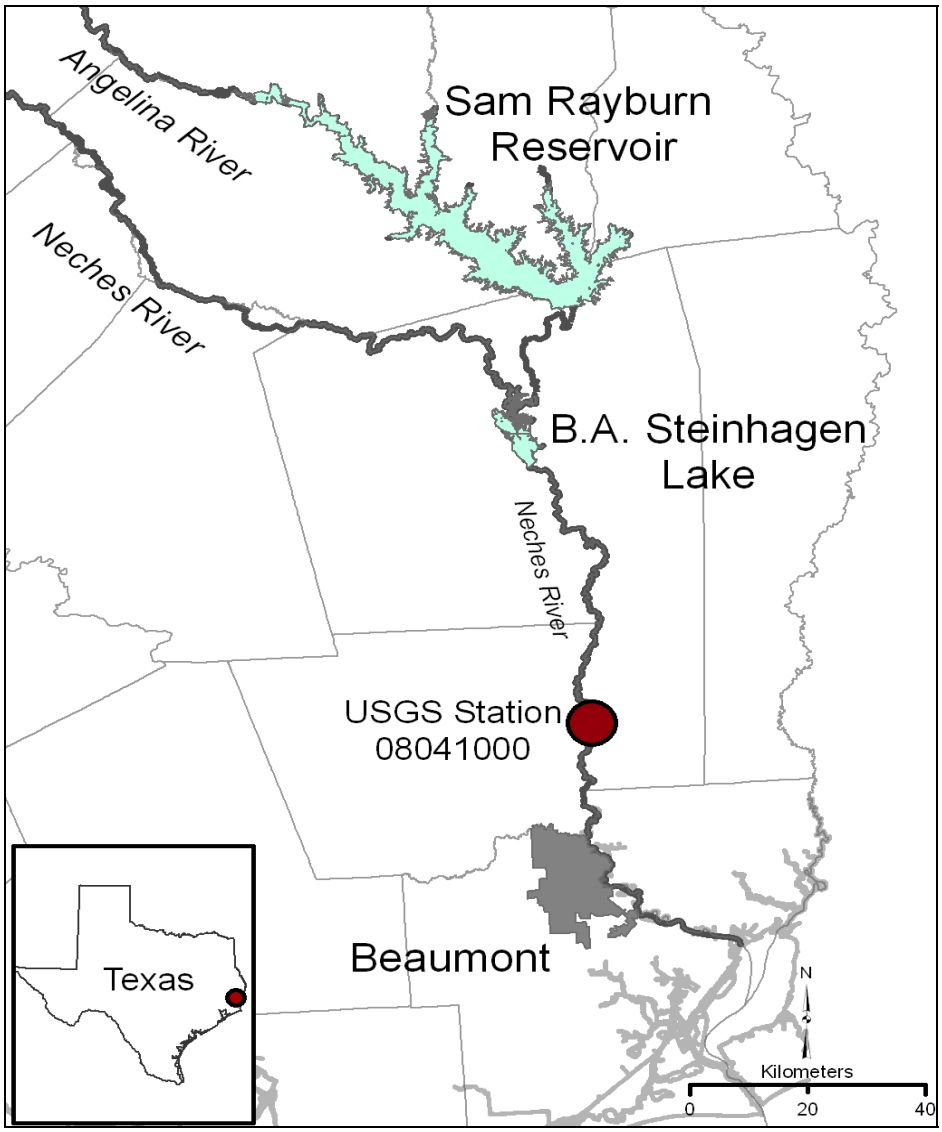

Figure 1. Location of Example USGS Gage

The differences in the flow distribution between the 1922-64 period and the period from 1965-present are shown in Figures 2 and 3. Figure 2 shows the time history of the log daily flows for the two periods, and Figure 3 shows the daily flow exceedance curves for the two periods. There are major differences in streamflow during the two periods due to flow regulation. From Figure 2 it can be seen that the range in flows is substantially reduced after 1965. The peak flows on the left side of Figure 2 are cut by roughly 50%. The average flows listed on Figure 3 for both periods of record are essentially identical, while the median flows after impoundment are higher by about a thousand cfs or 38%, possibly reflecting the effect of upstream hydroelectric releases.

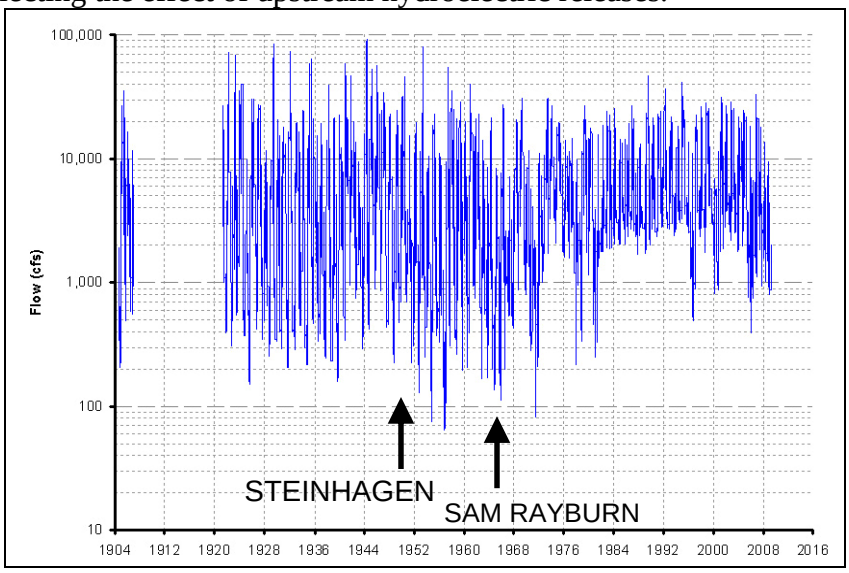

Figure 2. Daily flows at Evadale for period of record

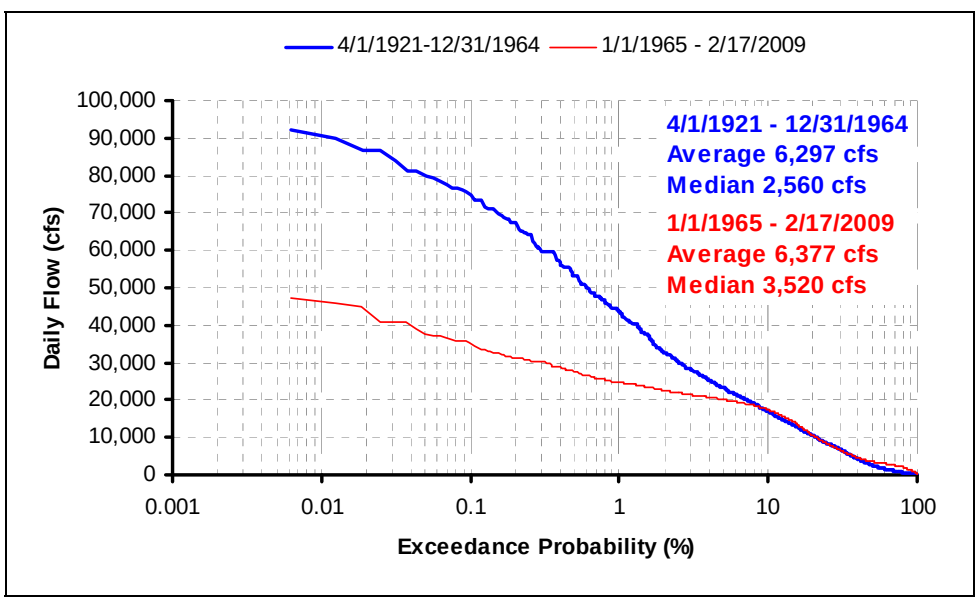

Figure 3. Flow exceedance plots for 1922-64 and 1965-2009

A first step in developing an understanding of how the relevant water quality parameters are affected by different flow conditions is developing correlation plots. To conduct the

analysis, available water quality data at TCEQ Station 10580, which is at the same location as the USGS gage, were downloaded from the TCEQ's SWQM website. Figure 4 shows a plot of nitrite-nitrate-N along with flow data. The starting point in the mid-1970s is true for most water quality parameters, at least those that are readily available and thus suitable for an overlay analysis.

Another point to consider with this example is that over time there have been changes in our ability to measure this and other parameters. Figure 5 shows a similar plot of ammonium-N concentrations and flow that illustrates the period of record available and also the limitations and variability of laboratory reporting limits over time. Since 1998, most of the results are reported as <0.05 mg/L. A similar pattern of non-detects was found for nitrite-nitrate-N on Figure 4 and total phosphorus (not shown). Figures 6 and 7 are similar plots for copper and zinc, showing a pattern of decline over time. At this writing we have no knowledge of significant changes in the watershed that would affect the actual levels of Cu and Zn. The lower concentrations over time appear to be simply the result of better analytical techniques. Nevertheless, at this station at least, we still don't have the ability in routine monitoring programs to quantify the actual stream concentrations of many water quality parameters. These plots illustrate the point that at this station where flows consist largely of reservoir releases, the concentrations of most water quality parameters tend to be quite low with much of the data being reported as lower in concentration than can be measured with techniques routinely employed.

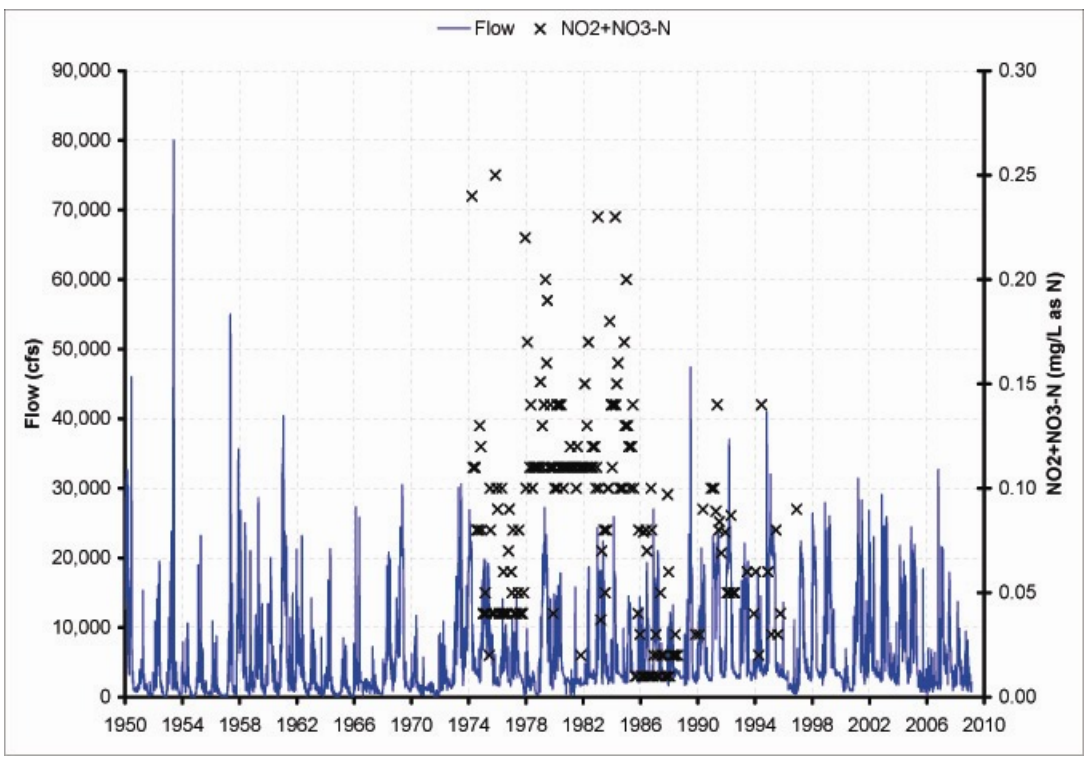

Figure 4. Nitrite-Nitrate-N observations over time with flows

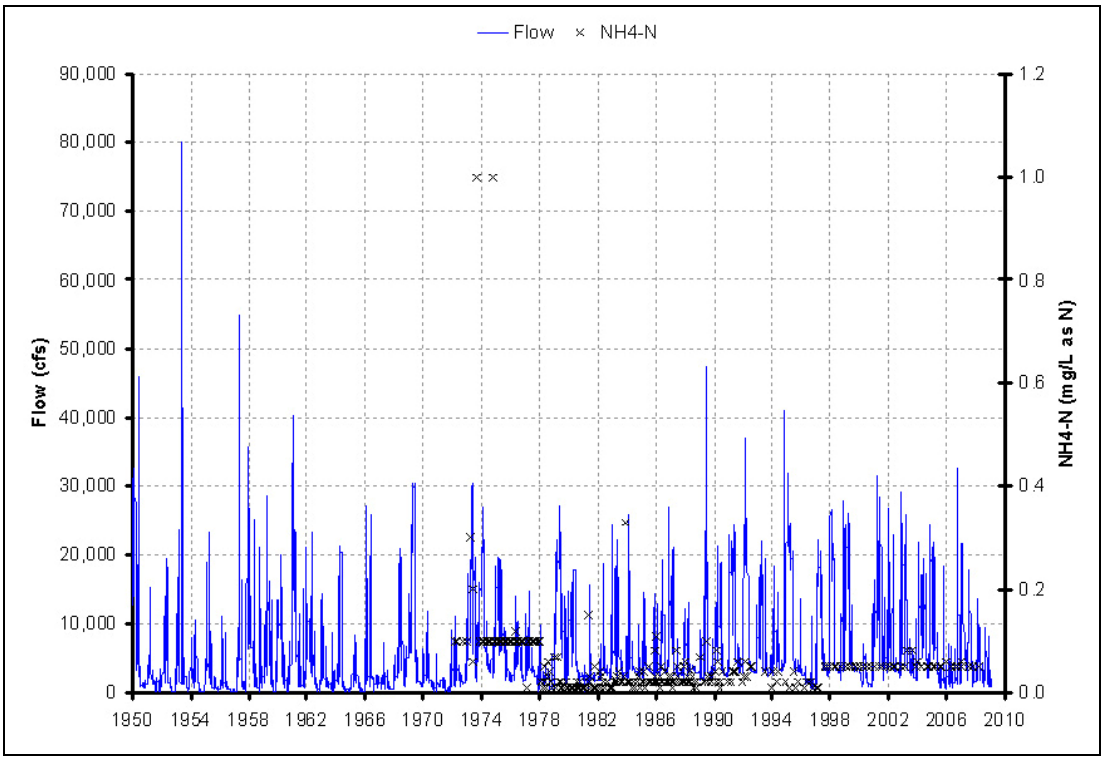

Figure 5. Ammonium-N concentration over time

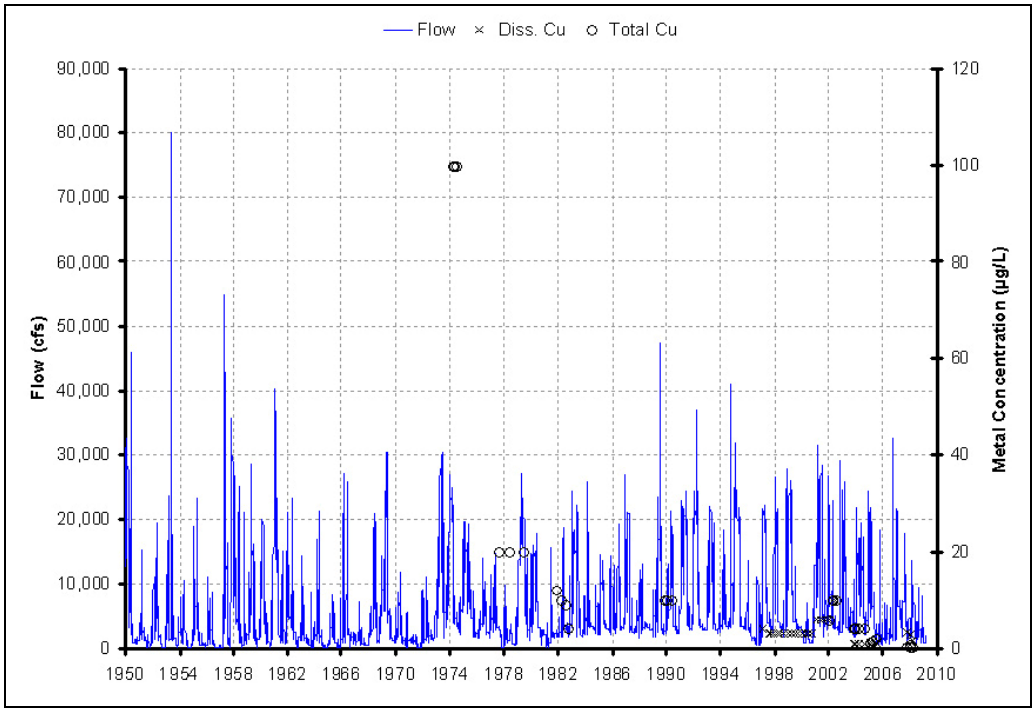

Figure 6. Total and Dissolved Copper data with flow over time

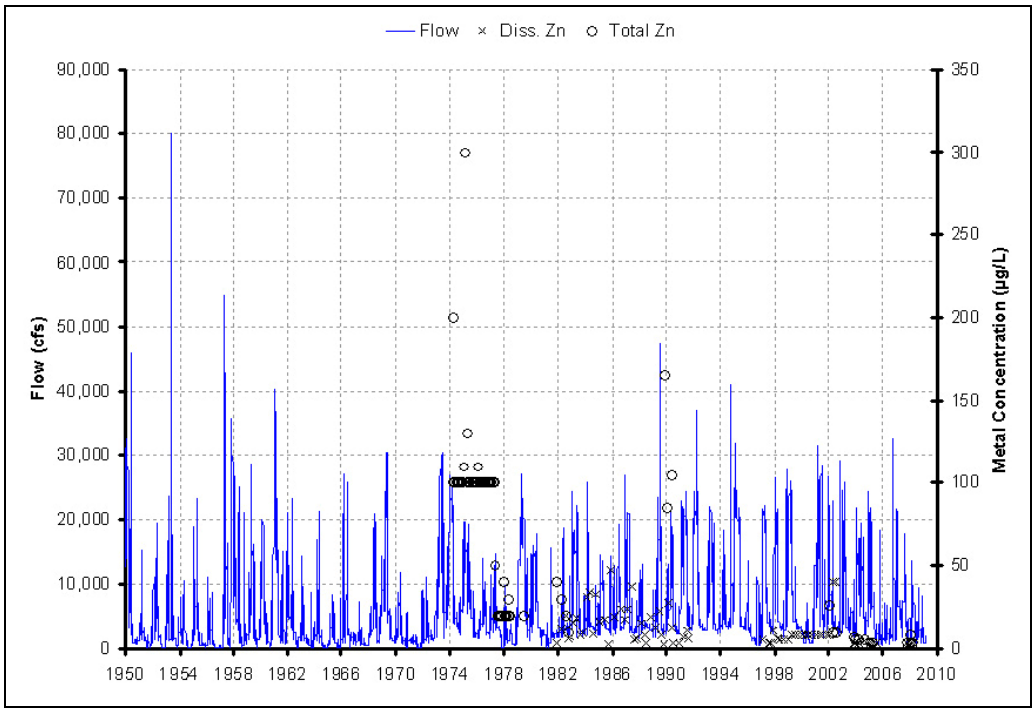

Figure 7. Total and Dissolved Zinc data over time

There are, however, some parameters that have been measured over a significant amount of time and that can be related to flow. Figure 8 shows a plot of conductivity versus log flow. There is a substantial pool of conductivity observations which show the expected decline in conductivity as flow increases. The regression relation explains about 15% of the observed variation. A similar type of relation is shown for the dissolved oxygen (DO) deficit (DO saturation concentration minus measured DO) on Figure 9. Using the deficit formulation has the effect of reducing the variation due to seasonal temperature differences, but in this case, the regression relation still explains only about 10% of the variation. It is interesting in that it indicates that as flow increases there would be a slight increase in deficit or decline in DO, opposite to the conventional water quality wisdom where higher flow brings more velocity and aeration and thus higher DO levels. Part of the explanation may lie with reservoir releases that are sometimes relatively low in DO, tempered by a substantial distance (roughly 60 km) from the reservoir to the station. Higher flows can also result in increased loadings of oxygen demanding compounds. There is also the situation of small but intense rains introducing organic matter from the watershed that decreases DO, but does not have a major effect on flow. The third relation shown is for TSS versus log flow on Figure 10. Here the data would suggest that there is no relation between TSS concentration and flow, and that very few observations over 100 mg/L are found. This is consistent with a regulated stream.

This example station, located in a relatively high precipitation part of the state with little development in the watershed, and a substantial amount of flow regulation, has specific water quality conditions. The concentration of nutrients, metals and suspended solids tends to be low and these parameters might not be greatly affected by changes in flow.

One might conclude from this situation that, based solely on streamflow, small modifications of streamflows not likely have a significant water quality impact. However, because of the number of other variables that influence water quality, predictions of how water quality parameters will change with future hydrologic conditions are difficult to make.

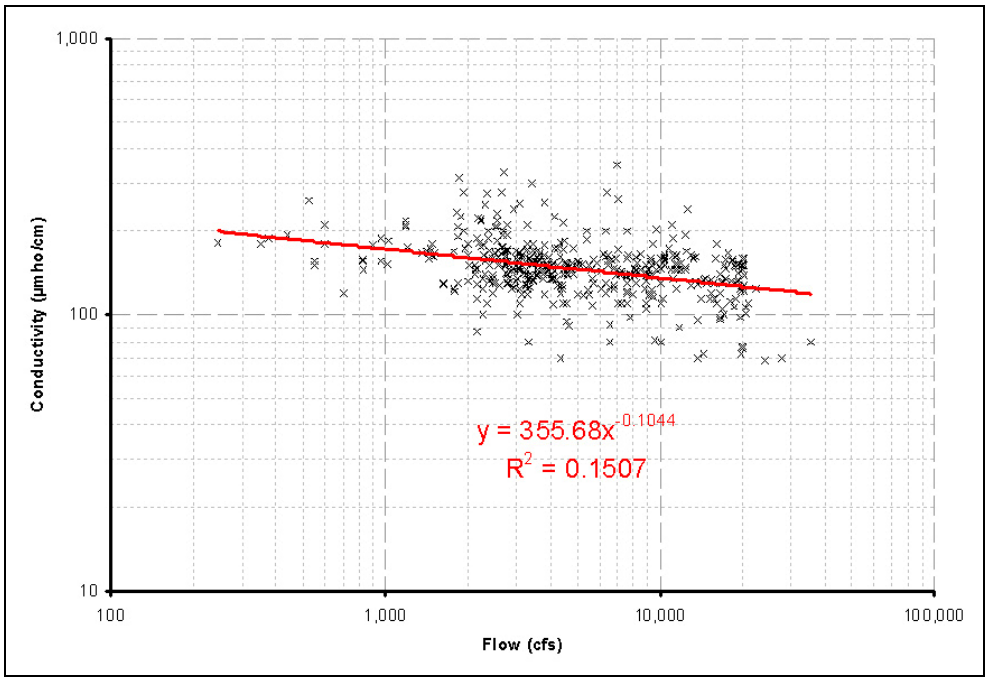

Figure 8. Conductivity versus Flow at Evadale

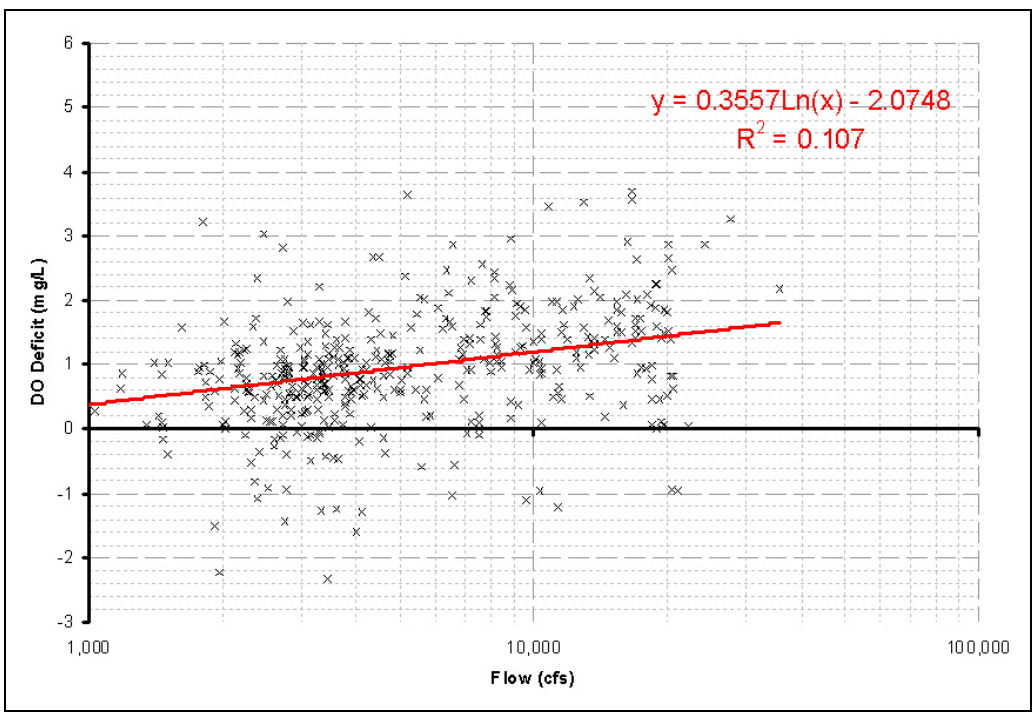

Figure 9. DO Deficit versus Flow

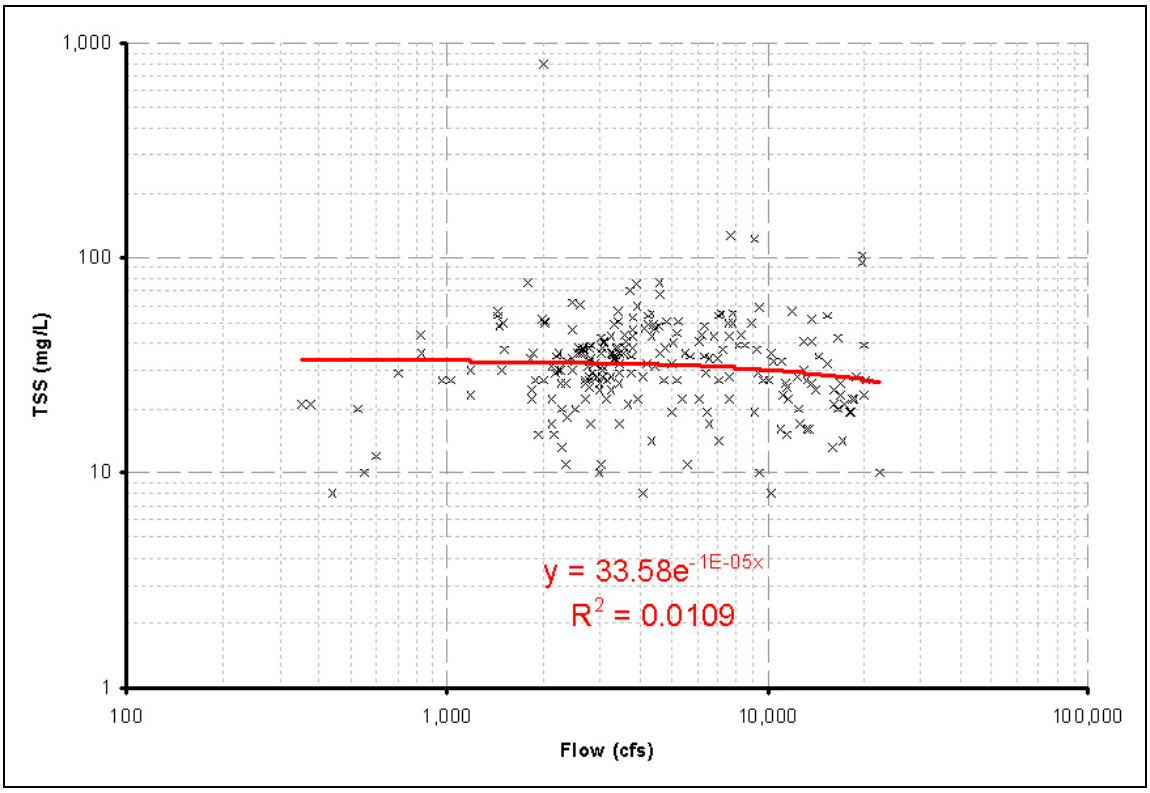

Figure 10. Total Suspended Solids versus Flow

While that may be the case for the Evadale example, it would not necessarily be true for other stations in other parts of the state or with different upstream conditions. A significant relation between flow and total nitrogen content in the Trinity River is shown in Figure 11. At this station, there is a substantial amount of upstream flow regulation and also the addition of wastewater discharges that are relatively rich in nitrogen. In this case, changes in river flow could have a substantial effect on the nitrogen concentrations and load transported.

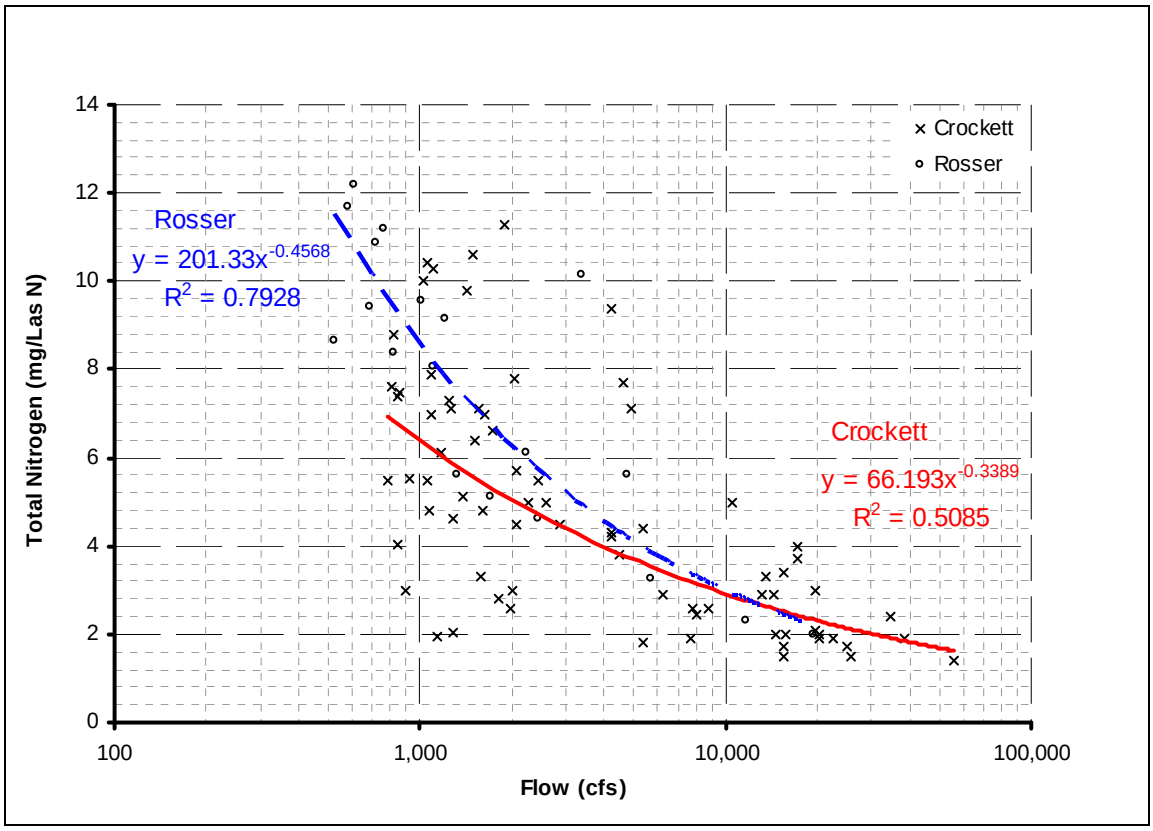

Figure 11. Total N and Flow on the Trinity River above Lake Livingston

The inverse relation between flow and total N concentration shown on Figure 11 is a consequence of a base flow nitrogen source from wastewater discharges and limited inputs from landscape sources. Without such an effect, an opposite pattern might be expected. This can be seen on Figure 12, TCEQ Station 10585, USGS 08033500, Neches River near Rockland, where there is relatively little upstream wastewater influence and no significant flow regulation. In this case, higher flow tends to produce somewhat higher total N concentrations, although there is a great deal of variation.

The key point is that the relation between flow and various water quality parameters can be quite variable. While the effects of major influences such as flow regulation and wastewater discharge are reasonably well understood, postulating a general relationship may be very difficult. The effort involved in examining the relationship with actual data is relatively modest and may be confounded without examining changes in land use

patterns and other causative factors in the contributing watersheds. In light of the fact that the BBESTs may not know how actual flows will be affected, where there is any expectation that a hydrology-based flow recommendation would have the potential to affect actual flows, examining the relation to water quality should be performed. It is important that subsistence flow levels do not create conditions that would compromise water quality and that base and higher flow conditions continue to provide ecologically important functions.

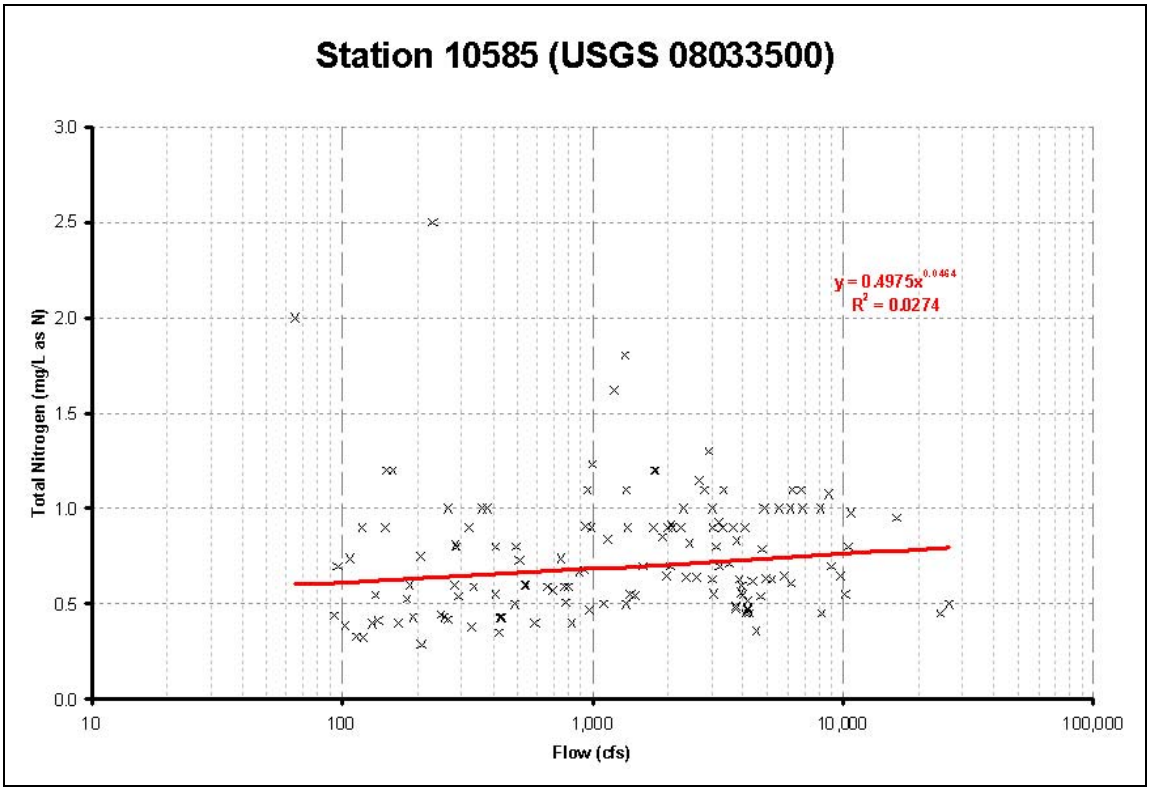

Figure 12. Total N versus log flow at TCEQ Station 10585, Neches River near Rockland

SECTION 5. SUMMARY AND RECOMMENDATIONS

The BBESTs will need to determine how the recommended flow regime affects water quality, consistent with maintenance of a sound ecological environment. In the absence of more detailed information, one alternative would be to use the 7Q2 value in lieu of the hydrology-based subsistence flow calculation. Evaluating higher flow recommendations may be more difficult, especially when considering unknowns, such as possible effects downstream of the point under consideration, associated with implementation of environmental flow standards.

The BBESTs may need to determine whether flow recommendations above the subsistence level, i.e. base flows and high flow pulses, are adequate to maintain water quality conditions. If a standards attainment problem or concern currently exists, then a more rigorous assessment of the recommended flow regime may be required. As part of that assessment, water quality data sources would need to be identified and evaluated. With sufficient data, a relation between flow and quality parameters could be developed.

Assuming that a suitable relationship between flow and quality responses has been identified, the next step would be to assess any potential effects of the initial hydrology-based flow regime on water quality to determine if an adjustment is needed. The assessment should consider the site (flow gauging station) where the environmental flow regime was developed as well as downstream areas. The downstream assessment should consider potential future changes, if known, in the distribution of water quality parameters and changes in the longer term loadings of somewhat conservative parameters such as solids, nutrients, and toxics. This loading dimension could be important if reservoirs were located downstream of the point under consideration, as they tend to retain and accumulate materials contributed in a range of flows.

In the case of the Evadale example, the effect of reservoir regulated flows and ambient water quality conditions has been to make the concentrations of most water quality parameters relatively low and stable. With that as a base condition at this example station, it is difficult to imagine that a change in flows would produce a significant adverse effect on water quality. However, that conclusion may well be different at other stations.

Determining water quality responses to a proposed flow regime poses some challenges. It is important that the recommended flow regime prevent degradation or non-attainment of existing water quality standards. But simply relying on the standards may not be sufficient. It is entirely possible that there could be a water quality effect that, although it did not produce a situation where the standards were not attained, could still be considered adverse to some degree in maintaining a sound ecological environment. In considering such adverse impacts, there may be situations where it is possible to define a change in a flow regime based on water quality improvements considered desirable.

It should be recognized that because this type of water quality assessment has not been routinely produced, site-specific procedures and details may need to be developed. In

some cases, it may be possible to quantify an expected difference in a nutrient or trace metal input in response to a potential change in flows but have no quantitative means to assess the ecological significance of the change. This type of situation should be viewed as a step in the evolution of the process of developing a flow regime and encourage agencies and other workers in the field to sustain monitoring and research, which improves understanding of flow-water quality relationships in Texas aquatic ecosystems.

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WORKING DRAFT

Use of Hydrologic Data in the Development of Instream Flow Recommendations for the Environmental Flows Allocation Process and the Hydrology-Based Environmental Flow Regime (HEFR) Methodology.

Senate Bill 3 Science Advisory Committee for Environmental Flows

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Document Version Date: April 20, 2009

Report # SAC-2009-01-Rev1

PREFACE

This document is the first revision (REV 1) of the Working Draft of Report # SAC-2009-01 first published on February 9, 2009. The new material included in this revision is as follows:

1. An expanded Section 2.2 that provides additional details on the ecological roles and benefits of various flow components;

2. A new Section 5.6 that describes a new hydrographic separation algorithm MBFIT as well as the IHA EFC hydrographic separation algorithm;

3. A new Section 5.7 that describes the new “alternative frequency-based approach” for episodic events calculations; and

4. A new Section 5.8 describing decision points required in applying HEFR.

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SECTION 1
INTRODUCTION

Environmental flows, which include flows in rivers and streams and freshwater inflows to bays and estuaries, have not been addressed uniformly in water development project planning and permitting in Texas. Senate Bill 3 (SB 3), passed by the Texas Legislature in 2007, set out a new regulatory approach to protect such flows through the use of environmental flow standards developed through a local stakeholder process culminating in Texas Commission on Environmental Quality (TCEQ) rulemaking. SB 3 directed the use of an environmental flow regime in developing flow standards and defined an environmental flow regime as a schedule of flow quantities that reflects seasonal and yearly fluctuations that typically would vary geographically, by specific location in a watershed, and that are shown to be adequate to support a sound ecological environment and to maintain the productivity, extent, and persistence of key aquatic habitats.

This document provides an overview of how hydrologic data may be used in the identification of instream flow recommendations pursuant to the requirements of SB 3. As such, it describes one piece of the collaborative process envisioned by SB 3 for the identification of flows to maintain a sound ecological environment in rivers and streams.[1] Other disciplines such as biology, geomorphology, and water quality, although not discussed directly in this report, also warrant specific attention to ensure that instream flow recommendations are based on the broadest set of information available.

It is important to recognize that the provisions of SB 3 dealing with environmental flows are structured specifically to provide a mechanism for protecting certain levels of flow for environmental purposes while at the same time allowing for the use of surface water to meet other needs, including human water needs. The discussion in this document pertains only to the scientific aspects of establishing appropriate environmental flow requirements for river and streams and does not consider the needs of other users or uses for which surface water flows may be required.

Section 2 of this document provides background information on relevant legislation, flow regime concepts, and hydrologic data. Section 3 highlights resources and methods that can be used to generate instream flow recommendations using hydrologic data. Section 4 introduces decisions that must be made when using hydrologic data to define flow recommendations.[2] Clarifying examples are provided throughout this document to provide context to the reader. Such examples are solely intended to illustrate the types of factors that could be considered and should not be construed as recommendations.

This document originally was prepared by the Texas Parks and Wildlife Department (TPWD) at the request of the SB 3 Science Advisory Committee (SAC), with comments from the Texas

[1] Freshwater inflow recommendations for bays and estuaries are not addressed in this document. They are discussed in another companion document.

[2] Section 4 is largely based on a previous document entitled "Decision Points Relevant to using Hydrology Data to Quantify Environmental Flow Recommendations" that was provided to the SAC in draft form in October, 2008.

Water Development Board (TWDB) and TCEQ. Members of the SAC have reviewed, edited, and expanded the document and have provided recommendations regarding the application of the information and procedures presented in the document pursuant to the requirements of SB 3.

SECTION 2
BACKGROUND

2.1 INTERSECTION OF SENATE BILLS 2 AND 3

In 2001, Senate Bill 2 (SB 2) created the Texas Instream Flow Program (TIFP) which mandated that TPWD, TWDB, and TCEQ conduct studies to determine appropriate methodologies for determining flow conditions in the State's rivers and streams necessary to support a sound ecological environment.[3] Priority studies of the lower Sabine, middle Trinity, middle and lower Brazos, lower Guadalupe, and lower San Antonio rivers are to be completed by December 31, 2016. The TIFP is intended to be transparent and to strive for compatibility with existing programs. The methodology provides a general framework for studies across the State but recognizes that individual studies must be tailored to address basin and stream conditions.

Senate Bill 3, passed in 2007, established an aggressive schedule for determining environmental flow standards adequate to support a sound ecological environment in the State's river basins and bay systems.[4] These standards must consist of a schedule of flow quantities, reflecting seasonal and yearly fluctuations that may vary by location.[5] The SB 3 schedule does not allow for the development of multi-year site-specific instream flow studies such as those mandated by SB 2. Instead, SB 3 requires that environmental flow standards be predicated upon the best science and data currently available; it is intended that adaptive management be employed to refine the flow standards in the future.[6] In order to effectively utilize the results from the TIFP studies through the adaptive management process, it is considered desirable for the initial SB 3 flow standards to be consistent with the environmental flow regime framework that is to be applied in the TIFP studies for structuring environmental flow recommendations.

The immediate task for developing the flow standards required under SB 3 is to identify in a short time frame and without the benefit of completed TIFP studies one or more scientifically-based methods for determining an environmental flow regime at a particular location on a stream that will support a sound ecological environment and maintain the productivity, extent, and persistence of key aquatic habitats. The extent to which such an environmental flow regime conforms to the basic structure of that being proposed for application in the TIFP studies is an important consideration. Incorporating the results of TIFP studies into SB 3 environmental flow regimes may be greatly facilitated if the initial environmental flow regime recommendations are consistent with the TIFP flow regime components.

2.2 INSTREAM FLOW REGIME COMPONENTS

Variations in the magnitude, frequency, duration, timing, and rate of change of stream flows are all critical components of a natural flow regime (Poff et al., 1997). Variability in stream flow is

[3] Texas Water Code § 16.059 (Vernon 2008).
[4] Texas Water Code § 11.02362 (Vernon 2008).
[5] Texas Water Code § 11.1471(c) (Vernon 2008).
[6] *See* Texas Water Code §§ 11.02362(m) and (p) (Vernon 2008).

manifested to stream biota as a change in habitat availability. Consequently, the life histories of stream fishes and other aquatic organisms are adapted to the seasonal and interannual variability of low, base, and high flow components. Hydrologic pattern and variability are therefore key determinants of aquatic community structure and stability (Poff and Ward, 1989; Poff et al., 1997; Richter et al., 1996, Dilts, et al., 2005).

Alterations to a natural flow regime may result in decreased richness, diversity, and abundance of aquatic species inhabiting lotic systems. While the elimination of high flows can result in reduced species densities and community diversity (Robinson et al., 1998), stable flow regimes that lack seasonal and interannual variability may favor generalist and non-native species (Tyus et al., 2000). In addition, seasonal and interannual flow variability may benefit native species that have developed life history strategies in response to natural flows. Thus, providing a flow regime based on the natural flow paradigm should provide ecological benefits in stream systems (Dilts et al., 2005).

To date, most instream flow recommendations in Texas have used a single "minimum" flow standard, which may vary by month and location (see discussion on Lyons Method below). Conversely, instream flow recommendations based on a flow regime concept (such as the regime concept found in SB 3) consist of multiple flow regime components (or levels) with specific characteristics. Following the recommendation of the National Research Council (NRC, 2005), and consistent with Maidment et al. (2005), the TIFP (2008) uses a framework that consists of a set of four components of a flow regime intended to support a sound ecological environment. These instream flow regime components are:

- Subsistence flows,
- Base flows,
- High flow pulses, and
- Overbank flows.

Subsistence flows are low flows that occur during times of drought or under very dry conditions (TIFP 2008). The primary objectives of subsistence flows are to maintain water quality criteria and prevent loss of aquatic organisms due to, for example, lethal high temperatures or low dissolved oxygen levels. Secondary objectives may include providing life cycle cues based on naturally occurring periods of low flow or providing refuge habitat to ensure a population is able to re-colonize the river system once more normal, base flow conditions return.

Base flows represent the range of "average" or "normal" flow conditions in the absence of significant precipitation or runoff events (TIFP 2008). Base flows provide instream habitat conditions needed to maintain the diversity of biological communities in streams and rivers. Habitat quality and quantity are important for survival, growth, and reproduction of fish and other aquatic organisms (e.g., mussels and benthic macroinvertebrates, other vertebrates, and flora). Base flows can also support the maintenance of water quality conditions and can contribute to the alluvial groundwater that supports riparian habitats, which are important components of river ecosystems. The structure and function of riparian areas are dependent on flow regimes and these areas serve to connect surface and subsurface hydrology with adjacent uplands (NRC 2002). For riparian vegetation, if the water table drops below the stream level,

older, more mature trees may survive, but younger trees might die and seedlings may not successfully take root. Even mature vegetation might not survive if the water table remains below the root zone for an extended period of time.

High flow pulses are short duration, high magnitude (but still within channel) flow events that occur during or immediately following rainfall events (TIFP 2008). High flow pulses serve to maintain important physical habitat features and connectivity along a stream channel. Many physical features of a river or stream which provide important habitat during base flow conditions cannot be maintained without appropriate high flow pulses. High flow pulses also provide longitudinal connectivity along the river corridor for many species (e.g., migratory fish), lateral connectivity to near-channel features (e.g., connections to some oxbow lakes), and can support the maintenance of water quality.

Overbank flows are infrequent, high magnitude flow events that produce water levels that exceed channel banks and result in water entering the floodplain (TIFP 2008). A primary objective of overbank flows is to maintain riparian areas associated with riverine systems. For example, overbank flows transport sediments and nutrients to riparian areas, recharge floodplain aquifers, and provide suitable conditions for seedlings. Overbank flows also provide lateral connectivity between the river channel and the active floodplain, supporting populations of fish or other biota utilizing floodplain habitat during and after flood events. Other objectives for overbank flows include the movement of organic debris to the main channel, providing life cycle cues for various species, and maintaining the balance of species in aquatic and riparian communities.

Additional (albeit not comprehensive) ecological roles for these different flow components based on Richter et al. (2006) and Richter and Thomas (2007) are summarized below:

<u>Subsistence Flows</u>

- Sustain a minimum level of interconnection between pools
- Provide sufficient flow to preclude lethal temperature and dissolved oxygen levels.
- Purge invasive species

<u>Base Flows</u>

- Provide habitat of sufficient depth and velocity, without excessive velocity which would require finding shelter
- Maintain water tables levels for riparian vegetation
- Enable fish to move longitudinally to feeding and spawning areas
- Keep fish and amphibian eggs wet and suspended
- Provide drinking water for terrestrial animals

<u>High Flow Pulses</u>

- Provide migration and spawning cues for fish
- Move fine sediments and expose cobbles and rocky substrate
- Fill backwater areas and provide some lateral connectivity
- Restore normal water quality conditions following prolonged dry periods.
- Prevent riparian vegetation from growing in the channel
- Scour macrophytes

Overbank Events

- Provide migration and spawning cues for fish
- Provide lateral connection with oxbows, riparian habitats, and floodplain areas
- Shape physical habitats
- Drive lateral movement of the river channel
- Provide nursery areas for juvenile fish
- Recharge the floodplain water table
- Deliver sediments and nutrients to the floodplain and estuaries
- Create key habitat features such as snags
- Maintain diversity in floodplain forest

In addition to identifying individual flow regime components such as the four discussed above, it is important to adequately characterize the components themselves. Important aspects of these flow regime components, particularly the higher flow conditions, may include flow magnitude (rate and/or volume), duration, timing, frequency, and rate of change. Each of these characteristics may have important ecological implications and thus may need to be quantified (Poff et al., 1997; TIFP, 2008). For example, rise rates that are too rapid may wash aquatic organisms downstream before they can find shelter along the river margins. Conversely, fall rates that are too rapid may lead to stranding of aquatic organisms in shallow areas. However, from the standpoint of achieving environmental flow requirements associated with a water right on a stream or river, it is also important to recognize that fully satisfying the need for the episodic (i.e., high flow pulse and overbank) flow regime components often may be dictated more by the natural stream itself and local hydroclimatology than the water right activity. The diversions authorized by a water right or group of water rights may be of such magnitude that they simply cannot significantly impact high flow pulses or flows that cause overbanking.

2.3 HYDROLOGIC CONDITIONS VARY THROUGH TIME

Hydrologic conditions[7] vary through time (e.g., dry, average, and wet periods); recognition of this supports the development of commensurate instream flow recommendations. For example, base flow recommendations during wet conditions could be greater than base flow recommendations in dry conditions and fewer high flow pulses might be needed in average conditions than in wet conditions. This recognition can generate flow recommendations that appropriately balance the needs of both water users and the ecosystem.

In the Caddo Lake/Big Cypress Creek Collaborative Process, different low flow (i.e., base flow) requirements were established for wet years, average years, and dry years.[8] A similar distinction was made in the Savannah River (Georgia) instream flow recommendations (NRC, 2005).

[7] Hydrologic conditions could also be referred to as “climatic conditions,” or “zones” in the parlance of the Texas Consensus Criteria for Environmental Flow Needs (CCEFN; TWDB, 1997), or “water year types” in the parlance of the Klamath River Instream Flow Recommendations (Hardy and Addley, 2001).
[8] October 1, 2008 presentation to SB 3 SAC

Hydrologic conditions do not have to be assigned on an annual basis; they can be associated with any assignment period of interest (see Assignment Period discussion below).

The refinement of flow recommendations considering these varying hydrologic conditions may avoid imposition of unnecessarily stringent flow requirements, particularly if these conditions can be related to biological needs.

2.4 AVAILABILITY AND CONSISTENCY OF HYDROLOGIC DATA

Hydrologic data have several advantages for characterizing riverine systems over many other forms of environmental data in that they are relatively consistently and continuously measured at numerous locations and are also easily obtainable from the USGS.[9] These characteristics, along with the comparatively simple nature of the data themselves, mean that hydrologic datasets can be evaluated using fairly generic statistical approaches and tools. Thus, hydrologic data typically provide the most convenient, initial understanding of riverine systems.

While hydrologic data provide only one perspective, it can be an important one. In its review of the Texas Instream Flow Program, the National Research Council (NRC, 2005) stated that

> *"Hydrology is potentially the most critical element of instream flow studies and has been considered the "master variable" because the biology, physical processes, and water quality components directly relate to it (Poff et al., 1997)."*

Furthermore, the NRC (2005) noted that

> *Hydrologic desktop methods can be very useful in obtaining a ballpark estimate of instream flow needs in rivers for which detailed instream flow studies have not yet been conducted.*

In the context of SB 3, a reasonable approach might be to use hydrologic data to develop initial values for a flow regime and then modify selected values where additional information (e.g., water quality, biology, and geomorphology) is available. This is consistent with the approach taken on the Savannah River, as summarized in SAC (2004):

> *[The Savannah River program] include[s] the use of a desk-top method for establishing initial environmental flow values, an expert panel to review results and make decisions regarding what measures to implement, and adaptive management procedures to address scientific allowances for uncertainty… The environmental flow results from the desk-top analysis were treated as "place holders" for follow-on expert functional analysis of their site-specific ecological significance.*

This approach is also consistent with current water permitting practices in Texas, as TCEQ frequently uses the hydrology-based Lyons Method (discussed below) for establishing

[9] http://waterdata.usgs.gov/tx/nwis/current/?type=flow

environmental flow conditions for smaller water rights and more complex approaches for larger water rights.

SECTION 3
METHODS FOR USING HYDROLOGIC DATA TO DEVELOP INSTREAM FLOW RECOMMENDATIONS

3.1 AVAILABLE RESOURCES

There are several resources available for obtaining information on how to use hydrologic data for evaluating and establishing environmental instream flow recommendations. Two particularly relevant sources are briefly discussed here. Additional sources are provided as citations.

The Instream Flow Council has described and summarized a number of methods for assessing instream flow requirements (Annear et al., 2004). Over 30 techniques are grouped into three broad categories: Standard Setting, Incremental, and Monitoring/Diagnostic. Standard Setting methods (e.g., the Lyons Method) set limits to define threshold flow regimes and can be done relatively quickly using hydrologic data but are not considered as rigorous as methods that also use biologic data. Incremental methods (e.g., the SB 2 TIFP method) analyze one or more variables to enable assessment of different flow management alternatives. Incremental methods are often considered more scientifically accepted but also require more resources to execute since site-specific data must be collected. Monitoring/Diagnostic methods are those methods that can be used to assess conditions and how they change over time. An example of this type of method is the Nature Conservancy's Indicators of Hydrologic Alteration method (IHA).

Based on recommendations from the Science Advisory Committee created by the Study Commission on Water for Environmental Flows (Senate Bill 1639 from 2003), TCEQ created a Technical Review Group (TRG) to review available instream flow assessment tools and to develop one or more desktop methodologies specifically applicable to Texas river and stream conditions. The term "desktop" refers to methods that can be applied using readily available information and do not require site-specific field studies.

The TRG focused its initial review on desktop methodologies that have been applied to Texas streams (TRG, 2008). These included the Lyons Method, the Consensus Criteria for Environmental Flow Needs, the Texas Method and IHA. After further deliberation the TRG chose to focus its final review on the Lyons Method and IHA.

Key observations relevant to SB 3 include

> *"…the Lyons Method has some scientific basis for its construction, but the degree to which its monthly flow factors effectively represent varying stream conditions across the State remains unresolved."*

and

> *In the absence of any further information and primarily for the sake of continuity with past practices, we reluctantly recommend that the TCEQ continue to apply the Lyons Method as a desk-top approach for permitting purposes.*

Furthermore, the TRG recommended that

> *…the IHA Method may be utilized as a tool to provide guidance to TCEQ with regard to the different flow regimes that might be considered important for protecting instream environmental uses. Nonetheless this method appears impractical for use as the primary desk-top method for establishing environmental flow requirements for small-diversion permits or amendments.*

The TRG operated under the (fairly safe) assumption that any recommended desktop method would only be applied to small diversions that have little possibility of impacting high flow pulses and overbank flows. Thus, the lack of high flow pulse and overbank information in the Lyons Method was not identified as a significant weakness; indeed, high flow pulse and overbank flow recommendations could be seen as a superfluous complexity in small diversion permits. While SB 3 contemplates a multi-tiered flow regime that protects a sound ecological environment, there still may be situations where all aspects of that flow regime, particularly the high flow requirements, may not be appropriate for inclusion as environmental flow conditions on a new water right because the water right activity is of such magnitude that it cannot significantly impact such levels of flow.

Other summaries of instream flow methods, including hydrology-based methods, include Acreman et al. (2005), Maunder and Hindley (2005), Acreman and Dunbar (2004), Arthington and Zalucki (1998), and Jowett (1997).

Several specific methods are discussed below. Each of these specific methods could be used in the context of a larger collaborative effort such as SB 3.

3.2 ADVANTAGES AND DISADVANTAGES COMMON TO ALL HYDROLOGIC METHODS

Hydrologic methods share certain advantages and disadvantages (relative to biological, geomorphological, and water quality methods) in common. Common advantages include: (1) relatively robust and consistent datasets at multiple locations, (2) the understanding that hydrology has been considered the "master variable" with regard to environmental instream flows (Poff et al., 1997), and (3) ease of use.

Common disadvantages include: (1) a lack of validation against biological, geomorphological, and water quality data (e.g., the methods are largely designed to mirror some fraction of historical hydrology and are not based on defined flow alteration - ecological response relationships), and (2) unsuitability where hydrologic data are lacking and cannot be synthesized.[10] Because of these disadvantages, the hydrologic methods are only recommended when sufficient data to define flow alteration – ecological response relationships are unavailable. In Texas, such data are probably currently unavailable on all river segments with the exception of the lower Colorado River. However, even though comprehensive datasets to define flow alteration – ecological responses are generally unavailable, some biological, geomorphological,

[10] Synthesizing hydrologic data involves a wealth of complexities that are beyond the scope of this document.

and water quality data will be available in each major river basin. Thus, following the application of any of these hydrologic methods, it is recommended that this available data be used to corroborate or refine selected hydrology-based flow recommendations, as appropriate.

Important advantages and disadvantages specific to each individual hydrologic method are provided below in the discussion of each method.

3.3 LYONS METHOD

The Lyons Method (Bounds and Lyons, 1979) is a standard setting desktop methodology that uses monthly median gaged flow records to produce monthly instream flow recommendations with the intent of approximating natural flow patterns. The Lyons Method specifies 40% of the monthly median flow from October to February and 60% of the monthly median flow from March to September as minimum flows. The Lyons Method is statistically weighted to provide higher flows during the spring and summer periods, considered most critical to the warmwater fishes found in Texas. The flow values (i.e., 40% and 60% of median) used in the Lyons Method were based on the amount of wetted perimeter of the stream channel supported by limited physiographic field measurements in the Guadalupe River downstream of Canyon Dam.

TCEQ frequently uses a modified version of the Lyons Method as the basis for establishing environmental flow restrictions for new water right permits and amendments when existing site-specific information is not available. TCEQ typically imposes a lower flow limit equal to the 7Q2 if the Lyons derived value is less than the 7Q2. The 7Q2 is defined as the lowest average stream flow for seven consecutive days with a recurrence interval of two years, as statistically determined from historical data, and has been used by TCEQ and others as a minimum flow threshold for protecting water quality. In addition, TCEQ often groups or averages similar monthly values together to produce a reduced number of environmental flow recommendations within the year.

Advantages of the Lyons Method are that it is a simple, hydrology-based, desktop approach for determining minimum flow requirements for habitat protection and is used by TCEQ as the basis for setting restrictions in water right permits. A key disadvantage is that although the calculation generates a flow recommendation analogous to the base flow component, it cannot be used to estimate other flow regime components. There has even been some concern with regard to its potential use for the quantification of base flows. In their review of the Lyons Method, the NRC (2005) stated:

> *Use of monthly medians in a hydrologic desktop method can also yield inconsistent degrees of protection for base flows. Monthly medians are computed using all river flows during the month – base flows, high flow pulses, and even floods are all rolled into the calculation of a monthly median. As a result, it is often hard to predict how closely the median, or a method like Lyons, will compare to base flows.*

Another possible disadvantage is that the Lyons Method does not generate different flow recommendations for different hydrologic conditions (e.g., dry, average, wet), which, particularly for larger water rights, is important.

3.4 CONSENSUS CRITERIA FOR ENVIRONMENTAL FLOW NEEDS (CCEFN)

The CCEFN was developed in the mid 1990s using a stakeholder process led by the TWDB to address water supply demands while recognizing environmental flow needs (TWDB, 1997). The CCEFN uses percentages of naturalized daily flow and provides a tiered set of recommendations for passing flows through reservoirs and past diversion points to provide downstream environmental flows based on calculations of naturalized flow. The CCEFN was developed for use in the water planning process and is used in regional and state water planning and by the TWDB for water supply planning studies and occasionally has been applied by TCEQ in water rights permitting.

The CCEFN defines three zones for the determination of applicable environmental instream flow requirements, with the delineation of these zones being different depending on whether the resulting environmental flows are being applied to a direct diversion from a stream or a reservoir on the stream. For direct stream diversions, Zone 1 conditions occur when streamflow is greater than the naturalized median flow, and this value of flow must be passed downstream before any water can be diverted. Zone 2 occurs when streamflow conditions are greater than the 25th-percentile naturalized flow, but less than the naturalized median (and the 25th-percentile naturalized flow must be passed downstream before any water can be diverted). Zone 3 applies when streamflow decreases to less than or equal to the 25th-percentile naturalized flow and prescribes the minimum flow needed for water quality maintenance. For Zone 3, the minimum flow requirement is a fixed threshold such as the 7Q2 or another flow value. For an on-stream reservoir, zones are defined based on storage in the reservoir at any give time, with Zone 1 conditions occurring when the storage is greater than 80% of the full conservation storage capacity. Zone 2 conditions occur when the storage is between 50% and 80%, and Zone 3 occurs when the storage is less than 50% of the full conservation storage capacity. The requirements for passage of inflows through the reservoir to provide environmental flows downstream for each zone are the same as those defined above for direct diversions, e.g., when the reservoir is in Zone 1, the naturalized median flow must be passed downstream.

The CCEFN is a desktop methodology that relies on naturalized flows to produce an environmental flow schedule for planning purposes.[11] While the CCEFN does generate different flow recommendations under different hydrologic conditions ("zones"), it does not generate high flow regime components; the flow restrictions are all analogous to either subsistence or base flows. It is also questionable as to whether naturalized flows should always be used as the basis for establishing the different flow quantities.

3.5 ECOLOGICAL LIMITS OF HYDROLOGIC ALTERATION (ELOHA)

The Ecological Limits of Hydrologic Alteration (ELOHA) uses existing hydrologic and ecological databases from many rivers within a region to generate flow alteration-ecological

[11] Note that while the CCEFN method was developed for daily flow values, its implementation in water planning necessarily uses the State's Water Availability Models (WAMs) that operate on a monthly time step.

response relationships and environmental flow targets. ELOHA envisions multi-step scientific and social processes that involve scientists and stakeholders:

Scientific Process:
Step 1: Build a hydrologic foundation
Step 2: Classify river segments
Step 3: Compute hydrologic alteration
Step 4: Develop flow alteration-ecological response relationships

Social Process:
Step 1: Determine acceptable ecological conditions
Step 2: Develop environmental flow targets
Step 3: Implement environmental flow management

Advantages of ELOHA include (1) a similarity to the SB 3 framework (e.g., scientific and social elements), (2) the use of existing data (e.g., daily gaged flows) and tools (e.g., TX-HAT to classify river segments and IHA to compute hydrologic alterations and develop environmental flow targets) to do a majority of the steps, and (3) application at a regional or basinwide scale.

A key disadvantage of ELOHA is that while some information for completing step 4 of the scientific process may exist, it is likely that sufficient information to effectively define flow alteration – ecological response relationships currently only exists on the lower Colorado River, and such information is not likely to be available on other rivers until more studies, such as the SB 2 TIFP, are complete. To date, ELOHA has not been implemented in Texas and no specific guidelines for how ELOHA can be used are available, thus it is uncertain how long this process would take.

More information on ELOHA may be found at www.Nature.org/ELOHA.

3.6 INDICATORS OF HYDROLOGIC ALTERATION (IHA)

The Nature Conservancy's Indicators of Hydrologic Alteration (IHA) is a software package that is used to assess streamflow conditions and how they change over time. The package was developed to provide hydrologic analysis in an ecologically-meaningful manner. The software program assesses 67 ecologically-relevant (in the opinion of the IHA authors) statistics derived from daily hydrologic data. IHA requires an input file of daily streamflow data which typically can be obtained from the USGS. To adequately capture annual and inter-annual variations in the flow record, 20 or more years of continuous daily flow data are recommended (Richter et al., 1997). The USGS currently lists 480 active gages on their website;[12] additional flow data may be available at selected locations from river authorities and other entities.

IHA also has a feature called the Environmental Flow Components (EFC) model in which each day is assigned one (and only one) of five flow regime categories: extreme low flow, low flow, high flow pulses, small floods, and large floods; an algorithm parses the hydrograph accordingly

[12] http://waterdata.usgs.gov/tx/nwis/current/?type=flow

based on user defined parameters and then generates summary statistics corresponding to each flow regime component.

To date the IHA method has not been fully implemented for any projects in Texas, although there have been applications elsewhere, often in conjunction with another method such as the Range of Variability Approach (RVA). In Texas, the EFC algorithm of IHA has been used in development of the Hydrology-based Environmental Flow Regime (HEFR) method (see discussion below) and in the Caddo Lake/Big Cypress Creek Collaborative Process. IHA software is readily available and relatively easy to use. Although the technique does not directly provide an environmental instream flow prescription, it can be used to support instream flow studies. It can also be useful in determining the characteristics of the natural hydrograph that have been most altered (Annear et al., 2006). While IHA statistics reflect conditions associated with intra-annual variations in hydrologic regimes, ecosystem processes that operate at longer time scales may not be adequately addressed (Annear et al., 2006).

More information on IHA may be found at www.Nature.org/IHA.

3.7 TEXAS HYDROLOGIC ASSESSMENT TOOL (TX-HAT)

The USGS Hydroecological Integrity Assessment Process (HIP) is a suite of software tools that can be used for stream classification, addressing instream flow needs, and assessing hydrologic alterations. A key computational foundation for HIP is a software package called the Hydrologic Assessment Tool (HAT). HAT was recently customized for Texas under a contract between the USGS and TCEQ and is known as TX-HAT (USGS, 2007). HAT and TX-HAT have identical statistical computations and are essentially synonymous for purposes of this discussion.

HAT has many of the same statistical features as IHA. Relative to IHA, it has an expanded list of statistics, but does not parse the hydrograph into flow regime components. A recent comparative review of IHA and HAT was performed by Hersh and Maidment (2006).

HAT/TX-HAT has not been applied in Texas for the purpose of developing environmental instream flow requirements and the stream classifications have not been thoroughly vetted.

More information on HIP/HAT may be found at
www.fort.usgs.gov/Resources/Research_Briefs/HIP.asp.

3.8 HYDROLOGY-BASED ENVIRONMENTAL FLOW REGIME (HEFR)

The Hydrology-based Environmental Flow Regime (HEFR) method is a new, relatively flexible computational approach for developing a flow regime matrix that is consistent with the Texas Instream Flow Program in the sense that it identifies multiple flow regime components and hydrologic conditions across different months, seasons, or years. HEFR was initiated by TPWD with input from other agencies and organizations as an alternative to the Lyons Method for use in water right permitting. Although the method as a whole has not been peer reviewed, the EFC algorithm and IHA software have been used extensively. In addition, HEFR forms the

framework for the environmental flow recommendations in the Brazos River Authority's Systems Operation draft water right permit pending at the TCEQ.

Following a HEFR technical workshop (February 24, 2009), a number of enhancements and modifications were suggested and implemented. This work has been completed at the direction of the SAC. Alternative methods of hydrographic separation and methods of identifying and characterizing high flow pulses and overbank events have been evaluated and implemented. The current version of HEFR includes both the original TPWD methods and the new alternative methods.

The method is based on simple summary statistics of individual flow regime components. Either the EFC algorithm (in the IHA software) or the Modified BFI with Threshold (MBFIT) method (implemented in a Microsoft Excel™ spreadsheet) is used as a convenient tool to parse a hydrograph into individual flow regime components. Excel is then used to efficiently develop summary statistics of these flow regime components. Other software tools could be used for either or both of these steps.

In the context of SB 3, the HEFR methodology has several advantages, including: (1) it is computationally efficient, allowing for repeated tests and exploratory analyses, (2) there is significant flexibility in setting parameters to parse the hydrograph as well as summary statistics of the flow regime components,[13] (3) the results have the same format as expected results from the TIFP studies, and (4) it provides an initial set of recommendations that reflect key aspects of the natural flow regime including multiple flow components and hydrologic conditions (Poff et al., 1997). Disadvantages of this method are: (1) that there is no track record of application and (2) there are few precedents for some of the decisions that must be made by the analyst.

[13] Two examples where this might be helpful include: (1) different options could be selected for stream segments corresponding to Exceptional, High, Intermediate, and Limited Aquatic Life Use subcategories, and (2) different options could be selected for small versus large watercourses, based on evidence that small streams require a larger proportion of average flow than large streams for an equal amount of protection (Jowett, 1997).

SECTION 4
DECISION POINTS WHEN USING HYDROLOGIC METHODS

This section introduces common decision points encountered when using hydrologic data to help define environmental flow recommendations.

The decision points herein are considered to be applicable to any hydrology-based instream flow method. Specific methods will generally require additional decisions related to the exact computations used.

Many of the decision points described herein have been discussed and addressed in other contexts, such as TRG (2008), the ongoing work being performed in support of the LCRA-SAWS Water Project,[14] and applications of the Indicators of Hydrologic Alteration method (IHA) throughout the country.

In this section, the word "analyst" is used to generically refer to an appropriate decision maker(s). In the real world, this may include the Environmental Flows Advisory Group (EFAG), SAC, Basin and Bay Expert Science Teams (BBESTs), Basin and Bay Area Stakeholder Committees (BBASCs), or other persons or entities.

1. Number of Instream Flow Regime Components

The analyst must decide how many flow regime components to use and what aspects of the hydrograph they should represent. As discussed above, the TIFP uses four flow regime components (subsistence flows, base flows, high flow pulses, overbank flows[15]). IHA has five flow regime components (extreme low flows, low flows, high flow pulses, small floods, large floods), but can easily be constrained to fewer components.

All selected flow regime components must subsequently be defined. Both NRC (2005) and TIFP (2008) include definitions that may be suitable (see also Section 2.2). Once results from the hydrologic analysis are available, it may be appropriate to revise either the number of flow regime components or the definitions of the components to better reflect site-specific circumstances and conditions.

2. Geographic Scope of all Instream Flow Recommendations and Spatial Extent of Individual Instream Flow Recommendations

The analyst must identify the geographic scope of watercourses that will be assigned flow recommendations, as well as the spatial extent of each individual instream flow recommendation if such recommendations are applied to river reaches instead of point locations. Examples of information that may guide these decisions include (1) the reaches specified in the TIFP, (2) appropriately selected control points defining key hydrologic features such as major stream segments or downstream of an existing reservoir, (3) bodies of "state" water in the watershed of interest, (4) TCEQ classified segments (note that many classified segments exist within the pools

[14] www.lcra.org/lswp/index.html

[15] The high flow pulse and overbank flow recommendations may include a range of flow magnitudes and characteristics.

of major reservoirs), or (5) streams included in a particular GIS coverage (e.g., the NHDinGEO Dataset, http://nhd.usgs.gov/index.html). A flow recommendation quantified at a USGS gage may apply upstream to the next USGS gage, downstream to the next USGS gage, both, or other. One complicating factor that can arise when applying a hydrology-based flow recommendation (computed at a gage) to other locations is computing the influence of intervening drainage areas and tributaries.

It should be noted that the SAC, with support from the State agencies, also has prepared a separate document dealing with the geographic scope and spatial extent of instream flow recommendations. This document provides more in-depth information regarding the important factors that must be considered when establishing the locations within a basin where environmental instream flow recommendations are to be established (SAC, 2009).

3. Hydrologic Period of Record

In any hydrology-based method, the analyst must decide whether or not to use the entire data record, and, if not, the analyst must decide which period to use. While this decision can take many forms, the three most common are (1) natural (the closest to pre-human impact achievable), (2) post-human impact or regulated (beginning with identifiable changes in hydrology), or (3) the entire period of record. One perspective holds that the natural period of record provides information on the flow conditions that the ecosystem (including biological and geomorphological components) at the location of interest has evolved under (BIO-WEST, 2008). This perspective is purported to facilitate protection of a sound ecological environment as well as the potential restoration of the natural system or portions of the natural flow record that could be restored, as opposed to attempting to protect some modified version of the natural system, with the full knowledge that complete reconstruction of the natural system may not be realistic. As an example of this perspective, the TRG (2008) concluded that "whenever feasible, historical pre-impact flow records should provide the basis for evaluating environmental flow targets." The key here is the word "feasible", suggesting that the state of the hydrologic/ecologic system being considered may play an important role in determining which hydrologic record should be used for establishing environmental flow recommendations. As another example, the second recommendation in the NRC (2005) Executive Summary states that "state-of-the-science programs use natural flow characteristics as a reference for determining flow needs." Conversely, depending on the extent of human impacts, certain aspects of the lotic ecosystem may have adapted to the more recent flow regime and some components of a natural flow regime may no longer be appropriate (e.g., large overbanking events in highly developed floodplains or downstream of a major reservoir). For locations with little to no human impact, it is generally recommended that the entire flow record be used in order to work with the most robust dataset possible. TCEQ frequently uses the entire flow record when applying the Lyons Method. These decisions regarding the hydrologic period of record should appropriately be made on a site-specific and case-specific basis.

A related issue is where to "break" the flow record if pre- or post-human impact is desired to be reflected in the environmental flow recommendations. Statistical tools, such as IHA and TX-HAT, have specific capabilities to help identify statistically different periods, although professional judgment and historical knowledge are also required. The analyst may also encounter breaks in a flow record that require concomitant decisions, such as choosing a period

of record without a flow break or filling in breaks using a nearby gage with an acceptable flow correlation. In addition, depending on project objectives, the analyst may have a specific reason to include, or exclude, the 1950s drought of record in their analysis; although, for conducting water availability evaluations for a proposed water use, the drought of record (which often is the 1950s drought) is always included to provide a meaningful representation of the anticipated variations in the available water supply. Finally, the analyst must decide if the desired period of record is long enough to support a hydrologic analysis and is representative of hydrologic variability at the site (this decision must be made on a site-specific basis; however, as generic guidelines, the IHA manual recommends at least twenty years and the TRG (2008) recommends 30 years; see also Huh et al. (2005).

The hydrologic period of record decision point includes many complexities and this discussion is not comprehensive. The goal of this section is simply to introduce the subject and provide examples of this decision made by other groups.

4. Hydrologic/Climatic Condition

This issue is relevant if the analyst believes that wet periods should have different environmental criteria than dry periods. If multiple hydrologic conditions (or "zones" or "climatic conditions") are desired, the analyst must: (1) decide how many hydrologic conditions to employ, (2) define a "trigger" to determine which hydrologic condition a location is in at a given time, and (3) perhaps assign desired frequencies to each hydrologic condition. Examples of triggers include: (1) reservoir storage (i.e., percent full), (2) streamflow at the location of interest, (3) streamflow at a nearby relatively unimpacted flow gage, (4) near-term meteorological predictions, and (5) operating rules derived from a model simulation that predicts that desired flow frequencies will be met. Depending on the spatial extent of application of the calculated flow regime components, complicating factors may arise if different locations in the same basin have different hydrologic conditions at the same time; although, this usually means that different numbers of hydrologic conditions and triggers are needed to properly reflect conditions at different locations. Consideration may also be given to a distinct hydrologic condition appropriate for extreme droughts.

An example is helpful to illustrate the use of an unimpacted tributary as a trigger. The analyst may assume three hydrologic conditions, with dry occurring 25% of the time, average occurring 50% of the time, and wet occurring 25% of the time, with the trigger being nearby stream flows. When a nearby unimpacted tributary is flowing below its historical 25th percentile of flow, then the hydrologic condition at the environmental flow location would be "dry." Similarly, when the nearby unimpacted tributary is flowing between its historical 25th and 75th percentile of flow then the hydrologic condition would be "average." Flows above the 75th percentile indicate "wet" hydrologic conditions. <u>It is important to note that the frequencies and triggers in this example are not universally appropriate; local hydrologic regimes will frequently necessitate other decisions.</u>

5. Assignment Period

Flow regime components that consist of continuous flow recommendations may vary by time period (e.g., monthly or seasonal). Thus, the analyst must decide appropriate time periods for which to assign different values for these recommended flows. Complex episodic flow regime

components such as high flow pulses and overbank flows occur intermittently and thus must be associated with a recommended frequency of occurrence over the desired assignment period. The assignment periods need not be identical for all flow regime components. However, for all flow regime components where seasons are desired, the length and monthly assignments to such seasons must be decided.

6. Memory

The analyst must decide if there will be memory, or carry-over, from one assignment period to the next. If there is no memory, then each assignment period begins as a "clean slate" and the under- or over-achievement of episodic flow regime components in the previous assignment period(s) is moot. Conversely, if memory is included, then an accounting system for tracking changing flow requirements may have to be developed.

7. Flow Regime Component Characteristics Delineated

High flow pulses and overbank flows may be delineated using: (1) peak flow, (2) average flow, (3) duration, (4) volume, (5) rise and/or fall rate, (6) frequency, and/or other characteristics. The analyst must decide which of these (or other) characteristics are important to include in the environmental flow recommendations. Deviations between the characteristics used to computationally define these flow regime components and the characteristics explicitly included in final environmental flow recommendations may result in unintended consequences. For example, if high flow pulses are quantified in the historical record using a combination of average flow and duration, but recommendations simply specify average flow, high flow pulses of insufficient duration may result.

8. Subsistence Flows Less Than 7Q2

Some analytical methods may generate subsistence flows (or even base flows) that are less than the 7Q2. The analyst must decide if/when it is appropriate to recommend flows that may result in the contravention of water quality standards. In the modified Lyons approach frequently used by TCEQ, the 7Q2 flow is considered a minimum: "Where the 7Q2 value is greater than the Lyons numbers, 7Q2 is used" (Loft, 2008).

9. Number and Location of Control Points

The analyst must determine the requisite number and locations of control points at which to perform the hydrologic analyses. The previous discussion of the spatial extent of instream flow recommendations (item 2 above) and information contained in the document titled "Geographic Scope of Instream Flow Recommendations" prepared by the SAC and the State agencies provide additional guidance regarding the number and location of control points. However, the application of hydrologic methods, by their very nature, requires that the stream locations considered essentially be at streamflow gaging sites unless credible streamflow data can be synthesized.

A list of active USGS flow gages in Texas is available at
http://waterdata.usgs.gov/tx/nwis/current/?type=flow.

10. Flow Recommendations in the Absence of a Flow Gage

There may be locations where instream flow recommendations are required or desired but a flow gage does not exist (e.g., tributaries that do not have a flow gage). In these cases, one option would be to translate the flow record at a nearby gage to the location of interest, e.g., using drainage area ratios (see, e.g., Asquith et al., 2006) and then perform the hydrologic analysis as usual. Another option would be to translate a flow recommendation itself from a nearby location. In either case, the analyst must determine that such translations are hydrologically realistic and meaningful; for many tributary/mainstem combinations, this may not be possible. The translation of either flow data or flow recommendations may be improved by limiting such translations to within a single stream classification. Information on stream classifications can be obtained from Hersh and Maidment (2007), Arthington et al. (2006), and Snelder et al. (2005).

11. Daily Average versus Instantaneous Flow Data

Daily average flow data are readily available[16] and are generally satisfactory for subsistence flow and base flow determinations. Daily average data also may be satisfactory for developing high flow pulses and overbank flow recommendations, or a method using instantaneous flow data may be desired. Instantaneous flow data from the USGS are not as thoroughly quality controlled as daily average flow data, are not available at all stations, and typically start in the late 1980s.[17] For these reasons, a pre-human impact flow record is unlikely to be available and a flow record in excess of 20 years is also unlikely. Typically, the more rare an event is (e.g., a large flood), the more important it is to use instantaneous data and the longer the period of record necessary to accurately quantify the expected frequency of the event. Previously developed flood models may be helpful to quantify flood events where data records are of insufficient duration.

While the use of daily average flow data is clearly unacceptable for the strict quantification of extreme flood events in the context of engineering and flooding impact determinations, the analyst may decide that, with some professional judgment, the use of daily average flow data is acceptable for setting realistic high flow pulse and overbank environmental flow recommendations.

12. Overbank Recommendations

Overbank flows are infrequent, high flow events that exceed channel banks and result in the inundation of the adjacent floodplain habitats. This periodic connection between the stream and the floodplain is critical for maintaining ecosystem health. It is important that overbank flows be recognized, to the extent practicable, in establishing instream flow recommendations to support a sound ecological environment in rivers and streams. However, instream flow requirements that would result in deliberate releases from reservoirs designed to produce overbank flows which would not otherwise occur naturally may raise issues of liability and may not be technically achievable in some situations.

[16] http://waterdata.usgs.gov/tx/nwis/current/?type=flow
[17] http://ida.water.usgs.gov/

SECTION 5
HYDROLOGY-BASED ENVIRONMENTAL FLOW REGIME (HEFR) METHODOLOGY

5.1 HEFR BASICS

HEFR was developed to efficiently use hydrologic data to populate a flow regime matrix. As a hydrologic method, it suffers from many of the same weaknesses as other hydrologic methods (see Section 3.2). However, unlike other hydrologic methods, HEFR can generate values for an entire flow regime in which the different flow regime components, hydrologic conditions, and component characteristics are internally consistent. The results are internally consistent in the sense that: (1) hydrologic conditions (e.g., dry, average, and wet[18]) are tied to percentiles of a distribution, and thus the recommendation under average conditions is guaranteed to equal or exceed the recommendation under dry conditions (and similar for wet versus average). (2) the hydrographic separation that generates the flow regime component values is performed using a single software tool (different tools are provided, but any given simulation will use only one), and (3) high flow pulse and overbank flow characteristics of duration, magnitude, and volume are generated using a consistent set of quantified flow regime components, as opposed to different statistical measures of the entire hydrograph (e.g., as in TX-HAT).

HEFR begins with the selection of a flow gage and a period of record. A hydrographic separation algorithm is then used to parse the daily hydrograph into the four (or more) flow regime components, based on user-specified parameters. This parsing results in each day of the hydrograph being classified as one of the four flow regime components. At the present time, Microsoft Excel is used to post-process the hydrographic separation and to generate summary statistics. These summary statistics are also specified by the user. Figure 1 on the following page outlines the important steps of HEFR.

Thus, the core foundation of HEFR is flow separation and statistical summaries of each flow regime component. The specific decisions and tools used in the current version of HEFR were identified through discussions and negotiations; however, they are not incontrovertible. Decisions and tools may change because of location, professional judgment, context, objectives, and/or convenience.

In the following sections, an example application of HEFR is presented as a convenient forum for describing the fundamentals of the method. At each decision point, guidance is provided related to the actual decision made, possible ranges of parameter values, and associated advantages and disadvantages. In this example, it is important to remember that the thought processes and guidelines are more important than the specific decisions and parameter values

[18] The flow recommendations corresponding to these hydrologic conditions can be conceptualized as small, medium, and large flow values appropriate for future dry, average, and wet periods. In the current version of HEFR, the recommendations corresponding to these hydrologic conditions are based on percentiles of the entire period of record used, not percentiles from historically-identified dry, average, and wet periods. Depending on the period of record used and the trigger definitions for the hydrologic conditions, identifying historical dry, average, and wet periods may not be possible.

themselves; other locations, other contexts, and the identification of site-specific data may all lead to different decisions. This example was developed for illustrative purposes only and has not benefited from the level of background research, collaboration, and site-specific knowledge that would be appropriate for a real-world application of the method.

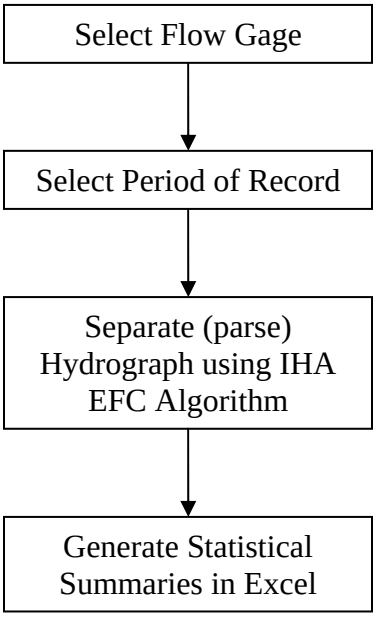

Figure 1. Flow Chart of HEFR Methodology

However, some level of review has been afforded to HEFR concepts and algorithms through a technical workshop (February 24, 2009). Feedback from the workshop has promoted further evaluation of the methods and development of alternative techniques. The alternative techniques are now a part of the HEFR program and available for use. Following the example application of the default HEFR method is a discussion of an alternative hydrographic separation algorithm (Section 5.6) and an alternative high flow pulse and overbank calculation methodology (Section 5.7).

5.2 EXAMPLE APPLICATION OF HEFR: NECHES RIVER AT EVADALE

5.2.1 Gage Selection

The Neches River at Evadale (USGS gage #08041000) was selected for this example because it has a long period of record (April 1921 to the present) and is located in a SB3 priority one basin.

As shown in Figure 2, this gage is located upstream of the City of Beaumont and downstream of both B.A. Steinhagen Lake and Sam Rayburn Reservoir (on the Angelina River). Deliberate

impoundment of Steinhagen Lake began in April 1951[19] and deliberate impoundment of the much larger Sam Rayburn Reservoir began in March 1965.[20] The surveyed volume at the top of the conservation pool for Steinhagen Lake is 66,972 ac-ft;[21] similarly, the surveyed volume at the top of the conservation pool for Sam Rayburn is 2,876,033 ac-ft, or approximately 43 times larger than Steinhagen.

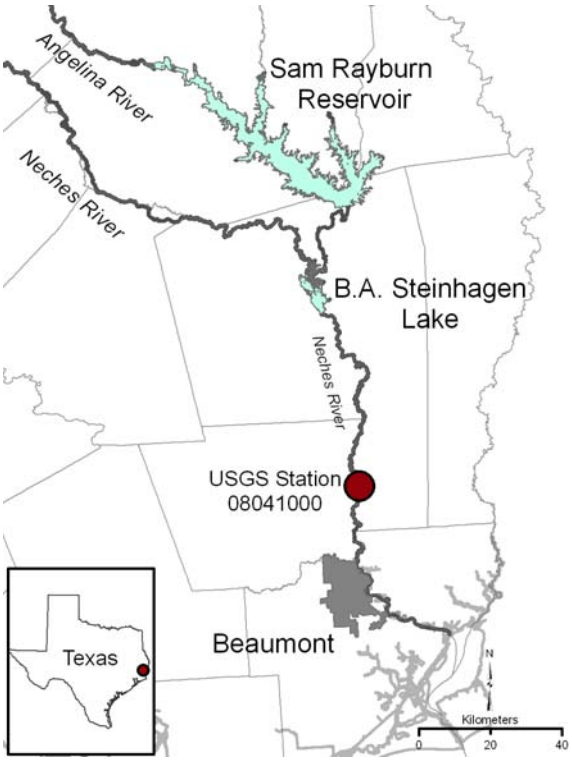

Figure 2. Site Map for USGS Gage 08041000

5.2.2 Period of Record

In the absence of site-specific data, for purposes of this example, it was decided to use the natural period of record. This period of record reflects the flow conditions that the ecosystem (including biological and geomorphological components) originally evolved under, but does not reflect contemporary changes (e.g., enhanced low flows due to reservoir operation) that certain aspects of the ecosystem have since adapted to. For a real world application of HEFR, both the natural and more recent hydrology, as well as the current configuration of the system and objectives of the analysis, should be considered (see Hydrologic Period of Record discussion above).

[19] http://www.swf-wc.usace.army.mil/townbluff/Information/History.asp
[20] http://www.swf-wc.usace.army.mil/Samray/Information/History/index.asp
[21] http://wiid.twdb.state.tx.us/ims/resinfo/viewer.htm?DISCL=1&

To eliminate unnecessary complexities in the statistical interpretations, only full years of data are used; partial years are omitted. Also, calendar years (instead of USGS water years) are used. Based on these considerations, the period of record was selected to begin on January 1, 1922. Because Sam Rayburn was impounded in 1965, the end of the period of record for this analysis was selected to be December 31, 1964. This results in 43 years of data, which meets the guidelines of the IHA software (in which 20 years or more are recommended) and the guidelines of the TRG (2008; which recommended 30 years). In a real world application of HEFR, the analyst should consider the potential impacts of all upstream reservoirs (e.g., Lake Palestine in this case) and should perform additional analyses to establish that the selected period of record is representative of hydrologic variability at the analysis location.

5.2.3 Using IHA to Parse the Hydrograph

Figure 3 shows a close-up of the hydrograph of the Neches River at Evadale from April 1, 1936 through September 30, 1936. This figure will serve as an example of how the EFC algorithm can be used for hydrographic separation. An alternative hydrographic separation technique is presented in section 5.6.

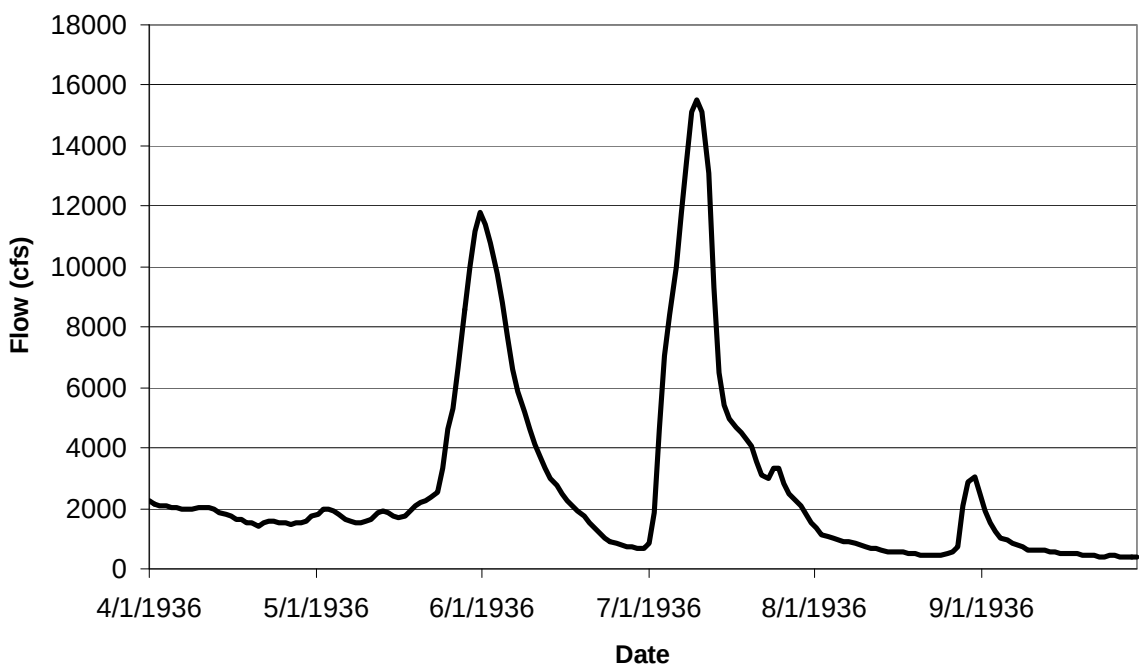

Figure 3. Hydrograph at Evadale, April 1, 1936 through September 30, 1936

In order to perform the analysis, the number of flow regime components must be selected. Though the TIFP and IHA both incorporate the flow regime component concept, the terminology

is not shared and there are subtle differences. For this example, the four flow regime components used in the TIFP are selected. These correspond to subsistence flows (i.e., extreme low flow in IHA), base flows (low flows), high flow pulses (same), and overbank flows (small and large floods). For consistency in this discussion, the TIFP terminology is used throughout this document, even though screen captures of the IHA tool show the IHA terminology.

The next decision to be made is the parameterization of the EFC algorithm in IHA. Figure 4 is a screen capture of this tool, with the selections used in this example.

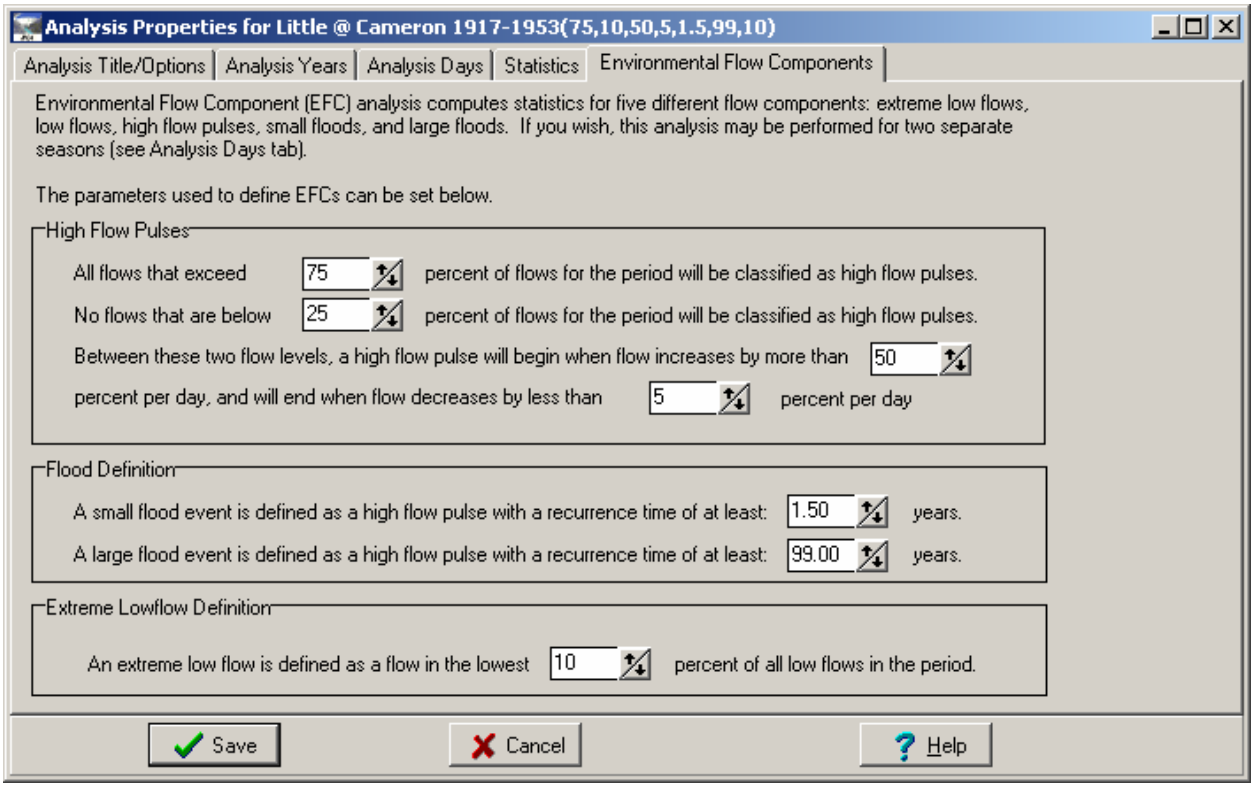

Figure 4. Screen Capture of EFC Tab in IHA

IHA sorts through all days in the period of record and assigns each date to one of two groups: (1) Group 1 contains potential subsistence and base flows, and (2) Group 2 contains potential high flow pulses and overbank flows. These assignments are performed using the first four parameters in Figure 4. The 75 percent designation for the first parameter forces IHA to classify all dates with flows in excess of the 75th percentile (of all flows) to be in Group 2. The second parameter, the 25 percent designation, forces IHA to classify all dates with flows less than the 25th percentile (of all flows) to be in Group 1.

The third and fourth parameters are the rate of change parameters. These parameters are relevant only for dates with flows between the 25th and 75th percentiles of all flows. In this middle 50% of the flow record, any given date can be assigned to either Group 1 or Group 2, depending on the rate of change and the previous date's assignment. For Day i (i.e., any given day that is

assumed to be between the 25th and 75th percentiles), if Day i-1 (i.e., the day before Day i) is a Group 1 day and the increase from Day i-1 to Day i is less than 50%, then Day i is also a Group 1 day. If this increase is greater than 50% then Day i begins a Group 2 event and is classified as a Group 2 day (i.e., a storm is assumed to occur between Day i-1 and i). Conversely for Day i, if Day i-1 is a Group 2 day, then Day i is also a Group 2 day, unless the flow from Day i-1 to Day i decreases by less than 5% (the algorithm is trying to identify the flat tail end of a storm pulse) in which case it is a Group 1 day.

At this point, the entire hydrograph is parsed into Group 1 and Group 2 days. Group 2 days are then distinguished using the fifth and sixth parameters in Figure 4. The fifth parameter sets the lower bound for overbank flows at the 1.5 year return flow in our example application. This value is based on a scientific and literature rule of thumb that the 1.5 year flow typically approximates a bank-full condition (Dunne and Leopold, 1978). A different return period could be chosen to reflect site-specific information on bank-full flow rates. The sixth parameter is set to 99 years, which effectively removes the "large flood" category from the hydrographic separation and forces IHA to assign all flows in excess of the 1.5 year flow as one category of overbank flows ("small floods"). In this way, the large flood flow regime component is eliminated from the discussion and all storm events that are estimated to be greater than bank-full are incorporated in the overbank flow component.[22] In this example, the entirety of any Group 2 event (which consists of a consecutive series of dates based on the algorithm above) is classified as an overbank flow if any day of the event exceeds the 1.5 year return period threshold. If no dates in the Group 2 event exceed this threshold, the entire event is classified as a high flow pulse. It is sometimes helpful to think of high flow pulses and overbank flows as events, in the sense that not all days exceed the bank-full condition (in the case of overbank), or even have particularly high flow rates (in both cases). This is by design, but if it conflicts with the professional judgment of the analyst, it can be ameliorated by different parameter selections.

Finally, the Group 1 days are distinguished using the last parameter in Figure 4. In this case, the bottom 10% of the Group 1 days are assigned to subsistence flows and the remaining 90% of Group 1 days are assigned to base flows.

Using these EFC parameters, Figure 5 shows the same data as Figure 3 with the flow regime components identified.[23] For reference, the 25th percentile of all flows (i.e., the lower threshold for high flow pulses) is calculated by IHA as 860 cfs, the 75th percentile of all flows (i.e., the upper threshold for high flow pulses) is 8400 cfs, and the 1.5 year flow is 21,070 cfs. In Figure 5, the storm events appear to be reasonably well represented by the hydrographic separation algorithm, although the first storm event seems to be identified a little late (the rate of increase never quite exceeds 50%, so the high flow pulse is triggered only when the flow exceeds 8400 cfs) and the second pulse appears to end a little early (there are two dates on the trailing limb of the hydrograph with identical average flows, thus the rate of decrease is less than 5%, triggering

[22] The TIFP contemplates the possibility of various sizes of overbank flow recommendations. The capability of IHA to separate out "small floods" from "large floods" may be used to help identify different overbank flow sizes, although this was not done in the example presented herein.

[23] This figure was generated in Excel. IHA can conveniently generate similar figures; however the analyst must recognize that in IHA the flow regime component correctly assigned to a particular date is actually designated by the color and symbol of the previous date. This is a recognized minor bug in IHA (personal communication, Tom Fitzhugh).

the end of the high flow pulse). Figure 5 does not illustrate subsistence or overbank flow components because the flows in this time period were not low or high enough, respectively.

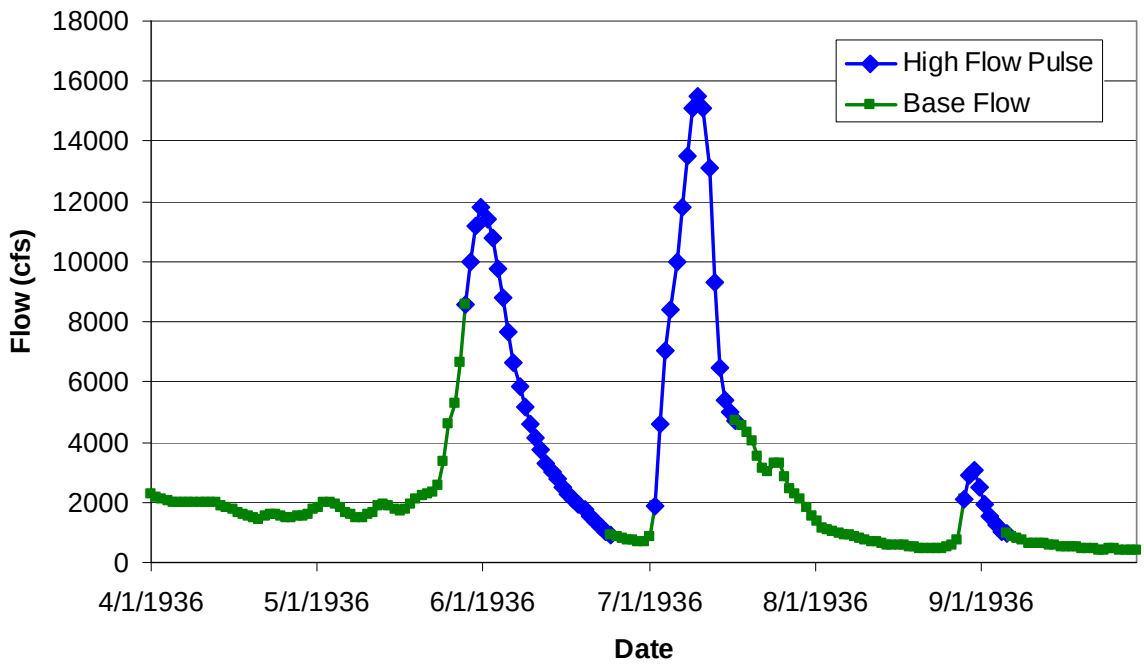

Figure 5. Hydrograph at Evadale with Hydrographic Separation

While IHA does not have infinite flexibility to parse the hydrograph, the analyst can tune the EFC parameters to improve the separation, based on their professional judgment. Other hydrographic separation algorithms are also available. It is recommended that the analyst carefully inspect the hydrographic separation, and decide which method and parameter set is most appropriate for a given location and objective. However, it is also recommended that the analyst recognize that the HEFR methodology solely uses percentiles of each component's distribution (typically the 25th, 50th, and 75th percentiles), thus values at the far tails of the distribution are not particularly relevant.

Thus, to parameterize the EFC algorithm in IHA, several decisions must be made. The first important decision is whether or not the analyst desires the distinction between Group 1 and Group 2 days to be based primarily on magnitude, primarily on rate of change, or a balance of both. For example, if the analyst wants this distinction to be based primarily on magnitude, then parameters 1 and 2 are set close to each other (or even identically), at a level that the analyst believes approximates the distinction between base flows and high flow pulses. Because parameters 1 and 2 are close to each other (or the same), the rate of change parameters are relevant to only a small portion (or none) of the hydrograph. If the analyst wants the distinction between groups 1 and 2 to be based primarily on rate of change, then the first parameter is set to a high value and the second parameter is set to a low value. In this case, a large fraction of the hydrograph is assigned based on the rate of change parameters. In the example provided here, 50% of the hydrograph is assigned solely due to the flow magnitude on that day and 50% of the

hydrograph is assigned based on the rate of change. The 50% and 5% values (parameters 3 and 4) are selected, based on professional judgment, to have IHA classify significant storm pulses as high flow pulses, from beginning to end. It is very useful for an experienced hydrologist to look at several storm events in the flow record to ensure that the assignments are occurring as desired. If not, different parameters may be used.

The second important decision relates to the distinction between (in-bank) high flow pulses and overbank flows. Site specific data are very helpful here; it is possible that existing reports or a site visit and analysis may provide the flow magnitude associated with bank-full.[24] In the absence of site-specific or regional information, a return period similar to 1.5 years is often used.[25]

Some of these decisions also affect the high flow pulse frequency calculations in subtle ways. Combinations of a high lower high flow pulse threshold (i.e., the 25th percentile in this example) and a low overbank threshold (1.5 year return flow in this example) result in fewer overall high flow pulses. Fewer high flow pulses, especially when combined with short assignment periods (e.g., monthly), increase the likelihood that zero frequencies (per assignment period) will be generated using the existing methodology.

Finally, a distinction is made between subsistence flows and base flows using the last (seventh) parameter in Figure 4. This value should be selected such that the historical occurrence of subsistence flows is reasonably consistent with the recommended future occurrence of subsistence flows.

It is not expected that a single EFC parameter set would be applicable to all locations in Texas. Rather, some customization at the basin, or even sub-basin, level is to be expected. Different parameter sets, and/or different hydrographic separation algorithms, might be useful for locations with distinctive variations in flow characteristics or known ecology.

Using the selected parameters, IHA is run and the outputs are saved.

5.2.4 Using the HEFR Excel Tool

The HEFR Excel tool is designed to import IHA output files, make additional modifications to the hydrograph separation, and generate summary statistics.

In HEFR, the user selects the folder corresponding to the desired IHA outputs. HEFR then automatically loads all of the relevant output files and performs statistical computations. To provide a balance between integrity of the calculations and ease of use for the analyst, Visual Basic for Applications (VBA) code is used to write the Excel functions (where possible) and perform calculations directly (where Excel functions are inadequate). In this way the analyst can

[24] IHA uses daily average flows and some adjustments may be necessary if bank-full is determined using instantaneous flow data.

[25] IHA uses an empirical calculation of return interval and does not fit the hydrologic data to a distribution, e.g., as in USGS (1982).

follow most of the calculations by examining the associated functions in Excel, but the analyst cannot inadvertently corrupt the original model itself.

Using certain parameter sets in the EFC algorithm, unrealistically long high flow pulses were identified by IHA. This occurs, in part, because IHA does not identify a new high flow pulse on Day i, unless Day i-1 is a Group 1 day[26]. Said another way, an existing high flow pulse does not end unless the flow drops below the 25th percentile or the flow drops from one day to the next by less than 5% (based on the above example). However, in the judgment of the analyst, multiple consecutive high flow pulses may be deemed more appropriate. HEFR has the capability to separate long high flow pulses into individual high flow pulses, based on the multipeaks_multiplier parameter. When, in the midst of an IHA-designated high flow pulse that has declined from its initial peak flow rate, the flow increases from Day i-1 to Day i by more than 50% (if multipeaks_multiplier is set to 1.5), a new high flow pulse is designated in HEFR. In this way, a long high flow pulse is broken into a series of shorter high flow pulses. Because overbank flows are simply high flow pulses where one or more days exceed the 1.5 year return flow magnitude, overbank flows can also exhibit the same behavior and can be separated using the multipeaks_multiplier for overbank flows. It should be noted that when the multipeaks_multiplier is used to split up a long overbank event, each individual piece is classified as an overbank event, even if that piece would not qualify as an overbank event on its own.

The multipeaks_multiplier is more sensitive for smaller, flashier rivers. For larger rivers like the Neches River at Evadale, when the flow is already high (as in a high flow pulse), it is rare for the flow to jump up by an additional 50% from one day to the next. Probably for this reason, the multipeaks_multiplier value of 1.5 has little effect on the flow separation at Evadale. As an alternative example, Figure 6 shows a more flashy location (Little River near Cameron) where the multipeaks_multiplier calculation in Excel is used to split a long high flow pulse identified in IHA into four distinct, consecutive, high flow pulses.

When contemplating the use of the multipeaks_multiplier option, the analyst should carefully consider if there actually is a problem to be solved. Long high flow pulses and overbank flows may be appropriate for a particular location and may not need to be separated. The analyst should also evaluate if long high flow pulses and overbank flows are caused by multiple discrete storms or a single storm across tributaries with different travel times.

[26] This perceived problem also occurs more often when the Group 2 lower threshold (25th percentile) is low and the rate of decline (5%) is also low.

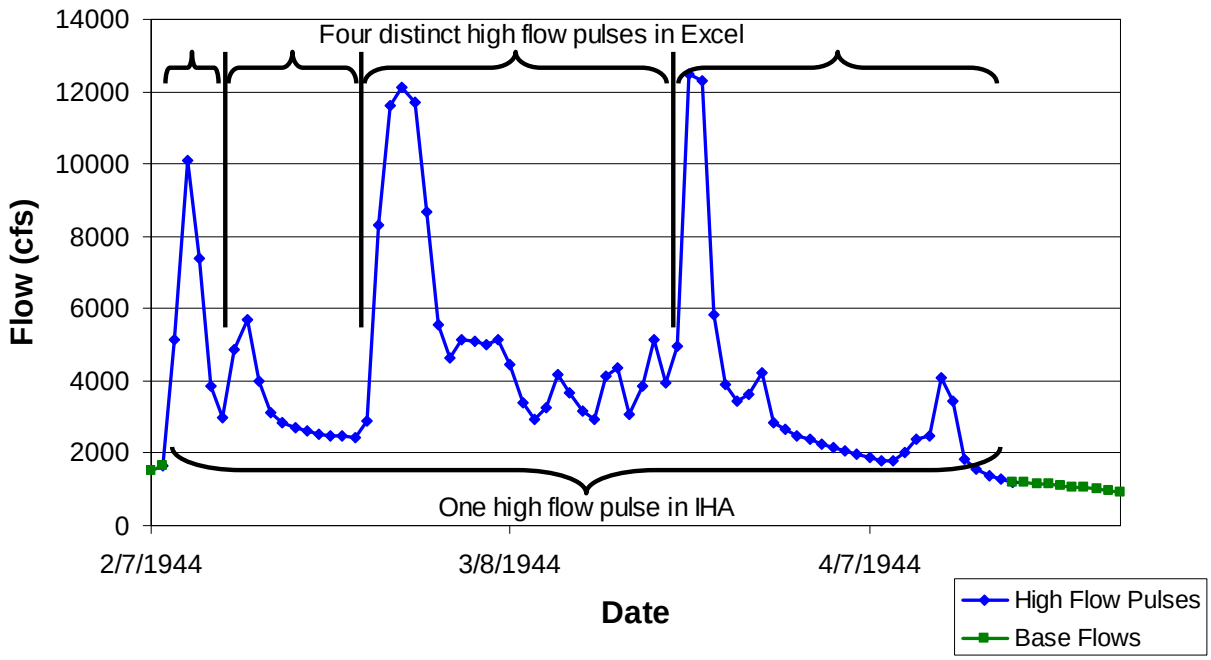

Figure 6. Example Application of Multipeaks_Multiplier

Currently in HEFR, subsistence flows are conceptualized as both a flow regime component and a hydrologic condition. The hydrologic conditions of subsistence, dry, average, and wet are selected to occur 2.5%, 22.5%, 50%, and 25% of the time, respectively.[27] The implication is that during the driest 2.5% of the time, only subsistence flows are recommended. In the other 97.5% of the time, a combination of base flows, high flow pulses, and overbank flows are recommended.

HEFR generates results on a monthly and/or seasonal basis (see below). The user can select an arbitrary number and length of seasons. For this example, the seasonal assignments are as follows: Winter (Dec-Feb), Spring (Mar-May), Summer (Jun-Aug), and Fall (Sep-Nov). For this example, months were aggregated into seasons based on traditional seasonal definitions but also to group months with flows that might provide similar ecological/biological cues and functions

HEFR performs the following calculations.

Subsistence Flows

All subsistence flows are binned by month and the median (in this example) for each month is calculated. The recommended subsistence flow is the greater of this calculated flow and a user-input "water quality protection" flow, as entered by the user; the published 7Q2 value was used as the "water quality protection" flow in this example. If the user enters a value of zero for the water quality protection flow and no subsistence flows have occurred in a given calendar month over the entire period of record, then HEFR posts the text "N/A" for "not applicable" in the flow

[27] The sum of these frequencies must be 100%. Based on site-specific evaluations of the flow record, alternate selections for the number of hydrologic conditions, and their associated frequencies, should be considered.

matrix for that month. This sometimes happens in spring months where subsistence flows do not occur. The HEFR Excel sheet "Baseflows" also contains a table of the count of subsistence flows by month. The user should examine this table to judge the reasonableness of subsistence flow recommendations in the event that only one, or a very few, subsistence flows were identified in a given month. For example, even if only one subsistence flow day was ever identified in the month of April over the period of record, that one day may form the subsistence flow recommendation (depending on its value relative to the user-input water quality protection flow). This dependence of the flow recommendation on a single daily flow value is undesirable and should be carefully considered.

At this time, it is helpful to quantify the frequency at which historical flows were equal to or less than the subsistence flow recommendations. This information can help to guide the selection of the appropriate recommended frequency for subsistence flows in the future. In this way, HEFR can be self-centering. If the subsistence flow recommendation is a relatively high flow value, then it should be recommended to occur at a relatively high frequency and vice versa.

Subsistence flows are generated in HEFR on a monthly and seasonal basis. The analyst can choose to use either.

Base Flows

All base flows are binned by month and the minimum, 25th percentile, 50th percentile, 75th percentile (i.e., 25th, 50th, and 75th in this example), and maximum for each month are calculated. The recommended base flow for the dry hydrologic condition corresponds to the greater of the 25th percentile flow and the water quality protection flow. The recommended base flow for the average hydrologic condition corresponds to the greater of the 50th percentile flow and the water quality protection flow, and the recommended base flow for the wet hydrologic condition corresponds to the greater of the 75th percentile flow and the water quality protection flow.

The correspondence of dry, average, and wet to the 25th, 50th, and 75th percentiles is based on professional judgment and is deemed consistent with the recommended frequencies of 22.5%, 50%, and 25% of the time, respectively. Different percentiles may be needed, depending on the hydrologic and climatic conditions in different parts of the state. If different percentiles are selected, it may be appropriate to also select different frequencies of occurrence.

The published 7Q2 value (which is used as the water quality protection flow in this example) at Evadale (1,839 cfs, based on data from 1966 to 1996) lies at the 43rd percentile (57th percent exceedance level) of the 1922-1964 period. This 7Q2 value is relatively high, likely due to releases from Sam Rayburn for downstream water rights and hydropower generation, leading to all of the HEFR-calculated subsistence flow recommendations and many of the HEFR-calculated base flow recommendations being replaced with the 7Q2 value in this example (see discussion of 7Q2 above).

Base flows in HEFR are generated on a monthly and seasonal basis. The analyst can choose to use either. In this example, seasonal base flows are presented (Figure 7 below) for brevity and because they reasonably mimic the monthly HEFR outputs.

High Flow Pulses

This section represents the default methods used to identify high flow pulses. An alternative method of identifying and characterizing high flow pulses is presented in Section 5.7.

For each high flow pulse the duration, volume, and minimum, 25th percentile, 50th percentile, average, 75th percentile (i.e., 25th, 50th, and 75th in this example), and maximum flows are determined. In addition, the date of the peak flow (the daily flow with the greatest magnitude rather than from a peak flow file) is identified for seasonal assignment. Currently the high flow pulse is assigned to the season during which the peak flow of the event occurs; this may be modified if site-specific conditions warrant such a change.

From this population of high flow pulse events, the 25th, 50th, and 75th percentiles of duration, volume, and peak flow are determined. These are used to assign each event to the dry, average, wet, or none categories. In this example, all three pulse characteristics of peak flow, volume, and duration were used to classify high flow pulses. Thus, if an event exceeds the 75th percentile of all three characteristics (duration, volume, and peak flow), then the event is classified as a "wet" high flow pulse. If the event exceeds the 50th percentile, but not the 75th percentile, of all three characteristics, then it is classified as an "average" high flow pulse. If the event exceeds the 25th percentile, but not the 50th percentile, of all three characteristics, then it is classified as a "dry" high flow pulse. If the event does not exceed the 25th percentile of all three characteristics, it is classified as "none." Because of the nature of joint distributions, fewer than 25% of the high flow pulses will be categorized as wet. Similarly, fewer than 50% will be average and fewer than 75% will be dry. The user can select any combination of these three high flow pulse characteristics to classify high flow pulses as dry, average, or wet.

It is important to recognize that even though the upper threshold of high flow pulses is set at the expected bank-full value (in this example, the 1.5 year flow), the recommended high flow pulses are significantly less than bank-full. Only the maximum high flow pulse peak flow approximates bank-full. Because of the skewed nature of the peak flow distribution, the 75th percentile can be as low as 20% of bank-full flow. Thus, in this categorization, even "wet" high flow pulse recommendations are well below bank-full. This behavior may lead the analyst to select higher percentiles for flow recommendations, and/or modify the high flow pulse recommendations based on other disciplines (e.g., geomorphology and biology).

At this point the dry, average, and wet high flow pulses are binned by season and year (e.g., two dry pulses in winter 1940, one dry pulse in winter 1941, and no dry pulses in winter 1942). Associated frequencies are calculated as: (1) the frequency corresponding to the dry sized high flow pulse recommendation is based on the frequency of dry and larger (i.e., dry, average, and wet) events, (2) the frequency corresponding to the average sized high flow pulse recommendation is based on the frequency of average and larger (i.e., average and wet) and (3) the frequency corresponding to the wet sized high flow pulse recommendations is based on the frequency of wet pulses. The median and 75% percentile of these frequencies are presented to help the analyst make a frequency recommendation. HEFR uses the 75th percentile of frequencies for the recommendation because of the skewed nature of this distribution. Only those high flow pulses that meet the dry, average, and wet criteria are included in the frequency

calculation, thus the frequency recommendations are, by definition, based on historically observed patterns of dry, average, and wet high flow pulses.

In the current version of HEFR, the flow regime component characteristics of high flow pulses that are delineated are peak flow, duration, volume, and frequency. Statistics describing the rise rate and fall rate are not included, but could be added.

High flow pulses in HEFR are currently generated on a seasonal basis.

Overbank Flow Events

Overbank flow events are calculated similarly to high flow pulses, with the exception that multiple hydrologic conditions are not considered. The overbank flow recommendation corresponds to the median of the flow characteristics selected by the user (any combination of duration, volume, and/or peak flow; all three were used in this example) of all overbank events. The recommended frequency is simply the number of observed events that exceed the selected median characteristics divided by the period of record (e.g., if 20 overbank events were identified in a 28 year period of record, the recommendation would be a return interval of 1.4 years).

In this example, the overbank flow multipeaks_multiplier was set to 1e9. This value is used to turn off additional processing of the overbank flows identified by IHA.

When IHA is parameterized with an overbank peak flow return interval of 1.5 years, overbank-sized flows will occur somewhat more frequently than once every 1.5 years. This is because the 1.5 year flow is calculated (as is customary) using the distribution of annual maximum flows. Relatively wet years may have multiple large events, but only the largest from each year is used in the calculation. Depending on the results of the calculation, several events in that wet year might actually exceed the calculated 1.5 year flow. This is the same statistical subtlety that causes the 7Q2 flow to occur across seven consecutive days more often than about once every other year.

The overbank flow recommendation in HEFR is associated with a return interval (as opposed to a monthly or seasonal frequency) and is independent of hydrologic (dry, average, wet) conditions.

5.3 EXAMPLE MATRIX

Figure 7 shows the resulting populated flow regime matrix for the Neches River at Evadale.

Overbank Flows	Return Period (R) : 2.7 (years)		Duration (D) : 49 (days)	
	Volume (V) : 1743452 (ac-ft)		Peak Flow (Q) : 30000 (cfs)	
High Flow Pulses	F: 0	F: 0	F: 0	F: 0
	D: 18	D: 22	D: 17	D: 12
	Q: 14125	Q: 15550	Q: 11825	Q: 8570
	V: 352171	V: 433473	V: 278202	V: 90605
	F: 1	F: 1	F: 1	F: 1
	D: 11	D: 14	D: 9	D: 9
	Q: 10500	Q: 10500	Q: 8850	Q: 3700
	V: 148305	V: 233782	V: 89449	V: 52621
	F: 2	F: 1	F: 1	F: 1
	D: 7	D: 7	D: 6	D: 6
	Q: 4903	Q: 8735	Q: 3630	Q: 2373
	V: 57962	V: 93710	V: 36786	V: 22191
Base Flows (cfs)	4910	5700	2110	1839
	2350	3670	1839	1839
	1839	2258	1839	1839
Subsistence Flows (cfs)	1839	1839	1839	1839

Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Winter			Spring			Summer			Fall		

Hydrologic Conditions	
	Wet (75th %ile)
	Average (50th %ile)
	Dry (25th %ile)
	Subsistence

High Flow Pulse Characteristics	
	F = Frequency (per season)
	D = Duration (days)
	Q = Peak Flows (cfs)
	V = Volume (ac-ft)

Figure 7. Example Flow Regime Matrix for the Neches River at Evadale

If this were a real application, a couple of characteristics of this matrix would require further thought:

1. Many of the high flow pulse frequency recommendations are zero. Given that most locations in Texas can be assumed to have within-bank storm flows, a recommendation of zero high flow pulses may imply a poor representation of the hydrology in the flow regime matrix. Frequencies of zero are probably a result of some combination of several factors:

   - Frequency calculation methodology is too restrictive. Options other than the methodology described herein may be more appropriate.

   - Qualifying high flow pulse criteria are too stringent. The methodology described herein requires "wet" high flow pulses to meet all three of the "wet" criteria for magnitude, duration, and volume. This limits the pool of qualifying "wet" high flow pulses with which to determine recommended frequencies. Similar arguments can be made for "average" and "dry" high flow pulses. Lower criteria (e.g., 15th, 40th, and 60th percentiles for dry, average, and wet, respectively) may result in smaller but more frequent high flow pulse recommendations.

   - Window of hydrograph that IHA can designate as high flow pulses is too narrow. In the example described herein, high flow pulse days are constrained to days with a flow greater than the 25th percentile that are also not part of an overbank flow event (i.e., a Group 2 event with a peak flow greater than the 1.5-year flow rate). Decreasing the 25th percentile to a lower value may increase the number of high flow pulses (and the resulting frequency recommendation), although it will also tend to reduce base flow recommendation values. Similarly, increasing the overbank cutoff (e.g., 1.5-year to 2-year return period) may increase the number and size of high flow pulses.

- Assignment period is too short. Instead of three-month seasons, four- or six-month seasons may be used.

It is likely that "flashy" locations characterized by short, intense storm events will require different options or parameters than those applicable to mainstem locations with very large drainage areas. It is recommended that these options be explored to identify high flow pulse recommendations with reasonable magnitudes and frequencies at each location of interest.

2. All of the subsistence flows and many of the base flow values were replaced with the 7Q2 value (1,839 cfs). This 7Q2 value should be double-checked and its use as a minimum flow for protection of water quality may be reevaluated in light of its location at the 43rd percentile of flows in the period of record used. Or conversely, consideration may be given to using post-development hydrology, instead of the natural hydrology, for the HEFR analysis since this more recent hydrologic record was used by TCEQ to calculate the 7Q2 value.

3. Soar and Thorne (2001) have estimated bank-full at this location at approximately 7,770 cfs. The National Weather Service has estimated bank-full at this location at approximately 7,200 cfs, with minor lowland flooding at about 30,000 cfs.[28] This site-specific information suggests that some of the recommended high flow pulse magnitudes exceed the bank-full condition. This, and other site-specific information, should be used to select the most appropriate demarcation between high flow pulses and overbank flows in the EFC hydrographic separation algorithm.

These items are in addition to the blanket recommendation of guidance from site-specific data, other disciplines, etc.

5.4 IMPLICATIONS OF HEFR CALCULATIONS

Many of the calculations described in the example above are hard-wired into the current version of HEFR, however, in many cases changes to the calculations are relatively straightforward.

The percentile and frequency decisions in HEFR are often internally consistent in the sense that higher flows are naturally associated with lower frequencies. In this way, HEFR attempts to mimic (with a limited number of flow regime components) fractions of the period of record used. Site-specific data may be used to guide percentile and frequency decisions in HEFR and/or used to replace HEFR-generated flow recommendation values.

User-defined values in the HEFR methodology are based on existing data and information relevant to the location of interest, professional judgment, and (at times) the context under which decisions are being made. Because the recommended frequency is based on the historical frequency of occurrence, the HEFR flow recommendations are internally consistent. For example, if the analyst sets parameters to specify larger "wet" high flow pulses, fewer such high flow pulses will be observed in the historical period of record and the recommended frequency will consequently be diminished.

[28] http://ahps.srh.noaa.gov/ahps2/hydrograph.php?wfo=lch&gage=evdt2

As an example of this, consider Figure 8 on the next page, which is a flow duration curve for the USGS gage "Neches River at Evadale" from January 1, 1922 through December 31, 1964.

In Figure 8, the y-axis represents flow and the x-axis represents the percent of time that each flow value is equaled or exceeded in the flow record. In HEFR, a flow recommendation that mimics some pattern of historical hydrology (e.g., natural, regulated, or otherwise) is desired. Suppose that the analyst made decisions that resulted in a high flow pulse peak flow of 15,000 cfs (the solid red line in Figure 8). In this case, the historical frequency (approximately 7%) is used to guide the assignment of recommended future frequencies for this flow magnitude (i.e., presumably 7% or less frequent). Similarly, if the analyst made decisions that resulted in a high flow pulse peak flow of 13,000 cfs (the dashed green line), the historical frequency of 15% is used to guide the selection of recommended future frequencies. Either way, the magnitude and frequency recommendations can be made to be coherent and thus the recommendations are internally consistent. This is not to say that all flow recommendations are inherently equal; some high flow pulse magnitudes provide different ecological benefits than others. However, in the absence of site-specific data, it is reasonable to identify a finite number of flow regime components and recommend them at reasonable frequencies – this is the goal of HEFR.

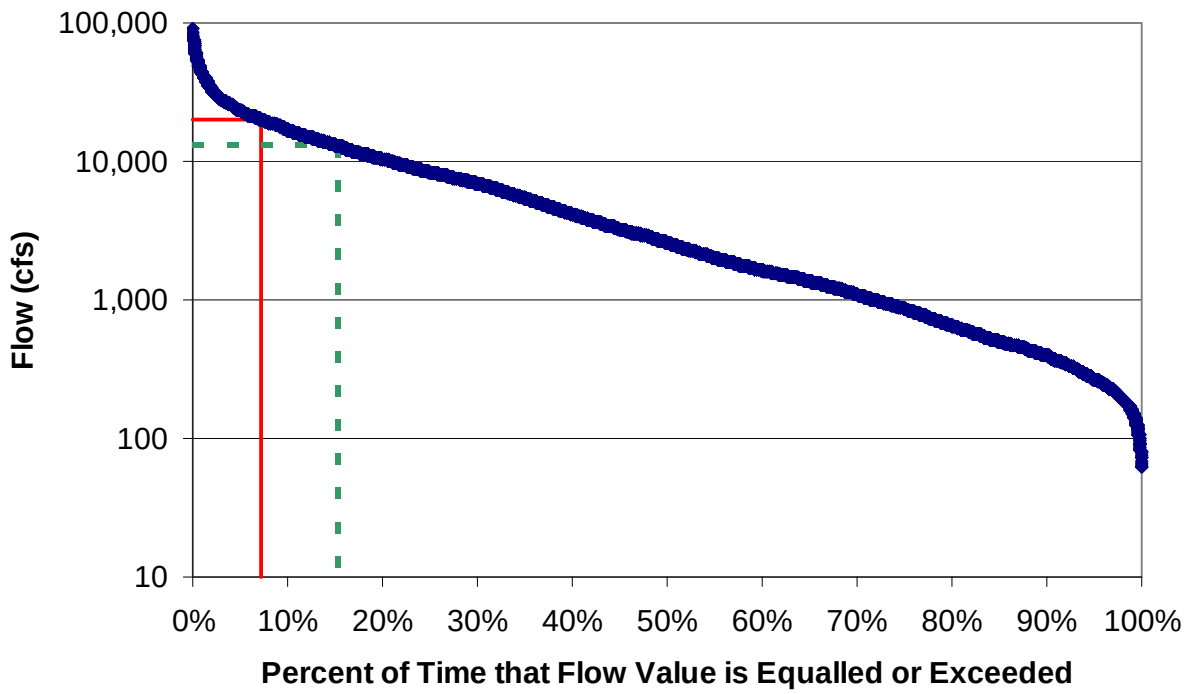

Figure 8. Flow Duration Curve for Neches River at Evadale (1922-1964)

Similarly, the decisions regarding hydrologic conditions are internally consistent. In the example described herein, the wet hydrologic condition occurs during the wettest 25% of the time, and is

set at the 75th percentile of the flow regime component characteristics. If the analyst wanted to select a "soaked" hydrologic condition that occurred during the wettest 10% of the time (i.e., that supersedes the wet condition in that portion of time), then flow regime component characteristics commensurate with the 90th percentile would be appropriate. In this way, hydrologic conditions are realistically tied to appropriate flow levels.

Ultimately, this internally consistent behavior of HEFR reduces the likelihood of illogical or nonsensical combinations of flow recommendations.

5.5 HYDROLOGIC DECISIONS NOT NEEDED TO RUN HEFR

The decision points listed below are necessary for a realistic application of the HEFR methodology, but are not explicitly needed to run the HEFR computations and therefore were not discussed in the Evadale example given above.

Geographic Scope of all Instream Flow Recommendations and Spatial Extent of Individual Instream Flow Recommendations
Number and Location of Control Points
Flow Recommendations in the Absence of a Flow Gage
In a given application of HEFR, only one flow gage is used. Therefore any decisions regarding the geographic scope of all instream flow recommendations, the spatial extent of individual instream flow recommendations, the number and location of control points, and how to synthesize data at a location without a flow gage, are made outside of the HEFR methodology.

Memory
Memory from one assignment period to the next is conceptualized as an implementation question and is not included in any HEFR calculations. An advantage of having memory is that extended wet periods could reduce near-term future instream flow requirements, allowing increased water diversion or storage under a new water right. Conversely, extended dry periods could increase near-term future flow requirements and help an ecosystem recover from drought conditions. A disadvantage is complexity. An accounting system for tracking changing flow requirements may have to be developed.

Daily Average Versus Instantaneous Flow Data
IHA solely uses daily average flow data; therefore, the HEFR methodology solely uses daily average flow data. This implicitly assumes that if the 1.5-year flood flow corresponds to bank-full (on an instantaneous flow basis), then the 1.5-year flood flow using daily average data will also be associated with a bank-full condition, even though the actual flow values are lower on a daily average basis than on an instantaneous basis.

Hydrologic/Climatic Condition – Trigger
As discussed above, HEFR has four hydrologic conditions built in to the methodology. However, in the current version of HEFR, the trigger for determining which condition is occurring at a particular location at a given time is independent of the HEFR flow analysis and, thus, is not included in HEFR. An example of how this could work is as follows. Reservoir storage could be used to determine the appropriate hydrologic condition at any given time. If the

four hydrologic conditions are subsistence, dry, average and wet, and their associated desired frequencies of occurrence are 2.5%, 22.5%, 50%, and 25% of the time, then reservoir storage volumes (or elevations) that occur with exceedance frequencies of 97.5%, 75%, and 25% could be determined and used as the designated trigger values for determining whether the subsistence, dry, average or wet hydrologic condition is in effect. All of this is independent of the HEFR calculations.

5.6 HYDROGRAPHIC SEPARATION

A defining characteristic of HEFR that distinguishes it from many other hydrologic methods for establishing environmental flow recommendations is an initial hydrographic separation step. Hydrographic separation is used to categorize each day of the period of record as one flow component.[29] It is also important to remember that HEFR presupposes that the days in episodic storm events are classified on an event basis: all of the days in an entire storm event are classified as high flow pulse, if the event meets the requirements of a high flow pulse. Similarly, all of the days in an entire storm event are classified as overbank, if the event meets the requirements of an overbank event (i.e., not solely those individual days that are "over the bank").

In this section, hydrographic separation concepts are introduced. The IHA EFC algorithm is briefly summarized, and an additional hydrographic separation approach is presented and discussed.

5.6.1 Hydrographic Separation Concepts

Hydrographic separation is the science (and art) of distinguishing between different flow classes (or components). Traditionally, hydrographic separation is termed base flow separation and focuses on distinguishing between sources of flow, e.g., between groundwater derived flow (usually termed base flow) and storm event derived flow (usually termed runoff). However, terminology and conceptual models vary depending on project objectives. Indeed, a wide range of flow sources could be identified, from long-term regional groundwater flow paths, to shorter interflow through the soil, discharge from alluvial aquifers, and direct precipitation on the stream surface. Distinguishing between these sources of water is frequently important in traditional hydrologic and water resources studies. Useful references include Ward (2009), Smakhtin (2001), Chapman (1999), and Eckhardt (2008).

For the purposes of establishing an appropriate environmental flow regime in the context of Senate Bill 3, multiple flow components are desired, some of which are at least partially derived from groundwater or alluvial sources (subsistence and base flows) and some of which are more a result of storm events (high flow pulses and overbank events). Because of the focus on ecosystem roles, the traditional distinction between various groundwater and runoff sources does

[29] In the current version of HEFR, these flow components are subsistence flow, base flow, high flow pulse, and overbank events. Other options could be used. Note that the IHA software uses the terminology "flow component," even though, as pointed out in Ward (2009), since each day gets one and only one such assignment, these might more appropriately be termed categories or classes. Because of the variability of terminology in the literature, in this document and context, the words component, category, and classification will be used interchangeably.

not necessarily fit in the context of environmental flow recommendations. For the purposes of SB 3 efforts, it is perhaps less important to identify the source of water than the ecological role, or ecological significance, of varying flow magnitudes and other flow characteristics. Put simply, the hydrographic separation in HEFR is a hydrological activity for an ecological purpose and is therefore not synonymous with traditional base flow separation methodologies. In the development and application of the EFC algorithm in IHA, one consideration for the use of the term "low flow" in lieu of "base flow" has been to avoid the traditional connotation of "base flow" being purely groundwater derived (Ryan Smith, personal communication). In this light, it is more desirable to separate the hydrograph into biologically and ecologically meaningful components than components based on the water source. A description of the primary objectives of the different flow components considered important for describing environmental flow prescriptions as used in HEFR is provided in Section 2.2.

For efforts associated with SB3, it is important to identify the ecologically and biologically important components of the flow regime to develop recommendations that provide ecological benefits such as those listed in Section 2.2. Very small runoff events, while classified as runoff by traditional hydrographic separation algorithms, may not provide any of the ecological benefits associated with high flow pulses. Similarly, during the leading and trailing limbs of storm hydrographs, fish may not be hiding in velocity shelters and may be exploiting habitats made available by these flows. Thus the ecological role of some leading and trailing limbs may be more akin to base flows than high flow pulses. Conversely, very high flows, even if sustained for a period, may not serve the habitat functions of base flows, even if identified as base flows by a particular hydrographic separation algorithm. Hence, the ecological benefits associated with the various flow conditions are not solely dependent on flow rate, but also on volume, timing, rate of change, and duration (e.g., to move significant sediments, higher flows for sustained periods may be required).

Because of these complexities, it is helpful to define a conceptual model of the various hydrographic flow components that are known to play important roles in supporting a sound ecological environment in a particular stream segment before completing a hydrographic separation analysis. The varying ecological characteristics of different stream segments are likely to require different definitions of flow components in order to achieve appropriate environmental flow prescriptions with HEFR.

There are currently two options for hydrographic separation that can be used in HEFR, both of which have user-defined options to provide flexibility. These are termed (1) IHA and (2) MBFIT and are discussed below.

5.6.2 IHA EFC Method

As discussed in the Evadale example above, IHA parses the hydrograph using a combination of flow magnitude and rate of change parameters, seven in total. These parameters can be tuned to the location of interest, based on project objectives. For example, the default IHA EFC parameter set used in HEFR (given in Figure 4) has fairly high rate of change parameters (50% increase and 5% decrease) for initiating and terminating high flow pulses. This is often

appropriate for flashy systems that change rapidly. Lower values may be appropriate for less flashy systems.

5.6.3 Modified BFI with Threshold Method (MBFIT)

The Base Flow Index Method of the U.S. Bureau of Reclamation[30] has been used to separate hydrographs into base flow and runoff components, where every day is assigned some amount of base flow and some days additionally have runoff flow. The method is based upon dividing the daily time series of flows into N-day windows and tracking the time series of minima in each window. The window length N is at the disposal of the user. This is basically a measure of the time for a storm hydrograph to substantially recede. In this respect, the BFI approach has some kinship with the traditional base flow separation techniques relying upon recession time-series behavior (details are given in Wahl and Wahl, 1995.) This is a purely empirical approach whose justification is based upon post facto applications, where the BFI seems to capture what is believed to be base flow behavior.

A modification of this method has been developed in Excel for use by HEFR. This modification differs from the BFI method in three respects: (1) rather than subdivide the daily flow time series into N-day windows, it uses a sliding centered window of N-day length, so each day of the time series has an associated window-minimum value, (2) the interpolation between "turning points" to create a base flow time series has been omitted because it is irrelevant to the one day – one category concept used in HEFR, and (3) upper and lower thresholds (similar to the magnitude thresholds in IHA) have been added that force the code to always assign a day to the high flow pulse or overbank categories if the flow exceeds the upper threshold (UT) and to never assign a day to the high flow pulse or overbank categories if the flow is less than the lower threshold (LT). The basic functioning of the algorithm is as follows: if the daily flow in excess of the associated minimum of (1) is less than the associated minimum of (1) times the parameter RF (Runoff Fraction, RF<1), that day is initially classified as a base flow, unless the flow exceeds the upper threshold.

In the MBFIT method, subsistence flows and overbank events are coded in similarly to the IHA EFC algorithm. Following the default HEFR parameter set, subsistence flows can be identified as the lowest 10% of the initially-classified base flows (i.e., the MBFIT method initially classifies each day as either a base flow or a high flow pulse. The bottom 10% of these initially classified base flow days then become subsistence flows.). Similarly, initially-classified high flow pulse events that exceed the 1.5 year return flow are then classified as overbank flow events. These parameter values (10% and 1.5 year) are adjustable by the user.

Two possible weaknesses of the MBFIT method in the context of ecological goals are that very small runoff events are frequently assigned to the high flow pulse category and occasionally flow days near the top of long storms are assigned to the base flow category. Careful selection of the N, RF, LT, and UT parameters can reduce the occurrence of these problems.

[30] http://www.usbr.gov/pmts/hydraulics_lab/twahl/bfi/

These upper and lower thresholds can be "turned off" by setting the upper threshold to 100% and the lower threshold to 0%. In this case, only the BFI sliding window calculation controls the results.

5.6.4 Comparison between Methods

In this section, the Neches River at Evadale and the Clear Fork Trinity River at Ft. Worth are examined to illustrate the behavior of the two methods with a few different parameter values. This discussion is far from comprehensive and is instead intended as a basis for preliminary evaluation and to inspire further analysis. In addition, any numerical conclusions reached in this section are only relevant to the methods and parameters used herein. Other parameterizations of these same methods would generate different results. Thus, this section is less a comparison of numbers than a possible template for how to evaluate hydrographic separation behavior at a location.

5.6.4.1 Neches River at Evadale

Figure 9 shows the hydrographic separation results at Evadale from November 1, 1936 through July 31, 1937 (a period that has an informative combination of storms) using the IHA EFC algorithm. In this simulation, data from January 1, 1922 through December 31, 1964 were entered into IHA. The parameter set for the HEFR-Def (HEFR Default) data series are shown in Figure 4 above[31]. The parameter set for the HEFR-Mod (HEFR Modified) data series are identical to those for HEFR-Def, with the exceptions that the increasing rate of change parameter was dropped to 25% per day and the decreasing rate of change parameter was dropped to 1% per day. These changes may be more appropriate for larger, less flashy, basins such as Evadale. As shown in Figure 9, the HEFR-Def method does not classify the December storm event as a high flow pulse (the rate of change never exceeded 50% per day and the peak never exceeded the 75th percentile of all flows). The HEFR-Def method also started the high flow pulse classification in Jan about one week following the initial rise of the hydrograph. The HEFR-Def method terminated the high flow pulse event in April well before the hydrograph completely receded from the storm event. HEFR-Def also did not classify the small storm in early May as a high flow pulse and it started the June high flow pulse three or four days following the initial rise of the hydrograph.

[31] Note that this is labeled HEFR-Def even though HEFR is not used in the generation of these figures. Only IHA is used, however, IHA is parameterized using the suggested HEFR default values (see Appendix A), thus the nomenclature HEFR-Def.

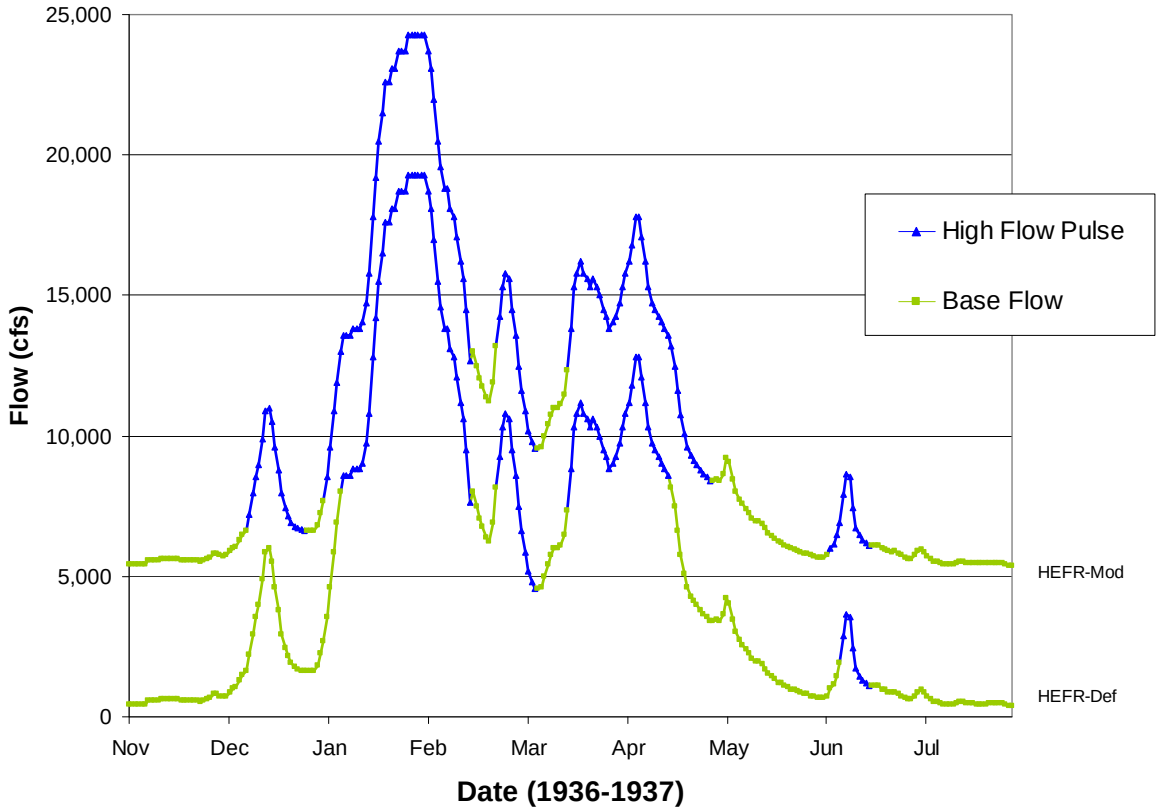

Figure 9. Hydrographic Separation Using IHA at Evadale.

The HEFR-Mod curve shows the same data, with the slightly different parameterization of IHA and also with 5000 cfs added to the values shown in the figure to allow a visual separation between the data series (5000 cfs was only added to the display, not to the data being analyzed in IHA). In this case, the December storm was classified as a high flow pulse (it exceeded the 25% per day increasing rate of change threshold). Also, the January storm was classified as a high flow pulse earlier in the event. Similarly, more of the trailing limb of the storm event in April was classified as a high flow pulse. Again, the small storm in early May was not classified as a high flow pulse, but the entirety of the June event was. In this curve, some base flows (especially in the lulls between storm events) exceed some high flow pulse days.

Figure 10 shows similar results for three permutations of the MBFIT method. The bottom curve shows the results of the MBFIT method using N = 5, f = 0.9, RF = 0.1, UT = 100%, and LT = 0%. This curve identifies some high flow pulse days in early November, it identifies the December storm as a high flow pulse, it captures much more of the trailing limb of the storm events than either of the IHA/HEFR methods, and it identifies several high flow pulse days in July, during a period of fairly low and steady flows. This curve also identifies a single base flow day in mid January, on the ascending limb of the storm event, as well as two base flow days at the peak of the storm in late January. This illustrates a key behavior of the MBFIT method with UT = 100% and LT = 0%. Because this parameterization looks solely at rate of change

parameters, large storm events with flat peaks or shoulders can have days that are classified as base flows. To reduce the likelihood of this occurring, a higher value of N is recommended. The middle curve (to which 5000 cfs has been added for display purposes) shows the same approach, only with N = 9. In this curve, the three base flow days in January are reclassified as high flow pulses. Also, somewhat more high flow pulse days are identified in November and July. Eight base flow periods remain in the nine months presented. The upper curve (to which 10,000 cfs has been added for display purposes) illustrates the impact of changing the RF parameter to 0.3. This increases the fraction of runoff that must be present in order to classify a day as a high flow pulse or overbank event. In this example, the primary effect of this change is to modestly increase the duration of the remaining base flow periods and add a new, single day, base flow in late April. In all three of these curves, there are multiple base flow days that exceed some high flow pulse days, in part because some fairly low flows are identified as high flow pulses (e.g., late July).

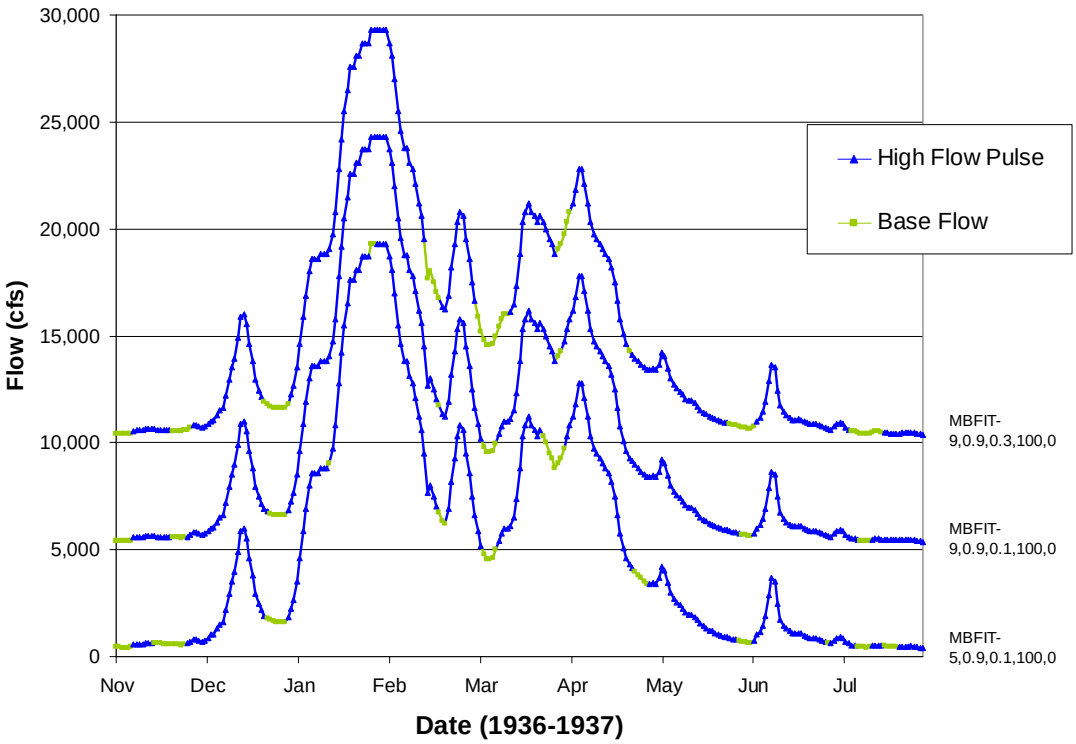

Figure 10. Hydrographic Separation Using MBFIT with UT = 100 and LT = 0 at Evadale

The MBFIT with UT = 100 and LT = 0 method is essentially comparing the minimum flow in a centered N day window (i.e., centered around the current day) to the minimum flow in an N day window centered N days prior to the current day, and another window centered at N days hence, and looking for changes in these minimum flow windows. Thus, portions of the hydrograph where the flow is clearly changing rapidly from one day to the next, but the flow reverses course

and is approximately equal N days prior or N days hence, can be classified as base flows. This is probably why base flows are identified at relatively high flow rates in late March.

Figure 11 illustrates the same time period for the MBFIT method using the UT set at the 75th percentile and the LT set at the 25th percentile. The lower curve is similar to the lower curve in Figure 10, with two main exceptions: (1) the entire storm event in January is classified as a high flow pulse, instead of having three days being classified as base flows (one on the ascending limb and two at the peak), and (2) the relatively steady flows in November and July are classified as base flows. The middle curve (to which 5000 cfs has been added for display purposes) shows the results using N = 9. At lower flow values, this curve is essentially indistinguishable from the lower curve (probably because the lower threshold of the 25th percentile forces low flows in both curves to be assigned to the base flow category). At medium flows, this middle curve has fewer base flow days. The upper curve (to which 10,000 cfs has been added for display purposes) shows the results using RF = 0.3. This curve exhibits slightly more base flow days at medium flow rates.

The high flow days classified as base flows in late March in Figure 10 are classified as high flow pulse days in Figure 11 because of the 75th percentile threshold.

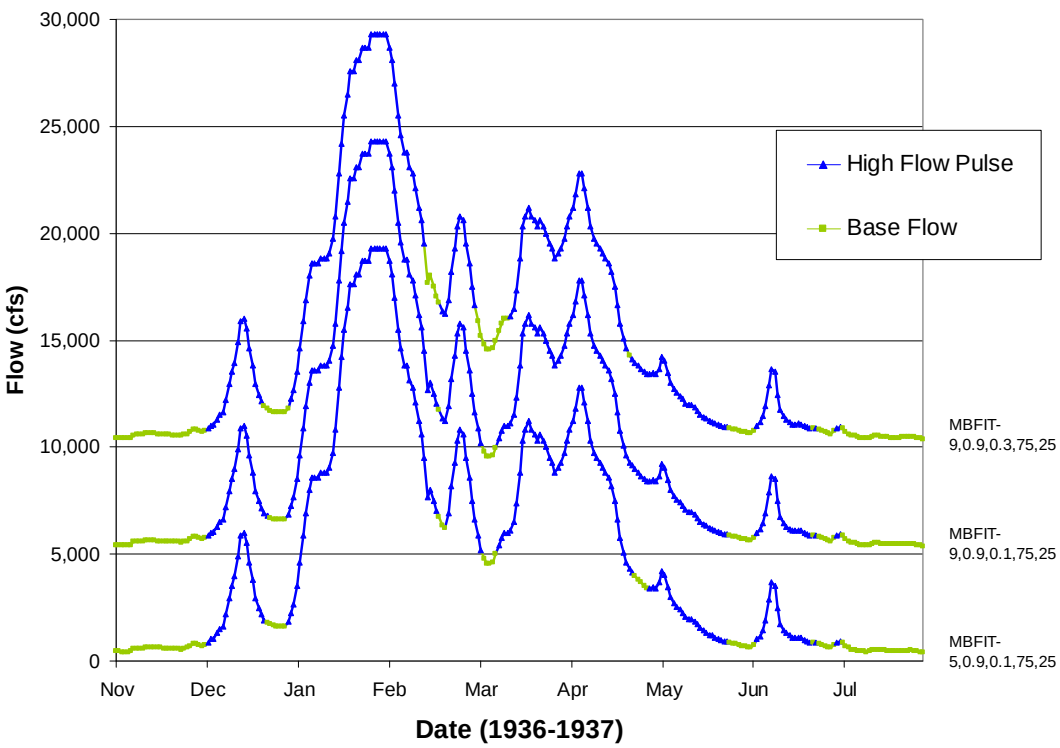

Figure 11. Hydrographic Separation Using MBFIT with UT = 75 and LT = 25 at Evadale

The selection of a hydrographic separation methodology (including parameterization) should be based on the professional judgment of the analyst and the capabilities of the algorithm to separate flow components that are ecologically meaningful. That said, it is sometimes helpful to

look at summary results. Figure 12 illustrates the monthly base flow statistics for the HEFR-Mod, MBFIT-100,0 (with N = 9, f = 0.1, RF = 0.1, UT = 100 and LT = 0) and MBFIT-75,25 (same N, f, and RF, with UT = 75 and LT = 25). In this figure, the 25, 50, and 75 (in the legend, following the underscores) simply denote the 25th, 50th, and 75th percentiles of the outputs. In the spring months, the MBFIT-100,0 curve is generally higher than the other methods, especially the 50th and 75th lines.

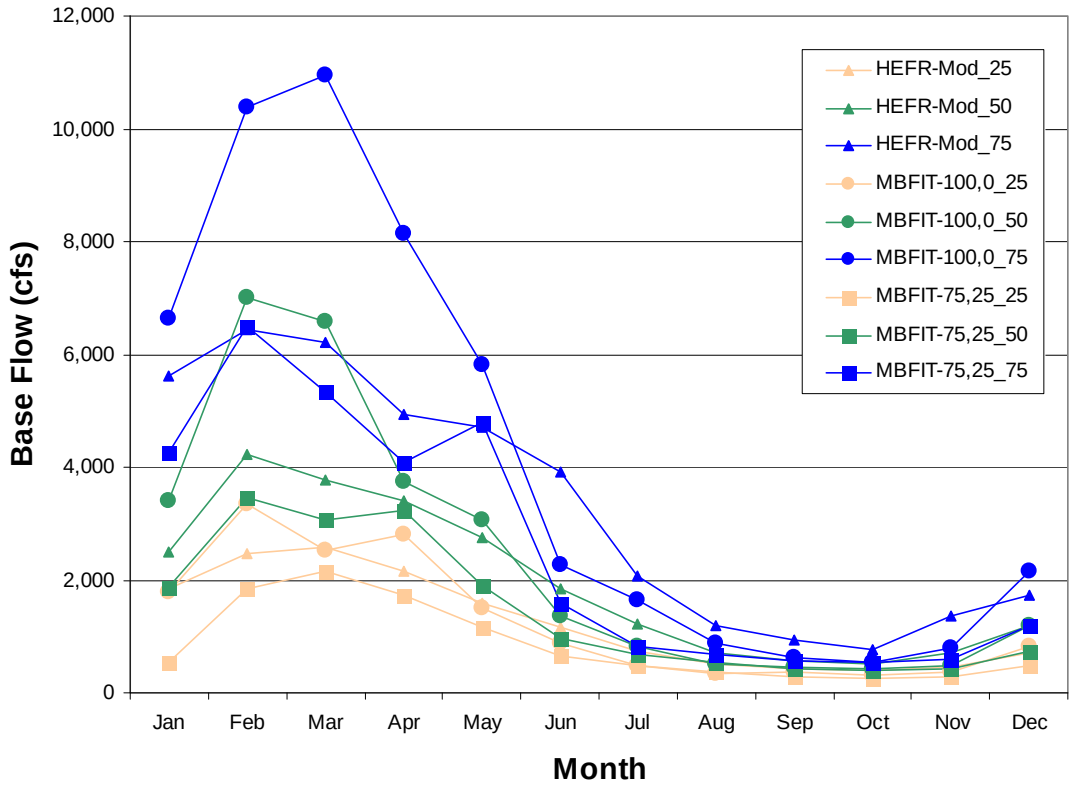

Figure 12. Summary Statistics of Three Hydrographic Separation Parameterizations at Evadale

5.6.4.2 Clear Fork Trinity River at Fort Worth

To provide a comparison of these methods at a substantially different location, the Clear Fork Trinity River at Fort Worth was selected. The period of record used herein is January 1, 1925 (the start of the first full year of data) through December 31, 1949 (the end of the last year before the impoundment of Benbrook Lake). The river is much more flashy than the Neches River at Evadale. To avoid dividing by zero in the calculations, zero flows were replaced with 1e-9 in the calculation spreadsheets. To improve the visual display of the results, a log y axis is used and zero flows are replaced with 0.1 cfs for these figures.

Figure 13 shows the hydrographic separation results for the HEFR-Def and HEFR-Mod simulations for a period with several informative storm events: December 1, 1943 through July

31, 1944. In general, HEFR-Def has a few more base flow days (because of the relatively elevated requirement for increasing rate of change). For example, there is a small storm event centered around February 10 that is classified as base flow in HEFR-Def, but as a high flow pulse in HEFR-Mod. Similarly, the first and third overbank events are shorter in HEFR-Def as compared to HEFR-Mod. Fifty-one percent of all initially-assigned base flows are zero, thus all zero flows are finally assigned as subsistence flows and all final base flows are greater than zero. Also, since 26% of this period of record had zero flow, the 25th percentile is zero and high flow pulses can begin at any non-zero flow value (depending on the rate of change parameter).

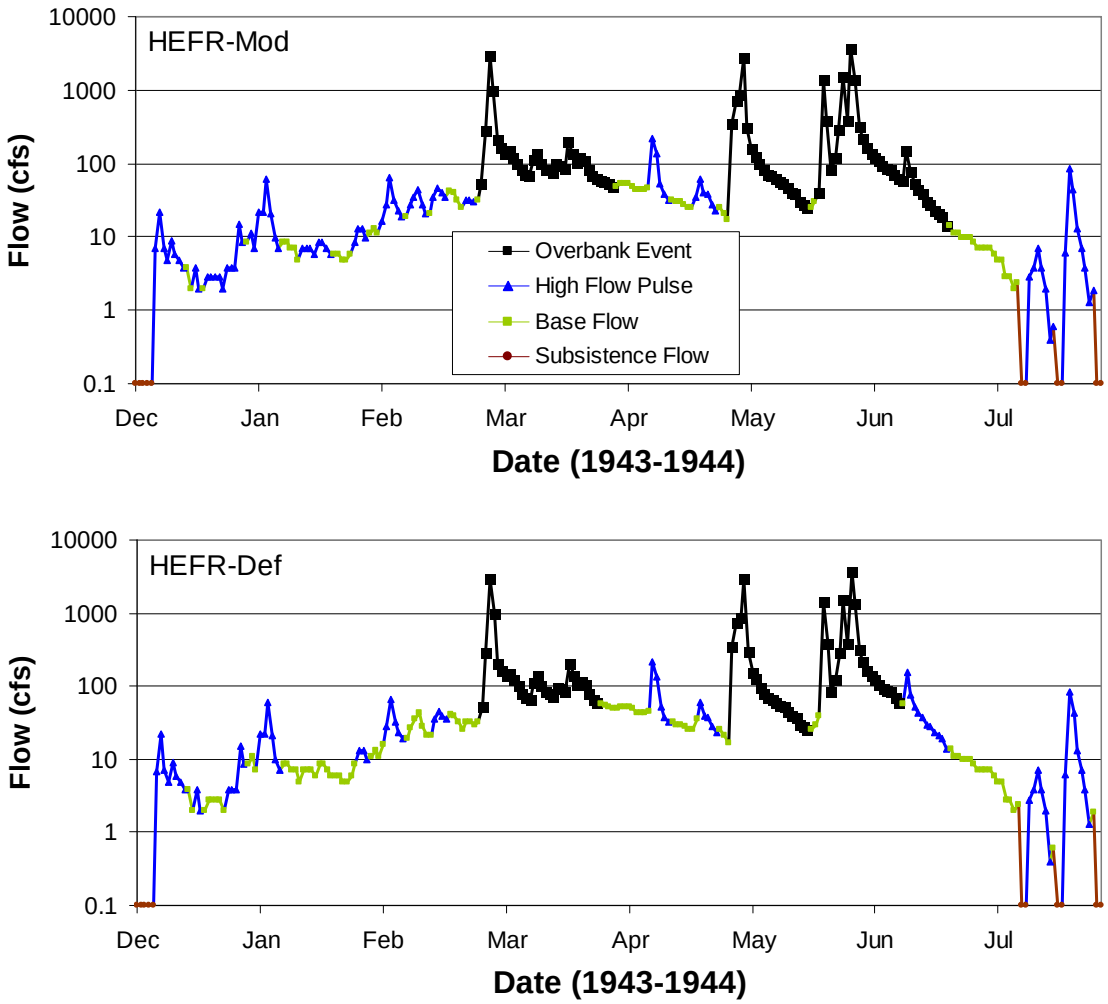

Figure 13. Hydrographic Separation Using IHA at Ft. Worth

It is important to remember that high flow pulse events are terminated when base flows are estimated (by the algorithm) to begin again. Overbank events are a subset of high flow pulse events. Therefore, in all hydrographic separation techniques described herein, overbank events are only terminated when base flows recommence. Overbank events are never directly followed by a high flow pulse event. High flow pulse and overbank events with multiple peaks (e.g., late

May in Figure 13) can be split into multiple consecutive events, at the discretion of the user, in HEFR using the Multipeaks_Multiplier function.

Figure 14 illustrates the separation results for three permutations of the MBFIT method with UT = 100% and LT = 0%. Because this is a flashier system than Evadale, N was set to lower values (3 and 5). In the lower panel, N is set to 3, f = 0.9, and RF = 0.1. As compared to Figure 13, the first overbank event ends much earlier, but the third lasts much longer. In the middle panel, N is increased to 5. The difference (as compared to the lower panel) is modest: a few short base flow periods become high flow pulses. In the upper panel, N is switched back to 3 and RF is increase to 0.3. This dramatically shortens the length of the third overbank event (to a length very similar in HEFR-Def). There are also a few more base flow days in the upper panel as compared to the lower panel.

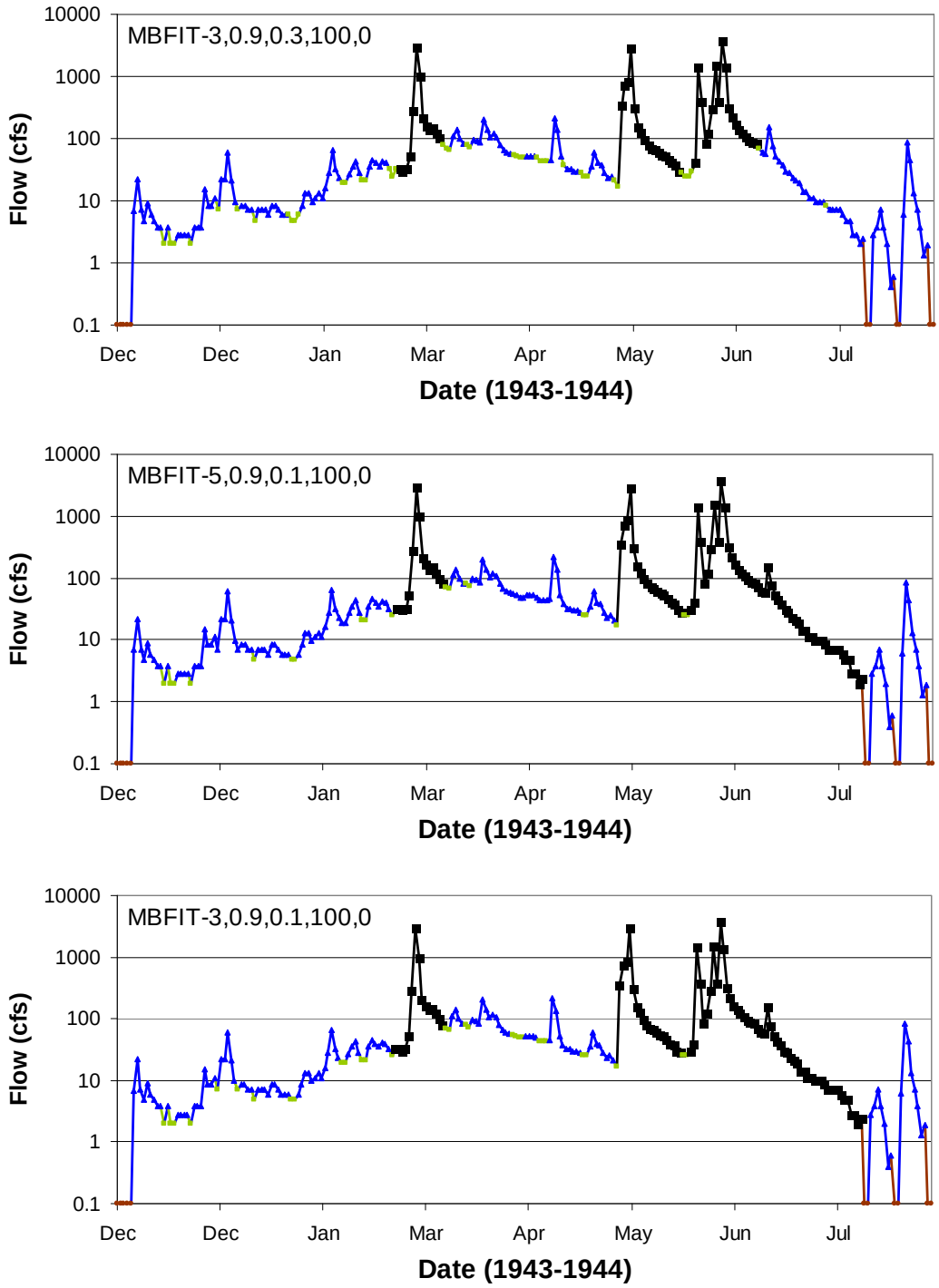

Figure 14. Hydrographic Separation Using MBFIT with UT = 100 and LT = 0 at Ft. Worth

Figure 15 shows the results for three variations of the MBFIT method, using the same combinations of N, f, and RF as in Figure 14 but with UT = 75 and LT = 25. In the lower panel, the first overbank is classified much like in the two HEFR methods (i.e., longer than in the

MBFIT parameterizations shown in Figure 13) and the third overbank is classified much like in Figure 13 (i.e., longer than in the HEFR methods). Thus, the MBFIT with UT = 75 and LT = 25 results in the longest overbank events. The middle panel (N = 5) sets the initial overbank event to an even longer duration. The upper panel shortens both the first and third overbank event durations and also adds some base flow days.

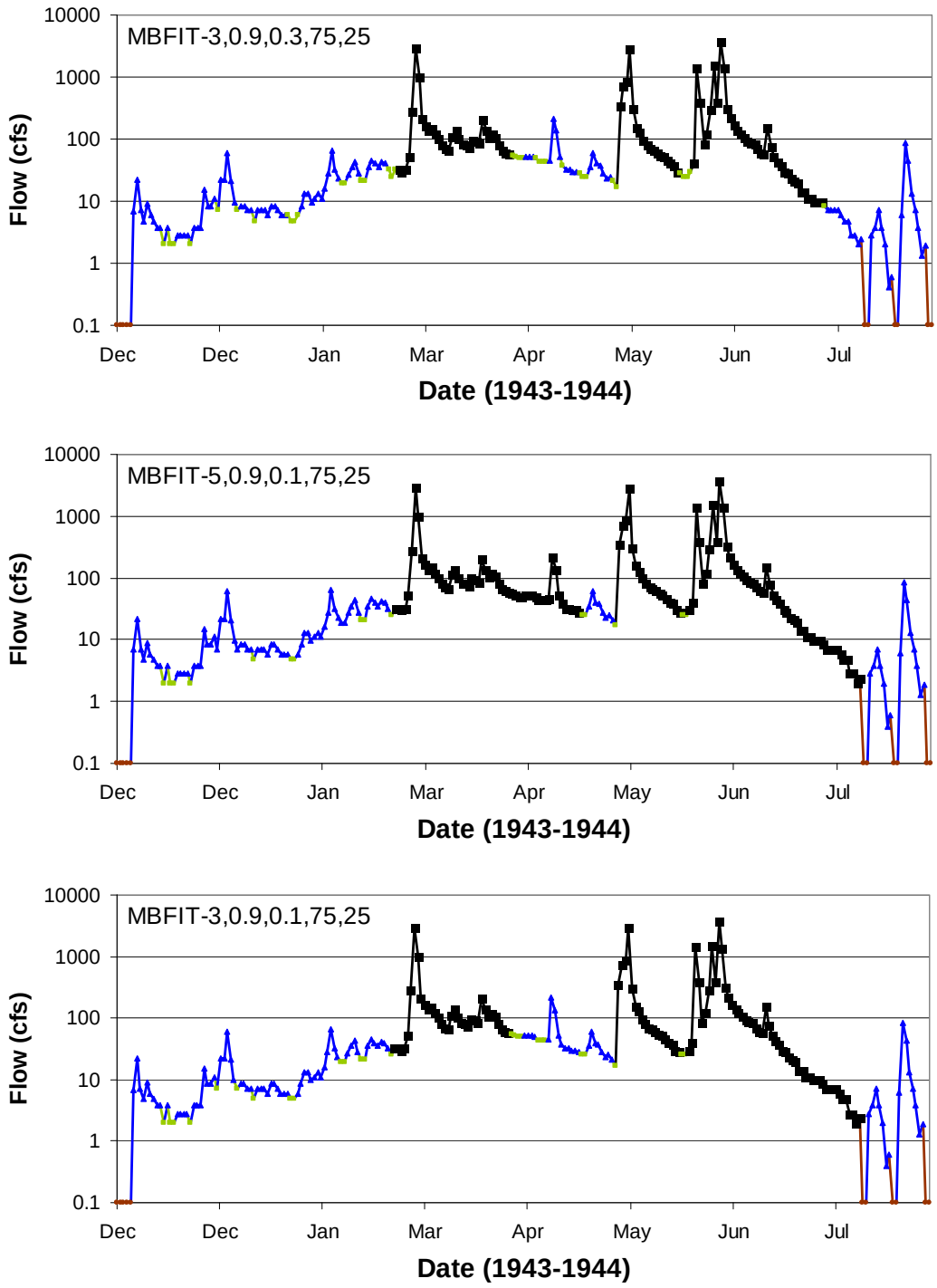

Figure 15. Hydrographic Separation Using MBFIT with UT = 75 and LT = 25 at Ft. Worth

Figure 16 illustrates a summary of the 25th, 50th, and 75th percentiles of the base flow outputs.

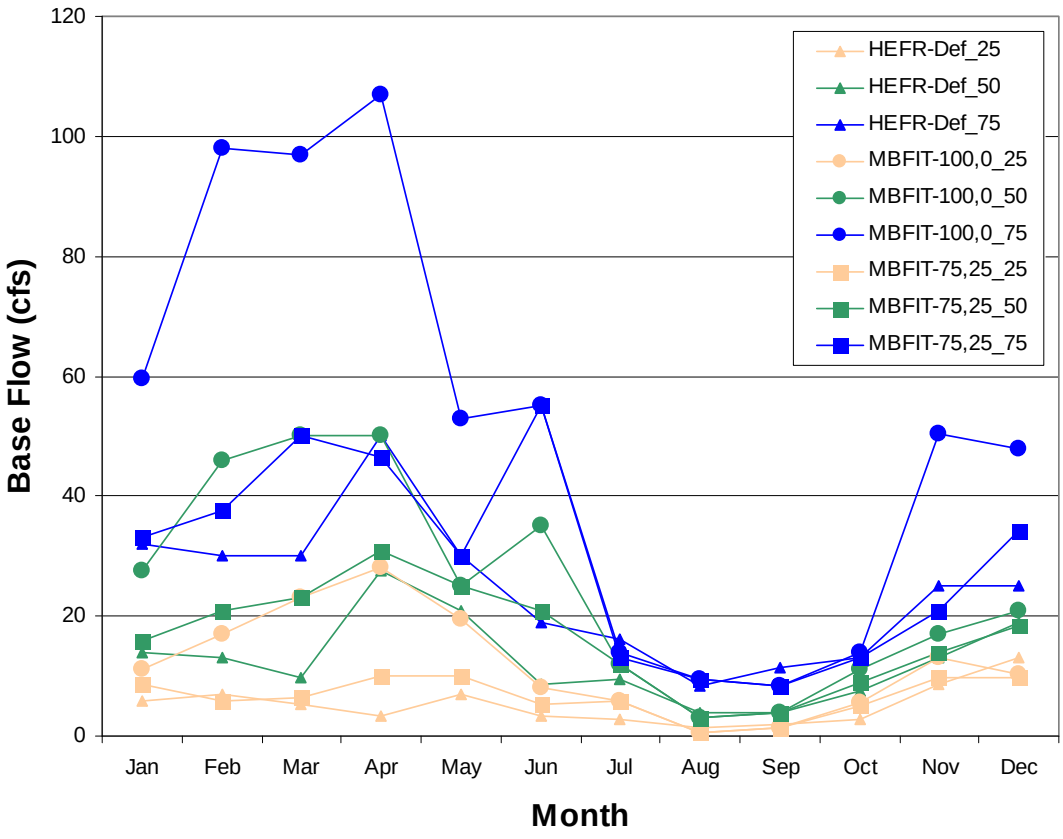

Figure 16. Summary Statistics of Three Hydrographic Separation Methods at Ft. Worth

Again, the MBFIT-100,0 method specifies much higher base flows in the spring months. To explore this, and other aspects of the hydrographic separation, an additional series of plots were generated for the Clear Fork Trinity.

Figure 17 compares the count of days assigned to the different flow components for the HEFR-Def and MBFIT-100,0 methods.

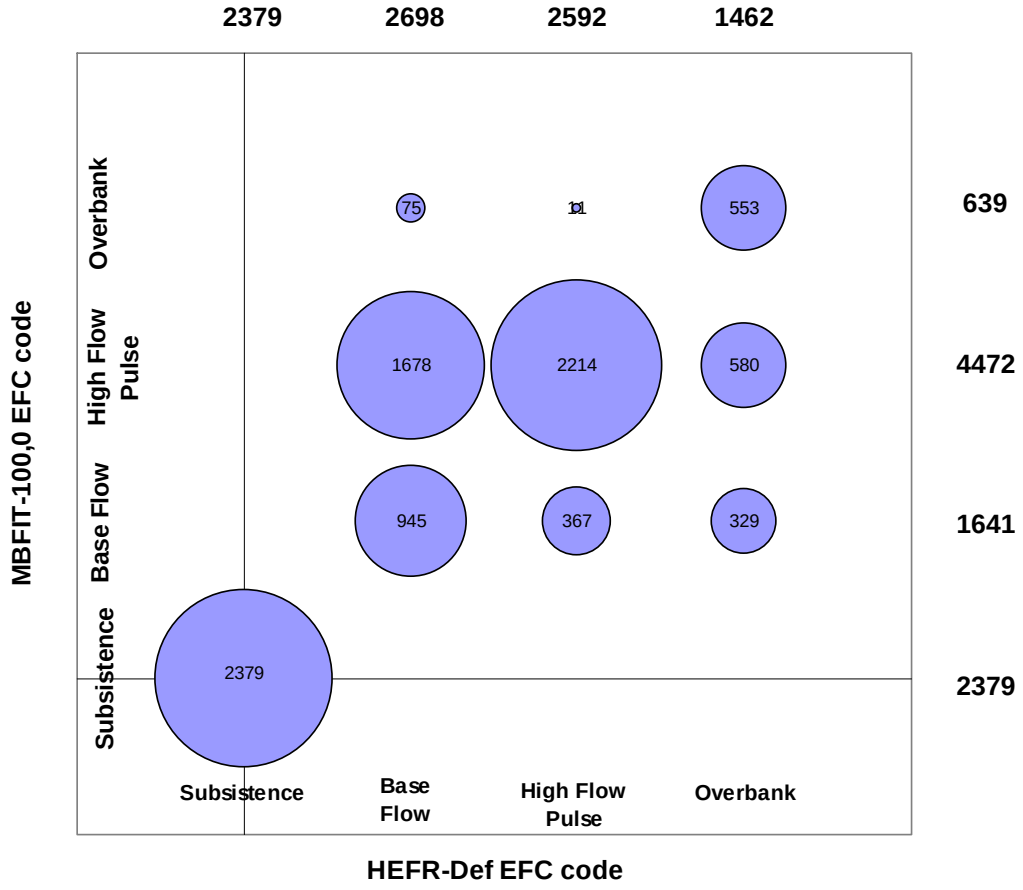

Figure 17. Bubble Chart of Flow Component Daily Counts at Ft. Worth

In this figure, bubbles along the 45° line count days that were assigned to the same flow component in both methods. Bubbles off of the 45° line count days that were assigned differently between the two methods. For example, there were 1678 days that were assigned to base flow by HEFR-Def, but were assigned to the high flow pulse category by MBFIT-100,0. Numbers along the top and right side of the figure denote subtotals. These results suggest that the MBFIT-100,0 method (as parameterized in this example and for this location) identifies many more high flow pulse days than HEFR-Def. Because of the preponderance of zero flow days, both methods identically designated all zero flow days as subsistence flows and no non-zero flow days as subsistence flows.

Figure 18 is a probability plot of base flows as identified by these two methods. This plot shows that the MBFIT-100,0 method results in a population of base flow days that have considerably higher flows than the HEFR-Def method (note the log y axis; this conclusion is consistent with Figure 16). Although, as shown in Figure 17, there are fewer base flow days identified by MBFIT-100,0 than HEFR-Def (2698-1641 = 1057 fewer base flow days).

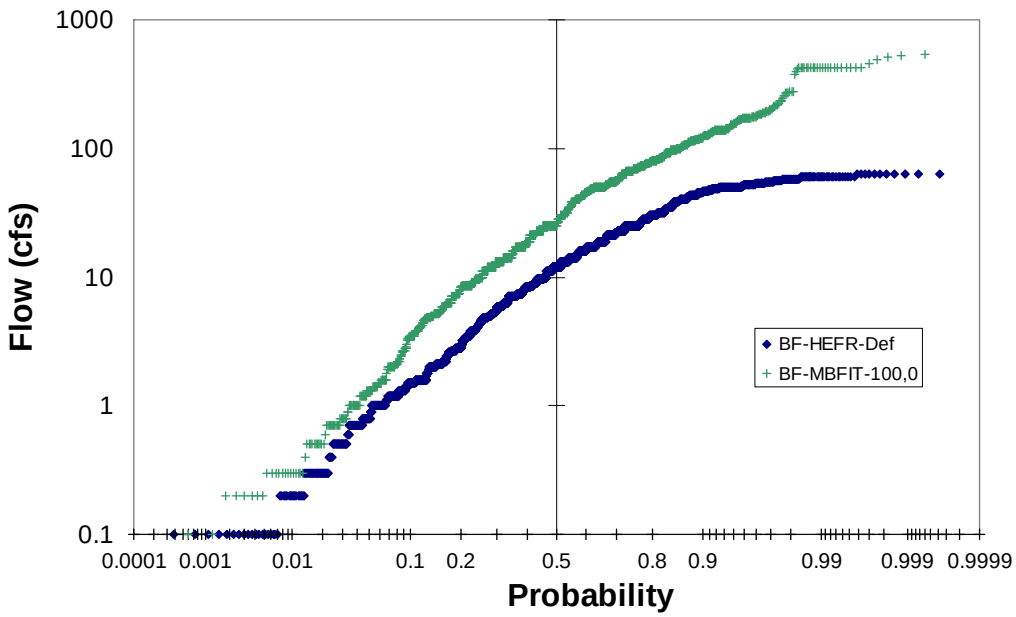

Figure 18. Probability Plot of Base Flows at Ft. Worth

Figure 19 shows a probability plot for high flow pulses. In the mid-portion of the distributions, the HEFR-Def method results in slightly higher flow rates (note that all high flow pulse days are shown, note just event peaks). Both methods are similar at the tails and both methods identify high flow pulse days as low as 0.1 cfs (i.e., zero cfs). This likely occurs when a storm event ends abruptly and is not designated to end until the flow holds steady (at zero). Increasing the minimum magnitude threshold in IHA from the lower 25th percentile to a higher value would help ameliorate this behavior in the HEFR-Def approach. Figure 17 shows that high flow pulse days are more commonly assigned by MBFIT-100,0 than HEFR-Def.

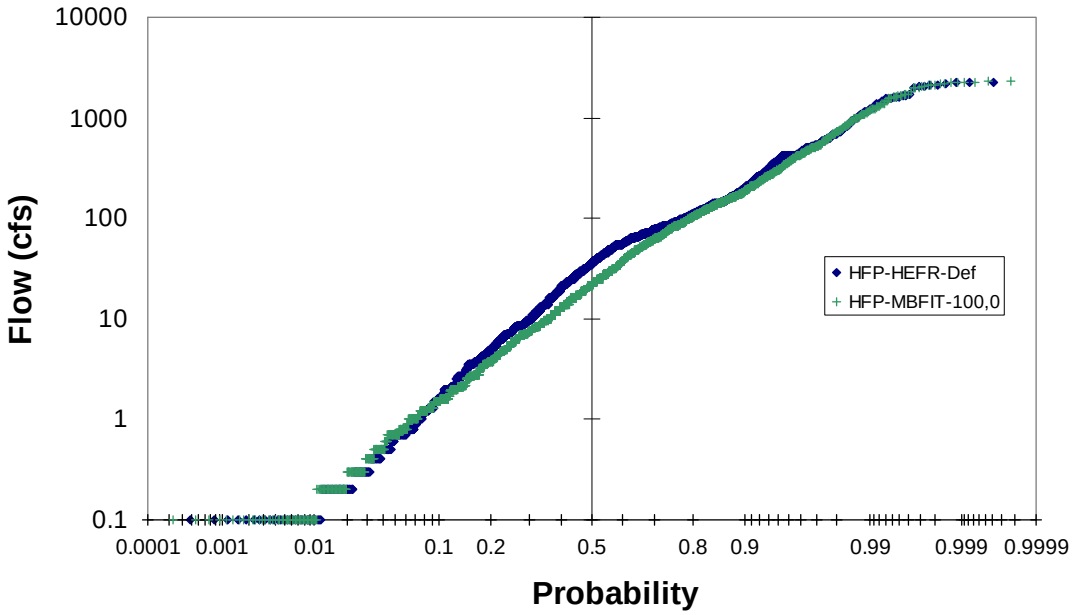

Figure 19. Probability Plot of High Flow Pulses at Ft. Worth

Figure 20 has a similar probability plot for overbank flows. In this plot, the two distributions cross. At the median value, the MBFIT-100,0 method is somewhat higher than HEFR-Def.

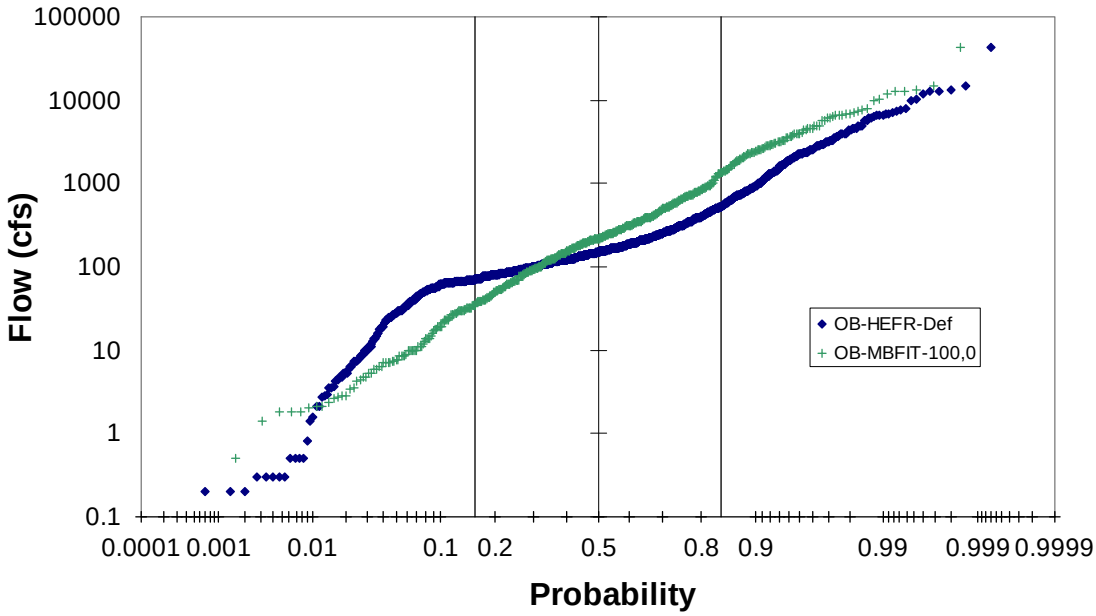

Figure 20. Probability Plot of Overbank Flow Event Days at Ft. Worth

In summary, as compared to MBFIT-100,0 (using these parameter sets):

- HEFR-Def has more overbank days, with a slightly higher median.
- HEFR-Def has fewer high flow pulse days, with slightly higher 25th, 50th, and 75th percentiles of flow (although not necessarily percentiles of event peak flow)
- HEFR-Def has more base flow days, with lower values.

5.7 EPISODIC EVENT METHODS

HEFR has two methods for calculating high flow pulse and overbank flow recommendations. The user can select either method, but should recognize that these methods differ not just in their computations, but also somewhat in their conceptualization and interpretation.

5.7.1 Original HEFR (Percentile-based) Approach

The original conceptualization for high flow pulse recommendations involves the following general steps:

1. Using the population of high flow pulses identified by IHA (or other hydrographic separation algorithm), individually determine the 25th, 50th, and 75th percentiles (or alternate user-input

percentiles) of event peak flow, event volume, and event duration for each season. Then identify high flow pulse events that meet or exceed the 75th percentile of all three characteristics (or a user-input combination of any/all of these three). This is the population of "wet" qualifying high flow pulses. Then identify high flow pulse events that meet or exceed the 50th percentile of the selected characteristics (but not the 75th percentile); these are the "average" high flow pulses. Those pulses that meet the 25th percentile of the selected characteristics (but not the 50th percentile) are the "dry" high flow pulses. Those pulses that do not at least meet the 25th percentile of the selected characteristics receive no qualifying designation and are not included in subsequent calculations.

2. Assign a frequency recommendation for "wet" high flow pulses as the 75th percentile of the historical frequency of occurrence of such pulses (rounded up if non-integer). Similarly, the "average" and "dry" frequency recommendations are equal to the 75th percentile of the historical frequency of occurrence of average (and larger) and dry (and larger) events, respectively.

Thus, the general approach in the original conceptualization of HEFR is to quantify percentiles of three flow characteristics, identify storm events that exceeded one or more of those characteristics, and set the recommended frequency based on the historical frequency. All calculations are performed on a seasonal basis. The user must select the desired percentiles as well as the desired suite of flow characteristics for classification (any combination of peak, volume, and/or duration).

Advantages:

1. Consistency with other aspects of HEFR. The use of "wet," "average," and "dry" and associated percentiles is consistent with the framework for base flows. This explicitly links larger (e.g., "wet") requirements to seasons where water is relatively plentiful.
2. Only pulses of a certain minimum size are considered. Very small pulses are unlikely to have meaningful biological effects and this method attempts to specify high flow pulses that will be meaningful.
3. Recognizes importance of three flow characteristics: peak, volume, and duration. While these characteristics are generally correlated in natural systems, in the future, as existing water rights are more fully exercised and if additional water rights are granted, these characteristics could become decoupled if only one is specified in an environmental flow requirement.

Disadvantages

1. Low seasonal frequencies can be problematic. A combination of large events and short seasons generally leads to recommended frequencies of zero, one, or two (frequencies must be integers). Recommendations of zero are not meaningful and there is a big difference between a frequency recommendation of one and two when looking at total water volume.
2. Lack of multi-year evaluation limits the size of recommended high flow pulses. The concept of limiting pulse sizes to only those storms that would occur at least once per season limits the size of high flow pulses that can be recommended.

5.7.2 Alternative Frequency-Based Approach

An alternate method of identifying high flow pulse and overbank event recommendations has been developed as an option in HEFR. Both the original method and the alternate method are based upon output of the hydrographic separation operation. Additionally, both methods are consistent with the concepts proposed by the TIFP in that they provide inter- and intra-annual variability in the recommendations for these episodic events.

In contrast to the original method that uses non-parametric statistics to identify qualifying high flow pulse characteristics, the alternate method uses frequency (or recurrence interval) to identify peak flows.

From a user-input standpoint, the analyst chooses a checkpoint frequency, or recurrence interval, for appropriate events occurring within each season. The analyst's choice is based upon graphical and tabular output generated by HEFR using the site-specific hydrological data series, combined with their knowledge of the system and understanding of the ecosystem roles of flows of different magnitudes and characteristics. Once events are chosen based upon checkpoint frequencies, the program determines peak flow (or a series of peak flows) for each checkpoint. Then for each peak flow, the program uses statistical regression analysis to identify a range of duration and volume characteristics associated with each peak flow. Use of the statistical regression method to identify duration and volume allows for accounting of variability across events with similar peak flows and allows for accounting of uncertainty in the regression.

Frequency Calculations

The first step of this method is to establish the expected frequency (or return period) of the observed peak flows from high flow pulses and overbank events.

A data series of peak flows is created that includes the peak of every high flow pulse event and overbank event identified by the hydrographic separation algorithm. This data series will often include more than one event per year; however traditional hydrologic frequency calculations are based on annual maxima series and consequently disregard events other than the maximum from each year (see, e.g., Section 18.6.1 of Stedinger et al., 1993). To help resolve this shortcoming in traditional calculations, Claps and Laio (2003) have investigated other statistical methods which are used in this alternative frequency-based approach. The advantages of this approach are that it maximizes the number of peaks used in the calculations and considers events smaller than the annual maxima. Additionally, frequency of occurrence within each season can be identified using seasonal sub-datasets.

Equation 6 of Claps and Laio (2003) and seasonal assignments provided by the user are employed by HEFR to generate a frequency curve (Figure 21) and a table of frequencies. As two examples of the interpretation of this figure, a peak flow of 10,000 cfs is expected to have a frequency of about 2.8 per year and 0.35 per Season 3 (Season 3 is from June to August).

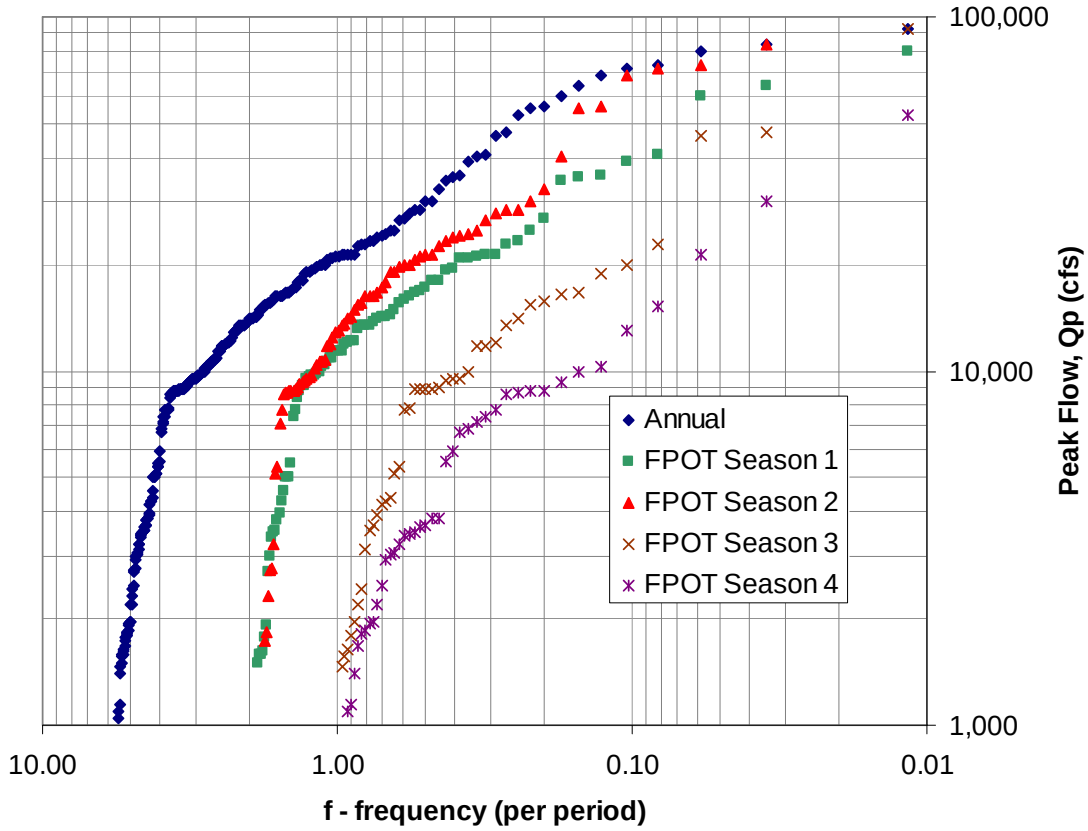

Figure 21. Frequency of Peaks Associated with High Flow Pulse and Overbank Events, Evadale 1922-1964.

Event Frequency Selections

The second step is for the analyst to use the frequency curve and tables, combined with knowledge of ecologically relevant high flow pulse and overbank event magnitudes, to select frequencies associated with these event magnitudes. For example, let Season 1 (Figure 21) be from December through February and Season 2 be from March through May. If the analyst knows that low-lying oxbows and backwater areas are inundated at a flow of 12,000 cfs (which is below bank-full) and that this should occur at (or near) the historical frequency in Seasons 1 and 2, the analyst could select a frequency of 2 per December – May window as a high flow pulse flow recommendation. The analyst may select several such levels, based on knowledge of the system.

Regressions of Peak Flow to Volume and Duration

The third step is to identify event volumes and durations associated with the desired peak flows (Qp).

This method has been developed using the correlation between historical peak flows and associated event volumes and durations. This method utilizes HEFR generated data series of peak flows, volumes, and durations developed for each high flow pulse and overbank event identified by the hydrographic separation algorithm. These data series are disaggregated by user-

specified seasons, whereupon separate univariate regression analyses are then performed across the entire period of evaluation. It must be acknowledged that some streams, e.g., streams highly influenced by diversions and impoundments, may yield a less consistent relation between peak flow, volume, and duration. It is up to the user to assess where such relations are most applicable.

Volumetric and durational analyses are performed separately, wherein two distinct forms of least-squares regression models are evaluated to assess which best fits the data (ln-ln and quadratic). The user can evaluate the fit of these regressions using either R^2 or Standard Error of the Estimate. The user can select the preferred regression form using either of these two criteria or can force another selection *a priori*. Ultimately, the user should carefully consider the regression form, the fit of the regression (particularly in the vicinity of desired Qp values), and the utility of the best-fit and prediction intervals on a case by case basis. This may require an iterative evaluation process and multiple HEFR runs.

The generated regression output (Figure 22) utilizes the calculated prediction intervals[32] estimated from the standard deviation of the prediction (this 68.3 percent confidence level is the default, although this too may be adjusted by the user) to calculate related volumes and/or durations for selected peak flows.

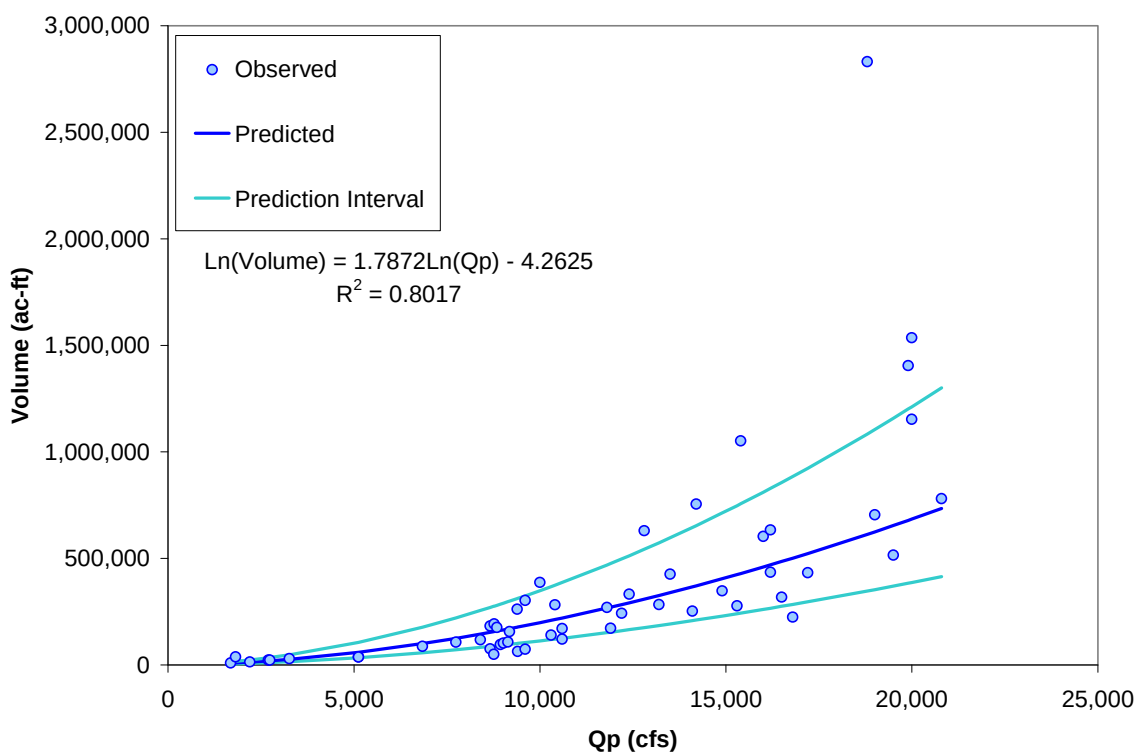

Figure 22. Volume vs. Peak Flow

[32] The prediction interval is the interval that is expected to contain a single future value of the dependent variable (i.e., volume in Figure 22) at a specified degree of confidence (Berthouex and Brown, 1994).

Development of Flow Component Table

An example of the high flow pulse characterization stemming from the alternate frequency method is provided in Figure 23. Three levels of high flow pulses have been maintained for consistency with the original method, however, these are not associated with "dry," "average," or "wet" hydrologic conditions. Rather, all three levels are considered simultaneously. In Figure 23, for volume and duration, the first number is the lower prediction interval, the second number is the upper prediction interval and the third number (in parenthesis) is the best-fit. "#N/A" values denote situations where the regression best-fit or prediction interval dropped below zero.

High Flow Pulses	Qp: 21,000 cfs of Recurring Frequency 5 per 5 years Volumes is 628,839 to 2,015,817 (1,322,328) Duration Is 24 to 61 (43)
	Qp: 12,000 cfs of Recurring Frequency 10 per 5 seasons Volumes is #N/A to 1,175,020 (482,322) Duration Is 2 to 39 (21)
	Qp: 5,000 cfs of Recurring Frequency 15 per 5 seasons Volumes is #N/A to 557,808 (#N/A) Duration Is #N/A to 21 (3)

Figure 23. Characterization of Pulses in One Season (Winter, Season 1)

In contrast to the original method where pulses are associated with wet, average and dry conditions, the alternate method recognizes that a wide overlapping range of pulse sizes can occur at any time. For example at the Evadale gage, many "wet" qualifying pulses occur during years that may otherwise be characterized as dry using other indicators like total annual volume.

To account for inter-annual variability that more closely mirrors pulse occurrence in the hydrological data, a long-term accounting period is proposed as an option. Figure 24 notes frequency of pulse occurrence as "number per 5 years" or "number per 5 seasons." Characterization of frequency in this way, over a term longer than just a single season, is consistent with the statistical probability techniques used to identify frequency. The choice of the accounting term (e.g., 5 years) is a decision point and should be consistent with basin characteristics.

Figure 24 also represents an aggregation of multiple high flow pulse and overbank analyses for different season sizes. Inspection of the frequency diagram (Figure 21) reveals similarities between winter and spring magnitudes, and similarities between summer and fall magnitudes. Based on these similarities, high flow pulse characterizations at the largest level are made on an annual basis (i.e., can occur any time during the year) and on six-month seasonal bases (i.e., must occur within the season) for the smaller events. Volume and duration characteristics are not shown in this chart; however, these would be determined using all pulses within the seasonal context attributed to each level of pulse.

Overbank flow events can be characterized on an annual basis (1.5-year event in this example) or over a longer term averaging period. The analyst would need to make a decision on what return period (frequency) best provides the ecological benefits described in Section 2.2.

Interpreting the Statistical Characterizations of Volume and Duration

The results of the alternate frequency-based HEFR algorithm for HFP and Overbank events include statistical characterizations of the relationship between Qp and volume and between Qp and duration. The characterizations yield a range around a central tendency based on historical patterns. The central tendency is the regression line, and upper and lower ranges are the prediction intervals based upon a user-specified confidence level. As these relations are developed from historical data that exhibit variability, there is potential for the relations or intervals to predict unreasonable results (e.g., negative volume at low flow). This underscores the importance of evaluating and choosing appropriate regressions, as well as understanding and interpreting the user-specified confidence level of the ranges. Further, this highlights a potential need to evaluate the data using other means that better characterize the relationships. Very simple but valuable tools provided in the HEFR program for evaluating the relationships are the data plots for volume vs. Qp and for duration vs. Qp. The HEFR results reported in the flow component matrix should always be compared and evaluated using these plots.

Alternate means of evaluating the relationships may include (1) piecewise regression (e.g., one regression for a low-flow range and a different regression for a high-flow range, with appropriate transitions between), (2) loess regression, or (3) a method employing running means, medians, or other percentiles of the data. These are not currently programmed into HEFR. Hydrologic patterns differ across Texas; the regressions in HEFR provide a useful set of tools that may be used as a first step in evaluation of site-specific hydrological characteristics.

Overbank Flows	Qp: 24,800 cfs of Recurring Frequency 3.3 per 5 years Volumes is 797,880 to 2,067,651 (1,432,765) Duration Is 28 to 61 (44)											
High Flow Pulses	Qp: 21,000 cfs of Recurring Frequency 5 per 5 years Volumes is 524,348 to 1,793,377 (1,158,863) Duration Is 21 to 55 (38)											
	Qp: 12,000 cfs of Recurring Frequency 10 per 5 seasons Volumes is #N/A to 1,181,460 (467,649) Duration Is 2 to 39 (20)											
	Qp: 5,000 cfs of Recurring Frequency 15 per 5 seasons Volumes is #N/A to 527,438 (#N/A) Duration Is #N/A to 21 (2)											
							Qp: 3,000 cfs of Recurring Frequency 5 per 5 seasons Volumes is #N/A to 423,349 (#N/A) Duration Is #N/A to 18 (1)					
Base Flows (cfs)	2470	5860	6340	6500	5460	5335	4058	2203	1400	1070	957	1500
	1450	3120	4180	4380	3820	3050	2060	1320	825	621	552	860
	850	1920	2500	2700	2625	1730	1240	855	558	437	425	488
Subsistence Flows (cfs)	118	129	143	0	0	0	280	266	270	230	230	204
	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
	Season1						Season2					

Hydrologic Conditions	
	Wet
	Average
	Dry
	Subsistence

High Flow Pulse Characteristics	
	F = Frequency (per season)
	D = Duration (days)
	Q = Peak Flows (cfs)
	V = Volume (ac-ft)

Figure 24. Potential Flow Regime Matrix

Advantages:

- Multi-year recommendation window allows for larger events and more closely matches inter-annual variability
- Regressions provide an explicit estimate of variability in volumes and durations associated with peak flows
- Flexibility in frequency selection allows user to apply knowledge to pick events of desired sizes
- Maximizes the number of peaks used in the calculations and considers the entire spectrum of event magnitudes
- Frequency of occurrence within each season can be identified using seasonal sub-datasets
- The user is allowed to select the seasonal assignments, number of levels, and frequency associated with each high flow pulse and overbank event level.

Disadvantages:

- Regression outputs need to be carefully examined to ensure that the best-fit and prediction intervals are reasonable in the vicinity of desired Qp values.

This calculation approach requires the user to make appropriate judgments based upon basin-specific information to select the seasonal assignments, number of levels, and frequency associated with each high flow pulse and overbank event level. This could be seen as a disadvantage (because it requires more effort on the part of the user) or an advantage (because it allows more site specific information to be applied).

5.8 DECISION POINTS REQUIRED IN HEFR

This section contains a discussion of decision points specific to the HEFR methodology. In general, the decision points discussed in Section 4 also apply.

1. Hydrographic Separation

HEFR has two methodologies for hydrographic separation: IHA and MBFIT. The IHA method has seven parameters that must be specified, the MBFIT method has eight (three of which are shared between the two methods). Thus, the analyst must select the method and then parameterize it. These decisions will be based on hydrologic characteristics at the location of interest as well as the objectives of the hydrographic separation. As discussed in Section 2, hydrographic separation for the environmental flows allocation process should consider the relevant site-specific ecological roles provided by flows of different magnitudes, volumes, and durations.

2. Seasonality

HEFR allows the user to specify both the number and length of seasons (from 2 to 12 seasons in a year, each from 1 to 11 months long). The analyst should consider the biological, sediment

transport, and water quality implications of different selections. For example, if an important endemic species is known to require a certain flow rate for successful spawning in a particular time frame, that time frame may be appropriately segregated as its own season in the calculations.

3. Percentiles

The analyst can input the percentiles associated with the three hydrologic conditions (dry, average, and wet). The default values for these are the 25th, 50th, and 75th percentiles, however these values are now at the discretion of the user. The selected percentiles should be reasonably consistent with the expected frequency of occurrence of each hydrologic condition.

4. Episodic Events Calculations

HEFR has two general approaches for characterizing episodic events: the original, percentile-based approach and the alternate frequency-based approach. The original percentile-based approach requires that the user select the flow characteristics desired for classification (any combination of peak flow, volume, and/or duration). The frequency-based approach requires that the analyst select the desired frequency of storm events in different seasons and across multiple levels. The analyst must also select either a specific regression form or the metric by which the algorithm will select regression forms (highest R^2 or lowest SEE).

5. Subsistence Percentile

The analyst must enter the percentile of the subsistence flow days identified by the hydrographic separation routine that will be used for the subsistence flow recommendation. The default value is 0.5 (i.e., the median).

6. Multipeaks_Multiplier

HEFR has the ability to separate consecutive high flow pulse and overbank days into discrete events based on a rate of change threshold. This capability is helpful if the hydrographic separation algorithm identifies high flow pulse or overbank events of excessive duration. While this method was developed to work with IHA outputs, it could also be applied to the hydrographic separation outputs from MBFIT.

5.9 SUMMARY

HEFR is a new calculation methodology for populating a flow regime matrix consistent with the TIFP environmental flow regime framework. The core of HEFR is hydrograph separation and summary statistics of the resulting flow regime components (calculated in Excel). Reasonable changes to specific parameter and statistical decisions, established in a collaborative manner, are an integral part of the HEFR approach. Parameter selections presented here are for example purposes only. Actual selections should be made through collaboration between the analyst and a multidisciplinary workgroup based on existing site-specific information and professional judgment.

Because of the integral nature of the hydrographic separation algorithm to the development of flow components, and hence environmental flow recommendations, it is necessary that hydrographic separation be performed identically during both the development of such flow recommendations and in the implementation phase of environmental flow recommendations.

Figures 7 and 24 illustrate how flow regime matrices with multiple flow regime components and hydrologic conditions may look for a rather complex representation of the environmental flow requirements at a particular location on a stream. Although these are the types of flow regimes that would be expected for most locations on major streams and rivers, under special circumstances, such as recommendations applicable for a small stream, a less complex flow matrix could be appropriate. In addition, for permits such as those involving only small run-of-river diversions, permit conditions may only need to include a subset of the flow components in this matrix.

As described herein, application of the HEFR program requires the specification of a number of parameters to define different flow levels and conditions that are used to describe a resulting environmental flow regime at a particular location on a stream or river. Determining optimal values of these parameters is not a straightforward process and depends on: (1) basin and site specific characteristics of hydrology, biology, geomorphology, and other related disciplines and (2) project specific objectives based on environmental, stakeholder, legal, management, and other concerns. Still, it is important to establish initial values of these parameters that can provide at least a starting point for the application of the HEFR methodology in the absence of all of the information that ultimately might be needed and considered in arriving at a final environmental flow recommendation. Appendix A presents such “default” values for the most important input parameters needed to initially apply HEFR. Again, it is anticipated that these parameter values very likely could change as the determination of final environmental flow recommendations at a particular location proceeds through the overall process.

SECTION 6
CONCLUSIONS

This document provides an overview of how hydrologic data can be used in the identification of instream flow recommendations as part of SB 3 efforts. As such, it describes one piece of a collaborative process envisioned by SB 3 for the identification of instream flow regimes to maintain a sound ecological environment. It does not address assessment techniques for environmental freshwater inflow determinations for bays and estuaries. In addition, information from other disciplines such as biology, geomorphology (physical processes), and water quality will be necessary to guide hydrologic analyses, address decision points, and refine/replace instream flow recommendations that are based on hydrologic data alone. It is important to remember that the hydrologic methods discussed herein have not been validated against biological, geomorphological, and water quality data and are not based on defined flow alteration - ecological response relationships. However, information from other disciplines can and should be used to corroborate or refine hydrology-based instream flow recommendations. The hydrologic analyses discussed herein constitute simply the first, and perhaps the easiest, step in the process of developing instream flow recommendations.

Specifically with regard to the establishment of instream flow recommendations for rivers and streams, the SAC offers the following observations:

- Pursuant to the requirements of SB 3, instream flow recommendations developed by the BBESTs must represent a flow regime that includes a schedule of flow quantities that reflects seasonal and yearly fluctuations that typically would vary geographically, by specific location in a watershed, and that are shown to be adequate to support a sound ecological environment and to maintain the productivity, extent, and persistence of key aquatic habitats.
- In order both to implement the SB 3 requirements and to effectively utilize the results from the TIFP studies through the adaptive management process, it is recommended that the initial SB 3 instream flow recommendations be consistent with the environmental flow regime framework that is to be applied in the TIFP studies, including, as appropriate, the following four flow regime components:
    - Subsistence flows
    - Base flows
    - High flow pulses
    - Overbank flows
- From the standpoint of achieving environmental flow requirements associated with a water right on a stream or river, it is important to recognize that fully satisfying the need for the higher flow components often may be dictated more by the natural stream itself than the water right activity, e.g., the diversions authorized by a water right or group of water rights may be of such magnitude that they simply cannot significantly impact high pulse flows or flows that cause overbanking.

- Environmental flow recommendations structured in accordance with a flow regime framework can incorporate, as appropriate, different levels of flow requirements to reflect monthly or seasonal variations and different hydrologic conditions (subsistence, dry, average, wet).
- Depending on local stream conditions and water rights characteristics, different aspects of the flow regime matrix can be used to describe environmental flow requirements for purposes of water rights permitting.
- In the absence of known flow alteration – ecological response relationships for specific locations or stream reaches within a basin, the application of hydrology-based instream flow methods to statistically define an environmental flow regime offers a useful approach for initially establishing instream flow recommendations consistent with the requirements of SB 3.
- For purposes of SB 3, the use of hydrology-based instream flow methods for establishing environmental flow recommendations in the absence of appropriate flow alteration – ecological response relationships assumes that maintaining the occurrence and frequency of certain key flow characteristics derived from historical records provides a flow regime that is adequate to support a sound ecological environment and to maintain the productivity, extent, and persistence of key aquatic habitats.
- However, it is recognized that with more rigorous scientific data and information such as that being developed through the TIFP studies, the environmental flow recommendations derived using hydrology-based instream flow methods are subject to revision and updating through the adaptive management process provided for in SB 3.
- The period of record selected for application of hydrology-based instream flow methods typically represents one of three conditions: (1) natural, pre-human impacts, (2) post-human impacts or regulated conditions, or (3) all historical development as reflected in the entire available flow data base, and the selection of the most appropriate period of record should consider such factors as the length of available daily flow records, historical changes in the basin that have influenced hydrologic conditions, the characteristics of historical and existing ecosystems, and the likely flow conditions under which the existing ecosystem evolved and has become adapted.
- Application of hydrology-based instream flow methods for establishing environmental flow recommendations requires numerous decision points regarding parameter values and assumptions and necessarily involves considerable expertise, experience, and professional judgment to achieve meaningful results.
- The Hydrologically-based Environmental Flow Regime (HEFR) methodology, developed by the TPWD with input from other agencies and organizations, provides a relatively flexible computational approach for developing a flow regime matrix this is consistent with the TIFP multi-tiered flow framework for describing key and essential instream flow requirements. In some cases, where data are available, it may be possible to use information on biology, water quality and sediment transport to adjust or refine the hydrologically-based flow regime recommendations.

- With application of the necessary expertise, experience, and professional judgment, the HEFR method can provide useful results that potentially can be used to structure appropriate environmental flow recommendations for rivers and streams that are consistent with and responsive to the requirements of SB 3.

SECTION 7
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SECTION 8
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APPENDIX A
DEFAULT VALUES FOR HEFR

This appendix contains suggested default values for developing a preliminary HEFR analysis. These values are suggested simply as a place to start. Optimum final values will depend on: (1) basin and site specific characteristics of hydrology, biology, geomorphology, and other related disciplines and (2) project specific objectives based on environmental, stakeholder, legal, management, and other concerns.

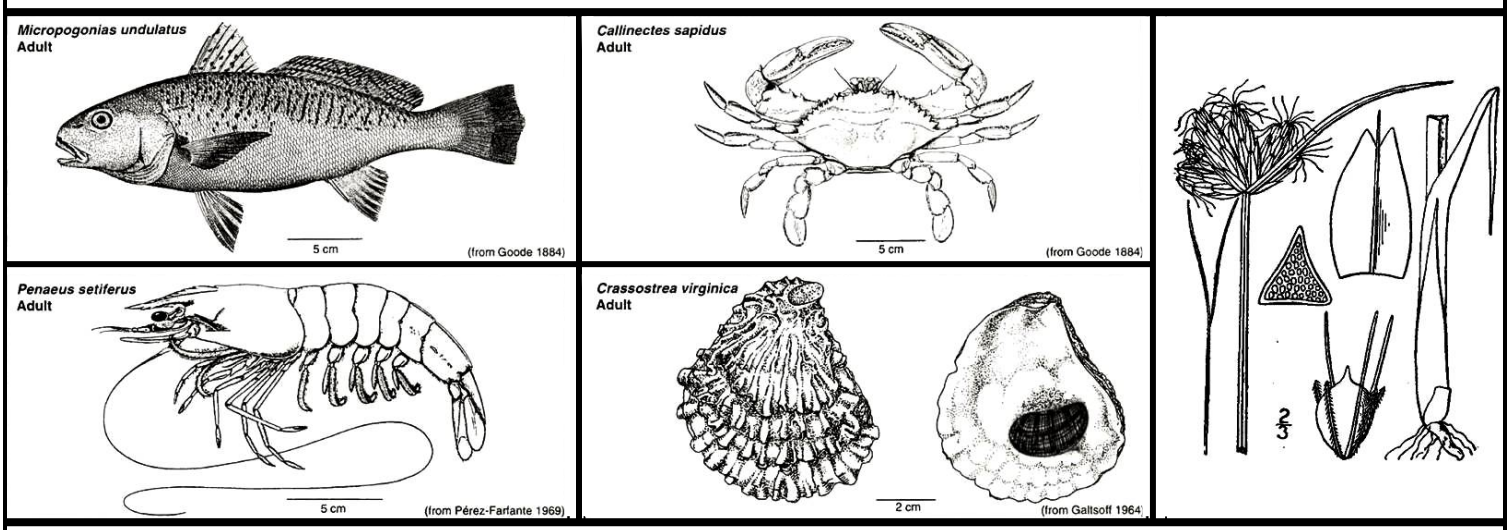
Characteristic	Default Value
IHA EFC – HFP Upper Percentile Threshold	75%
IHA EFC – HFP Lower Percentile Threshold	25%
IHA EFC – HFP Rate of Increase Trigger	50% per day
IHA EFC – HFP Rate of Decrease Trigger	5% per day
IHA EFC – Small Flood Threshold Recurrence Interval	1.5 years
IHA EFC – Large Flood Threshold Recurrence Interval	99 years
IHA EFC - Extreme Low Flow Threshold	10%
Excel – Multipeaks_Multiplier for HFPs	1.5
Excel – Multipeaks_Multiplier for Overbank Flows	1e9
Excel – Hydrologic Condition Frequencies	2.5% for subsistence conditions 22.5% for dry conditions 50% for average conditions 25% for wet conditions
Excel – Monthly Seasonal Assignments	Winter – Dec, Jan, Feb Spring – Mar, Apr, May Summer – Jun, Jul, Aug Fall – Sep, Oct, Nov
Excel – Subsistence Flow Percentile	0.5 (for 50th percentile)
Excel – Base Flow Percentile Assignments under Different Hydrologic Conditions	Dry: 25th percentile of base flows Average: 50th percentile of base flows Wet: 75th percentile of base flows
Excel – HFP Percentile Assignments for Volume, Peak Flow, and Duration under Different Hydrologic Conditions	Dry: 25th percentile of all three Average: 50th percentile of all three Wet: 75th percentile of all three
Excel – HFP Frequency Recommendation	75th percentile of historical frequencies
Excel – Overbank Flows Percentile Assignment for Volume, Peak Flow, and Duration.	50th percentile
Excel – Overbank Flow Frequency Recommendation	Average return interval of recommended event

Estuarine Focal Species Summary Report

For the

Sabine/Neches BBEST

Ecological Information to Support Environmental Flow Recommendations



(Patillo et al. 1997; USDA 2009)

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August 2009

Estuarine Focal Species Summary Report

For the

Sabine/Neches BBEST

Ecological Information to Support Environmental Flow Recommendations

Submitted to:

Sabine/Neches BBEST

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1.0 INTRODUCTION

Freshwater inflows have long been known to play a key role in the functioning of bays and estuaries. In 2007, the Texas Legislature passed Senate Bill 3, directing the development of environmental flow recommendations to protect a "sound ecological environment" and to maintain the productivity, extent, and persistence of key aquatic habitats in bays and estuaries (SAC 2009).

This document provides a summary of ecological information on focal plant and animal species within the Sabine-Neches Estuary (Sabine Lake) to support environmental flow recommendations by the Sabine/Neches Basin and Bay Expert Science Team (BBEST). As noted in SAC (2009), aquatic organisms in estuaries are influenced by the effects of inflow, notably on salinity, nutrients, and sediments rather than by the inflow itself. This differs from the response of riverine organisms, which do respond directly to velocity associated with river flow as an important ecological determinant.

The purpose of this report is to:

- Summarize the dependencies of focal species with regard to habitat conditions, especially as affected by freshwater inflow variation, salinity patterns and seasonality
- Provide graphical or tabular summaries of population abundance or biodiversity trends within the estuary
- Describe key relationships between inflow and salinity variation and the ecology of focal species at the individual or population level

Several previous reports on freshwater inflow to Sabine Lake were reviewed in addition to a large collection of scientific literature on Gulf of Mexico (GOM) estuaries and the focal species identified in this report. Relative to other major Texas estuaries, biological data for the Sabine Lake system has been collected for a shorter period of time. However, information regarding the life history and habitat requirements of many of the focal species was abundant in the literature. Range, abundance and biodiversity trend information specifically within Sabine Lake was less ample, but enough information was available to describe the freshwater inflow-ecology relationship for at least one life stage of these estuarine-dependent focal species.

Sabine Lake

Sabine Lake is a relatively large, shallow, brackish-water estuary located on the Louisiana-Texas state line that receives freshwater inflow from the Sabine and Neches Rivers. Sabine Lake is connected to the GOM by Sabine Pass, which is very long and narrow compared to other Texas tidal passes. The tidal range in Sabine Lake is generally in the range of 0.5 to 0.75 feet, and tides are generally minor except when amplified by wind. The maximum depth in Sabine Lake is less than 10 feet, although dredged portions of the rivers, canals and pass may be over 40 feet deep.

Sabine Lake is roughly divisible into three general environments that TDWR (1981) identified based on composition and nature of bottom sediments, salinity and faunal composition. The upper part of the lake includes the river-influenced environment, characterized by low salinity (generally less than 10 parts per thousand [ppt]), lower species diversity (mainly mollusks and crustaceans) and generally firm mud bottom sediments. The middle part of Sabine Lake has slightly higher salinities than the upper estuary and bottom sediment is largely bioturbated mud. The lower part of Sabine Lake is an open bay that is influenced by tidal interchange, with salinity ranging from 10 to 20 ppt, bioturbated mud bottom sediments, and relatively high species diversity (TDWR 1981).

2.0 SABINE-NECHES ESTUARY FOCAL SPECIES

Ten estuarine focal species were chosen to support environmental flow recommendations to the Sabine/Neches BBEST. The list of focal species were collectively identified by BIO-WEST, Inc. (BIO-WEST) in collaboration and coordination with the Biological Subcommittee of the Sabine/Neches BBEST, state agencies involved in the Texas Bays and Estuary Study Program, Louisiana Department of Wildlife and Fisheries (LDWF), and local universities. The Biological Subcommittee provided the initial guidance with regard to focal species, including those species that are sensitive to salinity and freshwater inflow, serve as valuable ecosystem indicators, or that have been identified as focal species in other studies within the northwestern Gulf of Mexico region.

A preliminary review was made of the Texas Parks and Wildlife Department's (TPWD) 2005 publication, *Freshwater Inflow Recommendation for the Sabine Lake Estuary of Texas and Louisiana*, in which eight commercially and recreationally important fish and crustacean species were chosen, including Atlantic croaker (*Micropogonias undulatus*), spot (*Leiostomus xanthurus*), Gulf menhaden (*Brevoortia patronus*), white shrimp (*Litopenaeus setiferus*), blue crab (*Callinectes sapidus*), brown shrimp (*Farfantepenaeus aztecus*), as well as two other species in which analysis was not provided due to low catch rates, spotted seatrout (*Cynoscion nebulosus*) and red drum (*Sciaenops ocellatus*). Several other species suggested by TPWD staff included sand seatrout (*Cynoscion arenarius*), hardhead catfish (*Ariopsis felis*), threadfin shad (*Dorosoma petenense*), oysters (*Crassostrea virginica*), Atlantic rangia (*Rangia cuneata*), bald cypress (*Taxodium distichum*), water tupelo (*Nyssa aquatic*), overcup oak (*Quercus lyrata*), river birch (*Betula nigra*), olney bulrush (*Schoenoplectus americanus*) and bulltongue (*Sagittaria lancifolia*).

Ultimately, ten focal species were chosen to include two wetland plants, two mollusks, three crustaceans, and three fish species (**Table 1**). This list of species was compiled with consideration of representing: a diversity of estuarine-dependent species across a number of taxa and trophic levels; species that "enjoy some prominence" (SAC 2009) or those that are economically important; species that are abundant in Sabine Lake or that utilize the estuary during a particular life stage; and species that are a key ecological component to the ecosystem. No state or federally threatened and endangered fish, crustacean, molluscan, or wetland plant species occur in Sabine Lake and therefore were not considered. Lastly, our focus for the estuarine focal species selection and freshwater inflow-ecology relationship summary was concentrated on aquatic species within Sabine Lake itself and its fringing marshes. Therefore, additional wildlife species associated with wetlands surrounding Sabine Lake were not included in this summary document. In a separate report (Fluvial Focal Species Summary [BIO-WEST 2009]), a number of recommended species more closely associated with the Sabine and Neches river basins were evaluated.

Table 1. Estuarine-dependent focal species identified to support environmental flow recommendations of the Sabine/Neches BBEST.

Wetland Plants	Bivalve Mollusks
Olney bulrush (*Schoenoplectus americanus*)	Atlantic rangia (*Rangia cuneata*)
Saltmeadow cordgrass (*Spartina patens*)	American oyster (*Crassostrea virginica*)
Crustaceans	**Fish**
White shrimp (*Litopenaeus setiferus*)	Atlantic croaker (*Micropogonias undulatus*)
Brown shrimp (*Farfantepenaeus aztecus*)	Spot (*Leiostomus xanthurus*)
Blue crab (*Callinectes sapidus*)	Gulf menhaden (*Brevoortia patronus*)

3.0 FOCAL SPECIES SUMMARIES

3.1 Wetland Plant Focal Species

Estuarine wetlands provide shelter, foraging and nursery habitat for many wading and migratory bird species as well as small mammals, fish, shrimp, crabs, and invertebrates. As described in TDWR (1981), the periodic inundation of deltaic and tidal marshes also provides a method for nutrient exchange processes and allows for the movement of detritus from the marshes into the open estuary. The plant communities themselves are structured by both ambient salinity levels and the degree of flooding stress, determined to a large extent by marsh elevation, river flood events and tidal inundation rates (Bertness and Ellison 1987; Flynn et al. 1995) and vary both regionally and over the course of the growing season.

While plant species dominance patterns within wetland communities are not well understood, they are likely related to gradients in salinity and hydrology (Mitsch and Gosselink 2000). Landscape patterns of species dominance are influenced over long time periods, whereas annual gross and net primary productivity of wetland plants can vary seasonally and between years as a result of short-term changes in hydrology (Mitsch and Gosselink 2000). These changes in seasonal and annual productivity may be attributed to individual plants' adaptations to the stressors of salinity and inundation.

Most of the estuarine or tidal fringe wetlands along the GOM formed around the bays that resulted from the flooding and filling of ancient river valleys. The Chenier Plain is a unique salt marsh area on the eastern edge of Texas into Louisiana, formed over the last 3,000 years by sediment input from the shifting of the Mississippi River mouth. Extensive wetlands less than five feet above sea level stretch inland four to fifteen miles along the entire GOM shoreline and a narrower discontinuous band of marsh borders Sabine Lake. Marshes cover most of the lower fifteen miles of the Neches valley, and extensive swamps extend another ten miles up the valley. Swamp and wetlands are also common in the lower fifteen miles of the Sabine valley.

Nearly 35,000 acres of vegetated intermediate, brackish, and salt marshes dominated by cordgrass (*Spartina* spp.) and saltgrass (*Distichlis spicata*) border Sabine Lake (**Figure 1**). Saltmeadow cordgrass (*Spartina patens*) is one of the dominant wetland plant species in brackish marshes around Sabine Lake, with areas dominated by the less salt-tolerant olney bulrush (*Schoenoplectus americanus*) also present (TPWD, *pers. comm*., July 2009). The Texas Point National Wildlife Refuge, the largest salt marsh bordering the estuary, is to the west of the Sabine Pass Ship Channel. Smaller marshes occur along the Sabine and Neches Rivers at the head of the estuary (Armstrong 1987). Most of the salt marsh to the east of the estuary has been designated a National Wildlife Refuge (USFWS 2009).

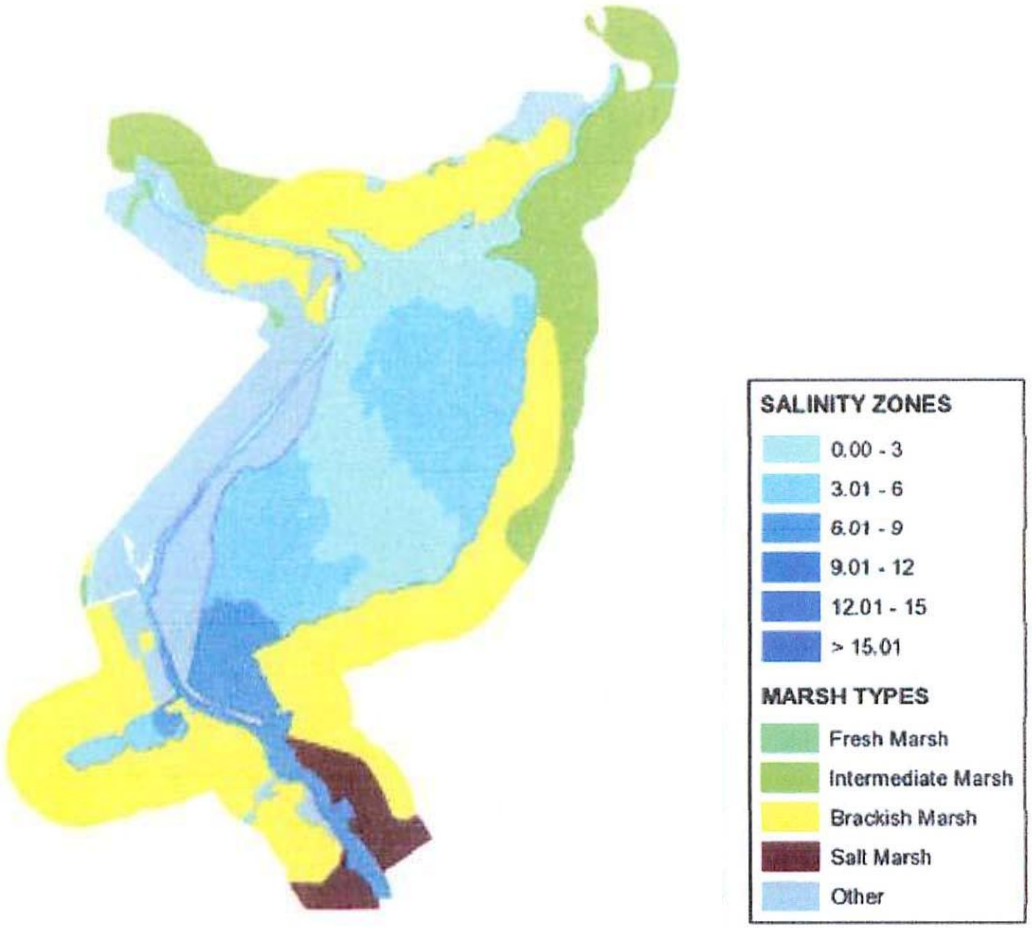


Figure 1. Wetland communities around Sabine Lake relative to a typical April salinity gradient (Source: TPWD 2005).

3.1.1 Olney bulrush (*Schoenoplectus americanus*)

General Description

Olney bulrush *Schoenoplectus americanus* is a member of the sedge family Cyperaceae. Common synonyms of this species that appear in the wetland literature are olney's three-square bulrush, chairmaker's sedge, *Schoenoplectus olneyi*, *Scirpus americanus*, and *Scirpus olneyi*. *S. americanus* is a medium height to tall, native herbaceous plant, that can grow as high as seven feet (Tiner 1987). The seeds, basal portions and rhizomes are eaten by wildlife including ducks, snow geese, nutria and muskrats. *S. americanus* is the single most important food source for muskrats along the Gulf Coast (Stutzenbaker 1999).

Marshes dominated by *S. americanus* occur along the Gulf Coast of Texas, the Chenier Plain of Louisiana, and the mid-Atlantic coast of Maryland and Delaware. It occurs in both low and high marsh habitats, but is most abundant on the high marsh (Ikegami 2006). It also occurs near ponds, lakes,

sloughs, swamps, beach pools and sandy flats, often in shallow water up to about one to 2.5 feet (Voss 1972). In mixed plant communities, *S. americanus* is most commonly mixed with *S. patens*. Other species associated with *S. americanus* vegetation communities can include *Spartina alterniflora*, *Spartina cynosuroides*, *Phragmites australis*, *Juncus roemerianus*, *Typha domingensis*, *Pluchea odorata*, *Distichlis spicata*, and *Limonium carolinianum*.

Ecological Relationship with Freshwater Inflow and Salinity

S. americanus can occur in fresh, intermediate and brackish marshes, surviving in salinities from 0 to 12 ppt (Howard & Mendelssohn 1999). However, *S. americanus* reaches its maximum productivity in intermediate marshes where salinities are generally below 3.5 ppt (Stutzenbaker 1999). The aboveground vegetation biomass of *S. americanus* is dependent on the presence of standing water, with biomass being greater during periods of standing water (Bhattacharje et al. 2009). *S. americanus* functions as a stress tolerator, being able to withstand temporary increases in salinity and inundation duration (Howard and Mendelssohn 2000). *S. americanus* tolerance exceeds that of *E. palustris* and *S. lancifolia* (Howard and Mendelssohn 1999).

Life History

S. americanus is a perennial sedge from long stout rhizomes, with single triangular stems that are in small groups. The ability of *S. americanus* to successfully colonize a wide range of habitats is the result of plasticity in clonal architectures. An individual *S. americanus* plant can send out one to three new ramets (consisting of a shoot, roots and a tuber) throughout the growing season.

Green shoots appear aboveground at the beginning of the growing season (generally around April along the Gulf coast) and green shoot production may persist into the winter (Ikegami 2006). Flowering occurs around May and June, although not all shoots flower. Seeds mature and are shed around September. The seeds remain dormant as long as they are submerged in water and thus become a component of the marsh seed bank. Germination and seedling establishment potentially occurs on exposed mudflats following marsh drawdown. The seed germination of this species is strongly regulated by salinity. At a salinity of 4 ppt, germination is reduced by 50 percent, and above 13 ppt no germination occurs (Palmisano and Newsom 1968). Thus, due to high salinity, seed germination is rare in salt marshes.

3.1.2 Salt meadow cordgrass (*Spartina patens*)

General Description

Saltmeadow cordgrass *Spartina patens*, also known as wiregrass or marshhay cordgrass, is a characteristic species of high salt marsh, typically occurring on slightly elevated surfaces where tides may be less regular and where soils may concentrate salts. *Spartina* is a relatively small genus consisting of approximately 14 species, geographically centered along the east coast of North and South America, with outliers on the west coast of North America and Europe. Members of the genus occur primarily in wetlands, especially estuaries (Partridge 1987).

S. patens is an important coastal grass species, occurring along the Atlantic coast from Canada to the Caribbean and Central America, and along the Gulf of Mexico coast into south Texas (Silander 1984). It can also be found along the shores of the Great Lakes. *S. patens* grows in all marsh types but reaches greatest abundance in intermediate to brackish marshes where it often forms meadow-like communities over large expanses (Stutzenbaker 1999).

Ecological Relationship with Freshwater Inflow and Salinity

S. patens is a halophyte with a high salinity tolerance that has the ability to secrete salts out of the plant and onto the leaf surfaces through salt glands, although growth reduction does occur at salinities above 12 ppt (Anastasiou and Brooks 2003). It is limited to high salt marshes because of its inability to tolerate the lower oxygen conditions at lower tidal elevations. The species lacks aerenchyma tissue that would allow it to oxygenate its rhizosphere in anoxic soils (Bertness 1991). Along the Atlantic and Gulf coasts, *S. patens* and *S. alterniflora* often occupy the same tidal marshes. *S. alterniflora* dominates the regularly flooded seaward margins of the marshes, while *S. patens* inhabits higher, less flooded areas (Gleason and Zieman 1981). Unlike *S. patens*, *S. alterniflora* can survive in either high or low salt marshes; however, it is restricted to low salt marshes by competitive displacement by *S. patens* (Bertness 1991).

Life History

S. patens is a rhizomatous grass with dark green stems, 0.3 to 1.2 meters tall, often forming dense, single species stands (Pfauth and Sytsma 1998). *S. patens* is commonly found growing in saline to brackish marshes, sandy beaches and low dunes, tidal flats and marsh ridges from normal high tide to about 4 meters above sea level. *S. patens* typically occurs from mean high water to approximately 0.5 meters above mean high water (Raupp and Denno 1979). A study in Connecticut found that 72 percent of *S. patens* occurred above mean high water (Lefor et al. 1987). This grass is adapted to a wide range of soils from coarse sands to silty clay sediments with pHs ranging from 3.7 to 7.9. *S. patens* will tolerate irregular inundations with salinities from 0 to 35 ppt (USDA 2009).

S. patens culms first appear in the spring, when they emerge through the thick, dead horizon of the previous year's growth (Denno 1980). The major production of roots, rhizomes, stolons, and upright culms occurs under the higher temperature and longer day lengths of the growing season. The highest standing crop occurs from July to October (Seneca 1974).

S. patens flowers from June to September. Seedlings emerge in May, but they do not appear to flower during their first season and produce limited flowers during their second season (Seneca 1974). Seedlings often colonize low sand flats where moisture is adequate for germination and growth (Seneca 1974). Although *S. patens* does produce viable seed, it reproduces primarily via rhizomes (Seneca 1974).

3.2 Bivalve Focal Species

Similar to crustaceans, bivalves play an important role in energy transfer in the estuarine food web. Additionally, adult bivalves are sessile organisms in the estuary and are therefore regarded as integrators of ecological conditions over time. They are filter-feeders and feed on phytoplankton and detritus in the water column by pumping water across the gills and trapping food particles that are then moved to the mouth. Estuarine bivalve species typically spawn in response to environmental conditions, and their free-swimming larvae stay within the estuary until they find adequate substrate to settle on and become sessile (Nelson et al. 1991; Patillo et al. 1997).

Estuary-dependent species occurring within Sabine Lake include Atlantic rangia (*Rangia cuneata*) and eastern oyster (*Crassostrea virginica*). *R. cuneata* is by far the most common bivalve in Sabine Lake (TDWR 1981).

Variability in physicochemical parameters such as temperature, salinity and dissolved oxygen, as well as the availability of food in the water column, and available substrate for recruitment are important in determining the size and location of bivalve populations in an estuary. To the extent available, the life history, physicochemical preference of specific life stages, and spatiotemporal abundance of focal bivalve species are described below.

3.2.1 Atlantic rangia (*Rangia cuneata*)

General Description

Atlantic rangia *Rangia cuneata* (Gray), also known as common rangia, is a small brackish water clam of the family Mactridae (marine bivalve clams) that is an important component of estuarine ecosystems. In low salinity estuarine areas, *R. cuneata* functions as a link between primary producers and secondary consumers. As a non-selective filter feeder, this species transforms large quantities of plant detritus and phytoplankton into clam biomass. *R. cuneata* was a food item of prehistoric Indians and it is still occasionally canned and eaten. Economically, it is more important as a source of shells for road building and industrial products.

R. cuneata is found along the GOM coast from Florida to Mexico and along the Atlantic coast as far north as Maryland and New Jersey (LaSalle and de la Cruz 1985). The highest concentration of clams along the Gulf coast has been associated with shallow water areas less than 6 meters deep, where they are common in a wide range of soft substrates.

This species occupies the fresher portion of Sabine Lake, and are usually scattered throughout the sediments rather than forming reef-like masses (Kane 1961; Harrel 1993). A distribution of *R. cuneata* within the Neches River and a portion of Sabine Lake was established by Harrel (1993). However, the overall distribution of *R. cuneata* in Sabine Lake is not well understood. The National Wildlife Federation (NWF) has a project underway to assess the distribution of Atlantic rangia colonies in Sabine Lake. Maps from previously collected sonar imagery along with a remote sensing survey using side scan

sonar will be used to map the estuary bottom and identify rangia colonies throughout Sabine Lake (**Figure 2**).

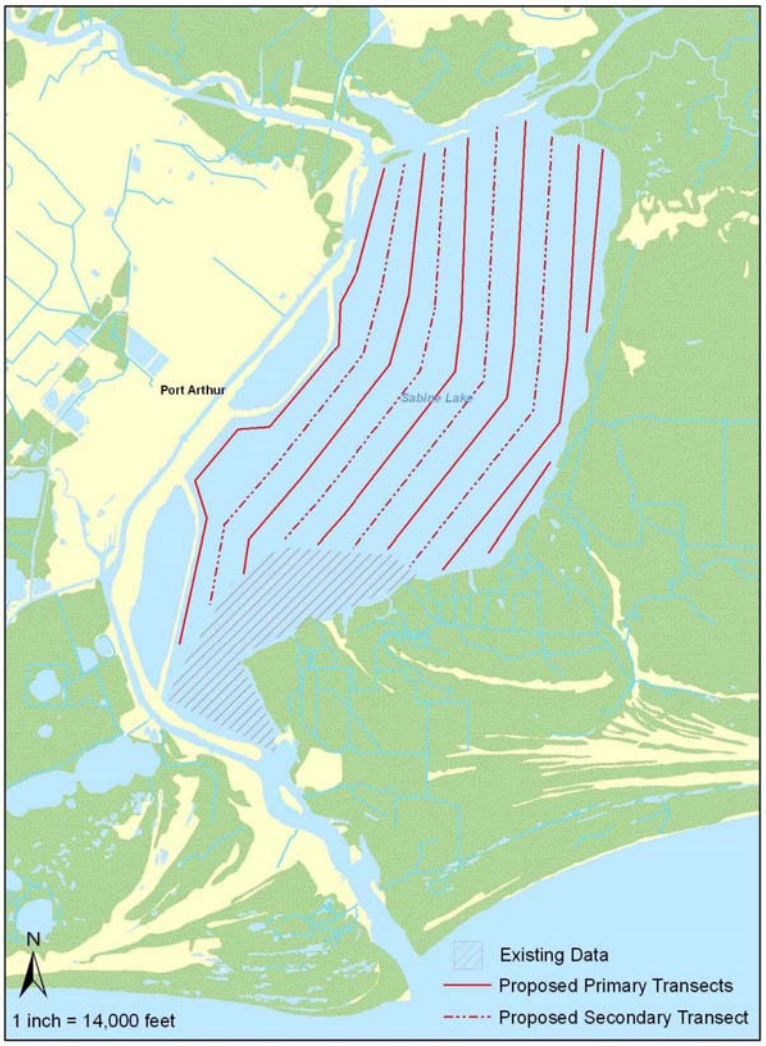


Figure 2. Transect locations for a proposed Atlantic rangia survey in Sabine Lake.

Ecological Relationship with Freshwater Inflow and Salinity

This species is a permanent resident in low salinity (0 to 18 ppt) regions of estuaries (Cain 1975), with populations most abundant in areas of 5 to 15 ppt. The distribution of *R. cuneata* in an estuary overlaps that of *C. virginica*, but *R. cuneata* becomes much more abundant farther up the estuary where the salinities are too low for oysters and for almost all other estuarine competitors or influents (Hopkins and Andrews 1970). A population of *R. cuneata* 40 to 50 kilometers above the mouth of the Neches River was found living in fresh water (salinity below 0.3 ppt) for at least 7 months of the year, and in salinity up to 13 ppt during low river periods, without apparent mortality (Hopkins and Andrews 1970).

Although adults are euryhaline, embryos are much more sensitive to salinity. Spawning at salinities between 2 to 10 ppt allows for the survival of the sensitive stages to the more eurytopic later larval stages (Cain 1973). Once the larvae have developed past the swimming stage and settled to the bottom as juvenile clams, salinity is probably not as critical (Cain 1976). The increased tolerance of the larvae permits good survival during its more stressful pelagic existence.

Life History

The life span of *R. cuneata* has not been confirmed, although it has been estimated between 4 and 15 years (LaSalle and de la Cruz 1985). Annual growth increments of *R. cuneata* in the GOM are reported to range between 0 and 20 mm per year (Fairbanks 1963). Adults range from 2.5 to 6 centimeters in length. *R. cuneata* possess both extracellular (blood and body fluid) and intracellular mechanisms of osmoregulation that enable them to respond to sudden salinity changes in many estuaries (Bedford and Anderson 1972). However, studies indicate the long-term welfare of a *Rangia* population is not the physiology of the adult individuals, but reproduction and recruitment (Hopkins et al. 1973; Cain 1975).

Although spawning may be continuous, peak spawning periods have been documented from March to May and from late summer to November in Louisiana (LaSalle and de la Cruz 1985). Spawning may be triggered by an increase in temperature and salinity. Cain (1975) and Jovanovich and Marion (1989) indicated that an increase in water temperature to 15 °C appeared to be important in the initiation of spawning. During spawning, gametes are released directly into the water and shelled larvae have been documented within 24 hours of fertilization (Chanley 1965). Although common in a wide range of soft substrates, Fairbanks (1963) reported that larvae were capable of selecting substrate for setting and preferred substrates high in organic content.

R. cuneata can be an important species in the low salinity zones of estuaries along the GOM and may comprise a large portion of the benthic macroinvertebrate biomass in these areas (Cain 1976; Brammer et al. 2007). A combination of low salinity, high turbidity, and a substrate of sand, mud, and vegetation appears to be the most favorable habitat for *R. cuneata* (Tarver 1972). *R. cuneata* are concentrated in areas where salinity seldom exceeds 18 ppt (LaSalle and de la Cruz 1985). Studies indicate optimum conditions for embryo development are water temperatures of 18 to 29 °C and salinities of 6 to 10 ppt. Embryos did not develop at 0 ppt salinity (Cain 1973, 1974). On the Gulf coast, *R. cuneata* tolerates water temperatures as low as 3 °C for at least a few hours, and as high as 32 °C for months, without conspicuous mortality (Hopkins and Andrews 1970).

Parasites and Predators

R. cuneata are parasitized by larvae of Fellodistomatid trematodes (Fairbanks 1963), although only large clams are infected. *R. cuneata* are preyed upon by fish, crustaceans, mollusks and ducks. Moon shell snails, *Polinices* spp., may be predators as suggested by drill holes in *R. cuneata* shells (Hoese 1973). *R. cuneata* are abundant in the diets of blue catfish, freshwater drum, spot, black drum, river shrimp, and blue crab in Louisiana (Darnell 1958, 1961). Ctenophores are also potential predators of *R. cuneata*,

which sometime appear in high abundance in certain times of the year. Ctenophores can cause mass mortality of *R. cuneata* larvae.

3.2.2 American oyster (*Crassostrea virginica*)

General Description

The American oyster is a species of oyster that is native to the eastern and GOM coastlines of North America. This species is also referred to as the Eastern oyster, Atlantic oyster, and Virginia oyster. As extremely popular seafood, oysters are of vital economic and cultural importance to the GOM region. Additionally, oysters provide a number of key ecosystem functions: oyster spawn and larvae comprise a large proportion of the planktonic biomass in Texas bays providing a vital food source for many planktivores; oyster reefs provide an important physical habitat for a diverse group of benthic organisms; and oyster filter feeding plays a key role in maintaining water clarity (Kennedy et al. 1996).

Oysters are filter feeders, feeding primarily on phytoplankton and suspended detritus (Langdon and Newell 1996). Oyster reefs are also highly utilized habitats in the estuarine environment, exploited by different species than those utilizing the marsh habitats (Zimmerman 1989). Many animals including fish, crabs, worms and meiofauna use oyster reefs as both a foraging and shelter resource.

Although oysters are present in a few areas, oyster reefs are not as well developed in the Sabine Lake and do not support a commercial fishery as in the other estuaries on the Texas coast. The American oyster occurs singly or as reefs, typically in the more saline part of the lake (**Figure 3**). One large reef is located along the Louisiana shoreline near Blue Buck Point, with another reef along the Texas shoreline approximately opposite the point (Kane 1961).

Ecological Relationship with Freshwater Inflow and Salinity

The oyster has a complex ecological relationship with freshwater inflow and salinity. While adult oysters are euryhaline (5 to 40 ppt salinities), oyster populations are dependent on estuaries for their food supply and in regulating the predator and parasite populations that prey on oysters (Buzan et al. 2009). Prolonged exposure to very low salinities or freshwater floods will cause mortality of oysters (Kennedy 1996). Larvae life stages require salinities that are not too high or low to settle, generally in the range of 10 to 27.5 ppt (Kennedy 1996). Optimal salinity conditions for oyster growth are 10-28 ppt, and freshet events that significantly lower salinities are extremely important to decrease predators and parasite infections that can decimate oyster reefs, including the oyster drill (*Stramonita haemastoma*) and dermo (*Perkinsus marinus*) (La Peyre et al. 2003).

Life History

American oysters have a lifespan of up to 20 years (Buroker 1983) growing to 100 to 115 millimeters in length in two years. Individuals can reach sexual maturity at four months. Spawning is initiated by a combination of factors including water temperature, salinity, and physiochemical interactions (Galtsoff 1964, Hofstetter 1977, Hofstetter 1983).

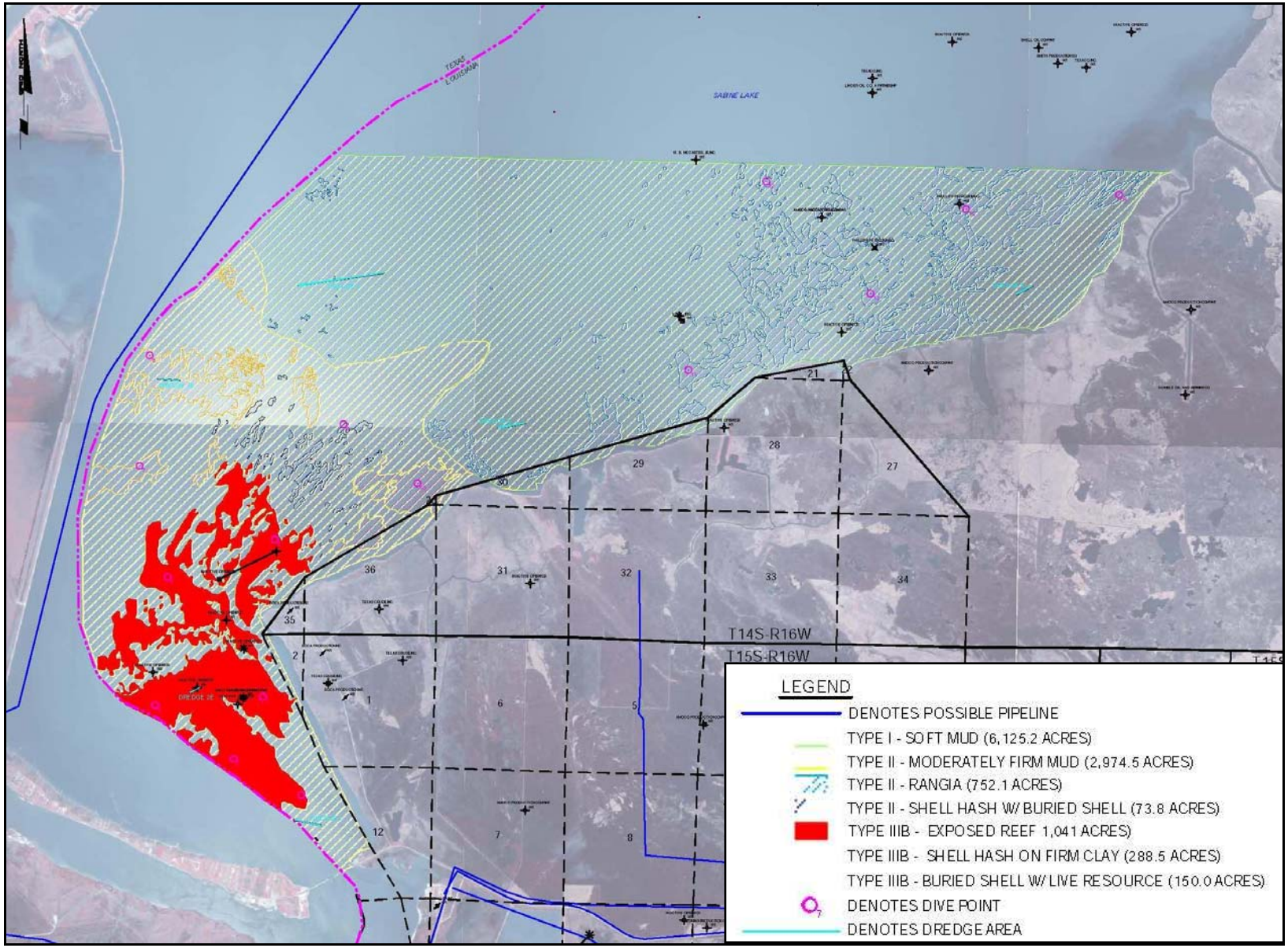


Figure 3. Oyster reef locations in Sabine Lake based on a side scan sonar survey in 2008. (Source: Shackelford 2008).

In southern waters, spawning occurs in all but the coldest months (Berrigan et al. 1991). Conditions generally required for spawning include water temperatures at or above 20°C and salinity higher than 10 ppt. When these conditions persist, spawning can continue year-round (Breuer 1962). The optimal salinity for growth and reproduction is 10-28 ppt (Wilson et al. 2005). Larvae will not settle and metamorphose into spat when salinity is less than 6 ppt (Wilson et al. 2005), while adults can live in salinities up to 35 ppt (Buroker 1983). After fertilization, oysters develop through several free-swimming larval stages before attaching to a hard substrate and becoming sessile. The rate of development through these stages is temperature dependent (Shumway 1996).

Larval oysters are induced to settle by the presence of hard substrate, such as shells, and by chemicals produced by adult conspecifics, so oyster reefs tend to be self-perpetuating. Unlike some regions, such as the Chesapeake Bay, oysters in Texas bays are almost always harvested in the reefs where they settle rather than moved post-settlement to designated growing locations. As a result, the entire post-larval life of these oysters will depend on specific conditions at the reefs.

Oysters can survive in salinities ranging from about 5 to 40 ppt, but growth is stunted below 7.5 ppt (Kennedy et al.. 1996). Oyster reefs which are subjected chronically or episodically to salinities that are too low due to excessive freshwater runoff may have problems ranging from complete or partial population mortality to stunted growth. Oysters grow optimally from approximately 10 to 25 ppt (Cake 1983). Salinities of greater than 25 ppt are not only suboptimal physiologically, but reefs that are located in regions of chronic or seasonally high salinities (>25 ppt) will have a greater mortality due to predation and to dermo, a protozoan parasite infection caused by *Perkinsus marinus* (Kennedy et al. 1996).

Temperatures in the GOM do not get low enough to cause oyster mortality, but oyster growth rate is slower in colder temperatures. In fact, the combination of physiological effects of low temperature and limited food supply, in general, can cause individual oysters to lose biomass in winter months (Hofmann et al 1992). Optimal temperature for oysters is approximately 25 °C and temperatures over 30 °C can cause cessation of filter feeding (Kennedy et al. 1996).

The timing and amount of food supply in the form of phytoplankton and other organisms that can be utilized by filter-feeding oysters may have strong impacts on both oyster productivity and size structure (Hofmann et al. 1992, 1995; Powell et al. 1995, 1997; Dekshenieks et al. 2000).

Because adult oysters are sessile, their distribution depends on where the larvae set and on subsequent survival of the young spat oysters (Stanley and Seller 1986). Oysters are capable of surviving in a wide range of habitat conditions, but they are more abundant under preferred habitat (general range) conditions. These habitat conditions include estuarine areas with oxygenated waters that are less than 4 meters deep with a tidal range of 0.5-2.7 meters (Stanley and Seller 1986).

Optimum temperatures for settlement and growth of larvae are ~20°C to 32.5°C (Calabrese and Davis 1970), while adult optimum temperatures range from 20 to 30ºC (Stanley and Sellers 1986). Larvae prefer to settle on clean hard or shell substrate, and adult oysters do well on various substrates, including mud that supports the growing community weight (Jenkins et al. 1997).

Disease/Parasites

Two major parasites impact *C. virginica* populations in the United States, *Haplosporidium nelsoni* (also known as MSX) and *Perkinsus. marinus* (also known as dermo) (Kennedy et al. 1996). However, only dermo is a problem in the Western GOM (Soniat, *pers. comm.*, 2005). It is known that dermo prefers high salinity waters (>15 ppt). Infection from this parasite usually occurs in the warmer months between an oyster's first and second year, then intensifies during the second year, killing the oyster before it reaches market size.

Dermo infections may be strongly affected by temperature and salinity regimes. The division rate of dermo cells within oysters is related to both temperature and salinity of the surrounding water (Hoffman et al. 1995). At salinities greater than 10 ppt, dermo cell division is primarily affected by and increases with temperature. Below 10 ppt salinity, dermo cell growth decreases sharply with salinity (Hofmann et al. 1995). In bays in the western GOM, oyster populations on reefs closer to freshwater inflow sources typically have lower dermo infection intensities than reefs farther down bay (closer to the seawater source at the bay's mouth), and episodes of salinity below 10 ppt are often associated with a reduction of dermo levels on reefs (see data on oystersentinel.org; MBHE 2005). However, salinities low enough to harm dermo populations can also stress oysters, so the ideal salinity regime to control dermo is one with episodic freshwater inflows that reduce salinity below 10 ppt, rather than continuously low salinities (Hofmann et al. 1995, Kennedy et al. 1996).

Dermo infestations tend to be most intense in summer, when temperatures are highest. Temperatures above 25 °C are associated with high oyster mortality from dermo, and the persistence of high intensity dermo infestations is dependent on extended periods of high temperature (Kennedy et al. 1996). Such periods are common during summers in Texas bays.

In Sabine Lake, dermo infection and intensity data is collected routinely at one Oyster Sentinel station in the southern portion of the Lake (**Figure 4**). Oyster Sentinel is a web-based scientific community which uses the American oyster as a bioindicator of estuarine health (http://www.oystersentinel.org/). On this website, temperature, salinity, and dermo infection data for juvenile and commercial sized oysters in Sabine Lake is reported from January 2006 through the spring 2009.

Figure 4. Dermo assessment location in Sabine Lake for the Oyster Sentinel program (http://www.oystersentinel.org).

Predators

Many important oyster predators are limited by low salinities (Kennedy et al. 1996). The most severe predation impact on oysters in the western GOM is from the oyster drill, *Thais haemastoma* (Soniat and Kortright 1998). Drill predation rates on oysters are limited by both low salinity and low temperature. Lower tolerance levels for drills (7.5 ppt, 12.5 °C) also constitute poor conditions for oysters (Kennedy et al. 1996), but drill predation is also reduced in moderate salinities in the range where oysters prosper. In the western GOM, significant losses to drills increase on reefs farther from freshwater sources (Soniat 2005).

A number of other oyster predators are also limited by low or moderate salinities (Longley 1994; Kennedy et al. 1996). In general, extended periods of salinities greater than 25 ppt allow predator populations to build up and are associated with high predation rates on oyster populations (Kennedy et al. 1996).

3.3 Crustacean Focal Species

As food for fishes and larger invertebrates, crustaceans play a major role in the transfer of food energy to higher trophic levels within coastal waters. Crustaceans are an important link in the estuary food chain between benthic and pelagic organisms (Turner and Brody 1983). Crustaceans are also a dominant food item in the diet of a variety of fish species. As with many fishes, the life histories of many Gulf crustaceans can be characterized as estuarine-dependent. These species typically spawn in the GOM, and their larvae are then carried inshore by currents. Juveniles generally remain in these estuarine nurseries for about a year, taking advantage of the greater availability of food and protection that estuarine habitats afford. Upon reaching maturity, individuals migrate from the shallow estuaries to the deeper GOM.

Estuary-dependent crustaceans occurring within the intertidal brackish marsh habitats within Sabine Lake include, but are not limited to, hermit crab (*Clibanarius vittatus*), mud crabs (*Rhithropanopeus harrisii*, *Neopanope texana*, and *Panopeus herbstii*), white shrimp, brown shrimp, pink shrimp (*Farfantapenaeus duorarum*), spiny lobster (*Panulirus argus*), blue crab, Gulf stone crab (*Menippe adina*), and stone crab (*M. mercenaria*) (Nelson 1992). Up to 15 species of penaeid shrimp can be expected to use the coastal and estuarine areas in the GOM; brown, white, and pink shrimp are the most numerous and comprise a substantial shrimp fishery. About eight species of portunid (swimming) crabs use the coastal and estuarine areas in the GOM. Blue crabs are the only species, however, that is located throughout the Gulf and comprises a substantial fishery. All of these species occur in a variety of habitat types in fresh, estuarine and shallow offshore waters.

Variability in physicochemical parameters, such as temperature, salinity, and dissolved oxygen, affect the suitability and selection of habitat by estuarine fish, crustaceans, and other organisms in their various life stages (Peterson et al. 2004). Therefore, for the purposes of this Summary Report and when available, life histories, physicochemical preferences of specific life stages, spatiotemporal abundance, and value are described below.

Based on the National Oceanic and Atmospheric Administration's (NOAA) Estuarine Living Marine Resources (ELMR) Program, relative abundance is defined using the following categories (Nelson 1992; Patillo et al. 1997):

- High abundant – species is numerically dominant relative to other species.
- Abundant – species is often encountered in substantial number relative to other species.
- Common – species is generally encountered but not in large numbers; does not imply an even distribution over a specific salinity zone.
- Rare – species is present but not frequently encountered.
- Not present – species or life stage not found, questionable data as to identification of the species, or recent loss of habitat or environmental degradation suggests absence.

When relevant, essential fish habitat (EFH) is described for particular species. EFH is defined as "those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity" (16 U.S.C. 1802(10)). The Gulf of Mexico Fisheries Management Council (GMFMC) designated EFH for adult and juvenile life stages of the following two focal species: white shrimp and brown shrimp.

3.3.1 White shrimp (*Litopenaeus setiferus*)

General Description

White shrimp (*Litopenaeus setiferus*), previously in the genus *Penaeus*, along with other penaeid species comprise a commercially important shrimp fishery in the GOM (Cook and Murphy 1971), the second most valuable commercial fishery in the U.S. (Patillo et al. 1997). Up until the 1930's, white shrimp were the major commercial shrimp in the GOM (Muncy 1984).

White shrimp range from the Atlantic Coast as far north as New York, down to Florida, along the coast of the GOM and down to Mexico (Perez-Farfante 1969). In the GOM, highest abundance of white shrimp occur off the coast of Louisiana in waters less than 9 meters deep (Muncy 1984) and are well established throughout Texas, Louisiana, and Mississippi bays and estuaries (Patillo et al. 1997). White shrimp have been found in the Sabine Lake system year round with peak abundances from July to December (TPWD 2005).

Morphology

Morphologically similar to brown shrimp, a few key characteristics help to differentiate between the two species. In white shrimp, the antennal flagella are 2.5 to 3 times the length of the body length (Perez-Farfante 1969), much longer than those of brown shrimp. Additionally, the adrostral sulcus is much shorter extending only to the epigastric tooth on the rostrum, versus the hind margin of the carapace in brown shrimp (Muncy 1984).

Ecological Relationship with Freshwater Inflow and Salinity

White shrimp are tolerant to a wide range of salinities and can be considered euryhaline (Zein-Eldin and Griffith 1969). However, they are generally found in lower salinity waters than brown shrimp (Turner and Brody 1983). **Table 2** provides the relative abundance by month of white shrimp in Sabine Lake during each life stage (adult, eggs, juveniles, larvae, and spawners) in five salinity zones. White shrimp have been shown to have a preference for low salinity nursery grounds, with postlarval shrimp most abundant at 5 to 10 ppt in Texas (Muncy 1984, cited from Gunter 1967), though they have been collected in salinities as low as 0.42 ppt (Perez-Farfante 1969) and as high as 37.4 ppt. In Texas, postlarvae enter nursery areas from April to November (Kilma et al. 1982). Juveniles appear to tolerate lower salinities ranges, less than 10 ppt (Zein-Eldin and Renaud 1986) and have been found upstream in rivers and tributaries (Patillo et al. 1997), as far as 160 kilometers in Louisiana (Perez-Farfante 1969).

NOAA (1998c) has documented adult white shrimp as being highly abundant in the high and decreasing salinity season (August through February) in Sabine Lake (**Figure 5**) and also being found offshore in salinities greater than 27 ppt (Muncy 1984).. Juveniles in Sabine Lake are highly abundant in lower

salinities, ranging from 0.0 to 0.5 ppt, particularly around April through December (Nelson 1992), though NOAA (1998d) NMFS Galveston Lab has documented juveniles as highly abundant throughout the year (**Figure 6**).

White shrimp are also tolerant to a wide range of temperatures, from 7 to 38 °C (Patillo et al 1997). Postlarval shrimp have been recorded in temperature ranging from 13 to 30 °C and juveniles ranging from 6.5 to 39 °C, with peaks of abundance around 15 and 33 °C (Zein-Eldin and Renaud 1986).

Life History

Adults inhabit both estuarine and coastal waters; however, adults spawn offshore at depths ranging from 8 to 30 meters from spring to early fall (Perez-Farfante 1969; Patillo et al. 1997) preferring salinities to be at least 27 ppt (Cook and Murphy 1969). Spawning also coincides with increasing temperatures in the spring time and ending with declining temperatures in the fall (Muncy 1984). White shrimp spawn offshore where they hatch and pass through a series of metamorphoses as planktonic larvae. After a period of about 2 to 3 weeks, postlarvae are transported by favorable currents and tides to estuary nursery grounds, around May to November (Perez-Farfante 1969; Muncy 1984). In nursery grounds that provide habitat and protection (Turner and Brody 1983), juveniles appear to tolerate lower salinities ranges moving farther upstream than brown shrimp (Muncy 1984). Juveniles approaching adulthood move out of estuaries back into coastal waters.

Depending on the life stage, white shrimp are neritic to estuarine and pelagic to demersal. Eggs and early planktonic larvae are found in nearshore marine waters, and postlarvae are later found in estuarine nursery grounds. Postlarvae seek areas of shallow water with muddy or sandy bottoms or marsh grass (Patillo et al. 1997) connected by passes to adjacent offshore, higher salinity areas with mud or clay bottoms (Anderson 1956). Juveniles prefer sandy and muddy habitats and adults prefer sand-silt-clay areas of high detrital content (Zein-Eldin and Renaud 1986).

Feeding Preferences and Predators

White shrimp tend to be omnivorous through their life stages, even as postlarve. Juveniles feed on organic-inorganic detrital matter, diatoms, and polychaetes, and the diet of adults is composed of much of the same (Zein-Eldin and Renaud 1986).

Finfish prey heavily on white shrimp, which serve as an important food source, link and integrator of the environment (Muncy 1984; Patillo et al. 1997). A number of predators feed on white shrimp, including tiger sharks (*Galeocerdo cuvier*), Atlantic sharpnose shark (*Rhizoprionodon terraenovae*), ladyfish, hardhead catfish, red snapper (*Lutjanus campechanus*), southern kingfish (*Menticirrhus americanus*), seatrout, red drum, and flounder (Patillo et al. 1997).

Table 2. Relative abundance of different life stages of white shrimp in Sabine Lake within selected salinity zones (CCMA, no date).

White Shrimp — Sabine Lake

SALINITY ZONE	LIFESTAGE	Relative Abundance by Month											
		J	F	M	A	M	J	J	A	S	O	N	D
0-0.5 ppt.	ADULTS	3	3	3	2	2	2	3	3	4	4	4	3
	EGGS	0	0	0	0	0	0	0	0	0	0	0	0
	JUVENILES	2	2	2	2	4	4	5	5	5	5	5	5
	LARVAE	0	0	0	0	0	0	0	0	0	0	0	0
	SPAWNERS	0	0	0	0	0	0	0	0	0	0	0	0
0.5-5 ppt.	ADULTS	3	3	3	2	2	2	3	3	5	5	5	4
	EGGS	0	0	0	0	0	0	0	0	0	0	0	0
	JUVENILES	2	2	2	2	5	5	5	5	5	5	5	5
	LARVAE	0	0	0	0	0	0	0	0	0	0	0	0
	SPAWNERS	0	0	0	0	0	0	0	0	0	0	0	0
5-15 ppt.	ADULTS	3	3	3	2	2	2	3	3	5	5	5	4
	EGGS	0	0	0	0	0	0	0	0	0	0	0	0
	JUVENILES	2	2	2	2	5	5	5	5	5	5	5	5
	LARVAE	0	0	0	0	0	0	0	0	0	0	0	0
	SPAWNERS	0	0	0	0	0	0	0	0	0	0	0	0
15-25 ppt.	ADULTS	3	3	3	2	2	2	3	3	5	5	5	4
	EGGS	0	0	0	0	0	0	0	0	0	0	0	0
	JUVENILES	2	2	2	0	5	5	5	5	5	5	5	5
	LARVAE	0	0	0	0	0	0	0	0	0	0	0	0
	SPAWNERS	0	0	0	0	0	0	0	0	0	0	0	0
>25 ppt.	ADULTS	•	•	•	•	•	•	•	•	•	•	•	•
	EGGS	•	•	•	•	•	•	•	•	•	•	•	•
	JUVENILES	•	•	•	•	•	•	•	•	•	•	•	•
	LARVAE	•	•	•	•	•	•	•	•	•	•	•	•
	SPAWNERS	•	•	•	•	•	•	•	•	•	•	•	•

Legend: Relative Abundance

NI	No Information	2	Rare
•	Zone Not Present	3	Common
0	Not Present	4	Abundant
		5	Highly Abundant

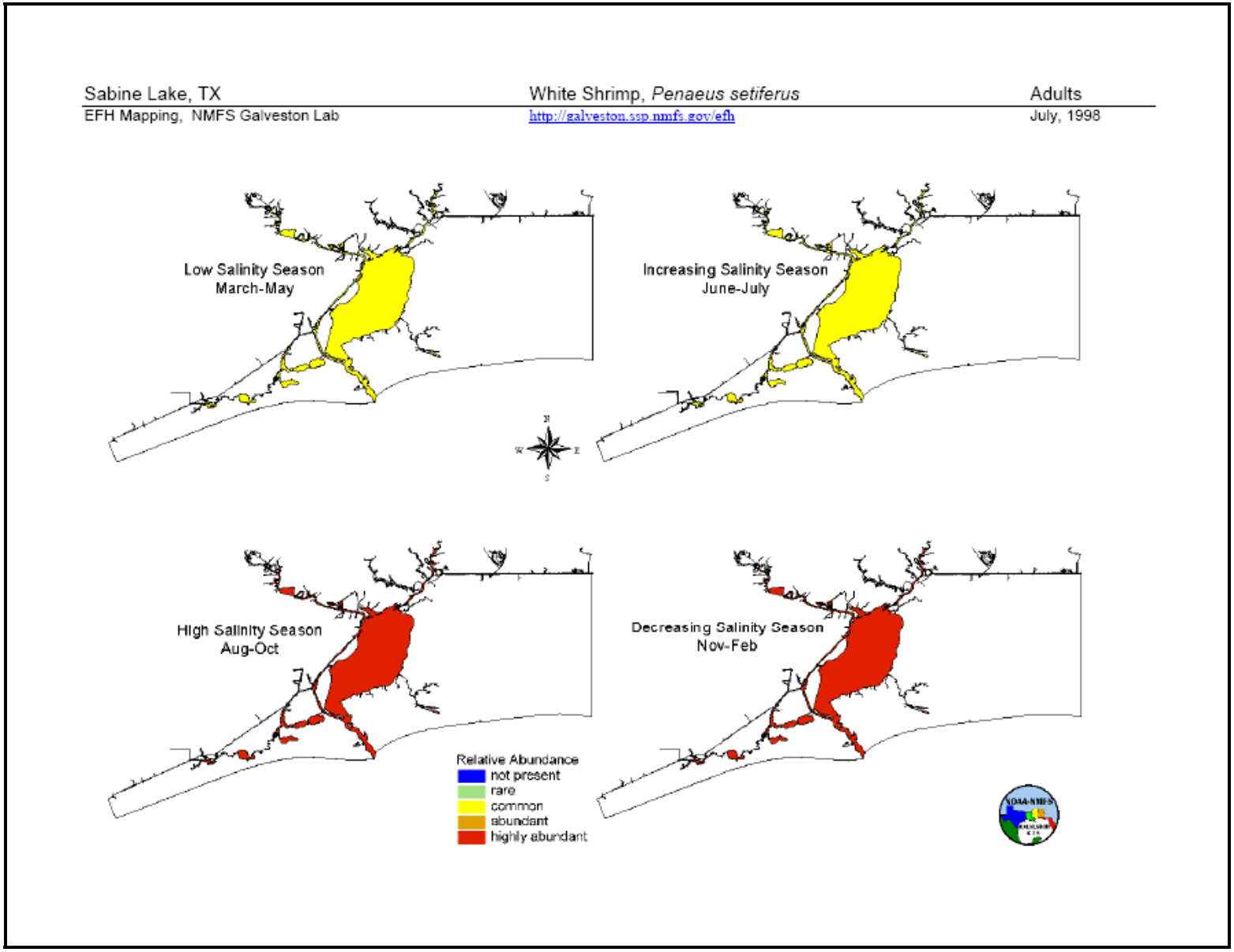


Figure 5. The seasonal relative abundance of white shrimp adults in Sabine Lake (NOAA 1998c).

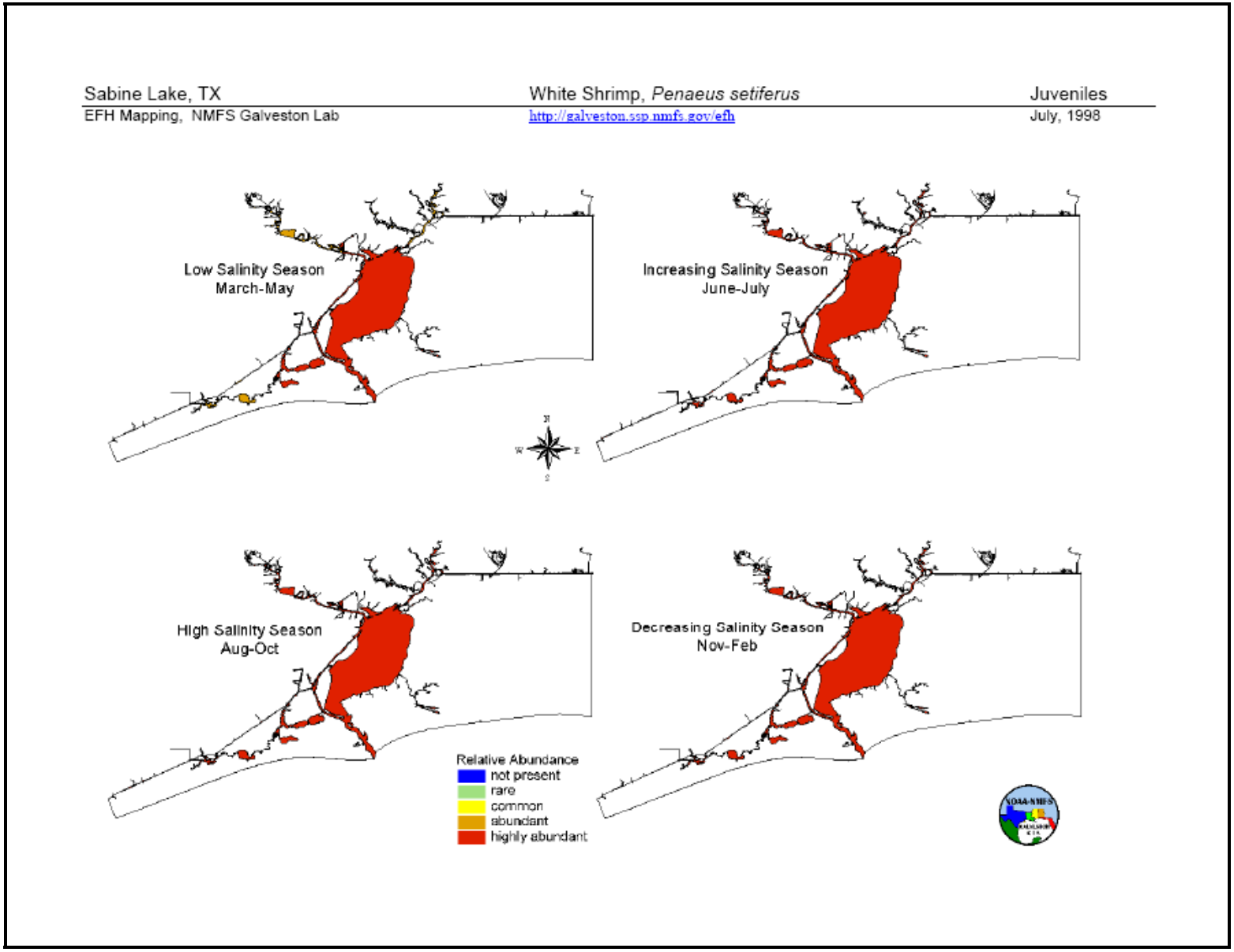


Figure 6. The seasonal relative abundance of white shrimp juveniles in Sabine Lake (NOAA 1998d).

3.3.2 Brown shrimp (*Farfantepenaeus aztecus*)

General Description

Brown shrimp, previously in the genus *Penaeus*, is an estuarine-dependent (Hass et al. 2004) shrimp species and member of the family Penaeidae. Brown shrimp, along with other penaeid species such as pink shrimp and white shrimp, comprise a commercially important shrimp fishery in the GOM (Cook and Murphy 1971), the second most valuable commercial fishery in the U.S. (Patillo et al. 1997). Brown shrimp extend from Massachusetts, around the tip of Florida, throughout the whole of the GOM, and south to the Yucatan Peninsula. In the GOM, brown shrimp are widespread throughout the bays and estuaries with centers of abundance in Texas, Louisiana, and Mississippi (Allen et al. 1980; Patillo et al. 1997). **Table 3** provides the relative abundance by month of brown shrimp in Sabine Lake during each life stage (adult, eggs, juveniles, larvae, and spawners) in five salinity zones.

Morphology

Brown shrimp are morphologically similar to white shrimp. Brown shrimp are characterized by the adrostral groove and crests extending almost to the hind margin of the carapace; well developed postrostral crest as far back as adrostral grooves; presence of gastrofrontal crests; and the absence of a dark, lateral spot between the third and fourth abdominal segment (Lassuy 1983b).

Ecological Relationship with Freshwater Inflow and Salinity

Adult brown shrimp are common within Sabine Lake at salinity zones between 5 to 25 ppt (Nelson 1992; CCMA, no date) during April to July. NOAA (1998a) also characterizes adult brown shrimp as common in Sabine Lake during the late spring and summer months when salinities are generally increasing (**Figure 7**). Juveniles are more abundant than adults in Sabine Lake, using the estuary as nursery habitat in salinities up to 25.0 ppt throughout the summer and fall and decreasing in abundance in late fall as the shrimp move out into the GOM (Nelson 1992; NOAA 1998b; CCMA, no date) (**Figure 8**). Brown shrimp are abundant in Sabine Lake during the larval life stage during April and May (Nelson 1992).

Life History

Adult brown shrimp reproduce and spawn offshore, usually between depths of 46 to 91 meters, but have been recorded as deep as 137 meters. Spawning occurs throughout the year, but primarily from September through May (Patillo et al. 1997; Haas et al. 2004). Planktonic larvae hatch after several hours and pass through a series of metamorphoses over a period of weeks, moving shoreward towards estuarine nursery grounds where postlarvae then settle (Baxter and Renfro 1967; Haas et al. 2004). Postlarve have been documented to move inshore primarily at night on incoming tides, taking on demersal habits in soft-bottom areas of estuaries (Lassuy 1983b). Postlarvae transform into juveniles around 25 millimeters total length (TL) in about four to six weeks (Perez-Farfante 1969) and spend about three months in nursery grounds (Cook and Murphy 1971) which provide protection from predation and feeding habitat (Lassuy 1983b). As they reach sizes of 90 to 110 millimeters, they begin migrating offshore (Patillo et al. 1997; Haas et al. 2004) from May through August, with peak months between June and July (Lassuy 1983b).

Adults then return to spawning depths offshore. The postlarvae that reach inshore waters and estuaries represent successful recruitment of the spawning season and will make up the bulk of the commercial fishery for a given year (Baxter and Renfro 1967); therefore survival within nursery grounds is extremely important (Haas et al. 2004).

Juveniles and subadults select shallow marsh areas and vegetation habitats within estuarine or nearshore areas over muddy and sandy substrates. Adults occur in the offshore neritic zone, associated with silty, sandy substrates (Lassuy 1983b; Patillo et al. 1997). Environmental conditions, habitat alteration, food availability, and substrate type affect brown shrimp abundance and distribution. The brown shrimp's habitat preference for vegetated areas may be affected by physicochemical parameters such as salinity, turbidity, and light; occasionally causing brown shrimp to inhabit areas with less coverage and food resources and making it more vulnerable to predation (Minello et al. 1989; Patillo et al. 1997).

Feeding Preferences and Predators

Larval stages of brown shrimp are planktivores, consuming both phytoplankton and zooplankton in the water column. Demersal postlarvae in estuarine nursery grounds feed at the vegetation-water interface, indiscriminately feeding on detritus, comprised primarily of *Spartina* (Jones 1973, cited by Lassuy 1983b). Juveniles and adults feed on a number of prey items, such as polychaetes, amphipods, and chironomid larvae, in addition to detritus and algae (Patillo et al. 1997).

Minello et al. (1989) describes predation as the most usual direct cause of brown shrimp mortality in estuarine nursery grounds in the GOM. As described above, brown shrimp prefer vegetated habitats for protection from predation. A number of predators feed on brown shrimp, including ladyfish (*Elops saurus*), hardhead catfish, sheepshead (*Archosargus probatocephalus*), pinfish, spot, and Atlantic croaker among many other fish as well as crustaceans (Patillo et al. 1997). In estuarine habitats, southern flounder are considered the major predator of juvenile brown shrimp as well as seatrout (Minello et al. 1989).

Table 3. Relative abundance of different life stages of brown shrimp in Sabine Lake within selected salinity zones (CCMA, no date).

Brown Shrimp — Sabine Lake

SALINITY ZONE	LIFESTAGE	Relative Abundance by Month											
		J	F	M	A	M	J	J	A	S	O	N	D
0-0.5 ppt.	ADULTS	2	2	2	2	2	2	2	2	2	2	2	2
	EGGS	0	0	0	0	0	0	0	0	0	0	0	0
	JUVENILES	0	0	0	3	3	3	3	3	3	3	3	0
	LARVAE	0	0	0	0	0	0	0	0	0	0	0	0
	SPAWNERS	0	0	0	0	0	0	0	0	0	0	0	0
0.5-5 ppt.	ADULTS	2	2	2	3	3	3	3	2	2	2	2	2
	EGGS	0	0	0	0	0	0	0	0	0	0	0	0
	JUVENILES	0	0	0	4	4	4	4	4	3	3	3	0
	LARVAE	0	0	0	0	0	0	0	0	0	0	0	0
	SPAWNERS	0	0	0	0	0	0	0	0	0	0	0	0
5-15 ppt.	ADULTS	2	2	2	3	3	3	3	2	2	2	2	2
	EGGS	0	0	0	0	0	0	0	0	0	0	0	0
	JUVENILES	0	0	0	4	4	4	4	4	3	3	3	0
	LARVAE	0	0	0	0	0	0	0	0	0	0	0	0
	SPAWNERS	0	0	0	0	0	0	0	0	0	0	0	0
15-25 ppt.	ADULTS	2	2	2	2	3	3	3	3	2	2	2	2
	EGGS	0	0	0	0	0	0	0	0	0	0	0	0
	JUVENILES	0	0	0	4	4	4	4	4	3	3	3	0
	LARVAE	0	0	0	4	4	0	0	0	0	0	0	0
	SPAWNERS	0	0	0	0	0	0	0	0	0	0	0	0
>25 ppt.	ADULTS	•	•	•	•	•	•	•	•	•	•	•	•
	EGGS	•	•	•	•	•	•	•	•	•	•	•	•
	JUVENILES	•	•	•	•	•	•	•	•	•	•	•	•
	LARVAE	•	•	•	•	•	•	•	•	•	•	•	•
	SPAWNERS	•	•	•	•	•	•	•	•	•	•	•	•

Legend: Relative Abundance

NI	No Information	2	Rare
•	Zone Not Present	3	Common
0	Not Present	4	Abundant
		5	Highly Abundant

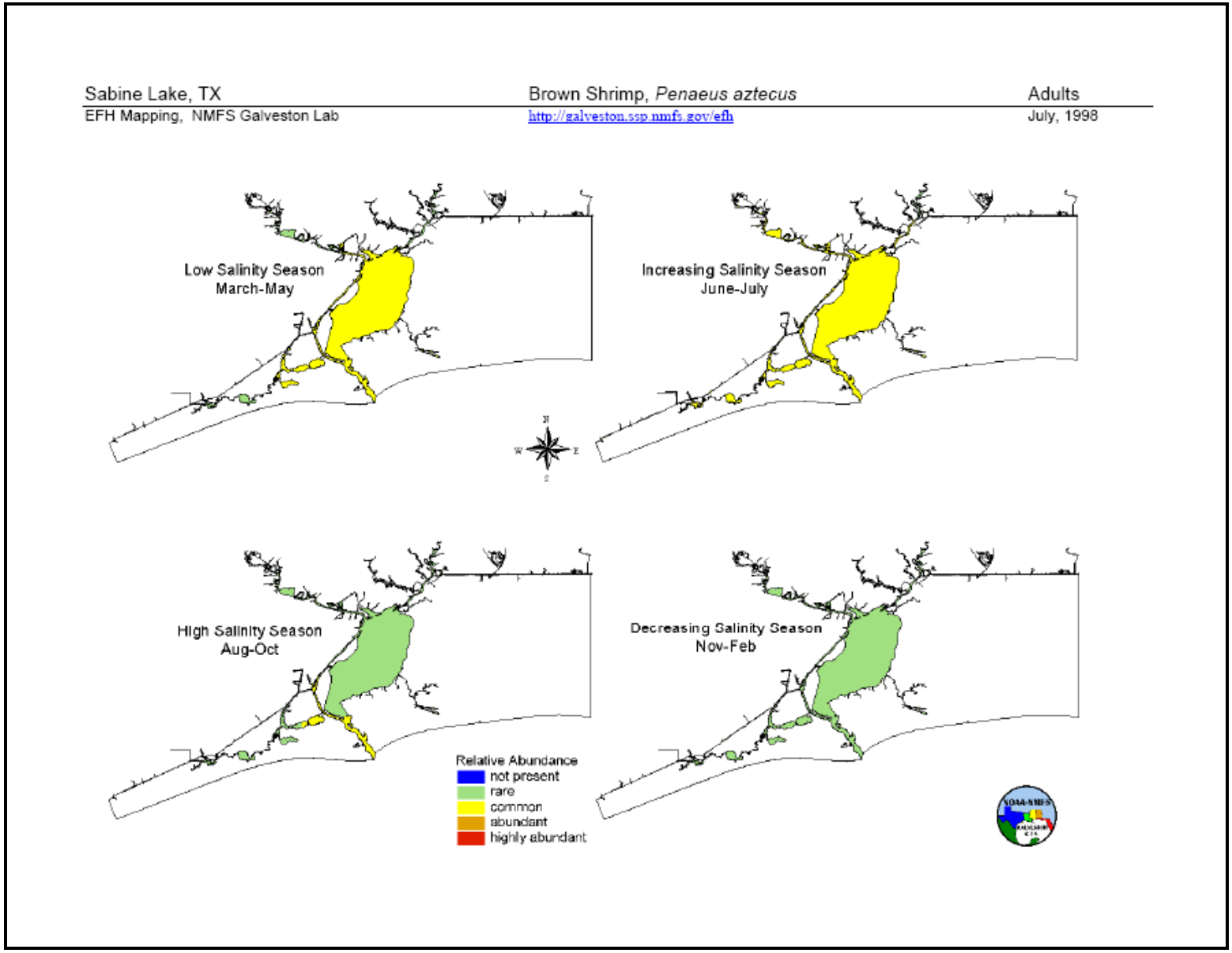


Figure 7. The seasonal relative abundance of brown shrimp adults in Sabine Lake (NOAA 1998a).

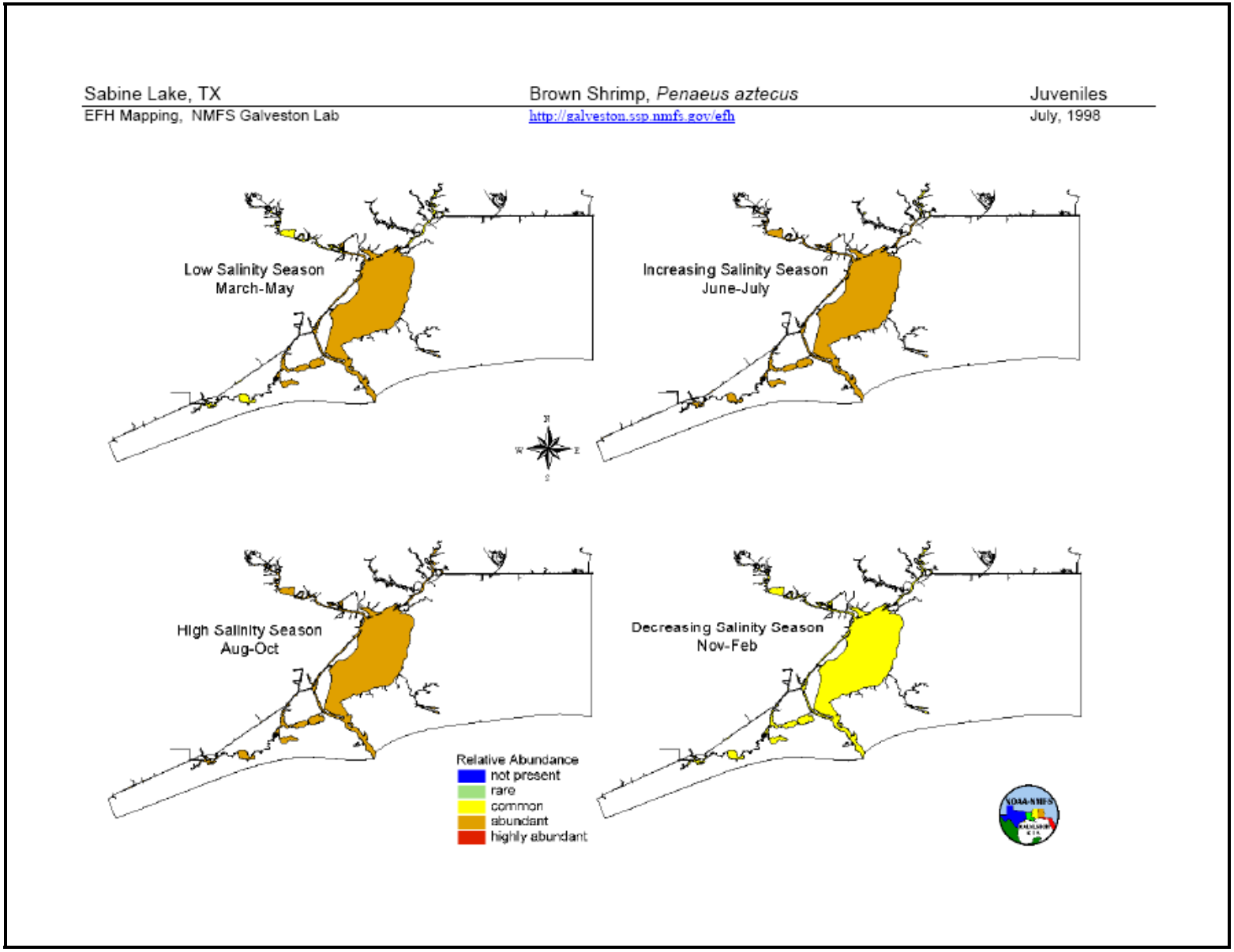


Figure 8. The seasonal relative abundance of brown shrimp juveniles in Sabine Lake (NOAA 1998b).

3.3.3 Blue crab (*Callinectes sapidus*)

General Description

Blue crab, *Callinectes sapidus* (Rathbun), is a member of the decapod family Portunidae, the swimming crabs. The blue crab performs a variety of functions in the estuarine ecosystem, and occupies a variety of habitats in fresh, brackish, and shallow oceanic waters. Blue crabs historically supported one of the largest commercial and recreational fisheries in the GOM. They have a large geographic distribution and are abundant throughout the nearshore and estuarine areas of the GOM and along the Atlantic coast from Nova Scotia to northern Argentina (Van Engel 1958). Blue crabs have also been introduced into coastal waters of Europe, the Mediterranean, and Japan (Van Engel 1958).

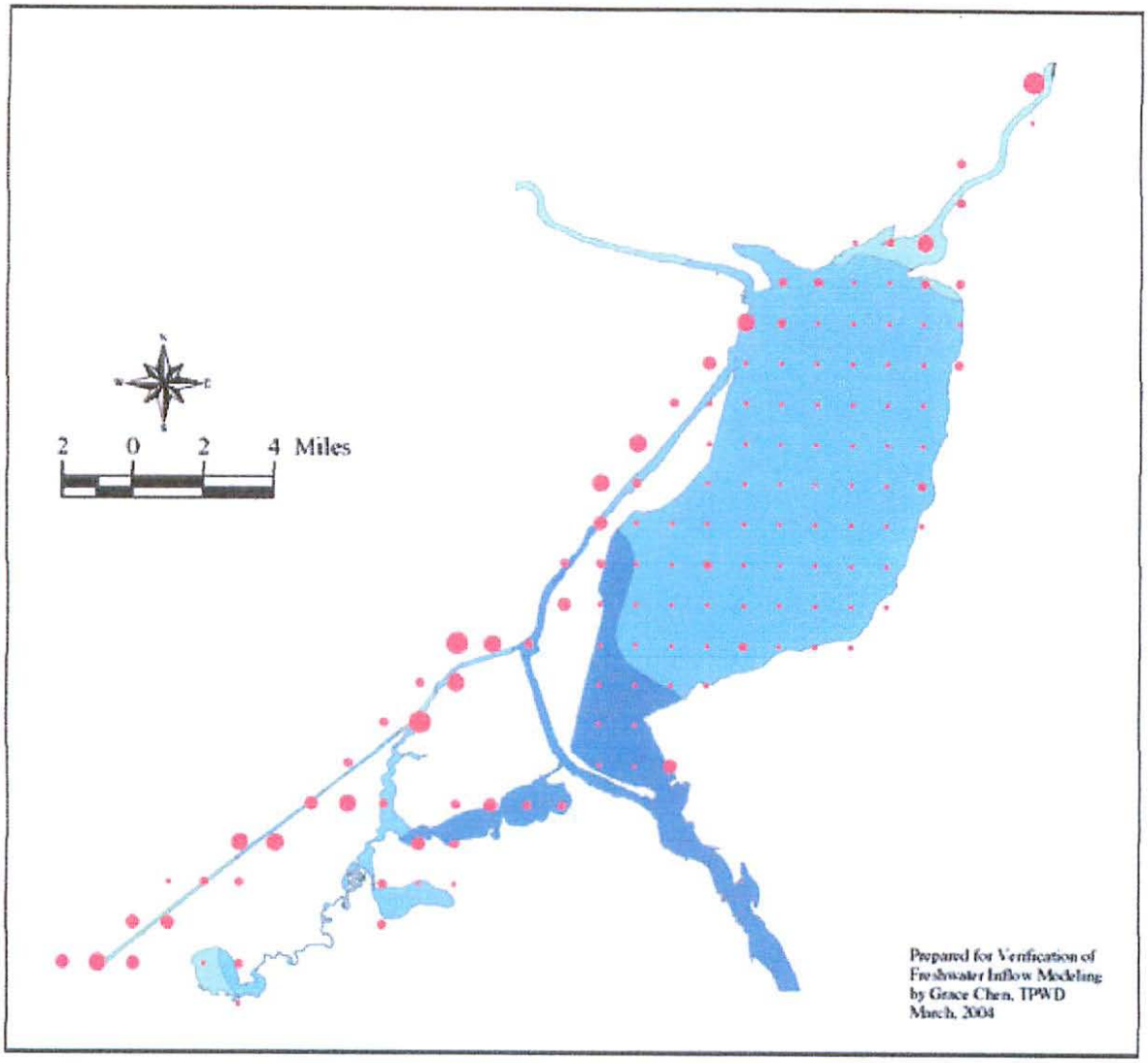
Blue crabs are highly abundant in Sabine Lake as both adults and juveniles (Pattillo et al. 1997). TPWD (2005) found blue crabs numerous throughout the year in Sabine Lake, with the highest abundances between February and July (**Figure 9**). Catch in the lowest salinity zone (0-3 ppt) was significantly higher than in any other salinity zone, and carapace width data indicated the majority were juvenile life stages (TPWD 2005).

Ecological Relationship with Freshwater Inflow and Salinity

Variations in salinity, temperature, pollutants, predation, disease, habitat loss, and food availability all affect blue crab survival. Overall populations are limited by post-settlement biotic processes that influence survival of small juveniles. Dissolved oxygen in the water column is also an important water quality parameter for blue crabs, with low levels of dissolved oxygen not only causing mortality of crabs but also impeding migration. The recruitment and dispersal of juvenile crabs into the estuary is influenced by factors such as freshwater inflow, causing flushing, salinity declines and low dissolved oxygen (Posey et al. 2005). Environmental conditions, such as temperature and salinity, can influence blue crab reproduction by the timing of molting and the spatial and temporal distribution of adult crabs in the estuary (Chazaro-Olvera and Peterson 2004). Adults show a differential distribution by sex and salinity, with males found in the lower salinity waters of the upper estuary, and females migrating along the salinity gradient between mating in the upper estuary and spawning in the high salinity waters of the lower estuary (Kennedy 2007).

Life History

Blue crabs spend most of their lives in estuaries and nearshore waters (Pattillo et al. 1997). Although there are few data about lifespan for GOM populations, typically the blue crab has an estimated life span of 3 to 4 years and can reach sexual maturity at 12 to 18 months (Kennedy 2007). Two spawning peaks typically occur in the GOM, one in late spring and the other during late summer or early fall. Blue crabs mate in low-salinity estuarine waters. Soon after mating, females travel to the saltier portions of the lower bays to prepare for spawning while the males remain dispersed in the upper estuary without migrating directionally along the salinity gradient (Pattillo et al. 1997, Kennedy 2007). Spawning occurs at the entrances to the estuary and lower bays between two and nine months after mating, which typically



Salinity Zones

Salinity (ppt)	% Bay Area	Mean CPUE	% Abundance
0.00 - 3	5.66	55.94	14.39
3.01 - 6	75.72	19.73	67.88
6.01 - 9	18.47	20.96	17.59
9.01 - 12	0.14	22.00	0.14
12.01 - 15	0.00	0.00	0.00
> 15.01	0.00	0.00	0.00

Species Abundance

CPUE (Catch per Hour)

- 0.00 - 12.67
- 12.68 - 34.80
- 34.81 - 72.00
- 72.01 - 162.00
- 162.01 - 301.50

Figure 9. Spatial distribution of blue crab collected in TPWD otter trawls in the Sabine Lake system between February – July (TPWD 2005).

takes place between August and September (Van Engel 1958; Williams 1965). Eggs hatch near the mouths of estuaries and the planktonic zoeal larvae are carried offshore (Pattillo et al. 1997) where they feed on phytoplankton and zooplankton while continuing to develop (Laughlin 1982).

Upon reaching the nektonic megalopal stage, blue crabs re-enter estuaries (Pattillo et al. 1997). Larvae and juveniles prefer submerged aquatic vegetation or flooded marshes as nursery habitat (Thomas et al. 1990). Juvenile crabs are widely distributed in estuaries and forage on diverse food sources and typically grow and molt for 0.5 to 1.5 years until they reach sexual maturity (Kennedy 2007). Larger juveniles and adults are demersal and prefer estuarine waters with soft sediments (Van Engel, 1958; Perry 1975). The adult crabs are omnivorous scavengers that feed on wide variety of plant and animal material.

Essential habitat for blue crab includes all habitats required during its life cycle, including offshore waters used for spawning and larval development and estuarine nursery grounds (Minello 1999, Guillory et al. 2001). Nursery habitats of critical concern include structured intertidal marshes, sub-tidal grass beds, and unvegetated soft sediment shoreline habitats where juveniles prefer to settle (Minello 1999, Jackson et al. 2001). Salt marshes in the northwest GOM are reticulated between stands of vegetation and interspersed tidal pools with tidal water level fluctuations generally less than one meter and relatively long inundation periods. As a result, marshes along the upper Texas and Louisiana coast are potentially more accessible for exploitation and may have greater value as nursery habitat for blue crabs that those of the Atlantic coast (Thomas et al. 1990).

Parasites and Predators

Infectious diseases of the blue crab have received less study than those of the American------ oyster and shrimp populations. While parasites may be common on crabs, most do not affect the life of the crab. Barnacles such as *Chelonibia patula*, worms and leeches attach themselves to the outer shell; gill parasites such as *Octolasmis muelleri* infect the gills (Overstreet et al. 2009); and small worms live in the muscles. Several pathogenic agents including viruses (two reported on the Gulf coast), *Vibrio* spp., *Hematodinium perezi* (dinoflagellate, only reported on the Atlantic coast), *Paramoeba perniciosa* (only reported on the Atlantic coast), *Loxothylacus texanus*, have the capacity to severely affect blue crab fisheries (Kennedy 2007).

Predators of the blue crab are numerous and vary throughout its life cycle. Juvenile and adult blue crab makes up part of the normal diet of red drum, Atlantic croaker, herons, sea turtles and humans.

3.4 Fish Focal Species

Life histories of many GOM fishes can be characterized as estuarine because these species are estuarine-dependent. These species typically spawn in the GOM, and their larvae are then carried inshore by currents. Juvenile fish generally remain in these estuarine nurseries for about a year, taking advantage of the greater availability of food and protection that that estuarine habitats afford. Upon reaching maturity, estuarine fishes may then remain in the estuary, migrate to sea to spawn (returning to the estuary between

spawning periods), or migrate from the shallow estuaries to spend the rest of their lives in the deeper GOM.

Estuary-dependent species occurring within open water and intertidal brackish marsh habitats within Sabine Lake include, but are not limited to gizzard shad (*Dorosoma cepedianum*), Gulf menhaden, bay anchovy (*Anchoa mitchilli*), hardhead catfish (*Ariopsos felis*), sheepshead minnow (*Cyprinodon variegatus*), Gulf killifish (*Fundulus grandis*), silversides (*Menidia* spp.), bluefish (*Caranx crysos*), crevalle jack (*C. hippos*), pinfish (*Lagodon rhomboides*), silver perch (*Bairdiella chrysura*), spotted seatrout, sand seatrout (*C. arenarius*), spot, Atlantic croaker, red drum, black drum (*Pogonias cromis*), striped mullet (*Mugil cephalus*), southern flounder (*Paralichthys lethostigma*) (Nelson 1992), threadfin shad (*D. petenense*), least puffer (*Sphoeroides parvus*), blue catfish (*Ictalurus furcatus*), and alligator gar (*Atractosteus spatula*) (TPWD, *pers. comm.*, July 2009).

Estuarine species serve as "integrators of the environment" whereby both abiotic and biotic factors can influence or constrain the relative value of estuarine nursery zones. Variability in physicochemical parameters, such as temperature, salinity, and dissolved oxygen, affect the suitability and selection of habitat by estuarine fish and other organisms in their various life stages (Peterson et al. 2004). Therefore, for the purposes of this Summary Report and when available, life histories, physicochemical preferences of specific life stages, spatiotemporal abundance, and value are described below.

Based on the NOAA ELMR Program, relative abundance for fish species are also defined using the same categories presented in *Section 3.3* (Nelson 1992; Patillo et al. 1997).

3.4.1 Atlantic croaker (*Micropogonias undulatus*)

General Description

The Atlantic croaker is an estuary-dependent (Lassuy 1983a; Pulich et al. 2002) sciaenid species found in coastal waters off the western Atlantic Ocean and in the GOM (Patillo et al. 1997). Within the GOM, Atlantic croaker are found from southern Florida to Mexico, most abundant off Louisiana and Mississippi (Lassuy 1983a), and considered one of the most common bottom-dwelling estuarine fish in the region (Patillo et al. 1997). The high abundance of Atlantic croaker within the GOM has made it one of the most important bottom-fish fisheries, as well as a recreationally important species (Patillo et al. 1997). Other common names include golden croaker, croaker, and hardhead.

Morphology

Atlantic croaker is characterized by a conical snout, subterminal mouth, and a row of barbels on either side of the mandible. The preopercular margin is serrated and the dorsal fin is deeply notched (McEachran and Fechhelm 2005). Young fish are silvery and older fish are a brassy yellow with short, irregular, oblique bars or streaks formed by spots on the scales above the lateral line (Hoese and Moore 1998; TPWD 1999).

Ecological Relationship with Freshwater Inflow and Salinity

Atlantic croaker salinity preferences are similar to that of blue crab; in Texas and Louisiana bays, juveniles and adults have been documented as most abundant in salinities less than 15 ppt (Pulich et al. 2002). In Sabine Lake, Nelson (1992) reported that Atlantic croaker adults are abundant in a wide range of salinity zones (0.0 to 25.0 ppt) and abundant from September to November. Juveniles are also reported as abundant in Sabine Lake within salinities ranging from 0.5 to 25.0 ppt, and are present throughout the whole year. Higher abundance of juveniles is typically associated with salinities ranging from oligohaline to mesohaline (0.5 to 12.0 ppt) (Weinstein et al. 1980).

Turbidity does not negatively affect Atlantic croaker, which is adapted for tactile feeding. High turbidity is associated with high organic loads and food availability as well as protection from predators (Diaz 1982). Weinstein et al. (1980) and Lassuy (1983a) described low salinity (0.5 to 5.0 ppt) and maximum turbidity zones of estuaries common habitat for juvenile Atlantic croaker.

Life History

Atlantic croaker spawns in marine waters from September to May with peak activity from October to November (Patillo et al. 1997; Petrik et al. 1999). Spawning occurs over the continental shelf at depths of at least 54 meters or near tidal passes and the mouths of bays and estuaries (Diaz 1982; Lassuy 1983a; Petrik et al. 1999). Early larvae are pelagic and planktonic, but become increasingly demersal as they age (Patillo et al. 1997). Larval croaker, 8 to 15 millimeters standard length (SL), appear to then actively move and/or are passively transported towards estuarine nursery grounds, primarily to marshes in the GOM (Diaz 1982).

Through spring and early summer, postlarvae and juveniles utilize estuaries and concentrate in shallow waters less than 1.2 meters deep near sources of fresh to brackish waters that have flowed through *Spartina* marshes and tidal flats (Lassuy 1983a). Diaz (1982) reported that the best combination of habitats for juveniles appear to be low salinity marshes interspersed with tidal creeks, where food items are particularly abundant and protection from predators is provided.

Prior to leaving estuaries, juveniles move to higher salinity areas within estuaries. As juveniles grow, ranging in size from 11 to 140 millimeters, they migrate to Gulf waters, around September to November (Lassuy 1983a). Lassuy (1983a) suggests that seaward migration is closely related to decreasing temperatures in estuarine waters. Adults move between estuarine and marine environments and are often associated with oyster reefs (Lassuy 1983a).

Atlantic croaker is associated with sandy and muddy bottoms along the coast and in estuaries (Lassuy 1983a; McEachran and Fechhelm 2005). As previously mentioned, juveniles are the dominant croaker life stage found in estuarine habitats and typically reside in marshes and tidal riverine habitats which provide an abundance of food and shelter. Within these habitats, Atlantic croaker is typically found in less than 1.8 meters in water depth. Additional habitat utilized as good nursery areas include subtidal channels and areas with soft bottoms and high detrital content (Weinstein et al. 1980; Diaz 1982).

Feeding Preferences and Predators

Atlantic croaker preys on a wide variety of organisms, the bulk of which include benthic invertebrates, such as mysids, decapods, amphipods, copepods, and polychaetes. Other prey includes mollusks, finfish, and detritus. Larvae and early juvenile fish (15 to 30 millimeters) are carnivores and feed on zooplankton in the water column, such as calanoid and harpacticoid copepods. Older juveniles and adults are opportunists, forcefully digging in the substrate in order to feed on benthic invertebrates. Adults also prey on some fishes in addition to bottom feeding. Detritus in the diet of Atlantic croaker appears to be a byproduct of feeding along the bottom, rather than for nutritive purposes (Diaz 1982; Lassuy 1983a; Patillo et al. 1997). A number of larger piscivorous fish species, such as bass (*Morone spp.*), red drum, and seatrout (*Cynoscion spp.*), are predators of Atlantic croaker (Patillo et al. 1997).

3.4.2 Spot (*Leiostomus xanthurus*)

General Description

Spot is a demersal sciaenid species found in estuarine and coastal waters of the western Atlantic Ocean and GOM, from the Gulf of Maine to the Bay of Campeche, Mexico. Spot are commercially harvested, primarily from Chesapeake Bay and the Atlantic coast; however, spot does contribute to the bottom-fish industry of Louisiana and Mississippi (Patillo et al. 1997). Spot is not a particularly important recreational species. Spot are associated with sandy or muddy bottoms and use estuaries as nursery grounds (McEachran and Fechhelm 2005). Massman (1954) reported that in Virginia, spot occurred in freshwater 35 kilometers upstream of brackish waters. Other common names include flat croaker, yellowtail, golden croaker, and spot croaker.

Morphology

Spot is a deep bodied fish characterized by a small, nearly horizontal mouth; deeply notched dorsal fin; and a single, large spot located behind the operculum. Spot have 12 to 15 oblique, dark streaks that may be indistinct in larger specimens and are silvery gray color, darker dorsally than ventrally (McEachran and Fechhelm 2005; Maier, no date). Spot are one of the smaller members of the Sciaenidae (Patillo et al. 1997).

Ecological Relationship with Freshwater Inflow and Salinity

Nelson (1992) reports adult spot as abundant in Sabine Lake at salinities up to 25 ppt from September to October; while juveniles are reported as common in similar salinities throughout the year. TPWD (2005) showed that spot selected salinities between 6 to 12 ppt in Sabine Lake.

Life History

Spot spawn offshore in moderately deep water over the continental shelf during from November through March in Louisiana (Cowan and Shaw 1988) and from November to April, with peaks from December to February (Patillo et al. 1997). Larvae are then transported inshore towards estuarine nursery grounds where transformation to juveniles occurs around 15 millimeters. Larvae exhibit a diurnal vertical

migration, where they are dense in mid-water and at the bottom during the day and at the surface during the night. Juveniles initially move into low salinity headwaters in the estuary during the spring and summer. As juveniles mature towards the end of their second year, they move from shallower, less saline, headwaters of tidal creeks, to seagrass beds or deeper, more saline areas within estuaries. Like many of these estuarine-dependent fish species, spot adults and juvenile commonly make inshore-offshore migrations (Patillo et al. 1997).

Feeding Preferences and Predators

Spot are selective planktivores in the early stages of their life eating organisms such as pteropods, larval pelecypods, and cyclopoid copepods. Juveniles and adults are nocturnal, opportunistic bottom feeders with prey items including benthic infauna. Feeding by juveniles in estuaries appears to be tidally influenced, taking advantage of prey available in marsh habitats during high tides, consisting of insect larvae, bivalves, and detritus (Patillo et al 1997).

Predators include a number of piscivorous fish, including silky sharks (*Carcharhinus falciformis*), longnose gar (*Lepisosteus osseus*), bass (*Morone* spp.), seatrout, flounders, and to seabirds such as cormorants (*Phalacrocorax* spp.) (Phillips et al. 1989; Patillo et al. 1997).

3.4.3 Gulf menhaden (*Brevoortia patronus*)

General Description

The Gulf menhaden is an estuarine-dependent (Christmas et al. 1982; Patillo et al. 1997; VanderKooy and Smith 2002) marine species found from freshwater to hypersaline environments. Other common names include shad, pogy, largescale menhaden, sardine, fatback, and bunker. Gulf menhaden range from Florida to Mexico and supports one of the most important clupeid and largest single-species (by weight) fisheries in the GOM (Christmas and Gunter 1960; Christmas et al. 1982; Lassuy 1983c). Gulf menhaden are taken by purse seines from both estuarine and nearshore marine waters, with centers of abundance in Mississippi (Christmas et al. 1982; Lassuy 1983c), Louisiana (Christmas and Gunter 1960; Christmas et al. 1982; Lassuy 1983c; Hoese and Moore 1998), and Texas (Christmas et al. 1982), including Sabine Estuary (Nelson 1992).

Morphology

Gulf menhaden are distinguished from other clupeids, particularly menhaden species, by being considerably smaller, having a large head, large scales, and a dark humeral spot usually followed by a series of smaller spots (Christmas and Gunter 1960; Hoese and Moore 1998; TPWD 1999; VanderKooy and Smith 2002).

Ecological Relationship with Freshwater Inflow and Salinity

As an inhabitant of both estuarine and marine waters, Gulf menhaden have adapted to a wide range of temperature and salinity tolerances. Nearshore bays and estuaries inhabited by adults range from 5 to 15 ppt, whereas offshore marine waters are characterized by higher salinities, greater than or equal to 30 ppt

(Christmas et al. 1982). Non-gravid and developing adults occupy mid-range salinities with high abundances at 20 to 25 ppt, though they are capable of ranges from 0 to 67 ppt (Patillo et al. 1997). Gulf menhaden adults have been documented as common in Sabine Estuary at a wide range of salinities from September through November (Nelson 1992). In general, postlarvae and juveniles also occupy a wide range of salinities from 5 to 30 ppt (Patillo et al. 1997). Nelson (1992) reports juveniles as highly abundant in Sabine Estuary during the summer months, abundant during the fall months, and common through the winter and spring months. TPWD (2005) showed that Gulf menhaden in the Sabine Estuary selected salinity ranges of 3 to 6 ppt.

Life History

Gulf menhaden life history is typical of most estuarine-dependent species in the GOM, spawning offshore in Gulf waters with recruitment and maturation in nearshore rivers, bays, and bayous (VanderKooy and Smith 2002), sometimes in waters of very low salinities considered to be in the freshwater range (Christmas and Gunter 1960).

Beginning around October, Gulf menhaden move from shallow inshore areas offshore, wintering on the inner and middle continental shelf, from 2 to 128 meters deep (Roithmayr and Waller 1963). Spawning occurs in these offshore waters over the continental shelf from October through March (Fore and Baxter 1972a) at temperatures between 15 and 18 °C and salinities greater than 25 ppt (VanderKooy and Smith 2002); though spawning is suspected to occur in some years from September to May (Christmas et al. 1982). The spawning season, which may be composed of as many as four to five spawning peaks, appears to coincide with relatively cool Gulf waters from approximately 25 °C in October to 18 °C in March (Christmas et al. 1982). Based on the distribution of eggs, Gulf menhaden spawning occurs mainly over the continental shelf between Sabine Pass, Texas and Alabama (VanderKooy and Smith 2002).

After a period of approximately 3 to 5 weeks, larvae are transported by currents into low salinity estuarine nursery areas (Fore and Baxter 1972b; Christmas and Gunter 1982). Peak influxes of larvae into estuaries along Texas and Louisiana occur in November-December to February-April, where they are carried into tidal creeks and ponds of marshes and estuaries (Patillo et al. 1997). While in estuaries, larvae metamorphose to juveniles as they reach 30 to 33 millimeters (Lassuy 1983c). After transformation, juveniles remain in the low salinity, nearshore marshes (Fore and Baxter 1972b; Lassuy 1983c; Hoese and Moore 1998) though they may move to deeper, open, higher salinity (Fore and Baxter 1972b) estuarine waters as reach lengths greater than 50 millimeters (Patillo et al. 1997). Juveniles were reported to have been collected in the lower Neches River, approximately 30 nautical miles upstream from Texas Point, at the Sabine Pass entrance, in salinities ranging from 0.16 to 20.4 ppt (Gunter and Christmas 1960).

Peak Gulf ward migrations of maturing juveniles and adults occur from October through January (Lassuy 1983c). Migration back into inshore estuarine waters by individuals of all age groups, including adults, occur early the following spring, March to April, following an overwintering or spawning season (Christmas et al. 1982; Lassuy 1983c) at depths of 1.8 to 14.6 meters (Patillo et al. 1997), where fish are

sexually inactive (Christmas et al. 1982) and returning primarily to feed in the food rich waters of estuaries. Inshore-offshore migrations are common for juveniles and adults, though both have been documented in estuaries and inshore areas year-round (Lassuy 1983c), including Sabine Lake (TPWD 2005).

Though the dependence of Gulf menhaden to lower salinity estuarine habitats is not well understood, metamorphosing larvae have rarely been collected in higher salinity marine waters, indicating a relationship between development and food availability. The shelter provided in estuarine habitats is also important for Gulf menhaden. Small (less than 20 hectares) marsh areas generally do not support large concentrations of menhaden unless they are part of a larger estuarine complex. Additionally, despite a lack of data related to physiological requirements for estuarine dependence, gonadogenesis of young Gulf menhaden is completed only in brackish, estuarine waters (Christmas et al. 1982).

Feeding Preferences and Predators

Gulf menhaden have two distinct feeding stages through their life cycle. Larval Gulf menhaden (30 to 33 millimeters) are selective carnivores (Patillo et al. 1997) in estuarine and marine waters, feeding primarily on zooplankton. The loss of teeth and elongation of gill rakers occurs during metamorphoses and juveniles and adults become omnivorous filter-feeders, consuming phytoplankton, zooplankton, detritus, and bacteria (Christmas et al. 1982; Lassuy 1983c).

Gulf menhaden are not only an economically important commercial fishery, but are also ecologically important. Because of their great abundance and schooling behavior, Gulf menhaden support a number of piscivorous fish and bird species including: mackerel (Scombridae), spotted seatrout, alligator gar, red drum, brown pelican (*Pelecanus occidentalis*), and osprey (*Pandion haliaetus*) (VanderKooy and Smith 2002). Additionally, larval Gulf menhaden are one of the dominant species of ichthyoplankton in the GOM during the winter, spawning months (Raynie and Shaw 1994).

4.0 SUMMARY

It is widely accepted that the Sabine-Neches estuary (Sabine Lake), like other Gulf Coast estuaries, is a highly dynamic environment that reacts to many drivers, one of which is freshwater inflow. Freshwater inflow studies are complex, usually involving an assessment of processes occurring across multiple spatial and temporal scales regarding the hydrology, water quality, geomorphology, and biology of the estuary. Several studies documenting the importance of freshwater inflows to the Sabine Lake system have been conducted over the last few decades. The Texas Department of Water Resources (1981) used indicators including freshwater inflows, circulation and salinity patterns, nutrients, and aquatic indicator species in their analyses. Methods for their analyses included statistical analysis of relationships among freshwater inflow, commercial fishery harvest and estuarine salinity, estimates of marsh freshwater inundation needs, estimates of nutrient exchange, records of historical freshwater inflow, and seasonal pulses (TDWR 1981). More recently, the Texas Parks and Wildlife Department (2005) also stressed the importance of the timing of inflow, in addition to volume, in maintaining an ecologically sound environment. The purpose of this biological summary document is to provide the Sabine-Neches BBEST with the background biological information on the selected focal species in Sabine Lake to allow for the examination of potential environmental flow regimes required for the Senate Bill 3 process.

Freshwater inflow influences the spatial distribution, abundance, and productivity of aquatic organisms in estuaries in several ways. In addition to creating the salinity gradient across the estuary, freshwater inflows also transport sediment and nutrients into the open bay and surrounding marshes. Seasonal flood pulses allow for high waters to inundate the floodplain and fringing marshes. During flood conditions, marsh habitats are inundated and nutrients and sediment are deposited in the marsh, helping to flush stagnant water, increase plant productivity, and maintain marsh elevation in the landscape. Phytoplankton also use these nutrients in the water column for primary production, forming the base of the estuarine food web.

The spatial distribution of wetland plants and bivalve mollusks are particularly related to the longer-term trends of freshwater inflow to the Sabine Lake system since they are sessile organisms, not capable of moving in response to changing environmental conditions. The spatial distributions of the crustacean and fish focal species are related to freshwater inflow on a seasonal basis due to their life cycles and their ability to move in response to changes in environmental gradients (salinity, temperature, etc.). However, the juvenile life stages of these species are typically less able to tolerate large changes in salinity and do not have the mobility of adults. Juvenile life stages require nursery habitats for shelter and food for successful development before they are able to survive in the open estuary and GOM. A map outlining the general trends in spatial distribution of the ten focal species is shown in **Figure 10**.

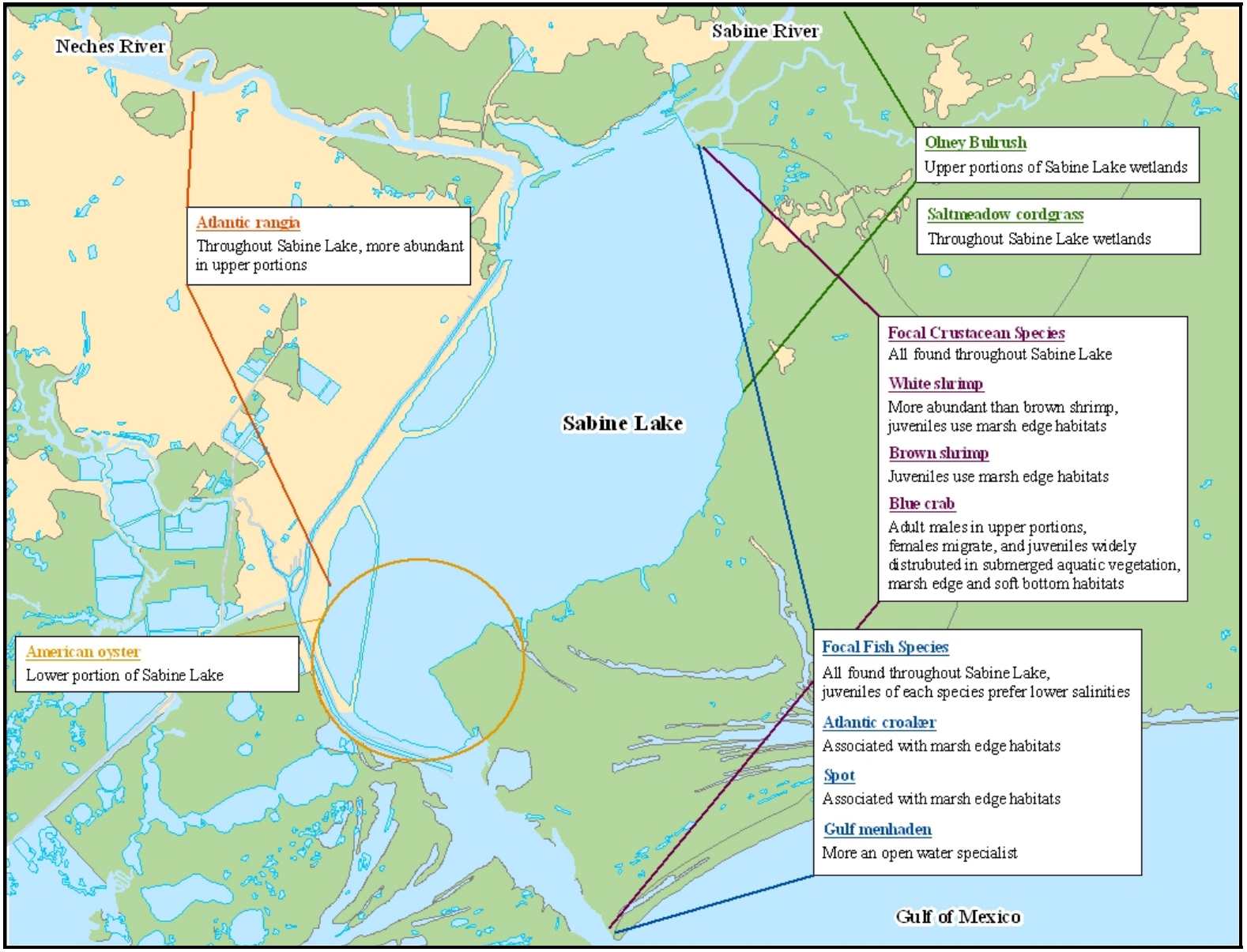


Figure 10. General spatial distribution patterns of focal species in the Sabine Lake system.

The timing of freshwater inflow to a bay has long been acknowledged as being extremely important in maintaining the ecological productivity of the system. Aquatic organisms respond to pulses of nutrients, alterations in salinity, and habitat conditions (e.g. temperature, dissolved oxygen, food availability), which may vary seasonally and with variations in freshwater inflow to the estuary. Historically, the discharge rates of Texas rivers have fluctuated on a seasonal basis. Monthly freshwater inflows usually peak in the spring and early fall, following patterns of increased rainfall and runoff that normally occur during these months (http://waterdata.usgs.gov).

As estuarine-dependent organisms, these species have developed a unique relationship with freshwater inflow that is related to all or a part of its life cycle. Freshwater inflow regimes directly influence the salinity regimes observed within estuaries. In Sabine Lake, NOAA (1998e) developed salinity seasons for Sabine Lake (prepared for Gulf of Mexico Fishery Management Council): decreasing salinity season (November to February), low salinity season (March to May), increasing salinity season (June to July), and high salinity season (August to October). These salinity seasons along with a general pattern of freshwater inflow from the Sabine and Neches Rivers to Sabine Lake is provided in **Figure 11**. Also shown in **Figure 11** are key temporal and ecological relationships of each of the ten estuarine focal species in Sabine Lake as they relate to the seasonal pattern of freshwater inflow. Key points outlined in Figure 11 regarding the freshwater inflow-ecology relationships for each of the focal species include:

- Atlantic rangia – spawning may be continuous during the year, but peak spawning periods have been documented from March to May and from late summer to November (Louisiana; LaSalle and de la Cruz 1985). Spawning may be triggered by an increase in salinity and temperature, and the larvae require some salinity for development, tolerating a range of approximately 2 to 10 ppt.
- American oyster – in southern waters, spawning occurs in all but the coldest months (Berrigan et al. 1991) with oyster growth optimal in salinities from 10 to 28 ppt.
- White shrimp – in Texas, postlarvae enter and utilize nursery areas from April to November (Kilma et al. 1982).
- Brown shrimp – juveniles are abundant in Sabine lake in summer and fall, decreasing in late fall as they migrate to the GOM (Nelson 1992, NOAA 1998b, CCMA).
- Blue crab – mate in low salinity waters of the upper estuary, where the males remain. Females migrate to the lower bays to spawn between two and nine months after mating, typically between August and September (Van Engel 1958, Williams 1965).
- Atlantic croaker – postlarvae and juveniles utilize estuaries and concentrate in shallow waters near sources of fresh to brackish waters during spring and early summer (Lassuy 1983a).
- Spot – enter estuaries as larvae in the spring and head to low salinity headwaters of the estuary and tidal creeks throughout the summer (Patillo et al. 1997).
- Gulf menhaden – generally spawn from October to March (Christmas et al. 1982), from Sabine Pass to Alabama with peak influxes to the estuaries in February – April (VanderKooy and Smith 2002, Patillo et al. 1997).

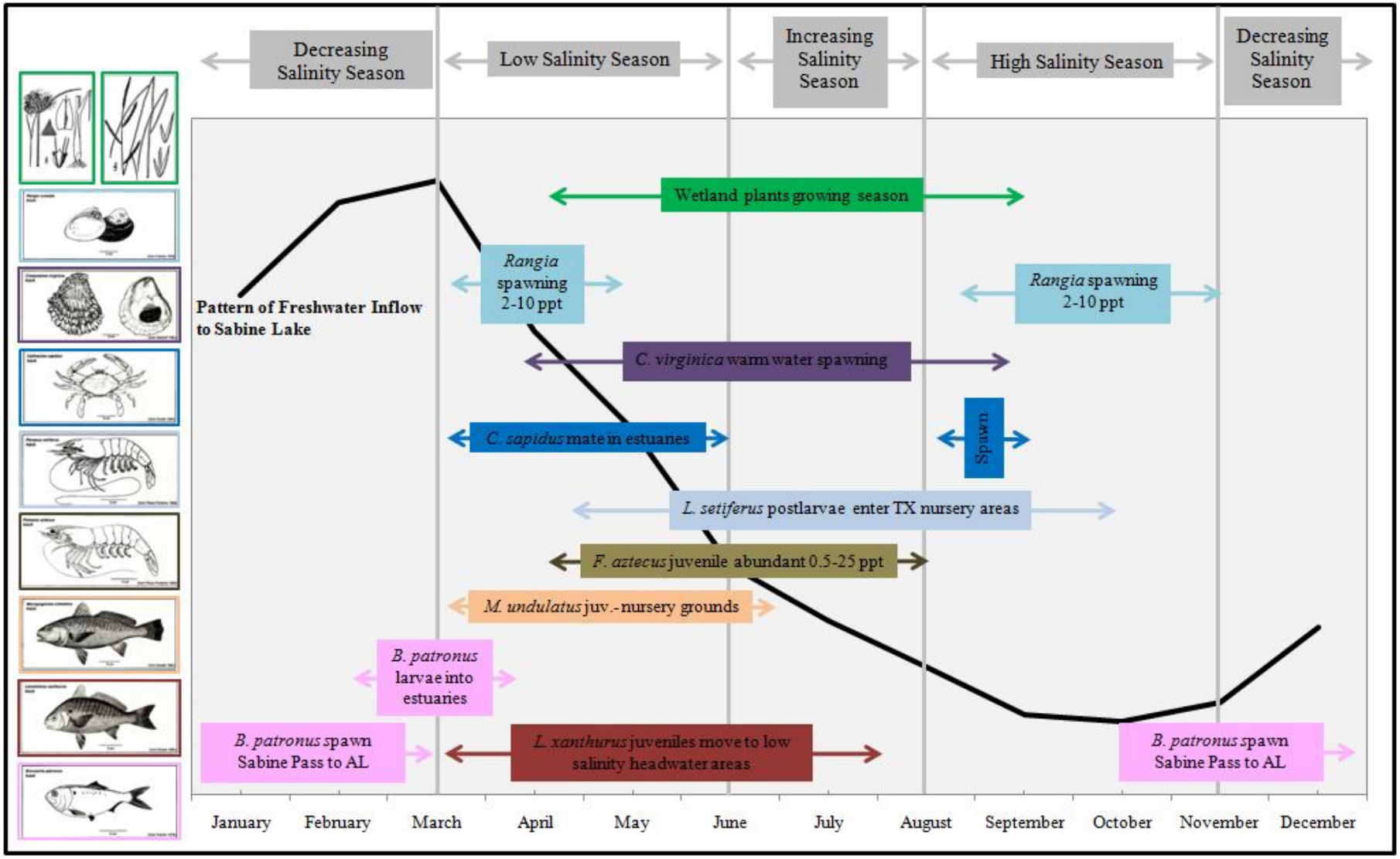


Figure 11. General ecological relationships of each focal species with the seasonal pattern of freshwater inflow to the Sabine Lake system.

Of primary importance to many of these species is the availability of estuarine habitats for nursery and foraging areas, where postlarval and juvenile life stages typically select for vegetative cover and lower salinity conditions. Crustacean and fish species also depend on the nutrients and shelter provided by freshwater inflows through adjacent marsh habitats and from tidal creeks. Economically, the bulk of commercial fisheries depend on the survival and recruitment success of these species established during their time in estuaries.

It is evident that maintaining the variability in freshwater inflows to estuaries is important. One aspect that is also clear is that the inflows to Sabine Lake tend not to be steady, but rather occur in high flow pulses or longer-term seasonal freshets. As examined in a freshwater inflow analysis for Matagorda Bay, Texas, simply meeting an average or median inflow at all times would not maintain the long-term average primary productivity in the estuary because the bulk of the essential nutrients that support the long-term average chlorophyll-a levels are supplied by the relatively infrequent high flow events that are a critical part of the system variability (MBHE 2008). The seasonal timing of inflows are also important, since pulses of flow and nutrients that occur in the spring and early summer would translate into chlorophyll-a more rapidly than they would if the same pulse occurred in the winter. However, these high-flow pulse or freshet events are largely due to natural storm events (including hurricanes) unrelated to managed river flows. An example of an inflow regime study that addresses these important pulse events was recently developed for the Matagorda Bay system, which typically receives less freshwater inflow than Sabine Lake, and the report provides an overview of the topics discussed in this document as related to Matagorda Bay (MBHE 2008).

Shifts in the overall magnitude and duration of freshwater inflow to Sabine Lake will also influence the spatial distribution, abundance and productivity of the focal species, although some species will be affected differently than others. **Table 4** provides potential general trends in the freshwater inflow-ecology relationships of the focal species in Sabine Lake in relation to hypothetical overall changes in the magnitude of freshwater inflow to the estuary. Generally, because many of these focal species are euryhaline, slight or moderate shifts in overall freshwater inflow between years will not greatly affect or impact many of these organisms. However, more dramatic responses in the species' distribution and abundance can be reasoned from individual salinity and habitat requirements, based on dramatic changes in inflows to the estuary, whether it be a large shift to less inflow or a large shift to more inflow (**Table 4**). The more tolerant species, such as spot, Gulf menhaden, and brown shrimp, primarily in their adult life stage, would likely not be significantly affected in either scenario. In a more saline environment, wetland plants and Atlantic rangia would be under higher salinity stress and would likely decrease in overall abundance and productivity. Atlantic rangia distribution in particular would likely be considerably reduced by increased salinity conditions, since even adults do not tolerate salinities above 18 ppt. Since white shrimp are highly abundant in Sabine Lake under current conditions and juveniles are found in nursery areas with relatively low salinities, it is likely than a dramatic decrease in freshwater inflow to the system would lead to a decrease in the abundance of white shrimp.

Table 4. Potential general trends in the freshwater inflow-ecology relationships of focal species in Sabine Lake; (~) – similar spatial distribution, abundance, and productivity; (↓), (↑) – implies decrease or increase in potential abundance and productivity, respectively, where size of arrow depicts the potential degree of change.

Estuarine Focal Species		**Life Stage**	**Shift in Annual Inflow (maintaining seasonal variability)**		
Common Name	**Scientific Name**		**Slight shift, more or less**	**Large shift to less inflow**	**Large shift to more inflow**
Olney bulrush	*Schoenoplectus americanus*	n/a	~	↓	↑
Saltmeadow cordgrass	*Spartina patens*	n/a	~	↓	↑
Atlantic rangia	*Rangia cuneata*	n/a	~	↓	↑
Eastern oyster	*Crassostrea virginica*	n/a	~	↑	↓
Blue crab	*Callinectes sapidus*	n/a	~	~	~
White shrimp	*Litopenaeus setiferus*	n/a	~	↓	~
Brown shrimp	*Farfantepenaeus aztecus*	n/a	~	↑	↓
Atlantic croaker	*Micropogonias undulatus*	Juvenile	~	↓	~
		Adult	~	~	↓
Spot	*Leiostomus xanthurus*	Juvenile	~	↓	~
		Adult	~	~	↓
Gulf menhaden	*Brevoortia patronus*	Juvenile	~	~	~
		Adult	~	~	↓

Brown shrimp, however, are generally found in higher salinities than white shrimp and might benefit from an increase in salinity in Sabine Lake. Oysters are also currently limited in distribution in Sabine Lake, occurring only in the lower portion since the upper estuary is too fresh for oysters to survive. A decrease in freshwater to Sabine Lake might allow for the extension of the oyster range to more northern portions of Sabine Lake, provided there were adequate substrate for spat settlement and sufficient freshwater inflows to regulate oyster parasites and predators.

Under the scenario of higher freshwater inflows to Sabine Lake, with a less saline environment, the same wetland plant species and Atlantic rangia would likely be more productive and more abundant. *S. americanus* thrives with inundation of the soil and less salt stress and *S. patens* would be similarly more productive under lower salinities. However, if inundation of the high marsh were to occur more frequently and for longer duration, *S. alterniflora* may outcompete *S. patens* in the brackish marsh and cattail or common reed may outcompete *S. patens* in the fresh and intermediate marsh areas. The Atlantic rangia population could extend further down in Sabine Lake under fresher conditions, since the necessary salinity conditions required for spawning may exist over larger spatial areas. In contrast to Atlantic rangia, oyster productivity and distribution would likely decrease under this higher inflow scenario.

The distribution of the more euryhaline species, fishes and crustaceans, though they may prefer low salinities during their juvenile life stages, would likely not be highly influenced by a more saline or less saline environment, though in both cases, a decrease in survivability, recruitment, and abundance is possible.

Shifts in the seasonal variability of freshwater inflow may also have an effect on the distribution, abundance and productivity of the focal species in Sabine Lake. A slight to moderate shift in variability, such as slightly increasing the magnitude of the spring freshet or having the fall freshet occur a few weeks later than average, will not likely cause such a change. However, a large shift in the inflow variability, such as inverting the seasonal inflow pattern or maintaining a constant flow to the estuary, will likely cause a decrease in the abundance and productivity of many or all the focal species in the estuary since their life cycles have developed around variations in inflow patterns.

Other factors influencing bay conditions are near-shore gulf salinity, meteorology, physiographic modifications, harvest pressures, adjacent land-use change, habitat alterations or losses, and large-scale GOM conditions. All of these factors can affect habitat and species distributions and productivity in the bay, as well as chemical constituents, the availability of food, fishing pressure, and for migratory species, the status of the larger population in the Gulf.

In conclusion, although ecological responses to freshwater inflow are complex, we feel that the focal species approach taken by the Sabine/Neches BBEST is appropriate for the SB3 objectives. To support the mission of guiding the establishment of freshwater inflow recommendations to Sabine Lake, we feel that a detailed evaluation of 1) the HEFR output from the most downstream gages or combination thereof and/or 2) any alternative inflow-regime hydrology prescription can be accomplished by overlaying the freshwater inflow to ecology relationships for the selected focal species as presented.

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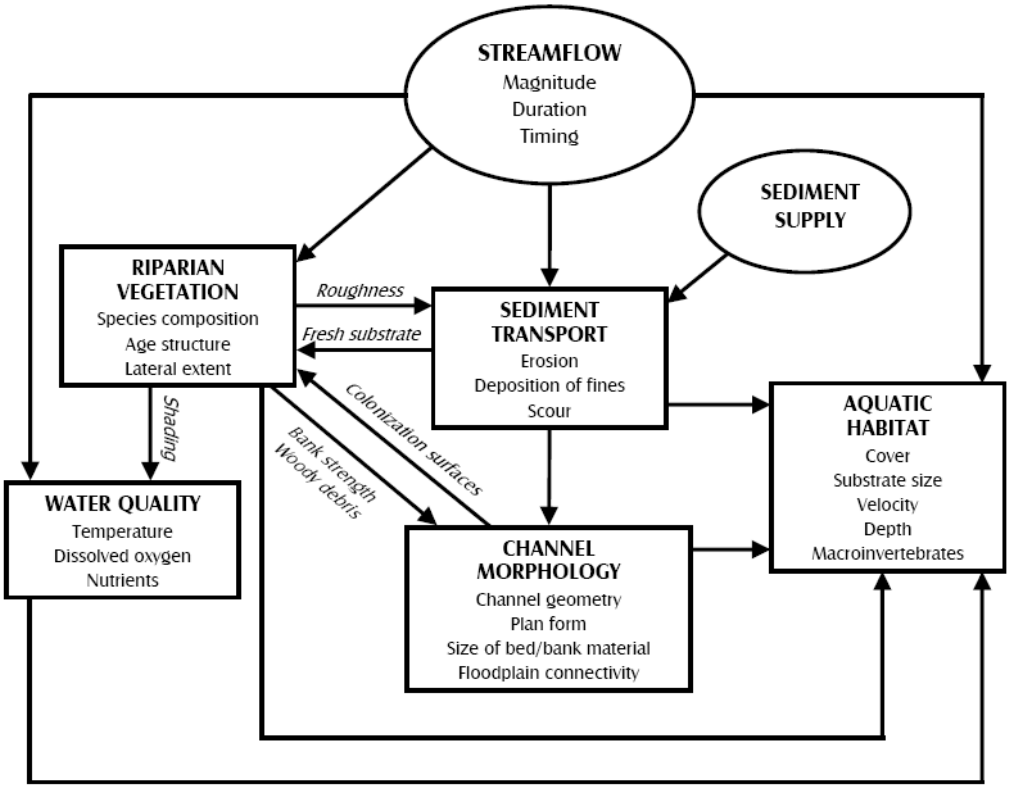
Fluvial Focal Species Summary Report

For the

Sabine/Neches BBEST

Ecological Information to Support Environmental Flow Recommendations



Submitted to:

Sabine/Neches BBEST

Prepared by:

BIO-WEST, Inc.
1812 Central Commerce Court
Round Rock, Texas 78664

August 2009

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1.0 INTRODUCTION

The magnitude, timing, and duration of instream flows play a key role in the functioning of riverine ecosystems. In 2007, the Texas Legislature passed Senate Bill 3, directing the development of environmental flow recommendations for both an instream flow regime and for a complete freshwater inflow regime to protect a "sound ecological environment" and to maintain the productivity, extent, and persistence of key aquatic habitats in the state (SAC 2009).

This document provides a summary of ecological information on focal aquatic and riparian species within the Sabine River and Neches River watersheds to support instream flow recommendations by the Sabine/Neches Basin and Bay Expert Science Team (BBEST). As noted in SAC (2009), flow regimes largely determine the quality and quantity of physical habitat available to aquatic organisms in rivers and streams as well as the physical and chemical conditions of that environment.

The purpose of this report is to summarize information for select focal species regarding:

- Basic life history and ecological information including environmental requirements for reproduction and recruitment into adult populations and habitats used by various life stages
- Spatial and temporal trends in population abundance or biodiversity within the basins (where available)
- Key relationships between flow variation and the ecology of the species at the individual or population level

Selection of focal species was conducted in conjunction with members of the Sabine/Neches BBEST Biology Subcommittee, as described in Section 2.0. In preparing this document, previous reports on environmental flows were reviewed in addition to a large collection of scientific literature on the Sabine and Neches Rivers and associated watersheds. Much of this information was already compiled in three separate locations: 1) a reference library of pertinent documents compiled and provided by the Sabine-Neches BBEST; 2) an extensive list of documents pertaining to the Neches and Angelina Basins provided by Dr. Matthew McBroom and colleagues from Stephen F. Austin State University (SFASU); and 3) the database compiled to support the ongoing FERC relicensing process at Toledo Bend Dam provided by Sabine River Authority (SRA) of Texas. In addition to these sources, an extensive collection of life history information on the selected focal species was also compiled and reviewed. Information regarding the life history, habitat, and flow requirements of several of the focal species was abundant in the literature, whereas data for others was sparse. Regardless, available data on the life history of each focal species is summarized in Section 3.0. Section 4.0 provides a synthesis of ecology-flow relationships from the 18 focal species identified, along with comments on the temporal and spatial distribution of flows critical for each.

Sabine and Neches River Systems

The Sabine River is formed by the junction of Cowleech Fork, Caddo Fork, and South Fork Creeks in southwestern Hunt County. It flows for approximately 555 miles before emptying into Sabine Lake near Orange, Texas. Average annual rainfall within the basin ranges between 37 inches at its source to 50 inches at its mouth. As a result of the abundant rainfall in this portion of the state, the Sabine discharges more water than any other Texas river. Three major reservoirs have been constructed in the Sabine basin. Lake Tawakoni, which sits at the junction of the South and Cowleech Forks, was completed in 1960 and impounds 936,200 are-feet of water used for municipal, industrial, and irrigation supply. Toledo Bend Reservoir, on the Texas-Louisiana border, was completed in 1969 and has a storage capacity of 4,472,900 acre-feet used for electric generation, recreation, and water supply. Lake Fork, located on Lake Fork Creek in the upper basin, was completed in 1980 for municipal and industrial use, and stores 675,819 acre-feet at conservation pool.

The Neches River, begins in eastern Van Zandt County and flows southeast for approximately 416 miles before emptying into Sabine Lake near Port Arthur, Texas. Two major reservoirs are located on the Neches River. Lake Palestine was completed in 1962, and enlarged in 1972. It has a storage capacity of 411,290 acre-feet. B.A. Steinhagen Reservoir, located between Jasper and Woodville, is used for municipal water supply, flood control, and electric generation. The Angelina River joins the Neches just above B.A. Steinhagen, and drains approximately one-third of the basin area. Sam Rayburn Reservoir is located on the Angelina River, and impounds 3,997,600 acre-feet. It is used for electric generation, municipal, industrial, agricultural, and recreational purposes.

Together the Sabine and Neches Rivers drain almost 20,000 square miles in eastern Texas. The diversity of fishes and aquatic organisms found in this region is higher than anywhere else in the state. Additionally, the rivers, streams, and reservoirs of this region serve important functions by providing water supply, electric generation, and recreational opportunities to local residents.

2.0 FOCAL SPECIES SELECTION

Eighteen riverine focal species were chosen to support environmental flow recommendations of the Sabine/Neches BBEST. The list of focal species was collectively identified by BIO-WEST, Inc. (BIO-WEST) in collaboration and coordination with the Biological Subcommittee of the Sabine/Neches BBEST, and state agency personnel involved in the Texas Instream Flow Program (TIFP). Expert opinion on freshwater mussels was also gathered from researchers at local universities (Dr. Neil Ford, UT-Tyler; and Charles Randklev, University of North Texas). Focal species included 14 fish taxa, two mussel species, and two floodplain vegetation species (**Table 1**). An attempt was made to select species which are known to be flow-dependent, use a variety of habitats, and exhibit multiple feeding and reproductive strategies. Special consideration was given to species of conservation concern, and economically important sport fish.

Table 1. Focal riverine/floodplain species identified to support instream flow recommendations of the Sabine/Neches BBEST.

Common Name	Scientific Name	River/Trib/Floodplain	Unique Distribution in Texas	Species of concern	Sportfish
paddlefish	*Polyodon spathula*	River	Limited	Yes	--
white bass	*Morone chrysops*	River	--	--	Yes
flathead catfish	*Pylodictis olivaris*	River	--	--	Yes
shoal chub	*Macrhybopsis hyostoma*	River	--	--	--
emerald shiner	*Notropis atherinoides*	River	--	--	--
blue sucker	*Cycleptus elongatus*	River	Limited	Yes	--
spotted bass	*Micropterus punctulatus*	River/Tributary	--	--	Yes
dusky darter	*Percina sciera*	River/Tributary	--	--	--
sabine shiner	*Notropis sabinae*	River/Tributary	East TX	--	--
harlequin darter	*Etheostoma histrio*	Tributary	East TX	--	--
freckled madtom	*Noturus nocturnus*	Tributary	East TX	--	--
ironcolor shiner	*Notropis chalybaeus*	Tributary	East TX	Yes	--
alligator gar	*Atractosteus spatula*	River/Floodplain	--	Yes	--
black/ white crappie	*Pomoxis spp.*	River/Floodplain	--	--	Yes
Texas pigtoe	*Fusconaia askewi*	River/Tributary	East TX	Yes	--
pistolgrip	*Tritogonia verrucosa*	River/Tributary	--	--	--
overcup oak	*Quercus lyrata*	Floodplain	East TX	--	--
water tupelo	*Nyssa aquatica*	Floodplain	East TX	--	--

3.0 SABINE-NECHES ESTUARY FOCAL SPECIES

3.1 Fish Focal Species

The magnitude, timing, and duration of flows are critical to the life cycle of riverine fishes. Such species have evolved to natural patterns in flow variability which creates a diversity of hydraulic habitats. Habitat diversity is important given that some species use shallow backwater habitats during larval and juvenile periods, but may shift to occupying swift riffles and runs as adults. Timing of flow related events are also important. Some species require high flows during spawning periods to initiate upstream migration to spawning areas. In contrast, low flows which provide ample amounts of backwater habitats may be important during certain time periods for successful recruitment and growth of juvenile fishes.

This section describes the life histories of the 18 focal species listed above (see Section 2.0), and attempts to elucidate any relationships between the ecology and these species and the magnitude and timing of flow events.

3.1.1 Paddlefish (*Polyodon spathula*)

Paddlefish *Polyodon spathula* were historically distributed throughout the Mississippi River drainage as far north and east as the Great Lakes Region and westward in the Missouri River system to Montana. They also occur in several large Gulf Coast drainages adjacent to the Mississippi, including the Trinity, San Jacinto, Neches, Angelina, Sabine, Cypress, Sulphur, and Red River drainages of eastern Texas. Paddlefish numbers have declined throughout their range over the last century due to overexploitation, river channelization, and reservoir construction which can submerge spawning grounds and block migration routes. In Texas, the species was extirpated from the San Jacinto River by the 1950's, and population declines had been observed in other drainages. As a result, TPWD classified the species as endangered in 1977 (Betsill 1999). The Sabine and Neches Rivers once supported commercial fisheries for paddlefish. However, now paddlefish populations are thought to be limited to the Neches River below B.A. Steinhagen reservoir (Pitman 1991), and an artificially supplemented population in Toledo Bend Reservoir.

Paddlefish typically inhabit deep slow-moving habitats within large rivers (>40 m wide, average depth >1 m) and reservoirs during the majority of the year (non-spawning period). In large rivers, they are often found in deep areas (2-15 m) of backwaters and lakes connected to the main channel which provide current velocity refuges and better feeding opportunities (higher zooplankton densities) (Southall and Hubert 1984). In natural riverine corridors, these habitats are created by deep eddies behind gravel bars and connected oxbows. In modified rivers, paddlefish often use deep eddies and backwaters created by wing dams and other man-made structures (Southall and Hubert 1984). Main channel habitats are typically used only for moving between feeding areas, and for upstream spawning migrations in the spring. Self-sustaining paddlefish populations also occur within some large reservoirs where there is

sufficient spawning habitat found in the inflowing rivers (Paukery and Fisher 2001). Within these reservoirs, paddlefish prefer open water over shallow littoral areas.

Large adult paddlefish can obtain weights up to 90 kg (≈200 lbs.) and lengths up to 213 cm (84 in) (Pitman 1991). Females typically weigh more than males due to their large ovaries which can make up 18% of total body weight when ripe (Pitman 1991). Growth is typically fast within the first four years of life and slows thereafter. In northern waters, paddlefish can live up to 55 years, but maximum age is approximately 14 years in southern climates such as Texas (Paukery and Fisher 2001). Paddlefish require 7-10 years to reach sexual maturity (Betsill 1999, Winemiller et al. 2005). Paddlefish feed by filtering zooplankton from the water using their finely spaced gill rakers. The long rostrum is thought to function as a sensory organ to aid in locating food, and as a stabilizer to keep the fish from nosediving due to the drag caused by water entering the open mouth during feeding (Pitman 1991).

Paddlefish spawn over relatively deep silt-free gravel bars of at least one meter deep (>4 m optimum) in rivers from February through June at water temperatures of 12-21˚C (Southall and Hubert 1984, O'Keefe et al. 2007). Fish may migrate long distances upstream (up to 240 km) to reach specific spawning locations. Although annual changes in photoperiod and temperature initiate spawning migrations, actual spawning activity is associated with a sharp rise in flow (Pitman 1991). Spawning often takes place over gravel bars which were previously dry under lower flow conditions. If water levels drop, eggs and larvae can become stranded, and spawning is ceased until another rise in river level occurs (Purkett 1961). Females release demersal eggs into the upper water column which are externally fertilized by nearby males. Fertilized eggs become adhesive and stick to the substrate. Paddlefish eggs hatch in 7-12 days depending on temperature, and larvae drift downstream as they develop. Although male paddlefish are capable of annual spawning, evidence suggests that wild female paddlefish require two or more years to develop mature ova, and therefore, do not spawn every year (Pitman 1991).

Paddlefish are a large-river fish whose life cycle is strongly tied to instream flows. They require deep, slow-moving, zooplankton-rich backwaters, oxbow lakes, or reservoirs in which to feed throughout the year (Pitman 1991). Perhaps even more important from an instream flow perspective are high flow pulses during early spring months (February through April) to stimulate upstream migration and spawning. These pulses should be of significant duration (at least 7 days) to ensure successful hatching of eggs and dispersal of larvae before water levels recede.

3.1.2 Blue sucker (*Cycleptus elongatus*)

The blue sucker *Cycleptus elongatus* is a large long-lived catostomid native to large rivers of the Mississippi Basin and occurring sporadically in some Western Gulf Slope drainages of Texas including the Sabine and Neches. Commercial harvest records from the Mississippi River indicate that the blue sucker was once abundant; however, they are now considered rare throughout most of their range and have been listed as threatened or endangered by several agencies including TPWD which has listed the species as threatened. Considerable taxonomic changes have occurred within the genus *Cycleptus* in recent years and have resulted in designation of two new species. The southeastern blue sucker *Cycleptus*

meridionalis, was recently recognized from Eastern Gulf Slope drainages of Alabama, Mississippi, and Louisiana (Burr and Mayden 1999). Additionally, recent molecular analyses have confirmed earlier suspicions based on morphology (Burr and Mayden 1999) that the Rio Grande *Cycleptus* population is divergent from *C. elongatus* populations in the Mississippi River and other western Gulf Slope drainages. A formal species description is currently being conducted for this species (Bessert 2006). Populations in the Sabine and Neches drainages are still recognized as *C. elongatus*.

Due to their specific habitat requirements and resulting collection difficulties, blue suckers are not particularly abundant in fish collections from the Sabine and Neches drainages. However, they have recently been confirmed from both the main-stem Sabine River (SRA et al. 2007) and the main-stem Neches (University of Texas at Tyler collections). Blue suckers are a large river fish which are rarely captured in smaller tributaries. However, blue sucker spawning was observed in the lower portions of Onion Creek, a tributary of the lower Colorado River (BIO-WEST 2007).

Blue suckers occupy deep high-velocity habitats over firm substrates (Rupprecht and Jahn 1980, Vokoun et al. 2003). In the lower Colorado River, Texas, adult blue suckers were fairly common in deep fast rapids over gravel, cobble, boulder, and bedrock substrates. They were most abundant at depths of 2.6 to 4.6 feet, and velocities of 2.0 to 3.3 ft/s. Blue suckers were the only species collected in abundance in these deep high-velocity rapids (BIO-WEST 2008).

Blue suckers feed on aquatic insects, mainly Trichopteran and Dipteran larvae and pupae, and can grow to over 800 mm (31.5 in) total length (Peterson et al. 1999, Moss et al. 1983, Cowley and Sublette 1987). Age and growth studies of blue suckers have yielded varying results. Previous studies using scale-aging have suggested that blue suckers live anywhere from 9-22 years (Rupprecht and Jahn 1980, Moss et al. 1983, Vokoun et al. 2003, Morey and Berry 2003). However, scale-aging is thought to underestimate the ages of large fish, and examination of annuli on opercular bones has suggested that southeastern blue suckers reach ages of 30+ years (Peterson et al. 1999, Burr and Mayden 1999).

Reproduction occurs in the early to late spring at temperatures of 12 – 20˚C when blue suckers migrate to spawning riffles where their adhesive eggs are deposited on the substrate (Moss et al. 1983, Semmens 1985, Peterson et al. 2000, Boschung and Mayden 2003, Mettee et al. 2003, Vokoun et al. 2003). In some instances, these migrations can cover distances of over 150 miles (BIO-WEST 2007). However, in the lower Colorado River, Texas, long migrations were only observed under extremely high-flow conditions. In years with low spring flows, blue suckers spawned on or near their "home riffles" (BIO-WEST 2007).

In the Colorado River study, seven different blue sucker spawning locations were identified from spring 2005 through spring 2007. Spawning was documented at three of these locations in more than one year. Spawning was typically witnessed from early February through early March at temperatures of 14-15˚C. Spawning blue suckers were most common in habitats ranging from 1.0 -2.3 ft deep with velocities of 1.0 – 3.0 ft/s and cobble or bedrock substrates (BIO-WEST 2007). Eggs hatch in about 6 days (Semmens 1985). Although larval blue suckers have occasionally been collected in backwater and off-channel

habitats (Fisher and Willis 2000, Adams et al. 2006), information on the ecology of young blue suckers is limited because juveniles are rarely collected (Morey and Berry 2003).

Due to the specific habitat affinities of blue suckers, sufficient instream flow to maintain at least some deep high-velocity rapids throughout the year is important. However, perhaps even more important, especially given recruitment concerns in some areas, is maintenance of adequate amounts of spawning habitat in early spring months. High flow pulses in the January through March period may also be important to stimulate upstream migrations. However, the complex relationship between flow, migration, and recruitment is poorly understood.

3.1.3 Shoal chub (*Macrhybopsis hyostoma*)

The species complex previously known as the speckled chub *Macrhybopsis aestivalis* is distributed throughout the Mississippi River drainage and Gulf Coastal drainages from the Choctawhatchee River in Florida to the Rio San Fernando in Mexico. However, recent analysis has split this complex into five species west of the Mississippi River (Eisenhour 2004). As a result of this work, the species inhabiting the Sabine and Neches Rivers has been reclassified as the shoal chub *M. hyostoma.* Since all *Macrohybopsis* species have similar life histories and exhibit similar habitat utilization, life history information presented herein refers to several species within the *Macrhybopsis* complex.

Shoal chubs are absent from collections taken in large tributaries to the Neches such as Village Creek (Moriarty and Winemiller 1997) and Pine Island Bayou (Kleinsasser and Linam 1987), demonstrating their affinity for large river habitats. They are present in collections from the main-stem Sabine River below Toledo Bend dam (SRA et al. 2007), and are thought to be common in the upper Sabine basin (Bart 2008). They are presumed present in the main-stem portions of the Neches River. However, they were not captured at three sites from the lower Neches sampled between 1999 and 2001 (USGS 2003). Recent analysis by Bonner and Runyan (2007) and Bart (2007) suggest that populations of shoal chubs in the lower Sabine River have declined in recent decades, although neither speculated on the causes of such declines.

M. hyostoma inhabit moderate to swift flowing waters over sandy and gravelly substrates in large rivers. In the Arkansas River basin, they prefer current velocities of 0.2 – 0.4 m/s and substrate composed of 60-90% pea-sized gravel with moderate compaction (Luttrell et al. 2002). In the Brazos River, *M. hyostoma* were most common in waist to chest deep water during the day, and seemed to move shallower at night (C.S. Williams, personal communication).

Shoal chubs are a small, short-lived species which reaches a maximum size of 76 mm over a life span of 1-2 years (Eisenhour 2004, Starrett 1951). They are a benthic-oriented fish which use taste buds located on their head, body, fins, and small barbels to feed along the bottom of turbid rivers. Food consists of aquatic insects, small crustaceans, and some plant material (Robison and Buchanan 1988). Bonner and Wilde (2002) found that *M. tetranema* from the Canadian River were well adapted to feeding under turbid conditions, and that prey consumption was not significantly affected by turbidities ranging from 0-4000

NTU. In the Brazos River, shoal chubs spawn from late March/early April through September/November depending on flows (Williams, in press). Nonadhesive semibouyant eggs (Platania and Altenbach 1998) develop as they drift in the current, hatching in about 25-28 hours (Robison and Buchanan 1988). Spawning is thought to occur during high flow pulses which prevent eggs and weak-swimming larvae from settling to the bottom and becoming buried (Bonner and Wilde 2000). Depending on channel morphology and current velocity, eggs can drift long distances (estimates up to 144 km) before hatching, and therefore, long stretches of unimpounded river may be required for successful reproduction (Platania and Altenbach 1998). A significant reduction in mean annual discharge, reduced frequency of flood events, and decreased turbidity levels seem to have extirpated *M. tetranema* in the Canadian River below Lake Meredith (Bonner and Wilde 2000, Bonner and Wilde 2002).

Studies suggest that perhaps the most important factor influencing *Macrhybopis* populations is maintenance of long stretches of uninterrupted flow in large turbid river systems to allow sufficient time for drifting eggs and larvae to mature. From a timing and magnitude standpoint, pulse events during typically low flow summer months may be important in initiating reproduction. Although maintenance of sand and pea-gravel run habitats are important for the species, this habitat is likely maintained in the Sabine and Neches mainstems under all but extremely low flow conditions.

3.1.4 Sabine shiner (*Notropis sabinae*)

Sabine shiners are a small stream-dwelling cyprinid fish with a somewhat limited distribution found in Gulf Coast drainages from the San Jacinto River of Texas east to the Big Black and Yazoo drainages of Mississippi. A disjunct population also occurs in three rivers in northern Arkansas and southern Missouri (Robison and Buchanan 1988, Williams and Bonner 2006). In the Sabine and Neches drainages, this species is relatively abundant in tributary and main-river habitats, and is known to be common in Village Creek (Neches drainage; Moriarty and Winemiller 1997), Banita Creek and LaNana Bayou (Angelina drainage; Williams and Bonner 2006), and the lower Sabine River (Bart 2008, Bonner and Runyan 2007). Evidently, the species is also found in low numbers in Toledo Bend Reservoir (LDWF). Although Sabine shiners are considered rare or uncommon due to their restricted range in Louisiana, Mississippi, and Arkansas (Williams and Bonner 2007), recent analysis by Bart (2008) suggests that *N. sabinae* populations may actually be increasing in the lower Sabine River and its tributaries.

Sabine shiners are typically collected in shallow flowing water, and are relatively uncommon in backwater and pool areas. Within these shallow runs and riffles there is often segregation among adult and juvenile fish, with juveniles occupying the shallower silty areas along the edges while adults occupy sandier areas near mid-channel. Although not exclusively found over sand, Sabine shiners do exhibit an affinity for sandy substrates (Moriarty and Winemiller 1997, Williams and Bonner 2006, Williams and Bonner 2007).

Sabine shiners obtain a maximum size of approximately 64 mm over a life span of 2.5 years. They are a benthic-oriented species which feeds primarily on detritus and benthic invertebrates (mainly Diptera and Ephemeroptera larvae). Depending on location, spawning occurs from April or May through September

or October. Individual females may spawn multiple cohorts of eggs over this extended spawning season. Eggs and larvae are thought to drift downstream as they develop, resulting in higher abundance of age-0 fish in downstream locations. As a result, structures which disrupt stream connectivity and block upstream migrations of juvenile and adult fish may negatively impact this species (Heins 1981, Williams and Bonner 2006, Williams and Bonner 2007).

Maintenance of stream connectivity and natural flow regimes are both identified as important for the conservation of this species (Williams and Bonner 2007). However, no detailed analysis of the instream flow requirements of this species has been conducted. This species does not inhabit particularly deep or swift habitats, and therefore, high flows are likely not crucial from a habitat perspective. However, maintenance of some flow over shallow sandy runs is important to provide habitat for this species, especially during the summer reproductive season. Also, periodic flushing-flows may be important to prevent siltation of sandy run habitats. High flow pulses in winter and spring may serve as stimulus for upstream migration of adults to counteract downstream dispersal of eggs and larvae.

3.1.5 Alligator gar (*Atractosteus spatula*)

The alligator gar is a large, long-lived, predatory fish which ranges throughout the Mississippi River system, as well as coastal rivers of the Gulf of Mexico from Florida to northern Mexico (Buckmeier 2008). In Texas, they occur in coastal streams from the Red River to the Rio Grande (Hubbs et al. 2008). Alligator gar are found in large rivers, reservoirs, oxbow lakes, and coastal bays and estuaries. They are documented in recent collections from the lower mainstem Sabine and Neches Rivers, as well as Village Creek (USGS 2003, SRA et al. 2007). They are most likely absent from smaller tributary streams. Alligator gar populations are declining throughout their range mostly due to fishing pressure and habitat alteration. Along with declining populations a shift in size structure to smaller individuals has been seen. As a result, management regulations have recently been implemented in several Southeastern states, including Texas. TPWD is currently conducting several studies to learn more about Texas alligator gar populations (Ferrara 2001, Buckmeier 2008). The species is listed as vulnerable by the American Fisheries Society.

Alligator gar can grow up to 10ft in length and reach weights exceeding 300 pounds over a life span of 30-50 years (Buckmeier 2008). They are opportunistic predators which feed on fish, invertebrates, and even birds. Due to their large size, adult alligator gar often prey on relatively large fish (>20 cm)(Goodyear 1967). Alligator gar spawn from April to June during spring flooding of vegetated backwater areas, oxbow lakes, and bottomland swamps (Buckmeier 2008, Ferrara 2001). They are non-guarding open substrate spawners with adhesive eggs that stick to plant materials. Larval fish have special cement glands that allow them to attach to plants or other substrate while developing (Simon 1999). Data from the Brazos River suggests that juveniles tend to remain in off-channel spawning areas such as oxbow lakes, while large adults are typically captured from the main river (Robertson et al. 2008). Alligator gar mature at 950-1400 mm total length which takes 10-14 years (Buckmeier 2008, Ferrara 2001).

Preferred habitat of alligator gar is deep slow-moving pools within the main channel of large rivers, as well as backwater areas and oxbow lakes. High flow pulses in spring months are critical to provide a connection between off-channel oxbows and the main river. Such floodplain habitats provide optimum conditions for recruitment and growth of juveniles.

3.1.6 White/black crappie (*Pomoxis annularis* and *P. nigromaculatus*)

Crappie are a widespread and popular gamefish that naturally occurred throughout the central and eastern U.S. including portions of Texas. Due to their popularity as a gamefish, and their high regard as a food fish, crappie have been introduced in ponds and reservoirs throughout North America, greatly expanding their range. There are two species of crappie – white crappie (*Pomoxis annularis*) and black crappie (*Pomoxis nigromaculatus*). White crappie can tolerate higher turbidity, and are thus more widespread in Texas. However, given that the two species occupy similar habitats, and exhibit similar life history traits, they will be treated collectively for this summary. In the Sabine and Neches drainages, both species are common to abundant in oxbow lakes, river mainstems, and lower reaches of major tributaries (Evans and Noble 1979, Kleinsasser and Linam 1987, Linam and Kleinsasser 1987, McCarty 1987, Moriarty and Winemiller 1997, Robbins 2000, USGS 2003, SRA et al. 2007), but are typically absent from smaller tributary streams (Rogers 1994, Kelly 1999, Geeslin 2001). Crappie populations also provide an extremely popular fishery in reservoirs within the Sabine and Neches basins (**Table 2**).

Crappie are most numerous in deep slow-moving pools, backwaters, oxbow lakes, and reservoirs, where they are often associated with submerged trees, brush, aquatic vegetation, or other cover (Edwards et al. 1982). They are typically absent from swift flowing portions of rivers and streams. Adults often suspend in deep water during most of the year, but move shallow to spawn during spring months.

Table 2. Ratings of crappie fisheries in each of the major reservoirs in the Sabine and Neches River basins based on information posted on the TPWD website.

River Basin	Reservoir	Rating	Comments
Angelina	Sam Rayburn	EXCELLENT	Year-round fishery
Neches	B.A. Steinhagen	GOOD	Best in spring
Neches	Palestine	GOOD	-
Sabine	Tawakoni	FAIR	Limited habitat
Sabine	Fork	EXCELLENT	-
Sabine	Toledo Bend	GOOD	Year-round fishery

Crappie have an average life span of 7-9 years, and can attain weights of 2.7 kg (≈6 lbs.). Young crappie (<150 mm) feed mainly on zooplankton and aquatic insects, whereas larger fish (>150 mm) are mostly piscivorous and feed mainly on small gizzard shad (*Dorosoma cepedianum*) (Edwards et al. 1982, Reid 1949, Muoneke et al. 1992). Where there is limited forage in the way of small fish, crappie >150mm will remain planktivorous and insectivorous, resulting in reduced growth rates and stunting of the population (Muoneke et al 1992, Obrien et al 1984). Spawning begins when the water temperature reaches 13-14°C, but peaks at 14-16˚C (Edwards et al 1982, Obrien et al 1984). This usually occurs from February through April in Texas. Males construct and guard nests in calm shallow water protected from the prevailing wind. Nests can be found over a variety of substrates, but usually occur in close proximity to some type of cover such as brush piles, submerged vegetation, or tree roots. Eggs are often attached to submerged vegetation and are closely guarded until hatching.

In the Brazos River system, white crappie were abundant in oxbows, but were uncommon in the main river channel. Periodic flooding resulted in a net movement of fish biomass from the oxbows to the river channel (Winemiller et al. 2004). Results suggest that oxbow lakes provide optimum conditions for crappie recruitment and growth, but that periodic connections with the main river were important for dispersal. Additionally, limited crappie populations in the river provide a source stock for recolonization of oxbows which occasionally dry up during extended periods without significant pulse events. Therefore, periodic connections between river and floodplain habitats such as oxbow lakes are an important component in sustaining crappie populations in lowland rivers.

3.1.7 White bass (*Morone chrysops*)

The white bass is a "true bass" (Family Moronidae) which is widespread throughout the Ohio and Mississippi River drainages of the central U.S. and has been widely introduced into reservoirs throughout Texas (Hubbs et al. 2008). In the Sabine and Neches drainages, white bass are mainly found in the major reservoirs and river segments immediately above or below these reservoirs, where they are a popular gamefish. They were present in low abundance from recent collections in the lower Neches River below B.A. Steinhagen (USGS 2003), and were absent from recent collections in the lower Sabine River (SRA et al. 2007). Table 3-2 summarizes information on white bass fisheries in each of the major reservoirs in the Sabine and Neches basins taken from the TPWD website.

White bass are habitat generalists typically encountered in large schools roaming pelagic areas of reservoirs. They are site feeders (Greene 1962) which feed heavily on shad (*Dorosoma* spp.) and other small fishes (Bonn 1952, Voigtlander and Wissing 1974, Van Den Avyle et al. 1983, Matthews et al. 1992). White bass typically live 4-5 years and reach lengths of 17-20 inches and weights approaching 5 lbs.

Table 3. Ratings of white bass fisheries from each of the major reservoirs in the Sabine and Neches River basins based on data posted on the TPWD website.

River Basin	Reservoir	Rating	Comments
Angelina	Sam Rayburn	FAIR	Limited numbers, but good fishing in spring
Neches	B.A. Steinhagen	POOR	Low numbers, fishery limited to early spring
Neches	Palestine	EXCELLENT	Popular in spring up Neches and Kickapoo Creek
Sabine	Tawakoni	EXCELLENT	Vital to local economy
Sabine	Fork	-	-
Sabine	Toledo Bend	FAIR	-

In spring (February through May in Texas), when water temperature is approximately 12-20˚C, white bass migrate from deep water reservoir habitats into flowing rivers and streams, where they spawn. Males typically migrate before females. Spawning takes place in relatively shallow flowing water (<3 m) and demersal adhesive eggs slowly sink to the bottom. Larvae hatch in 2-3 days (Mettee et al. 1996). If flowing streams are not accessible, white bass will also spawn on wind-swept points within a reservoir (Bonn 1952). In Texas, fishing the white bass "run" is extremely popular during spring months as large numbers of fish migrate into shallow confined areas of rivers and streams to spawn.

White bass are mainly reservoir inhabitants which are not directly affected by instream flows the majority of the year. However, maintaining at least moderate amounts of inflow into reservoirs during spring spawning season is important to provide adequate spawning habitat, and to provide fishing opportunities for anglers. This is especially important in popular fisheries such as Lake Palestine and Lake Tawakoni given the impact to local economies. Additionally, years of high spring inflows, and resulting high water levels in reservoirs, often leads to increased recruitment and growth of young white bass (Bonn 1952).

3.1.8 Dusky darter (*Percina sciera*)

The dusky darter is a fairly widespread species found in moderate to large streams within the Mississippi River drainage as far north as Illinois, Indiana, and Ohio, and in Gulf of Mexico drainages from the Mobile Bay system in Alabama south and west to the Guadalupe River in Texas (Page 1983). In the Sabine and Neches basin it is relatively common, and has been documented by several collections (Evans and Noble 1979, Kleinsasser and Linam 1987, Rogers 1994, Moriarty and Winemiller 1997, Kelly 1999, USGS 2003). Dusky darters are most common in the larger tributary streams, but are also found in main river collections (SRA et al. 2007). They are typically absent from collections in small headwater streams within the Sabine and Neches basins (Geeslin 2001).

Dusky darters usually occur in swift riffles and raceways over gravel substrates, and are often associated with some type of cover such as boulders or logs (Miller and Robison 1973). In the lower Colorado

River, Texas, dusky darters exhibited similar habitat utilization to other riffle-associated species such as: Texas logperch *Percina carbonaria*, suckermouth minnow *Phenacobius mirabilis*, orangethroat darter *Etheostoma spectabile*, central stoneroller *Campostoma anomalum*, burrhead/shoal chub *Macrhybopsis spp.*, and juvenile channel catfish *Ictalurus punctatus* (BIO-WEST 2008).

The dusky darter is a fairly large darter which obtains a maximum size of approximately 110 mm over a life span of 3-4 years. They feed on a variety of aquatic insects including midge, black fly, caddisfly, and mayfly larvae (Page 1983, Robison and Buchanan 1988), and are classified as a benthic invertivore by Goldstein and Simon (1999). In the Colorado River near Austin, Texas, dusky darters spawn from February through June over gravelly substrates (Hubbs 1961). They are classified as a brood hider and lithophil meaning they hide their eggs with benthic larvae beneath stones but do not take care of them. Eggs and larvae of dusky darters can survive at temperatures between 22 and 27˚C (Hubbs 1961).

Due to the preference of this species for shallow riffle habitat, dusky darters are considered flow-sensitive. Specific flow-related requirements of *P. sciera* include maintenance of sufficient flow to create swift riffle habitat over gravel bars and other areas of channel constriction. Maintenance of such habitat may be especially critical during the February through June spawning season.

3.1.9 Flathead catfish (*Pylodictis olivaris*)

The flathead catfish is a large ictalurid native to medium to large rivers and reservoirs in the Mississippi, Ohio, and Missouri River drainages as well as Western Gulf Slope drainages of Texas. They have also been introduced into several locations outside their native distribution, where the resulting impact on native fishes is a major concern (Brown et al. 2005). In the Sabine and Neches Rivers, flathead catfish likely inhabit all the major reservoirs, larger tributaries (Moriarty and Winemiller 1997, Kleinsasser and Linam 1987), and main river segments (SRA et al. 2007).

Habitat utilization by flathead catfish changes considerably as they grow. Young-of-the-year are typically found in swift shallow riffles with large cobble and boulder substrates. Juveniles of 4-16 inches in length distribute among a variety of habitats at intermediate depths. Adults are solitary and are most common in deeper areas around slow to moderate current and heavy cover such as rocks, riprap, or submerged logs (Minkley and Deacon 1959).

Flathead catfish can obtain weights approaching 100 pounds over a life span of approximately 20 years. Sexual maturity is reached in approximately 2-5 years at sizes of 15-20 inches. Small young-of-the-year catfish feed almost exclusively on aquatic insects. However, fish and crayfish gradually become more important in the diet as the fish grow. Large solitary adults feed mainly at night on live fish and crayfish. They are sedentary nocturnal predators which exhibit little movement (Vokoun and Rabeni 2006) and feed by ambushing prey. Spawning occurs in June and July when parents construct a nest in a natural cavity in the bank or under a boulder. Females may lay up to 100,000 eggs which are guarded by the male. After hatching the young catfish form a compact school for a few days before dispersing (Minkley and Deacon 1959, Robison and Buchanan 1988, Munger et al. 1994, Mettee et al. 1996).

Due to their large size and high regard as a food fish, flathead catfish are a popular sport fish in Texas. In fact, they were the preferred sport fish of 30,000 Texas anglers in a 1987 survey (Munger et al. 1994).

Flathead catfish do not make large migrations, and adults have relatively general habitat requirements. The most important flow-related requirement of flathead catfish is maintenance of riffle habitat for juveniles. This is especially important during post-spawn summer and fall months.

3.1.10 Emerald shiner (*Notropis atherinoides*)

Emerald shiners are widely distributed along the Gulf Coast from Alabama to Texas, northward throughout the Mississippi River drainage to the Great Lakes Region, and well into Canada. The Sabine and Neches Rivers are near the southwestern edge of the species' range, which is the Trinity River basin. In the Neches drainage, *N. atherinoides* is commonly collected from the mainstem river as well as the larger tributary streams (Rogers 1994, Kelly 1999, USGS 2003). Although the species has never been particularly abundant in the lower Sabine River, it is absent from recent collection there (SRA et al. 2007), and was categorized as having a declining population trend by Bonner and Runyan (2007). However, Bart (2007) did not list the species as declining in the lower Sabine River.

Most life history information on emerald shiners has been collected in northern waters. In Canada, emerald shiners are found in large schools near the surface water of large open lakes and rivers (Campell and MacCrimmon 1970). They are considered a pelagic species that only occasionally moves inshore. They can live three to five years in northern waters, and reach sizes of 127 mm total length. In northern lakes and reservoirs, they feed mainly on zooplankton, but also consume insects, algae, and plant material. In northern climates, they reach sexual maturity after approximately one year, and broadcast spawn from June through August at temperatures of 20-23˚C over deep water (2-6 m). The nonadhesive eggs sink to the bottom and hatch in 24-36 hours (Fuchs 1967, Dillon and Myers 1990). Little life history information exists from southern riverine populations of *N. atherinoides*.

Given limited life history information, instream flow requirements of emerald shiners are speculative at best. In the southern part of their range, emerald shiners occupy large turbid rivers. Maintenance of deep run and pool habitats, especially during the summer spawning season, are likely important to the species.

3.1.11 Spotted bass (*Micropterus punctulatus*)

The spotted bass (*Micropterus punctulatus*) is native to the Mississippi and Ohio River basins extending east to northwestern Florida (Hubbs et al. 1991). In Texas, spotted bass occur in the eastern half of the state from the Guadalupe River basin northeastward to the Red River basin. In the Sabine and Neches, they are common to widespread in tributaries, and main river habitats, and have adapted well to reservoirs (SRA et al. 2007, ANS 2006, Kelly 1999, Moriarty and Winemiller 1997, Rogers 1994, Kleinsasser and Linam 1987, Evans and Noble 1979). Due to their preference for flowing waters, they are typically not captured in area oxbow lakes (Robbins 2000, Cowan 1998, McCarty 1987) where the closely related largemouth bass (*M. salmoides*) predominates. Based on analysis of lower Sabine River fish community

data from 1948 through 2006, Bonner and Runyan (2007) suggested that abundance of spotted bass has increased in recent years.

Spotted bass are most abundant in clear to moderately turbid streams and rivers. Although the young can be captured from a variety of shallow water habitats, adult spotted bass typically inhabit deep runs and pools. They are more common in current than the largemouth bass, which prefers slow pools and other lentic areas (Ryan et al. 1970). Like most centrarchids, spotted bass use aquatic vegetation, submerged logs, rocks, and riprap for cover. They hide in thick cover and ambush prey, which includes aquatic insects, crayfish, and fish (Mettee et al. 1996, Robison and Buchanan 1988, Ryan et al. 1970, Smith and Page 1969).

Although typically smaller than largemouth bass, spotted bass obtain a maximum reported size of approximately 610 mm (24") total length over a life span of up to 11 years. Spawning occurs from April to June with water temperatures ranging from 17.2-25.6°C. Males make shallow nests, usually over rock or gravel substrate and guard them until the fry hatch (Hassan-Williams and Bonner 2009, Simon 1999, Mettee et al. 1996). Spotted bass often select dense cover such as brush piles for nesting (Vogele and Rainwater 1975). Eggs hatch in 2-5 days, and larvae remain in the nest area for 4-8 days (Hassan-Williams and Bonner 2009).

Spotted bass are a popular gamefish in Texas streams and reservoirs which can be very sporting on light tackle. However, they do not have particularly flow-sensitive life history or habitat requirements. Spotted bass often inhabit deep backwaters or eddies beneath swift flowing riffles and runs, where they move into current briefly to feed, and then move back into slack-water refuges. Maintenance of sufficient flow to maintain such habitat complexity is important.

3.1.12 Harlequin darter (*Etheostoma histrio*)

E. histrio is sporadically collected in tributaries of the lower Mississippi River drainage and adjacent Gulf Coastal drainages primarily below the Fall Line (Tsai 1968). In Texas, it occurs in small detritus-laden tributaries of the Cypress, Sabine, Neches, and Trinity Basins (Hubbs et al. 2008). Within collections from the Sabine and Neches drainages, harlequin darters are never particularly abundant, but are somewhat common in tributary streams (Rogers 1994, Moriarty and Winemiller 1997, Kelly 1999) and occasionally collected from main river habitats (SRA et al. 2007).

Although Tsai (1968) described harlequin darters as inhabitants of swift gravel riffles, Hubbs and Pigg (1972) suggested that harlequin darters in Texas and Oklahoma were typically captured over sand and detritus substrates. Although they were found near riffles that contained gravel, Hubbs and Pigg (1972) suggested they were typically captured along the edges over sand and logs and near fallen brush. They have also been described as inhabiting deep riffle detritus habitats (Page 1983).

Harlequin darters obtain a maximum size of 64 mm and live approximately 4 years. Their diet consists of benthic invertebrates such as midge, blackfly, caddisfly, and mayfly larvae. They spawn in February and

March (Hubbs 1985) by attaching adhesive eggs to submerged plants or detritus. Growth is relatively rapid, and females are able to spawn in their first year (Kuhajda and Warren 1989).

Instream flow-related habitat requirements of harlequin darters include maintenance of sufficient flow in tributaries to maintain riffle habitat and acceptable water quality conditions. These fish are not known to migrate long distances, although some authors have suggested that they may move to deep water of large streams during the breeding season (Kuhajda and Warren 1989).

3.1.13 Freckled madtom (*Noturus nocturnus*)

The freckled madtom is a small ictalurid distributed throughout the Mississippi basin as well as Gulf Coast drainages from Alabama to Texas. In Texas, they are limited to the eastern half of the state, from the Brazos River east and north to the Red River drainage (Hubbs et al. 1991). Within the Sabine and Neches Rivers, freckled madtoms are relatively common in collections from small to large tributaries, oxbow lakes, and main channel habitats (Evans and Noble 1979, Rogers 1994, Moriarty and Winemiller 1997, Cowan 1998, Kelly 1999, Robbins 2000, Geeslin 2001, USGS 2003, SRA et al. 2007).

Freckled madtoms are typically found in gravel riffles, often in association with complex habitat features such as sticks, root masses, submerged logs, and undercut banks. Individuals often find shelter in beverage cans (Hassan-Williams and Bonner 2009).

Freckled madtoms reach a maximum size of 138 mm standard length over a life span of 4.5 years. They feed on aquatic insect larvae such as mayflies, caddisflies, and midges. They are hole nesters (Simon 1999) which spawn in nests built in holes or cavities along the bank or under submerged debris in areas with some current and depths of 10-15 cm. Spawning takes place from May through July (Hassan-Williams and Bonner 2009).

Freckled madtoms are considered a fluvial specialist with a narrow range of habitat use. They are dependent upon complex riffle habitats. Sufficient instream flow to maintain riffle habitats in tributaries is important for maintaining populations of this species.

3.1.14 Ironcolor shiner (*Notropis chalybaeus*)

Ironcolor shiners are found in acidic lowland streams in parts of the Mississippi River drainage, and along the Gulf and Atlantic coasts from Texas to New York (Robison and Buchanan 1984, Mettee et al. 1996). In Texas, this species is reported as occurring only in far eastern and northeastern Texas streams from the Sabine River to the Red River, except for an isolated population in the headwaters of the San Marcos River (Hubbs et al. 2008). However, Kelly (1999) reported collecting three specimens from Piney Creek, a tributary of the Neches River within the Davy Crockett National Forest. Piney Creek was considered the least impacted stream in the ecoregion, and was the only stream out of ten sampled that contained *N. chalybaeus*. No specific information regarding collections of this species within the Sabine River drainage was located. Hubbs et al. (2008) listed *N. chalybaeus* as a species of "special concern", and it is considered "rare" in the Rare, Threatened, and Endangered Species of Texas Database maintained by TPWD.

Ironcolor shiners are often found in pools with moderate to sluggish current over substrates of sand, mud, silt, or detritus. It is usually associated with aquatic vegetation (Robison 1977). They obtain a maximum size of approximately 53 mm standard length over a life span of about two years. Ironcolor shiners are invertivore (Goldstein and Simon 1999) site feeders which feed on aquatic and terrestrial insects, small crustaceans, and filamentous algae. They spawn from March or April through September or October in Florida (Hassan-Williams and Bonner 2009). Adhesive demersal eggs are broadcast over sluggish pools with sand substrates (Robison and Buchanan 1988).

This species is most likely limited to small, swampy, low-gradient tributary streams within the Sabine and Neches basins and probably only uses mainstem habitats for occasional dispersion. Most of these smaller tributaries are unregulated and, excluding any with wastewater discharges or intense urbanization within the watershed, likely exhibit relatively natural flow regimes. Reproduction and recruitment by this species are probably not strongly affected by pulse flows, and it is speculated that low flows during summer months could potentially enhance recruitment by preventing disturbance of eggs and larvae (Winemiller et al. 2005). As a result of this species life history, watershed management practices which address urbanization, timber harvest, etc. may be more important than instream flow recommendations for preserving this species.

3.2 Freshwater Mussel Focal Species

Freshwater mussels of the family Unionidae occur worldwide. However, North America harbors the greatest number and diversity of these organisms, with nearly 300 species documented (≈51 species known from Texas). However, the combined effects of overharvesting, habitat alteration, and invasive species have made freshwater mussels one of the most endangered groups of organisms in North America (Morales et al. 2006, Howells et al. 1996).

Freshwater mussels are sessile long-lived organisms (30-100 yrs.) exhibiting complex life cycles. They are filter feeders which filter plankton, algae, and detritus from the water as it is circulated via incurrent and excurrent siphons. They are capable of limited movement by extending their muscular "foot" and dragging themselves through or along the substrate. However, dispersal is accomplished mainly through their unique reproductive strategy. To reproduce, males discharge sperm directly into the water. Sperm are inhaled by females during normal feeding and respiration. Fertilization of eggs takes place in brood pouches attached to the gills of the female. Fertilized eggs develop inside the female mussel into a larval stage known as the glochidium. Some individuals may retain glochidia for months, while others release them as soon after they develop. Microscopic glochidia are ultimately released into the water, where they drift in the current, and eventually attach to the fins or gills of fish. Parasitic glochidia may stay attached to fish for anywhere from 7 to 193 days, depending on environmental conditions and species involved. Juvenile mussels, which are often similar in size to glochidia but contain adult structures, then release from fish tissue and drop to the substrate. Juveniles evidently live buried in the substrate until they become sexually mature, when they migrate to the sediment surface. Adults typically remain partially

buried, with their incurrent and excurrent siphons exposed to allow for feeding and respiration (Strayer 2008, Morales et al. 2006, Howells et al. 1996).

Mussels exhibit an extremely patchy distribution within the aquatic landscape. They often occur in spatially-limited, dense, multi-species aggregations within a river, whereas they are absent or uncommon from other similar areas. Locations of mussel beds do not seem strongly linked to depth and velocity, since these conditions change with flow rate. Recent studies suggest that mussel beds typically occur in specific areas characterized by low shear-stress even under extremely high-flow conditions. The stable substrates in these areas allow the relatively immobile mussels to persist even under extremely high flow conditions which scour the substrate in other areas (Strayer 2008, Morales et al. 2006, Strayer 1999, Howells et al. 1996).

Two species of mussels [Texas pigtoe (*Fusconaia askewi*) and pistolgrip (*Tritogonia verrucosa*)] were identified for inclusion in the focal species list based on conversations with researchers who had conducted mussel surveys in the Sabine and Neches basins (Dr. Neil Ford, UT-Tyler; and Charles Randklev, UNT). Available life history and habitat information for these two species is summarized below.

3.2.1 Texas pigtoe (*Fusconaia askewi*)

The Texas pigtoe (*Fusconaia askewi*) has been reported from the Brazos, Neches, Sabine, and San Jacinto Rivers of Texas. It was listed as a species of concern by the TPWD Texas Wildlife Action Plan in 2005. Recent surveys in the Sabine and Neches basins confirm that the species is present to abundant in Village Creek and the Sabine River (Bennett 2007, Bordelon and Harrel 2004).

Texas pigtoe reaches a size of approximately 70mm in length (Howells et al. 1996). Although little information is published on habitat, based on conversations with experts, they are typically found in areas of relatively stable substrate such as coarse sand, gravel, or cobble. They were collected in the Sabine River in mixed mud, sand, and fine gravel in protected areas associated with fallen trees or other structures. The small, spineless, elongate-D shaped glochidia were present in specimens found in the Sabine River in July. No reports of host fish have been made for this species (Howells et al. 1996).

3.2.2 Pistolgrip (*Tritogonia verrucosa*)

In Texas, the pistolgrip (*Tritogonio verrucosa*) occurs from the San Antonio River drainage to the north and east. In the Sabine and Neches drainages, it is relatively widespread and has recently been reported from B.A. Steinhagen Reservoir, Village Creek, Sandy Creek, Attoyac Bayou, the Angelina River, the Sabine River, and the Neches River (Bennett 2007, Bordelon and Harrel 2004, Howells et al. 2000, Howells et al. 1996). Although relatively common in the Sabine and Neches drainages, this species is relatively uncommon in other Texas drainages (Howells et al. 1996).

Pistolgrips are reported to at least 170mm shell length in Texas (Howells et al. 1996). They are typically found in oxygen-rich riffles and runs. Although they are considered to be most abundant on stable substrates, they have been reported from a variety of substrates including rock, hard mud, and silt.

Regardless of substrate, they are often buried deeply. Pistolgrips are thought to have a short-term summer spawning season with spawning reported from April through August (Howells et al. 1996). The smallest sexually mature individual identified is an Age-6 female which was 59 mm in shell length. Glochidia are small and smoothly rounded (Howells et al. 1996).

Pistolgrips can produce gem-quality pearls, and therefore, they were heavily harvested in the Caddo Lake area during an early 1900's pearl rush. However, it is not sought after by modern Texas pearlers. Although they were used in the early 1900's by the shell button industry and the cultured pearl industry, they were never significantly harvested in Texas for this purpose (Howells et al. 1996).

3.3 Floodplain Plant Focal Species

Bottomland hardwood forests are the most common type of riverine forested wetlands on the upper coast of Texas and into Louisiana. They are found on the floodplains of rivers and streams where the floodplain soils are constantly renewed by continual sedimentation. The larger rivers of the wet upper coast, such as the Sabine, Neches, Trinity, and Brazos Rivers, have broad floodplains that support extensive forested wetlands.

Overbank river flooding is the primary source of water for forested wetlands. Flooding of these areas along the Sabine and Neches rivers occurs most years from January through April – May and the flooding persists for at least several weeks at a time (USGS, http://waterdata.usgs.gov). Only large rivers have large enough watersheds to maintain this kind of flooding. Most bottomland hardwood forests have flooding periods that range from a few weeks to several months.

Bottomland hardwood forests in the Sabine and Neches watersheds are dominated by willow oak, water oak, overcup oak, cherrybark oak, laurel oak, green ash, red maple, black willow, water tupelo and others. These forests are considered important habitats for birds, reptiles, and small mammals. Many river fishes such as gars, suckers, minnows, shiners, catfishes, bass, and sunfishes use flooded bottomland forests and swamps as feeding and breeding habitats. Bottomland hardwood forests also play an important role in controlling soil erosion, maintaining water quality, recharging groundwater, and preventing flood damage.

Overcup oak (*Quercus lyrata*) and water tupelo (*Nyssa aquatica*) are two tree species commonly found in bottomland hardwood forests of the southeast (**Figure 1**). Both the overcup oak and water tupelo are regarded as tolerant of inundation from overland and flood waters (Coder 1994), and their presence, health and persistence provide an indication of the overall health of bottomland hardwood forests in the Sabine-Neches watershed.

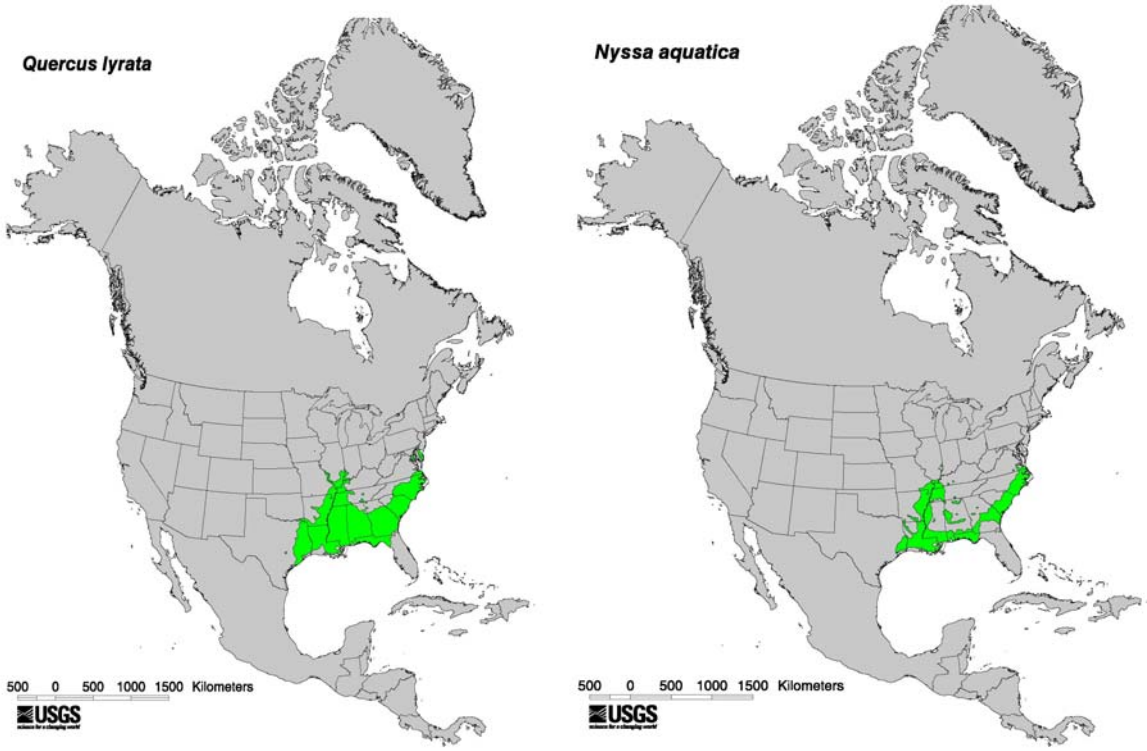

Figure 1. Nationwide distribution map for overcup oak (left) and water tupelo (right) (USGS 1999).

3.3.1 Overcup oak (*Quercus lyrata*)

Overcup oak (*Quercus lyrata*), also called swamp oak, swamp white oak, and water white oak, is a deciduous tree that grows up to 20 meters tall. It is tolerant of flooding (Broadfoot & Williston 1973, McLeod 2000) and grows slowly on poorly drained flood plains and swamp lands of the Southeastern United States (Burns & Honkala 1990). It may take 30 years before overcup oak produces acorns, and seed dispersal is dependent on overflow or flood waters. The acorns are eaten by water fowl and many small mammals. The trees also serve as habitat for wildlife. The quality of the lumber varies greatly and is cut and sold as white oak.

Overcup oak inhabits the wetter sites in bottom lands of the Coastal Plain from Delaware and Maryland south to Georgia and northwestern Florida; west to eastern Texas (**Figure 1**). It grows northward in the Mississippi Valley to southeastern Oklahoma, southeastern Missouri, southern Illinois, southwestern Indiana, and western Kentucky (Little 1979).

Overcup oak is found on poorly drained, alluvial, clayey soils mainly on southern river flood plains (Parker 1949, Putnam 1960). It is most prevalent on low lying clay or silty clay flats in first bottoms and terraces of the larger streams (Sternitzke & Putnam 1956). It is also quite common on the edges of swamps, sloughs, and bayous; in poorly drained depressions or sink holes on ridges; and in shallow

swamps and sloughs (Putnam & Bull 1932). Since it leafs out a month or more later than most species; it is better able to endure submergence from late spring floods. In tests, overcup oak survived continuous flooding for at least two growing seasons. In spite of its natural occurrence on wet clay sites, overcup oak grows best on sites with better drainage and soil texture.

The species most commonly associated with overcup oak are water hickory (*Carya aquatica*), willow oak (*Quercus phellos*), Nuttall oak (*Quercus nuttallii*), American elm (*Ulmus americana*), cedar elm (*Ulmus crassifolia*), green ash (*Fraxinus pennsylvanica*), sugarberry (*Celtis laevigata*), waterlocust (*Gleditsia aquatica*), common persimmon (*Diospyros uirginiana*), and red maple (*Acer rubrum*).

Trees begin bearing seeds about 25 years of age and good seed crops are produced every 3 to 4 years. Late freezes, after the flower buds have started to open have been known to kill the flowers and thus destroy the seed crop. In flooded areas, the acorns remain dormant over winter and germinate in the spring after the surface waters recede, making overcup acorns one of the few of the white oaks that do not germinate until spring. Seed production is prolific, but many young seedlings are killed by inundation during the first few growing seasons. Seeds germinate readily either in the open or in the shade, but because of the tree's relative intolerance to shade, reproduction persists only in openings (Putnam et al. 1960). Seedlings and stump sprouts generally are also able to grow through all competing ground cover except heavy peppervine, which sometimes develops into a tangled mat (Morris 1965). Successful regeneration depends on complete absence of fire and adequate seed.

Growth of seedlings is rated as average but varies greatly with site, soil, and the kind and degree of competition (Putnam et al. 1960). Eight-year-old trees on a backwater flat were found to vary from 12 to 75 mm (0.5 to 3 in) in diameter at groundline (Morris 1965). There is little information on early height growth, but based on site index figures, height growth might be expected to average 45 to 60 cm (18 to 24 in) per year (Broadfoot 1976).

Overcup oak develops a shallow, saucer-shaped root system. The heavy clay soils and wet sites where overcup oak typically grows restrict root development to relatively shallow depths. Although the seedlings initially produce taproots, these are replaced by a lateral root system. The root system of one large tree consisted of many small branching roots with no large main roots.

Seeds germinate profusely beneath complete canopy, but the seedlings invariably succumb or at least die back to the root collar within 3 years unless released. Many stands of overcup oak owe their development to tolerance of early season flooding that kills off earlier flushing species. It is frequently a lack of competition rather than an affinity for the backwater sites that allows this species to dominate.

3.3.2 Water tupelo (*Nyssa aquatica*)

Water tupelo *(Nyssa aquatica),* also called cottongum, sourgum, swamp tupelo, tupelo-gum, and water-gum, is a large, long-lived deciduous tree that grows in southern swamps and flood plains where its root system is periodically under water. It has a swollen base that tapers to a long, clear bole and often occurs

in pure stands. A good mature tree will produce commercial timber used for furniture and crates. Many kinds of wildlife eat the fruits and it is a favored honey tree.

Water tupelo trees are also one of the most flood tolerant tree species, surviving continuous flooding for as much as two growing seasons. It commonly grows in areas with saturated soils. Its shallow root system is characterized by morphological and physiological adaptations that are essential to survival and growth. Water tupelo are highly resistant to flooding and can also withstand moderate siltation (Broadfoot & Williston 1973).

Water tupelo grows throughout the Coastal Plain from southeastern Virginia to southern Georgia, and from northwestern Florida along the Gulf of Mexico to eastern Texas (**Figure 1**). It extends up the Mississippi River Valley as far north as the southern tip of Illinois.

Within its range, water tupelo grows in low, wet flats or sloughs and in deep swamps. Some of the better sites are in the sloughs and swamps along Coastal Plain rivers of the Southeast, such as the Roanoke and Santee, and in the large swamps of southwestern Louisiana and southeastern Texas. Surface water may disappear from water tupelo areas in midsummer or fall, but on better sites soil moisture remains at or near saturation level throughout most of the growing season.

In sloughs and moving water, water tupelo usually occupies the deeper parts and with bald cypress along the margins, while in deep, stagnant water the two species occupy much the same depths. Species associated with water tupelo throughout its range are black willow *(Salix nigra),* swamp cottonwood *(Populus heterophylla),* red maple *(Acer rubrum),* waterlocust *(Gleditsia aquatica),* overcup oak *(Quercus lyrata),* water oak *(Q. nigra),* water hickory *(Carya aquatica),* green and pumpkin ash *(Fraxinus pennsylvanica* and *F. profunda),* and sweetgum *(Liquidambar styraciflua).* Swamp tupelo *(Nyssa sylvatica* var. *biflora),* bald cypress *(Taxodium distichum),* and redbay *(Persea borbonia)* are the most common associates in the Southeast.

Water tupelo trees in forested wetland areas initiate seed production in about 30 years or when they are about 20 cm (8 in) in diameter. Stump sprouts have also been documented to seed (Priester 1979). Large trees normally produce a large crop each year with the seeds dispersed mainly by water. Intact fruit will float, and seeds submerged continuously in water may remain viable for over a year.

Seeds do not germinate until water recedes, which may be midway to late in the growing season. Partially shaded, wet, poorly-drained soils provide the best seedbed. Seeds buried 1 to 3 cm (0.5 to 1 in) deep in the soil have a better chance to germinate and establish seedlings than seeds on the soil surface. Seedling survival and development are best in full sunlight and in soil with a pH below 7.0 (Burns & Honkala 1990). Seedling development is better in saturated than in well-drained soil, in moving and aerated rather than stagnant water, and in shallow rather than deep water (Dickson & Broyer 1972, Dickson et al. 1965, Harms 1973). Provided their tops are above water, seedlings can generally survive continuous flooding even if it persists throughout the growing season. Water tupelo is able to survive where it is too wet for most other species because of anatomical and physiological adaptations such as roots that allow for oxidation of the rhizosphere and controlled anaerobic respiration (Hook & Brown

1973). Water tupelo is also a prolific stump sprouter, with the survival and development of sprouts related to timing and duration of flooding.

Water tupelo is classed as intolerant of shade. It will survive codominant but not overtopping competition, and develops in pure, dense stands. Fire is a major enemy of water tupelo. It scorches the thin bark, allowing entrance of rot-causing fungi. The forest tent caterpillar *(Malacosoma disstria)* is a serious enemy in some years and locations, although defoliated trees seldom die but may have lower growth rates than unattacked trees. A foliar disease, *Mycosphaerella nyssaecola,* has caused premature defoliation, but impact has been negligible.

4.0 SUMMARY

Due to the complex nature of river-floodplain ecosystems, the magnitude and timing of certain flow events may benefit some species, while negatively impacting others. For example, Rypel et al. (2009) found that growth of freshwater mussels in southeastern floodplain ecosystems was negatively correlated with annual flood pulse count and May and June discharge, while growth of bald cypress (*Taxodium distichum*) in the same systems was positively correlated with May and June discharge. This demonstrates how seasonal and interannual variability in streamflow can promote diversity in these complex ecosystems. Given the confounding interactions of flow-ecology relationships, synthesizing such relationships for 18 focal species is rather complex. To organize this task, the following section is divided into three sub-sections: 1) effects of flow on habitat of focal species; 2) effects of flow on migration and reproduction; and 3) effects of flow on food supply.

Habitat

A common approach of instream flow studies in diverse warmwater rivers is to combine species which exhibit similar habitat utilization into habitat guilds (BIO-WEST 2008, Austen et al. 1994). This simplifies analysis with the goal of representing the habitat needs at a community level. A recent study on the lower Colorado River, Texas, used a habitat guild approach, and included several of the focal species identified in this report (BIO-WEST 2008). In the Colorado River study, six habitat guilds were identified: Riffles, Shallow Runs, Deep Runs, Shallow Pools/Edge/Backwaters, Deep Pools, and Rapids. Additionally, species specific habitat suitability criteria (HSC) were developed at the lifestage level for spawning blue suckers.

As an example, **Figure 2** and **Figure 3** show the resulting habitat suitability criteria (HSC) for depth and velocity in the Riffles habitat guild. This data was collected and analyzed along with substrate selection for each of the habitat guilds and for spawning blue suckers (BIO-WEST 2008). An example of substrate selection was not provided in this report as it is acknowledged that substrate conditions in the Sabine/Neches system are different from the Colorado River. However, the depth and velocity information for the guilds should be informative for the focal species of the Sabine/Neches. For the Colorado River study, habitat suitability criteria were coupled with a two-dimensional hydrodynamic model at each study site to assess changes in each habitat type relative to discharge (BIO-WEST 2008). **Figure 4** provides an example of the relationship between each habitat type and discharge at the Bastrop study site on the lower Colorado River. Actual discharge values were removed from the figure as they are not applicable to the Sabine/Neches systems.

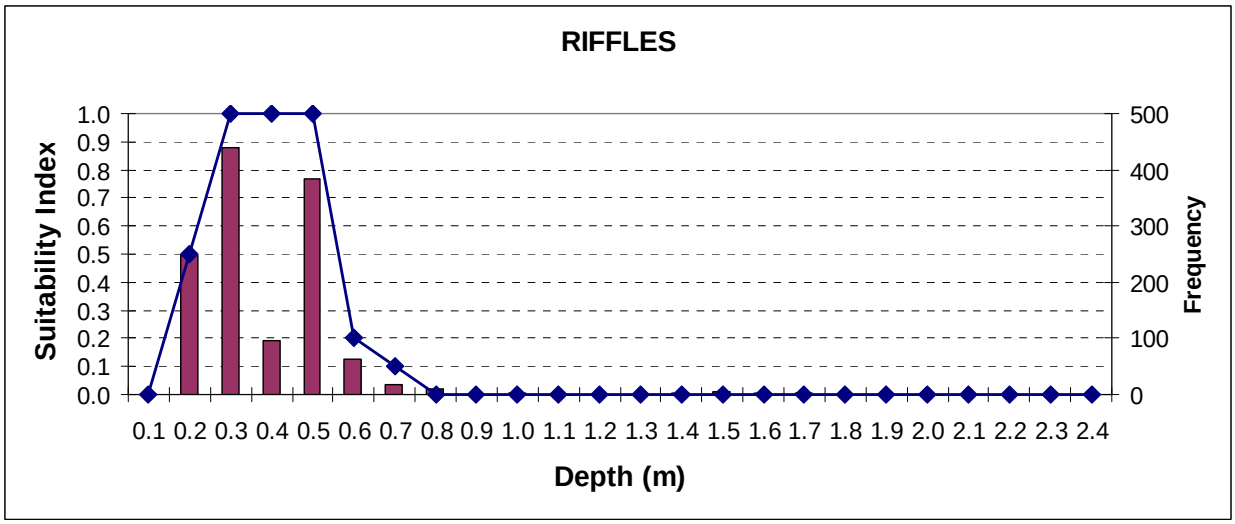

Figure 2. Frequency distribution and depth HSC values for the "Riffles" habitat guild in the lower Colorado River, Texas (BIO-WEST 2008).

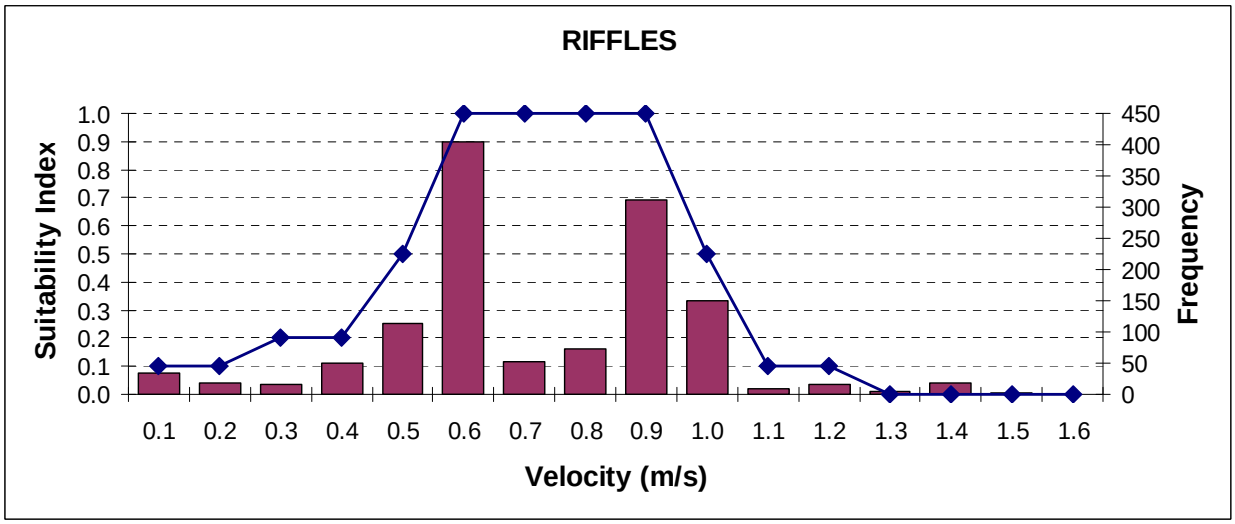

Figure 3. Frequency distribution and velocity HSC values for the "Riffles" habitat guild in the lower Colorado River, Texas (BIO-WEST 2008).

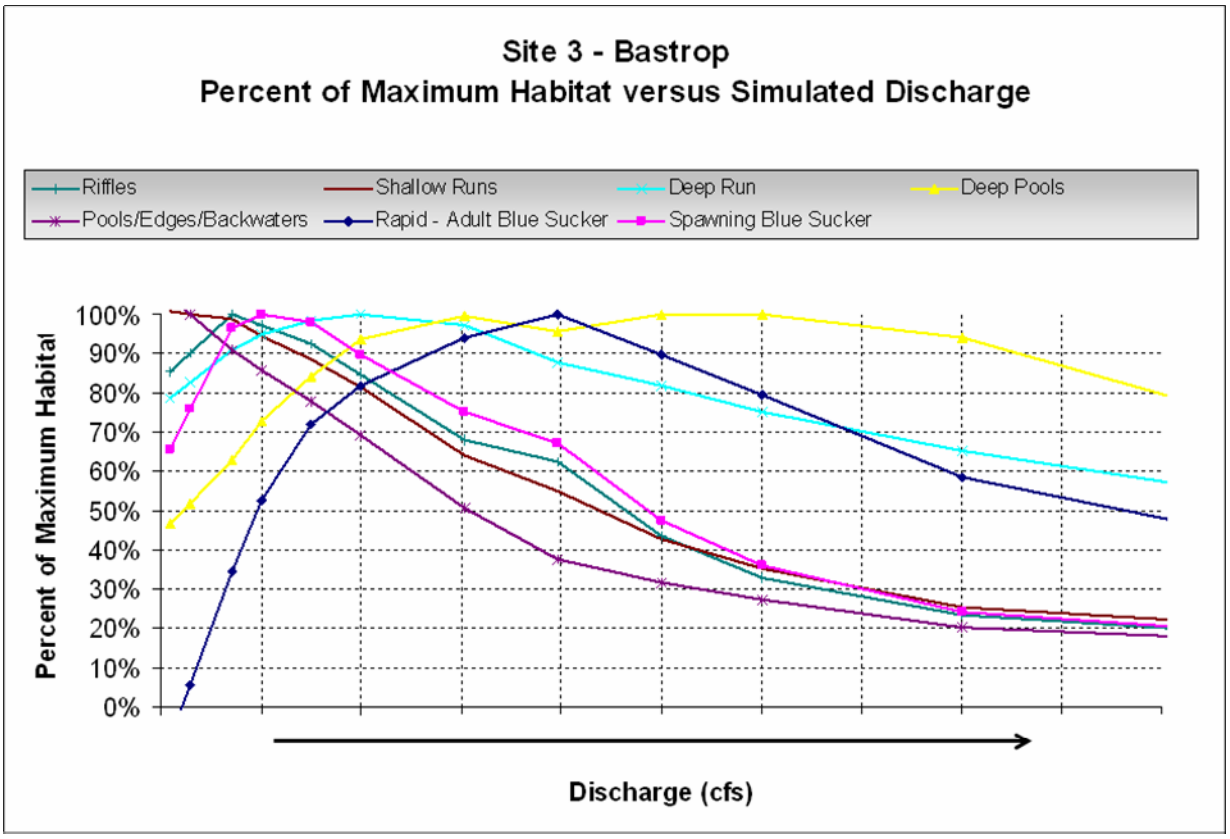

Figure 4. Percent of maximum habitat versus simulated discharge at the Bastrop study site on the lower Colorado River, Texas (BIO-WEST 2008).

Since relationships between discharge and habitat for each guild were recently described on the lower Colorado River, an attempt was made to assign each of the focal species identified in this report, where applicable, to one of the six habitat guilds based on available habitat and life history information. To include floodplain dependent species, which were not assessed in the Colorado River study, a seventh habitat category was added: Floodplain/Oxbow. **Table 4** provides the guild associations for each of the Sabine/Neches focal species. Freshwater mussel species were not included in this analysis since little information is available on their specific habitat preferences relative to depth and velocity.

Table 4. Habitat utilization guilds based on BIO-WEST (2008), and associated Sabine/Neches riverine focal species.

Habitat Guild	Original Colorado River Species	Sabine/Neches River Focal Species
Riffles	*Percina sciera** *Macrhybopsis spp*.* *Etheostoma spectabile* *Percina carbonaria* *Ictalurus punctatus* (juvenile) *Phenacobius mirabilis* *Campostoma anomalum*	*Percina sciera** *Macrhybopsis hyostoma** *Etheostoma histrio* *Noturus nocturnus* *Pylodictis olivaris* (juvenile)
Shallow Runs	*Notropis volucellus* *Cyprinella lutrensis* *Cyprinella venusta* *Pimephales vigilax* *Micropterus treculli* (juvenile)	*Notropis sabinae* *Notropis chalybaeus* *Notropis atherinoides* *Micropterus punctulatus* (juvenile)
Deep Runs	*Pylodictis olivaris** *Ictalurus punctatus* (adult) *Moxostoma congestum* *Micropterus treculli* (adult) *Carpiodes carpio* *Dorosoma cepedianum*	*Pylodictis olivaris* (adult)* *Micropterus punctulatus* (adult)
Shallow Pools/ Backwaters	*Micropterus salmoides* *Lepomis megalotis* *Lepomis macrochirus* *Lepomis cyanellus* *Cichlasoma cyanoguttatum* *Gambusia affinis* *Poecilia latipinna* *Fundulus notatus*	*Pomoxis* spp.
Deep Pools	*Ictiobus bubalus* *Cyprinus carpio*	*Polyodon spathula* *Atractosteus spatula* *Morone chrysops*
Rapids	*Cycleptus elongatus**	*Cycleptus elongatus**
Floodplain/Oxbow		*Atractosteus spatula* *Pomoxis* spp. *Quercus lyrata* *Nyssa aquatica*

* denotes species common to both studies.

Several caveats should be noted when considering habitat utilization and modeling results from the Colorado River study in the current framework. First, professional judgment was involved in assigning Sabine/Neches focal species to pre-determined habitat guilds. However, based on habitat information from the literature as well as previous fish sampling experience, each species fit well into one or more guilds. Additionally, the geomorphology and associated channel characteristics of the Colorado River are different than the Sabine or Neches rivers, which exhibit considerably more lateral floodplain connectivity. Therefore, specific habitat to discharge relationships in the Sabine/Neches system are likely different. Regardless, general trends in habitat associated with increasing discharge typically remain relatively constant across systems. For example, amounts of shallow riffle, shallow run, and instream backwater habitat peak at lower flows, whereas deep run and deep pool habitat peak at somewhat higher flow levels. Deep fast rapids habitat requires higher discharge and peaks at relatively high flows. Despite the caveats mentioned, this information is still useful. Associating Sabine/Neches focal species with the pre-determined habitat guilds, and assessing general trends in habitat availability to discharge relationships for each guild, should provide useful insight in determining important flow components to maintain habitat for focal species as discussed below.

Discharge-habitat trends for the six habitat guilds used in the Colorado River study at the Bastrop study site are evident in **Figure 4**. Shallow water habitat such as riffles, shallow runs, and shallow pools/backwaters peak under relatively low flows, and then decline under high flow situations. In contrast, deeper habitat types such as deep runs and deep pools peak under moderate flows. Rapids, the deepest and fastest habitat type, peaks under even higher flows. The one habitat type not addressed by **Figure 4** is floodplain/oxbow habitat which is primarily connected to the mainstem by overbanking flows. **Figures 5 and 6** are the compilation the six habitat guilds from the Colorado River (Altair study site) along with a hypothetical example of Floodplain/Oxbow habitat. **Figure 5** is specific to in-channel habitat, whereas **Figure 6** is expanded to show potential trends associated with overbanking flows.

A review of **Figure 5** shows the same trends witnessed in **Figure 4**, with shallow pools/backwater habitat and shallow runs experiencing the highest percentage of maximum habitat at the lower flows. Riffle habitat has a peak at slightly higher flows than shallow runs, but exhibits a rapid decline as discharge increases. Deep run habitat peaks next with Deep Pool and Rapids habitat peaking at considerably higher flows. Even during an in-channel condition, some floodplain/oxbow connectivity is anticipated during high flow pulses when various lower tiers of banks are topped. Yet, the amount of floodplain/oxbow habitat is only maximized at much higher flows when overbanking occurs as hypothetically depicted in **Figure 6**. **Figure 6** also highlights the caution of using instream flow models at higher flows in that predicted shallow run and riffle habitat shows increases in habitat as the banks are overtopped. This phenomenon is at best a very temporary habitat condition and thus the reason for typically separating in-channel vs. overbank habitat conditions.

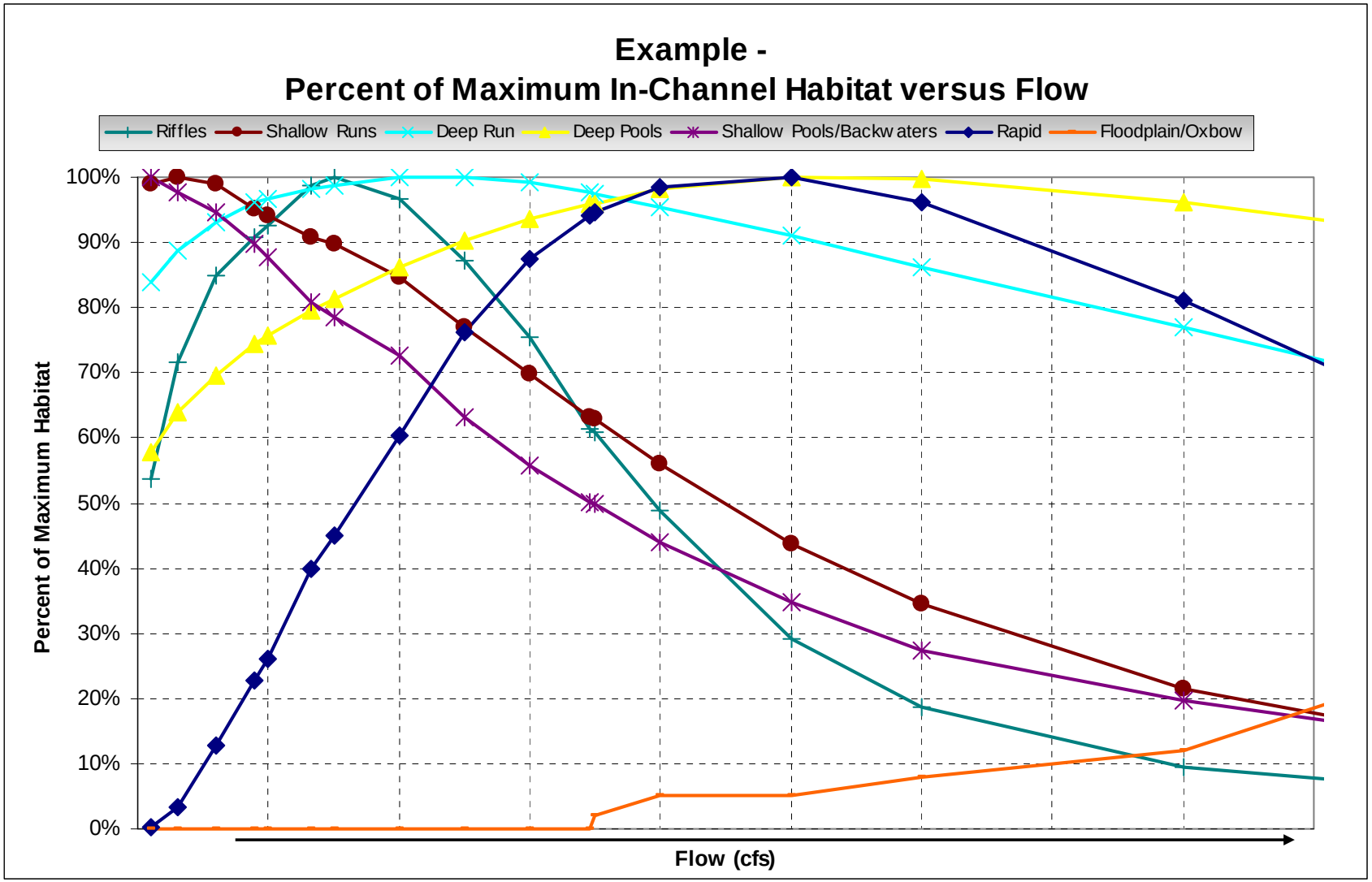

Figure 5. Habitat to discharge relationships for in-channel habitat associated with six habitat guilds on the lower Colorado River, Altair study site, and a theoretical habitat discharge relationship for floodplain/oxbow habitat.

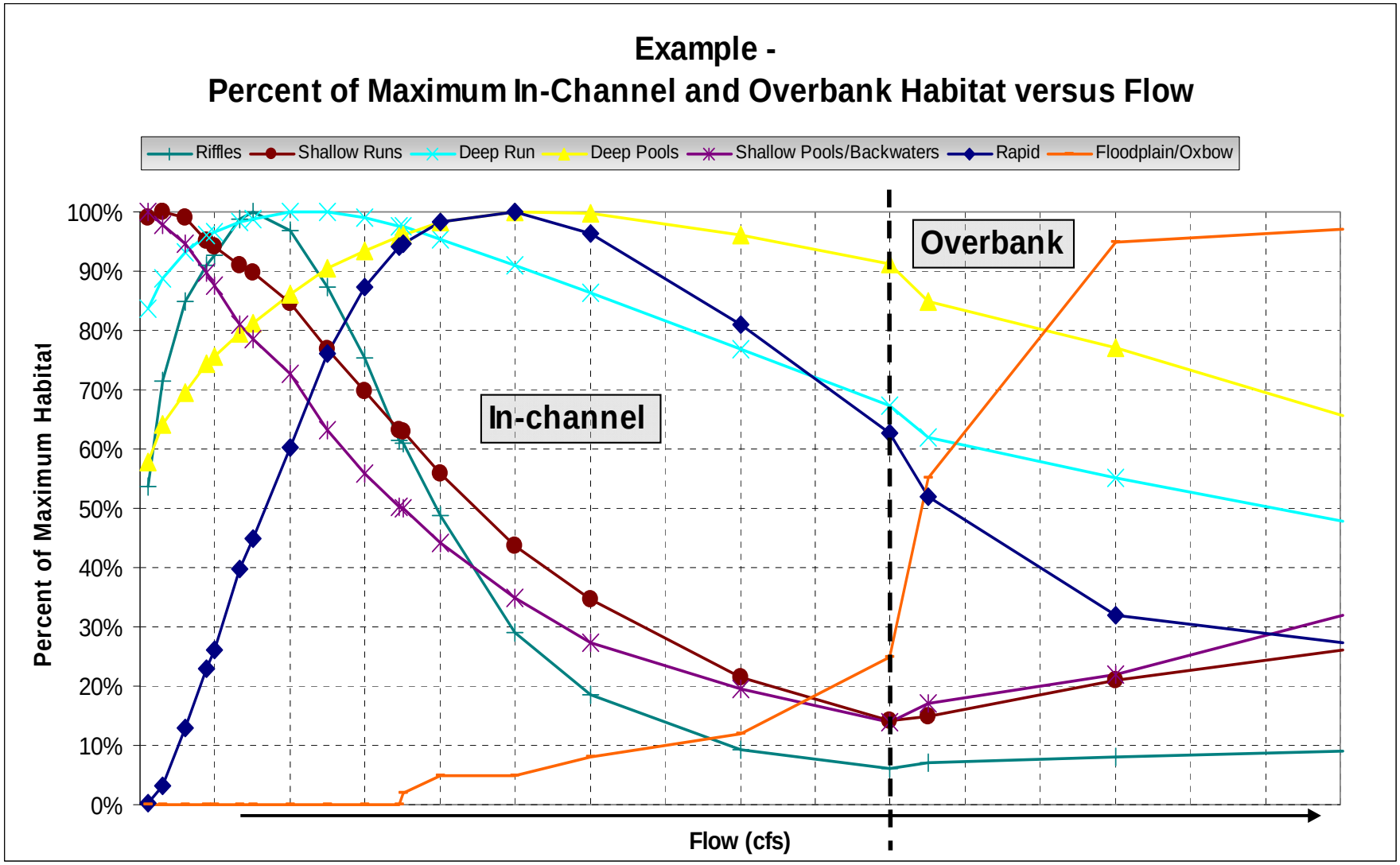

Figure 6. Habitat to discharge relationships associated with in-channel and overbank flows for six habitat guilds on the lower Colorado River, Altair study site, and a theoretical habitat discharge relationship for floodplain/oxbow habitat.

In linking **Figure 6** to **Table 4**, one can start to piece together the effects of changing flow conditions on Sabine/Neches focal species habitat. Lower flow conditions will provide increased habitat conditions for minnow and darter species whereas higher flows provide more habitat for blue suckers, with overbanking flows providing necessary floodplain connectivity for bottomland trees and oxbow habitat for alligator gar and crappie. This highlights the complexity of warmwater fisheries communities and the need for the BBEST to consider a flow regime.

From analysis of **Figures 5 and 6**, it is evident that substantial flow variation is necessary to maintain acceptable habitat conditions for all of the focal species/habitat guilds. Citing the importance of this variation, the SAC (2009) adopted the same framework for instream flow recommendations currently used by the TIFP, which identifies a regime of instream flow components including subsistence flows, base flows, high flow pulses, and overbank flows. Subsistence flows are infrequent periods of low flow that occur during drought, and are aimed mainly at maintaining water quality criteria and thus preventing loss of organisms due to high temperatures or low dissolved oxygen. Base flows provide a range of average flow conditions, not including significant rainfall or runoff events. They are meant to provide adequate amounts of instream habitat to maintain the diversity of biological communities. High flow pulses represent short-duration, high flow events that naturally occur following significant precipitation events. They move accumulated fine silts and sediments, and can provide important life cycle cues for some species. Overbank flows are infrequent extremely high-flow events that exceed channel banks and result in floodplain connectivity. These flows are important in providing sediments and nutrients to riparian areas, and providing habitat and connectivity for floodplain dependent organisms. **Figure 7** provides a conceptual overlay of the four TIFP instream flow components. Recommendations inclusive of all four components should provide a range of habitat for all of the habitat guilds. This biological overlay of habitat guilds per instream flow component may prove helpful to the BBEST in evaluating the hydrological HEFR output.

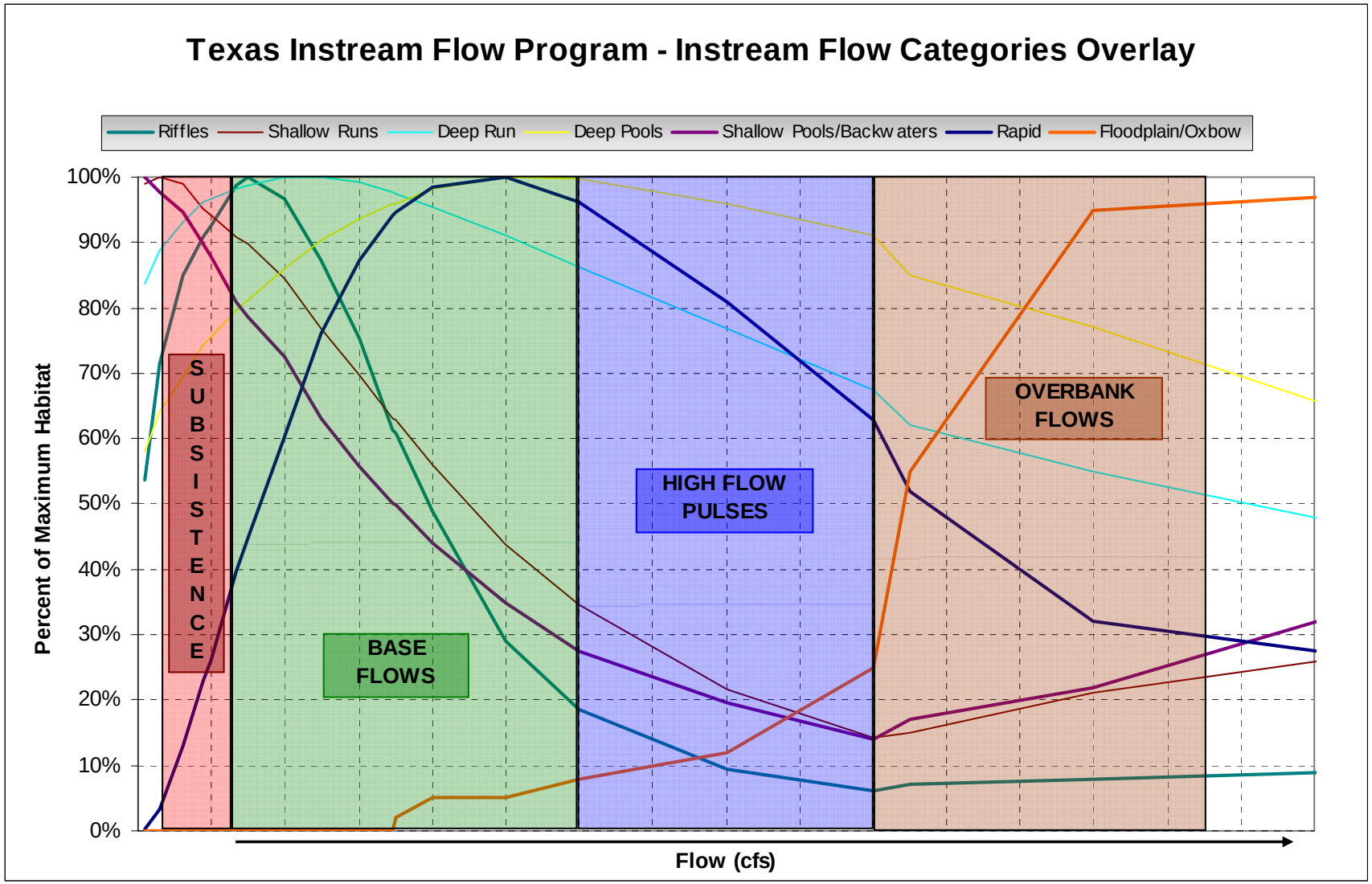

Figure 7. TIFP instream flow categories overlaid on an example of flow-habitat trends.

Migration and Reproduction

In addition to maintaining habitat, timing and magnitude of instream flows are also important reproductive cues for many species, including several of the focal species. For example, reproduction of paddlefish is strongly tied to high spring flows. Paddlefish often make long migrations upstream to specific spawning grounds. However, actual spawning is not initiated until a sharp rise in river level occurs. Additionally, if the river level suddenly drops, eggs and larvae can become stranded. As a result, spring (February through May) high flow pulses of at least 7 days in length may be important to ensure successful recruitment of this species.

Blue suckers have also been known to exhibit large spawning migrations which are evidently initiated by high flows. In the Colorado River, blue suckers spawn in February and March at temperatures of 14-15˚C. Although spawning habitat has been documented, little is known about factors affecting recruitment in this species.

White bass are a popular game fish in reservoirs within the Sabine and Neches Basins, which typically exhibit upstream spawning migrations in spring months. Maintenance of sufficient spring flows in river and tributary segments upstream of reservoirs likely benefits this species, as well as the anglers who seek them.

Shoal chub reproduction is also thought to be linked to high flow pulses which prevent eggs and larvae from settling to the bottom and becoming buried. Shoal chubs spawn multiple clutches of eggs over an extended spawning season lasting from April through September. Therefore, this species may respond favorably to maintenance of occasional high flow pulses during typically low flow summer months.

Overbank floodplain connectivity during spring months appears important for several species. Overcup oak and water tupelo both benefit from spring flooding of floodplain areas and the resulting influx of water and nutrients. However, neither actually germinates until water recedes. Connectivity to floodplain aquatic habitats such as oxbows also seems to benefit alligator gar and crappie. Young of both of these species are typically more common in floodplain pools and oxbows than in the main river channel.

Food Supply

Focal species identified in this study use a variety of feeding strategies. For example, paddlefish are planktivores which filter microscopic organisms from the water column. Freshwater mussels are also filter feeders. Many of the fish species identified feed on aquatic invertebrates (e.g., blue sucker, sabine shiner, shoal chub, dusky darter). Others are invertivores when young, but switch to piscivory as adults (e.g., flathead catfish, white bass, alligator gar, crappie). Maintenance of range of flows and timing of flows which promote healthy plankton and invertebrate communities are important for maintaining an adequate and diverse food supply for the focal species.

In conclusion, there is no question as to the high level of complexity in the fluvial environment of the Sabine/Neches system. As such, we feel that the focal species approach taken by the Sabine/Neches BBEST is appropriate for the SB3 objectives. We also feel that a detailed evaluation of the HEFR output or alternative Flow-regime prescription focusing on the flow-ecology relationships, migration and reproduction patterns, and food supply components for the selected species (as presented above) will prove valuable to the BBEST for the establishment of instream flow recommendations associated with SB3.

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MEMORANDUM

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TO: Sabine and Neches Rivers and Sabine Lake Bay Basin and Bay Expert Science Team Technical Committee

FROM: Jon S. Albright, Freese and Nichols, Inc.

SUBJECT: Analysis of BBEST Stream Gages

DATE: September 8, 2009

The Sabine and Neches Rivers and Sabine Lake Bay Basin and Bay Expert Science Team (BBEST) selected six United States Geological Survey (USGS) stream gages in the Sabine River Basin and six USGS stream gages in the Neches River Basin for hydrologic analyses. These gages will serve as the hydrologic basis for flow regime recommendations developed to satisfy the Senate Bill 3 (SB3) environmental flows process. The BBEST has employed Freese and Nichols, Inc. (FNI) to perform hydrologic analyses at these gage locations. This memorandum describes pertinent data regarding the stream gages, discusses the adequacy of these gages to evaluate flow trends in the Sabine and Neches River Basins and into Sabine Lake, and offers some analyses of flow trends observed at these gages.

Table 1 is a list of the selected gages. Figure 1 shows the locations of the selected gages, as well as other USGS gages in the watershed. In addition to the twelve stream gages, the BBEST also requested hydrologic analyses of the total inflows into Sabine Lake, for a total of thirteen analysis locations. Figure 2 is a graphic showing the period of record for each gage and the year major reservoirs were built upstream from the gage. Reservoir development and hydropower are probably the most significant causes of alterations to streamflow in the two basins. Data used in the analysis were obtained from the USGS website.[1]

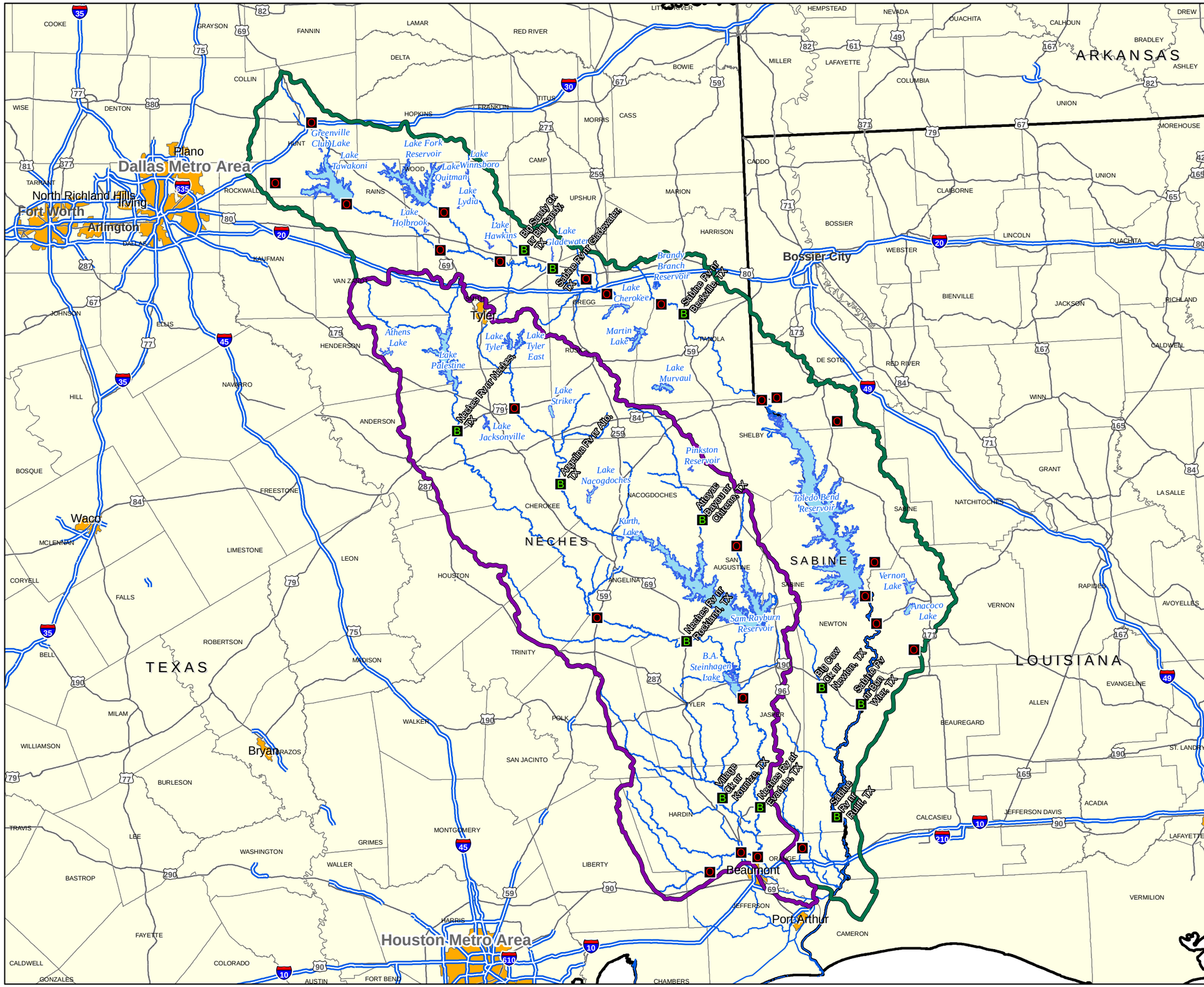
Two gages in each basin have minimally controlled or altered watersheds. In the Sabine Basin, Big Sandy Creek near Big Sandy has one small recreation reservoir, Lake Winnsboro, in its watershed. Big Cow Creek near Newton has very little modification in its watershed and represents nearly natural conditions. In the Neches Basin, Attoyac Bayou near Chireno is downstream from one small water supply reservoir, Lake Pinkston. Village Creek near Kountze has only a few water rights upstream.

[1] United States Geological Survey, Surface Water Daily Data for Texas, available on-line at http://waterdata.usgs.gov/tx/nwis/dv/?referred_module=sw

Table 1: Selected USGS Stream Gages

USGS Gage Name	USGS Gage Number	HUC	County	Datum NGVD 29 (Feet)	Start Date	End Date	# of Full Years of Record	Drainage Area [a] (Sq Mi)	Un-controlled Drainage Area [b] (Sq Mi)	Percent Un-controlled [b]
SABINE BASIN										
Big Sandy Creek nr Big Sandy*	8019500	12010002	Upshur	278.38	10/1/1939	9/30/2008	68	231	204	88%
Sabine River nr Gladewater	8020000	12010002	Gregg	243.85	10/1/1932	current	76	2,791	1,404	50%
Sabine River nr Beckville	8022040	12010002	Panola	190.00	10/1/1938	current	70	3,589	2,044	57%
Sabine River nr Bon Weir	8028500	12010005	Newton	33.42	10/1/1923	current	85	8,229	842	10%
Big Cow Creek nr Newton	8029500	12010005	Newton	134.69	5/1/1952	current	56	128	128	100%
Sabine River nr Ruliff	8030500	12010005	Newton	-5.92	10/1/1924	current	84	9,329	1,942	21%
NECHES BASIN										
Village Creek nr Kountze	8041500	12020006	Hardin	25.12	5/1/1939	current	69	860	860	100%
Neches River at Evadale	8041000	12020003	Jasper	8.25	4/1/1921	current	87	7,951	378	5%
Attoyac Bayou nr Chireno	8038000	12020005	San Augustine	169.58	8/1/1939	10/31/1954	14	503	489	97%
					10/1/1955	9/30/1985	29			
Angelina River nr Alto	8036500	12020004	Cherokee	204.30	3/1/1959	current	49	1,276	987	77%
Neches River nr Rockland	8033500	12020003	Tyler	88.41	12/1/1912 [c]	current	96	3,636	2,763	76%
Neches River nr Neches	8032000	12020001	Cherokee	264.06	3/1/1939	current	69	1,145	306	27%

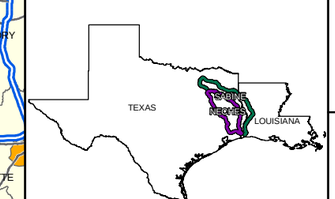
a Gage is currently out of service because of bridge construction at the gaging site.
b Uncontrolled drainage area is the portion of the gage's watershed located downstream from reservoirs.
c Start of continuous record. Rockland has incomplete data back to 7/1/1903.



Sabine and Neches River Basins

LEGEND

- B — BBEST SELECTED GAGES
- O — OTHER GAGES
- NECHES BASIN
- SABINE BASIN
- RESERVOIR
- RIVER
- LIMITED ACCESS
- HIGHWAY
- CITY
- COUNTY



0 6.25 12.5 25 Miles

FNI PROJECT NO.	TWD09238
FILE	H:\WR_PLANNING\WORKING\FINAL\LocationMap.mxd
DATUM & COORDINATE SYSTEM	NAD83 STATE PLANE TX NORTH CENTRAL (FEET)
DATE	AUGUST 2009
PREPARED BY	DLB

SABINE AND NECHES RIVER BASINS

LOCATION MAP

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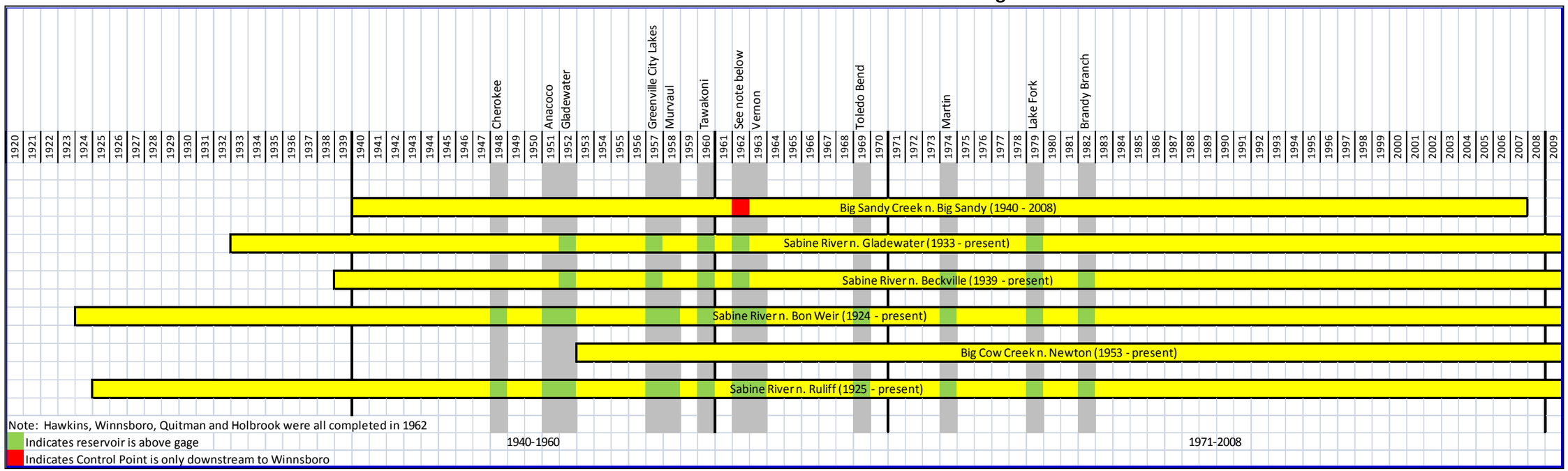
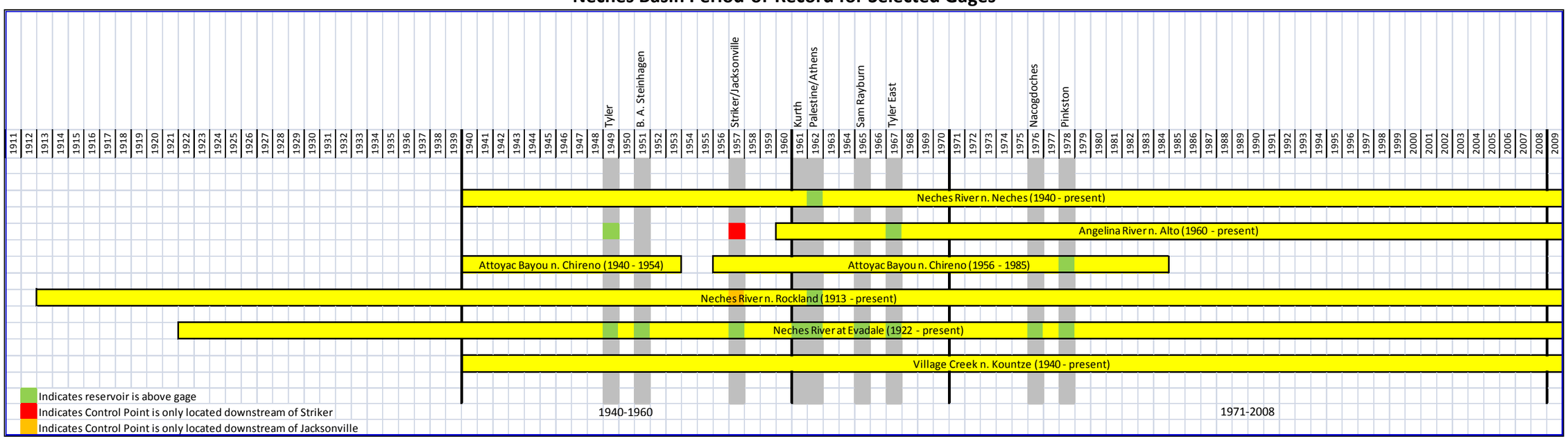
Fort Worth, Texas 76109-4895
817-735-7300

FIGURE 1

Figure 2:
Sabine Basin Period-of-Record for BBEST Selected Gages



Neches Basin Period-of-Record for Selected Gages



The Sabine River near Ruliff and the Sabine River near Bon Weir are downstream from Toledo Bend Reservoir. The Neches River at Evadale is downstream from Sam Rayburn and B.A. Steinhagen Reservoirs. All three reservoirs are used for hydropower generation. Although a significant part of the flow at these locations comes from natural runoff downstream from the reservoirs, the summer time flows at these gages are significantly higher than they would be under natural conditions because of the hydropower releases.

Most of the gages have long periods of record, covering the period from at least 1940 to the present day and representing both pre-reservoir and post-reservoir conditions. Gages with long periods of record are suitable for the statistical analyses required by this study. However, a few gages have shorter periods of record or gaps in the period of record. These gages were chosen to represent major tributaries or geographic regions in the basin and have the best periods of record available. The Big Cow Creek gage near Newton begins in 1953, but is one of the few on tributaries in the lower Sabine Basin and has a flow record representing natural conditions. The Angelina near Alto gage begins in 1960, but is the best gage for a major tributary in the Neches Basin. The Attoyac Bayou near Chireno gage was removed from service in 1985 and has a one-year gap in 1953-54. However, this gage measured basically natural flow for most of this period of record and represents another major tributary in the Neches Basin with minimal control.

Although a few gages have data back to the 1920s or even earlier, the quality of the records before 1940 is not as good as those after 1940. Occasional gaps in data or days of repeating data are common in these early periods.

Geographic Coverage of Selected Gages

The SB3 Science Advisory Committee (SAC) has developed guidance for the selection of stream gages for analyses as part of the SB3 process in the report *Geographic Scope of Instream Flow Recommendations*[2]. Although this document was not available to the BBEST at the time of gage selection, FNI analyzed several of the criteria in the geographic scope document, including coverage of:

- USGS Core Network of gages

[2] Senate Bill 3 Science Advisory Committee for Instream Flows: Geographic Scope of Instream Flow Recommendations, April 2009.

- Texas Commission on Environmental Quality (TCEQ) Water Quality Segments
- USGS Hydrologic Units
- TCEQ Ecoregions and Texas Parks and Wildlife Department (TPWD) Significant Stream Segments
- Identified geomorphic process zones

Based on these criteria, the twelve gages selected by the BBEST have sufficient geographic coverage to adequately represent the hydrologic conditions found in the two basins.

Three gages, the Sabine River near Ruliff, the Neches River at Evadale and Village Creek near Kountze, measure a significant portion of the inflow into Sabine Lake. However, there is still a large amount of flow into the Sabine Lake that is not measured by these gages. Estimates of total inflow into Sabine Lake have been developed by the Texas Water Development Board (TWDB). Therefore the BBEST added Sabine Lake as another analysis point rather than using gage data.

USGS Core Gages

In 2001, the USGS and the TWDB developed a list of Core Gages for the state of Texas[3]. These gages were selected based on regional representation, measurement of flow in large streams, measurement of outflow from the State, and suitability for long-term streamflow conditions assessment. Table 2 is a list of the fourteen USGS Core Gages in the Sabine and Neches River Basins. Figure 3 shows the location of these gages. Nine of the twelve BBEST gages are Core Gages. The Big Sandy, Bon Weir and Chireno gages are not Core Gages. Overall, the twelve gages selected by the BBEST have a reasonable representation of the Core Gage network. The core gages that were not selected either represent small parts of the basins, such as the Cowleech Fork gage, or can be represented by a nearby gage selected by the BBEST. The Cowleech Fork and Quinlan gages are each located on small watersheds upstream of Lake Tawakoni and are, therefore, rather unlikely to be proximate to points of diversion or impoundment in future water rights applications. In addition, the period of record of each of these gages is some 20 years less than that for the selected Big Sandy Creek gage. The Mineola

[3] Slade, Raymond M. Jr et al: Evaluation of the Streamflow-Gaging Network of Texas and a Proposed Core Network, Water Resources Investigation Report 01-4155, prepared for the USGS in Cooperation with the Texas Water Development Board.

Table 2: USGS Core Gages

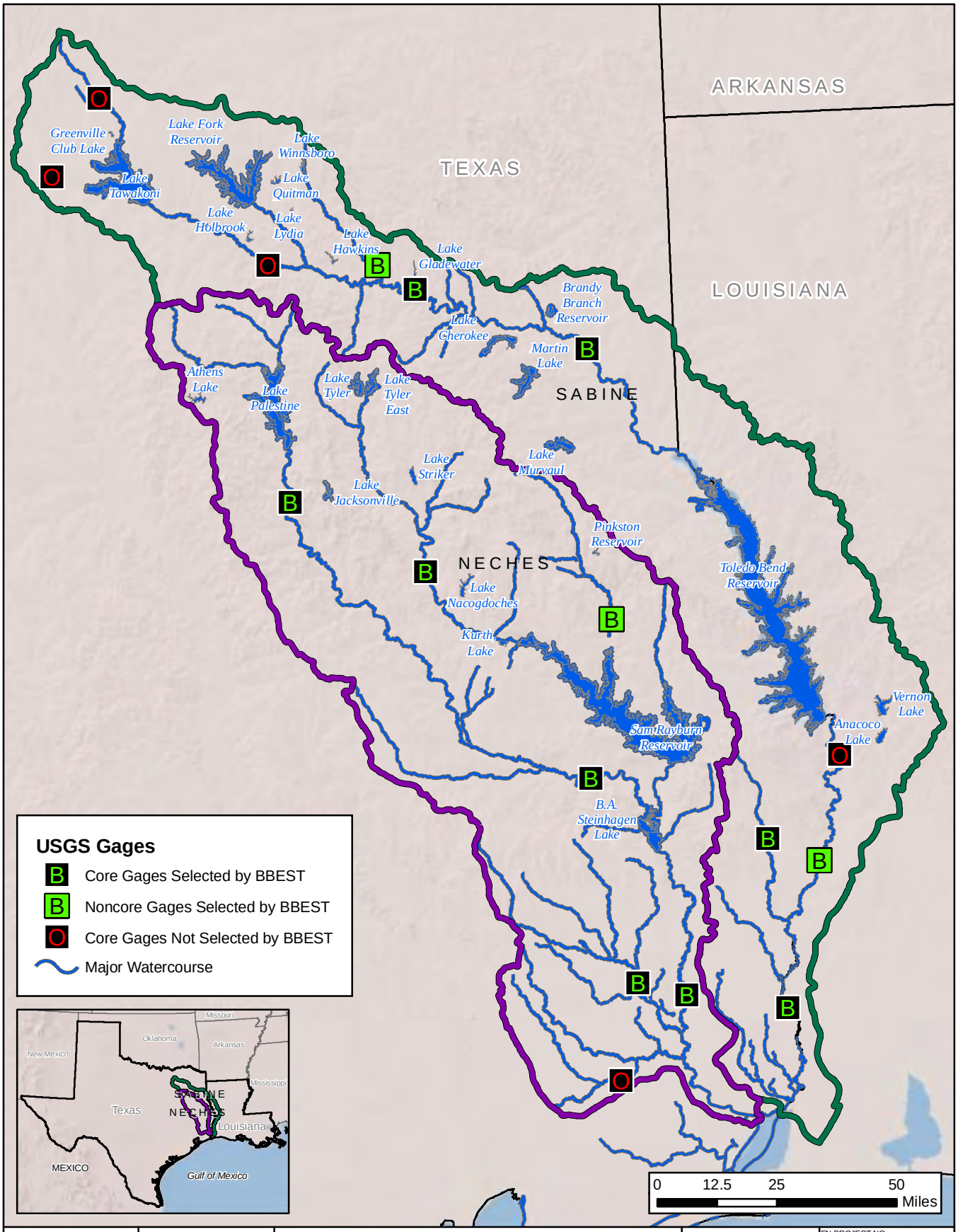
USGS Number	Gage Name	Selected by BBEST
08017200	Cowleech Fk Sabine Rv at Greenville, TX	No
08017300	S Fk Sabine Rv nr Quinlan, TX	No
08018500	Sabine Rv nr Mineola, TX	No
08020000	*Sabine Rv nr Gladewater, TX*	*Yes*
08022040	*Sabine Rv nr Beckville, TX*	*Yes*
08026000	Sabine Rv nr Burkeville, TX	No
08029500	*Big Cow Ck nr Newton, TX*	*Yes*
08030500	*Sabine Rv nr Ruliff, TX*	*Yes*
08032000	*Neches Rv nr Neches, TX*	*Yes*
08033500	*Neches Rv nr Rockland, TX*	*Yes*
08036500	*Angelina Rv nr Alto, TX*	*Yes*
08041000	*Neches Rv at Evadale, TX*	*Yes*
08041500	*Village Ck nr Kountze, TX*	*Yes*
08041700	Pine Island Bayou nr Sour Lake, TX	No

gage can be represented by the Gladewater gage which has a longer period of record. The Burkeville gage can be represented by the Beckville gage which has a longer period of record. Pine Island Bayou can be represented by the nearby Village Creek near Kountze gage which has a period of continuous record some 28 years longer.

TCEQ Classified Segments

The Texas Surface Water Quality Standards (TSWQS) identify water quality standards for classified and unclassified water bodies in the state. Based on the TSWQS, the Texas Commission on Environmental Quality (TCEQ) has divided the Sabine and Neches Basins into fifteen classified segments each[4]. Each basin also contains unclassified segments. All twelve gages selected by the BBEST are located within classified segments. Table 3 lists the twelve gages selected by the BBEST and their associated classified segments. Figure 4 shows locations of the classified segments in relation to the gages selected by the BBEST.

[4] Texas Commission on Environmental Quality: Atlas of Texas Surface Waters, available on-line at http://www.tceq.state.tx.us/comm_exec/forms_pubs/pubs/gi/gi-316/index.html, downloaded August 2009.



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N W E S

Sabine and Neches River Basins

USGS CORE STREAM GAGES

FIGURE 3

FN PROJECT NO.	TWD09238
FILE	H:\WR_PLANNING\WORKING\FINAL\Figure3.mxd
DATUM & COORDINATE SYSTEM	NAD83 STATE PLANE TX NORTH CENTRAL (FEET)
SCALE	1:1,800,000
DATE	AUGUST 2009
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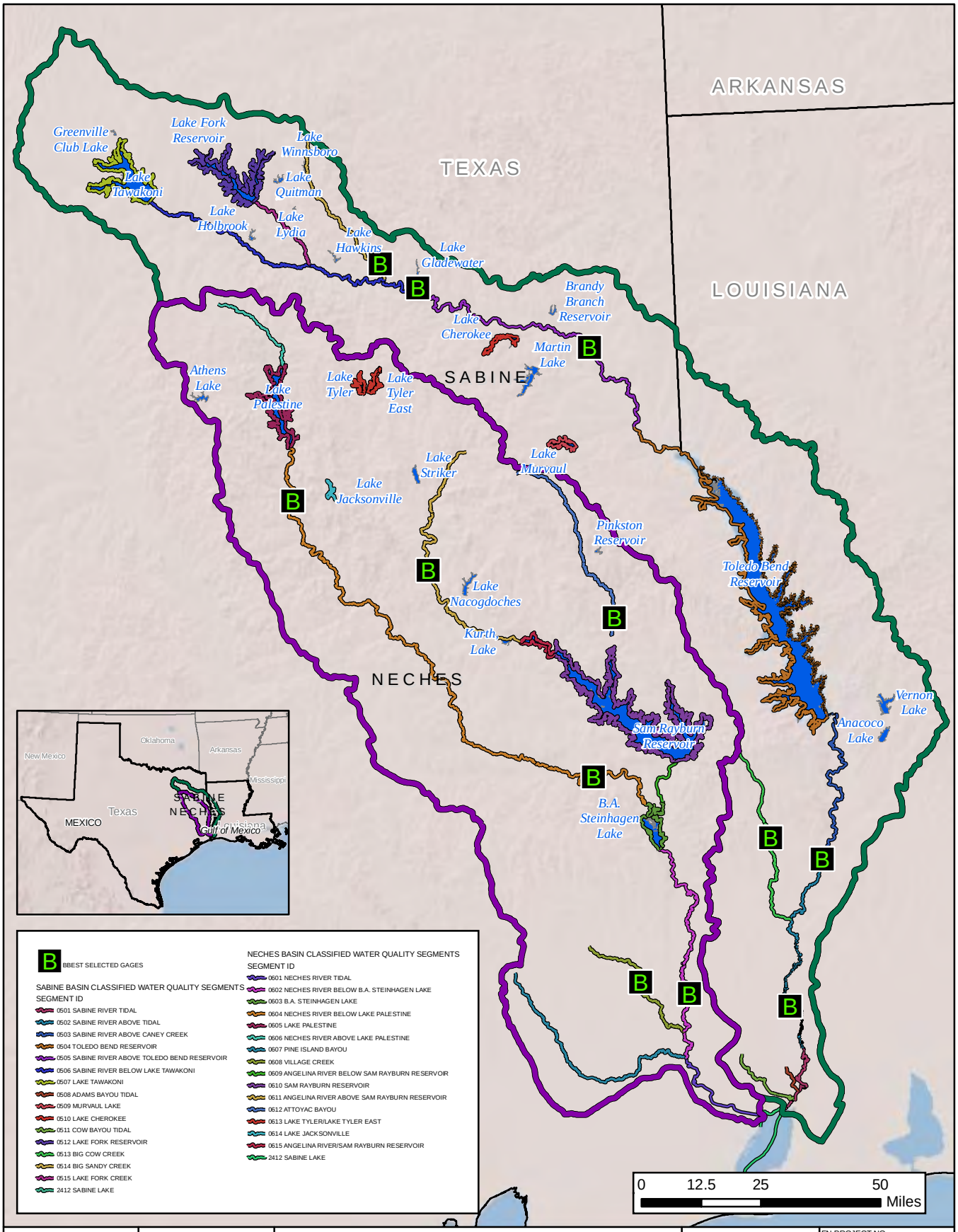
Table 3: Classified Segment Locations for Selected Gages

USGS Gage Name	USGS Gage Number	Classified Segment
SABINE BASIN		
Big Sandy Creek nr Big Sandy	8019500	0514 Big Sandy Creek
Sabine River nr Gladewater	8020000	0506 Sabine R below Lk Tawakoni (downstream end)
Sabine River nr Beckville	8022040	0505 Sabine R above Toledo Bend
Sabine River nr Bon Weir	8028500	0503 Sabine R above Caney Creek
Big Cow Creek nr Newton	8029500	0513 Big Cow Creek
Sabine River nr Ruliff	8030500	0502 Sabine R above Tidal
NECHES BASIN		
Village Creek nr Kountze	8041500	0608 Village Creek
Neches River at Evadale	8041000	0602 Neches R Below BA Steinhagen Lk
Attoyac Bayou nr Chireno	8038000	0612 Attoyac Bayou
Angelina River nr Alto	8036500	0611 Angelina R Above Sam Rayburn Res
Neches River near Rockland	8033500	0604 Neches R Below Lk Palestine
Neches River at Neches	8032000	0604 Neches R Below Lk Palestine

Five of the classified segments in the Sabine Basin are associated with reservoirs: 0504 (Toledo Bend Reservoir), 0507 (Lake Tawakoni), 0509 (Murvaul Lake), 0510 (Lake Cherokee), and 0512 (Lake Fork Reservoir). Three segments are tidally influenced and not suitable for streamflow analysis: 0501 (Sabine River Tidal), 0508 (Adams Bayou Tidal), and 0511 (Cow Bayou Tidal). (Tides affect the ability to measure streamflow, so that complete flow records are typically not available for tidally influenced segments.) Of the remaining seven segments, only 0515 (Lake Fork Creek) is not represented by a selected stream gage. The segment above Lake Fork is relatively small, and it is unlikely that future water rights would be granted in this reach.

In the Neches River Basin, six of the classified segments are associated with reservoirs: 0603 (B.A. Steinhagen Lake), 0605 (Lake Palestine), 0610 (Sam Rayburn Reservoir), 0613 (Lake Tyler/Lake Tyler East), 0614 (Lake Jacksonville) and 0615 (Angelina River/Sam Rayburn Reservoir). Segment 0601 (Neches River Tidal) is tidally influenced and not suitable for streamflow analysis. The BBEST did not select a gage in three segments: 0606 (Neches River



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N W E S

Sabine and Neches River Basins

TCEQ Classified Segments

FIGURE 4

FN PROJECT NO.	TWD09238
FILE	H:\WR_PLANNING\WORKING\FINAL\Figure4.mxd
DATUM & COORDINATE SYSTEM	NAD83 STATE PLANE TX NORTH CENTRAL (FEET)
SCALE	1:1,800,000
DATE	AUGUST 2009
PREPARED BY	DLB

above Lake Palestine), 0607 (Pine Island Bayou), or 0609 (Angelina River below Sam Rayburn Reservoir). The segment above Lake Palestine is rather small, and it is unlikely that any future water rights would be granted in this segment. Segment 0607 can be adequately represented by the adjacent Village Creek gage. Segment 0609 is the relatively short reach between Sam Rayburn Reservoir and Lake Steinhagen. It is unlikely that any future water rights would be granted in this reach. There are two gages in segment 0604 (Neches River below Lake Palestine): the Rockland and Neches gages. The other segments are represented by one gage each.

Overall, the twelve gages selected by the BBEST offer a reasonable representation of classified segments within the Sabine and Neches Basins.

USGS Hydrologic Units

The USGS divides river basins into subwatersheds known as Hydrologic Units. The Neches River Basin is divided into seven Hydrologic Units and the Sabine River Basin is divided into five Hydrologic Units. Table 4 lists the Hydrologic Units for the gages selected by the BBEST and Figure 5 shows the location of the gages in relation to the Hydrologic Units.

Table 4: Hydrologic Units for Selected Gages

USGS Gage Name	USGS Gage Number	Hydrologic Unit Code	Hydrologic Unit Name
SABINE BASIN			
Big Sandy Creek nr Big Sandy	8019500	12010002	Middle Sabine
Sabine River nr Gladewater	8020000	12010002	Middle Sabine
Sabine River nr Beckville	8022040	12010002	Middle Sabine
Sabine River nr Bon Weir	8028500	12010005	Lower Sabine
Big Cow Creek nr Newton	8029500	12010005	Lower Sabine
Sabine River nr Ruliff	8030500	12010005	Lower Sabine
NECHES BASIN			
Village Creek nr Kountze	8041500	12020006	Village Creek
Neches River at Evadale	8041000	12020003	Lower Neches
Attoyac Bayou nr Chireno	8038000	12020005	Lower Angelina
Angelina River nr Alto	8036500	12020004	Upper Angelina
Neches River nr Rockland	8033500	12020003	Lower Neches (upper end)
Neches River nr Neches	8032000	12020001	Upper Neches

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Sabine and Neches River Basins

USGS Hydrologic Units

FIGURE 5

FN PROJECT NO.	TWD09238
FILE	H:\WR_PLANNING\WORKING\FINAL\Figure5.mxd
DATUM & COORDINATE SYSTEM	NAD83 STATE PLANE TX NORTH CENTRAL (FEET)
SCALE	1:1,800,000
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In the Sabine Basin, only two of the five Hydrologic Units are represented by gages selected by the BBEST. The two northern most Hydrologic Units in the Sabine Basin, Lake Fork and Upper Sabine, are dominated by Lake Tawakoni and Lake Fork Reservoir. The flows in this region can be adequately represented by the Gladewater and Big Sandy gages. Streams in the Toledo Bend Reservoir watershed consist primarily of small tributaries that flow into the reservoir, and gage data are extremely limited. The Lower Sabine Hydrologic Unit is well represented by three gages, one on a tributary (Big Cow) and two on the main stem (Bon Weir and Ruliff).

In the Neches Basin, every Hydrologic Unit contains at least one gage except for the Middle Neches and Pine Island Bayou units. The Rockland gage, which is located at the very upper end of the Lower Neches Hydrologic Unit, can adequately represent the Middle Neches. The Village Creek near Kountze gage can adequately represent Pine Island Bayou.

TCEQ Ecoregions

As shown in Figure 6, there are four of the TCEQ Ecoregions in the Sabine and Neches River Basins: the Texas Blackland Prairies, East Central Texas Plains, South Central Plains, and Western Gulf Coastal Plain. Almost all of the two basins, and all of the BBEST selected gages, are in the South Central Plains Ecoregion. The Texas Blackland Prairie is only a small part of the upper reaches of the Sabine Basin, and the East Central Texas Plains is dominated by Lake Fork Reservoir and Lake Tawakoni. It is unlikely that new water rights would be approved in these regions. The Western Gulf Coastal Plain covers a small part of the lower portions of both basins and has limited gage data. The BBEST gages represent the dominant ecoregion in the two basins and can adequately represent the other smaller regions.

TPWD Ecologically Significant Stream Segments

TPWD has identified many of the reaches in the Sabine and Neches River Basin as Ecologically Significant Stream Segments. These segments are shown in red in Figure 6. Ecologically Significant Stream Segments are identified by biological function, riparian conservation areas, threatened or endangered species, high water quality and exceptional aquatic life, and high aesthetic value[5]. Most of the selected gages are on or near a TPWD-identified ecologically significant segment.

[5] Significant Stream Segment data obtained from Texas Parks and Wildlife Department GIS Lab

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Sabine and Neches River Basins

TCEQ Ecoregions and TPWD Ecologically Significant Stream Segments

FIGURE 6

FN PROJECT NO.	TWD09238
FILE	H:\WR_PLANNING\WORKING\FINAL\Figure6.mxd
DATUM & COORDINATE SYSTEM	NAD83 STATE PLANE TX NORTH CENTRAL (FEET)
SCALE	1:1,800,000
DATE	AUGUST 2009
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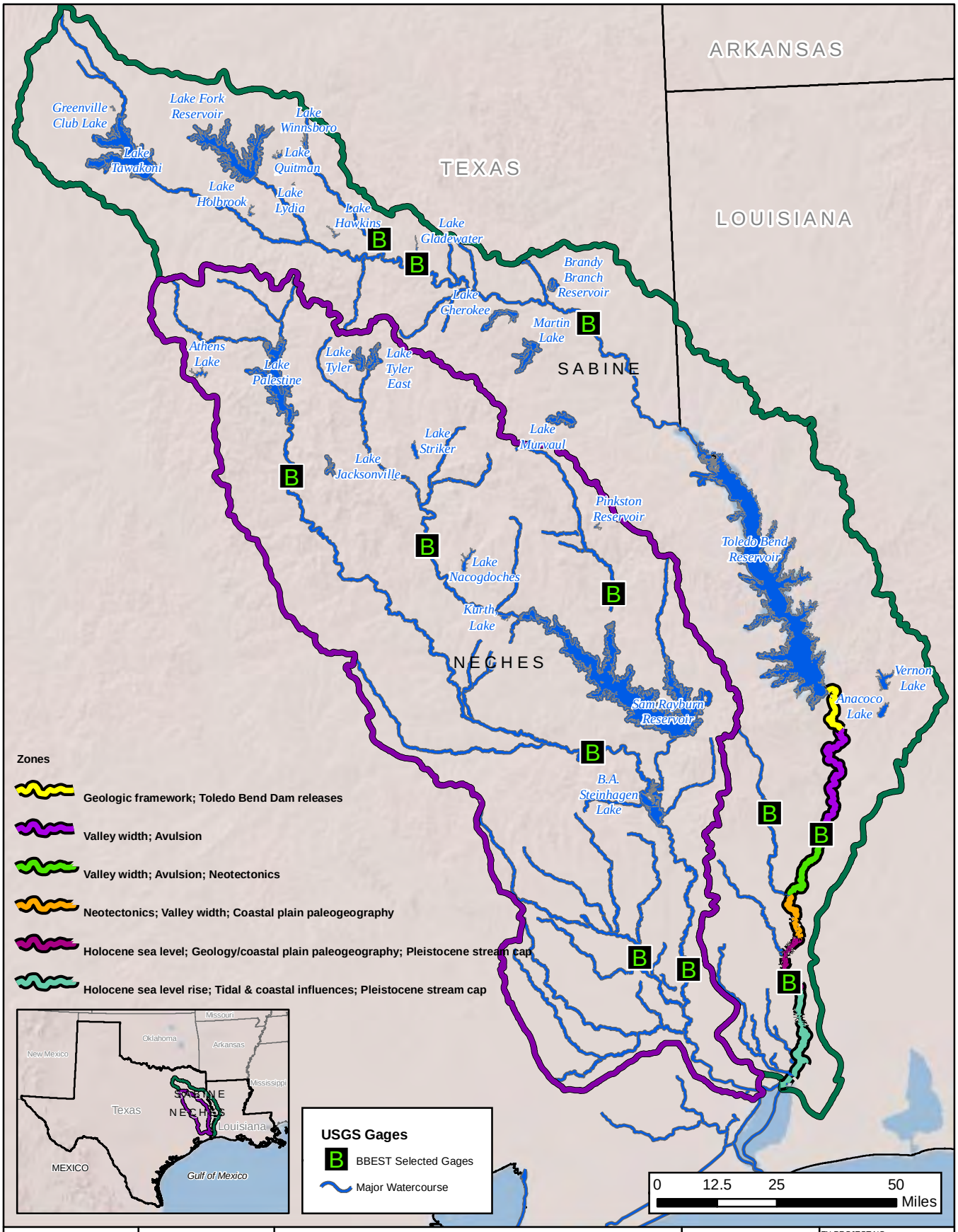
Geomorphic Process Zones

FNI has only been able to locate information on geomorphic process zones in the reach of the Sabine River below Toledo Bend Reservoir. This reach is one of the priority reaches identified for study in Senate Bill 2 (SB2) of the 77th Texas Legislature. These geomorphic zones are shown in Figure 7. Two selected gages, the Sabine River near Bon Weir and Sabine River near Ruliff, provide flow information for these zones.

Changes to Flow Characteristics over Time

Reservoir construction and operations has probably has the most significant potential to alter flows in the Sabine and Neches River Basins. There are fourteen major reservoirs in the Sabine Basin and ten major reservoirs in the Neches Basin. Table 5 shows the relationship between reservoirs and gages, and includes date of reservoir construction, reservoir storage capacity, and a comparison of the drainage areas of the reservoirs and gages. Figure 1 shows the locations of the reservoirs.

One way to assess significant changes to gage flows is graphing cumulative flow over time. Temporary increases in the slope of the line signal abnormally wet periods, and temporary decreases in slope typically indicate abnormally dry periods. However, if the overall slope of the line remains constant, there is no major change to flows over time. Persistent changes to the slope of the line may indicate significant changes in flow characteristics. Another way to look at changes over time is to graph annual total flow and examine the data for changes. This memorandum uses these techniques to identify trends for three gages: Neches River at Evadale, Sabine River near Gladewater, and Big Cow Creek near Newton. Similar graphs for the remaining gages may be found in Attachment A.



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Sabine and Neches River Basins

Geomorphic Zones

FIGURE 7

FN PROJECT NO.	TWD09238
FILE	H:\WR_PLANNING\WORKING\FINAL\Figure7.mxd
DATUM & COORDINATE SYSTEM	NAD83 STATE PLANE TX NORTH CENTRAL (FEET)
SCALE	1:1,800,000
DATE	AUGUST 2009
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Table 5: Relationship of Major Reservoirs to Gages in the Sabine and Neches River Basins

Sabine Basin

Gage Name	USGS#	Gage Drainage Area (sq-miles)	Controlled Drainage Area (sq. miles)	Reservoir, Completion Date, Capacity (ac-ft), & Drainage Area (sq-miles)													
				Anacoco	Vernon	Toledo Bend	Murvaul	Cherokee	Martin	Brandy Branch	Gladewater	Hawkins	Winnsboro	Quitman	Holbrook	Lake Fork	Tawakoni
				1951	1963	1969	Jun-58	Nov-48	Apr-74	1982	Aug-52	Sep-62	Sep-62	Jun-62	Nov-62	Jul-79	Dec-60
				22,100	55,400	4,412,300	44,000	40,800	76,200	29,500	6,100	11,300	7,600	6,900	7,700	673,000	884,200
				209	112	7,178	115	158	130	4	35	30	27	31	15	493	756
Big Sandy Creek nr Big Sandy	8019500	231	27										**11.7%**				
Sabine River nr Gladewater	8020000	2,791	1,387								**1.3%**	**1.1%**	**1.0%**	**1.1%**	**0.5%**	**17.7%**	**27.1%**
Sabine River nr Beckville	8022040	3,589	1,545					**4.4%**		**0.1%**	**1.0%**	**0.8%**	**0.8%**	**0.9%**	**0.4%**	**13.7%**	**21.1%**
Sabine River nr Bon Weir	8028500	8,229	7,387	**2.5%**	1.4%	**87.2%**	1.4%	1.9%	1.6%	0.0%	0.4%	0.4%	0.3%	0.4%	0.2%	6.0%	9.2%
Big Cow Creek nr Newton	8029500	128	0														
Sabine River nr Ruliff	8030500	9,329	7,387	**2.2%**	1.2%	**76.9%**	1.2%	1.7%	1.4%	0.0%	0.4%	0.3%	0.3%	0.3%	0.2%	5.3%	8.1%

Neches Basin

Gage Name	USGS#	Gage Drainage Area (sq-miles)	Controlled Drainage Area (sq-miles)	Reservoir, Completion Date, Capacity (ac-ft), & Drainage Area (sq-miles)									
				B.A. Steinhagen	Sam Rayburn	Pinkston	Kurth	Nacogdoches	Striker	Tyler & Tyler E.	Jacksonville	Palestine	Athens
				Apr-51	Mar-65	Jan-78	Jul-61	Jul-76	May-57	1949 & 1967	Jun-57	May-62	Nov-62
				66,972	2,876,033	7,380	14,769	39,523	22,865	80,198	25,732	395,402	29,475
				7,573	3,449	14.2	4	87.9	182	107	34	839	21.6
Village Creek nr Kountze	8041500	860	0										
Neches River at Evadale	8041000	7,951	7,573	**95.2%**	43.4%	0.2%	0.1%	1.1%	2.3%	1.3%	0.4%	10.6%	0.3%
Attoyac Bayou nr Chireno	8038000	503	14			**2.8%**							
Angelina River nr Alto	8036500	1,276	289						**14.3%**	**8.4%**			
Neches River nr Rockland	8033500	3,636	873								**0.9%**	**23.1%**	0.6%
Neches River at Neches	8032000	1,145	839									**73.3%**	1.9%

Values indicate percentage of gage drainage area controlled by reservoir

Text in bold letters indicates reservoir is directly upstream of control point without intervening reservoirs

Figure 8 shows the cumulative flow over time for the Neches River at Evadale. Units are in day-second-feet (dsf). (A volume of 1 day-second-foot is the volume accumulated by a flow of 1 cubic foot per second over a day.) The red markers show the approximate date of reservoir construction. For this gage, the most significant dates would be 1951 (B.A. Steinhagen Reservoir) and 1965 (Sam Rayburn Reservoir). Looking at this figure, it is unclear if the minor variations in slope of the line are the result of reservoir construction or normal flow variation. Overall, there appears to be no significant long-term trends in the data. Figure 9 shows the annual flows at Evadale. Again, there is no trend evident in the long-term flows. However, inspection of daily flow records at Evadale shows an increase in summer flows due to hydropower operations at Rayburn and Steinhagen Reservoirs. To illustrate this trend, instead of using the total annual flows, flows were summed for only the low-flow months of July, August, and September. Figure 10 shows the summer flows at Evadale from 1940 to 2008. Since about 1973, the summertime flows have increased significantly, probably from hydropower operation and flows to prevent salt water intrusion prior to installation of the salt water barrier. However, the cumulative flow and total annual flow charts imply that the overall volume of water passing the gage has not been significantly altered, only the seasonal distribution of those flows.

Figure 11 shows the cumulative historical flow for the Sabine River near Gladewater gage. Several reservoirs have been constructed upstream of this gage, including Lake Tawakoni and Lake Fork Reservoir. Although there is some variation in slope of the cumulative flow line over time, it is unclear to what extend these slope changes were caused by reservoir construction and operations. There does not appear to be a change in the overall trend of the line. Figure 12 shows the annual flows for the same gage. Again, there is little indication of a trend in flow over time.

Figure 8: Cumulative Historical Flow – Neches River at Evadale

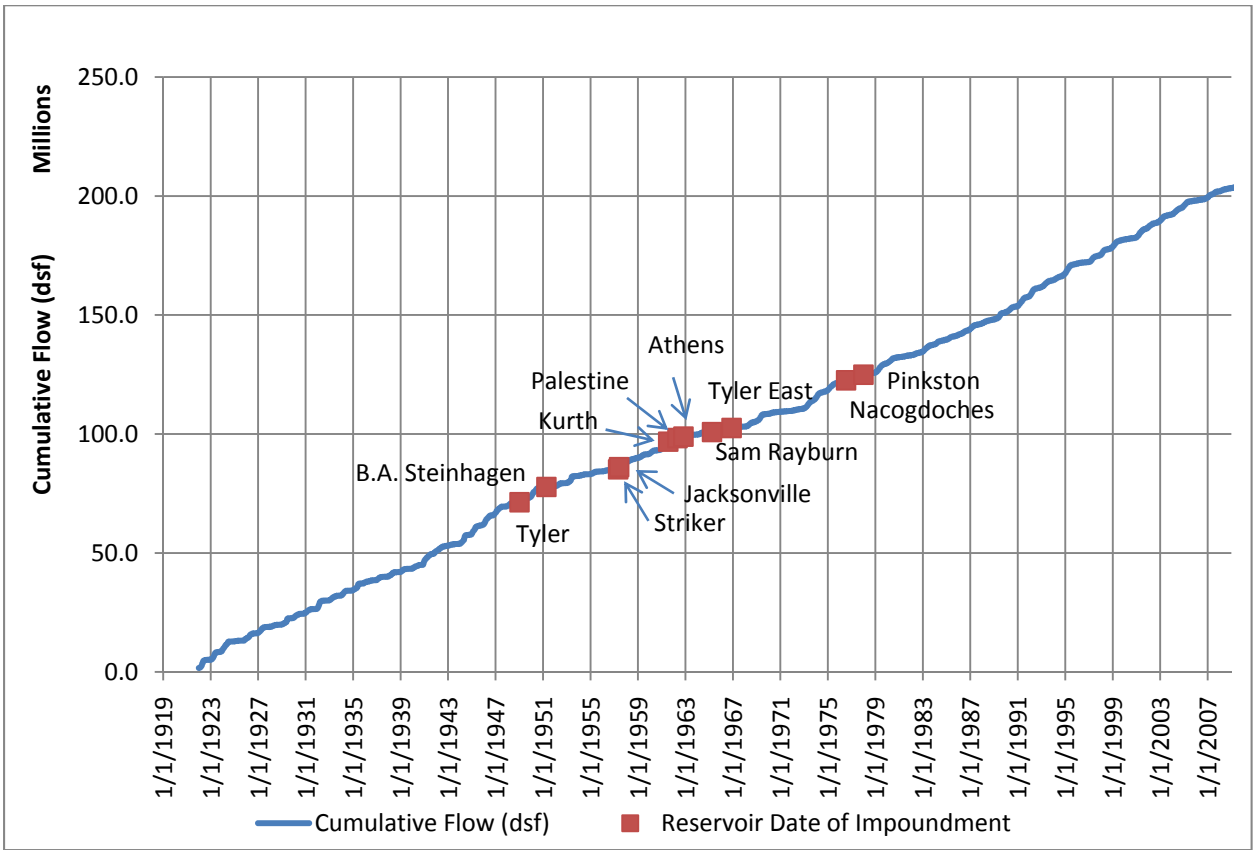


Figure 9: Annual Historical Flow – Neches River at Evadale

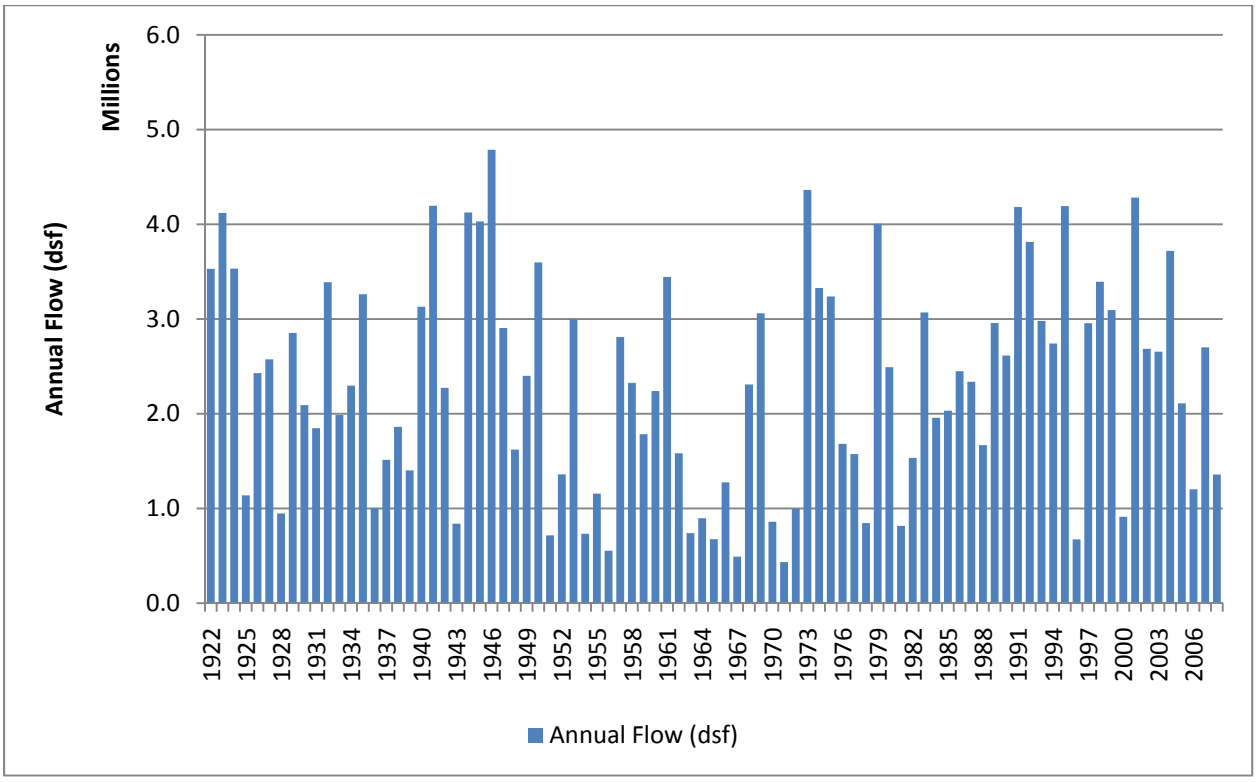


Figure 10: Total Summer Month Flows (July-September) – Neches River at Evadale

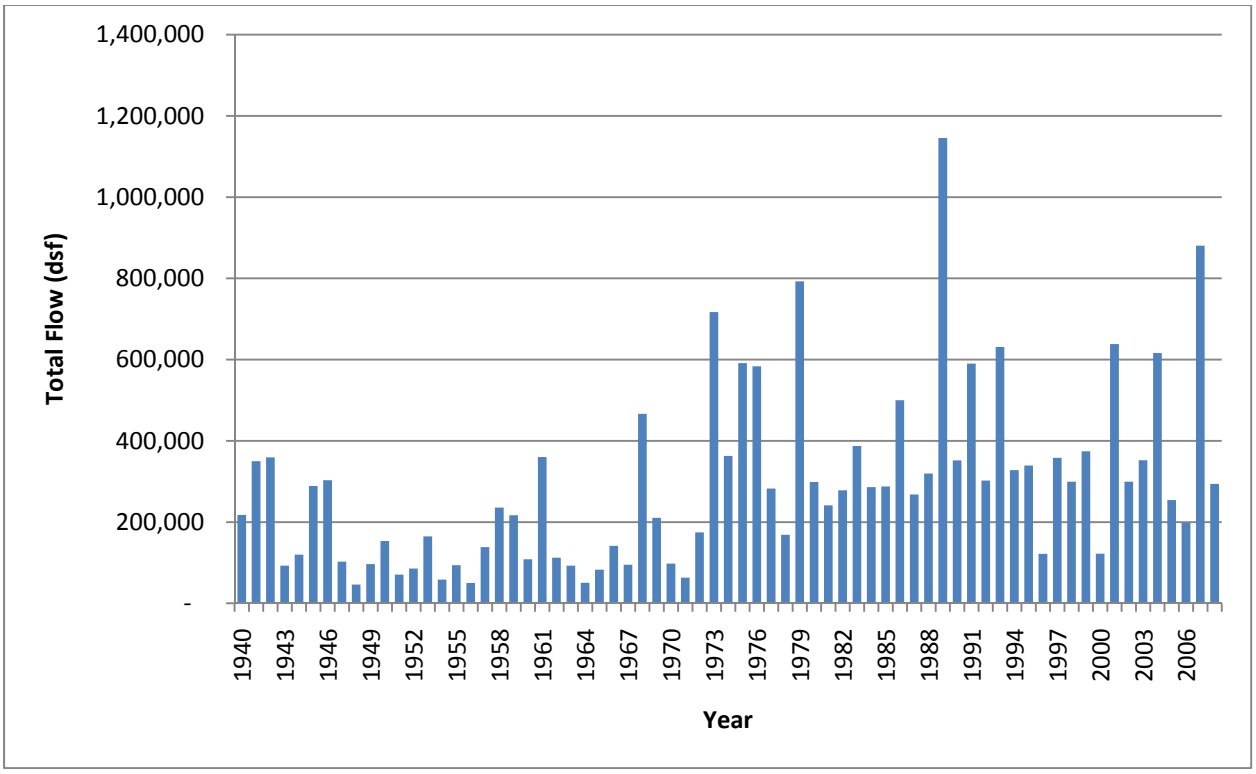


Figure 13 shows the cumulative flow for the Big Cow Creek near Newton gage. The watershed above this gage has very little apparent alteration. There are no major dams, return flows, or diversions upstream of the gage. However, the cumulative flows show a distinctive upward change in slope in 1973, indicating an overall period of higher flows. The annual flows in Figure 14 show a similar trend, but the trend is not as pronounced. The cumulative Village Creek near Kountze flow in Figure 15 (a similar gage in the lower Neches Basin) shows an identical trend. However, the longer period of record shows that the change in flow may be due to long-term climatic variation. The period from about 1951 through 1973 appears to be a period of low flow. The slope of the line for the Kountze gage prior to 1951 appears to be similar to the slope after 1973. The period from 1950 to early 1957 is considered to be the "drought of record" in most of the state, so it is not surprising that the cumulative flows show a drier period during

Figure 11: Cumulative Historical Flow - Sabine River near Gladewater

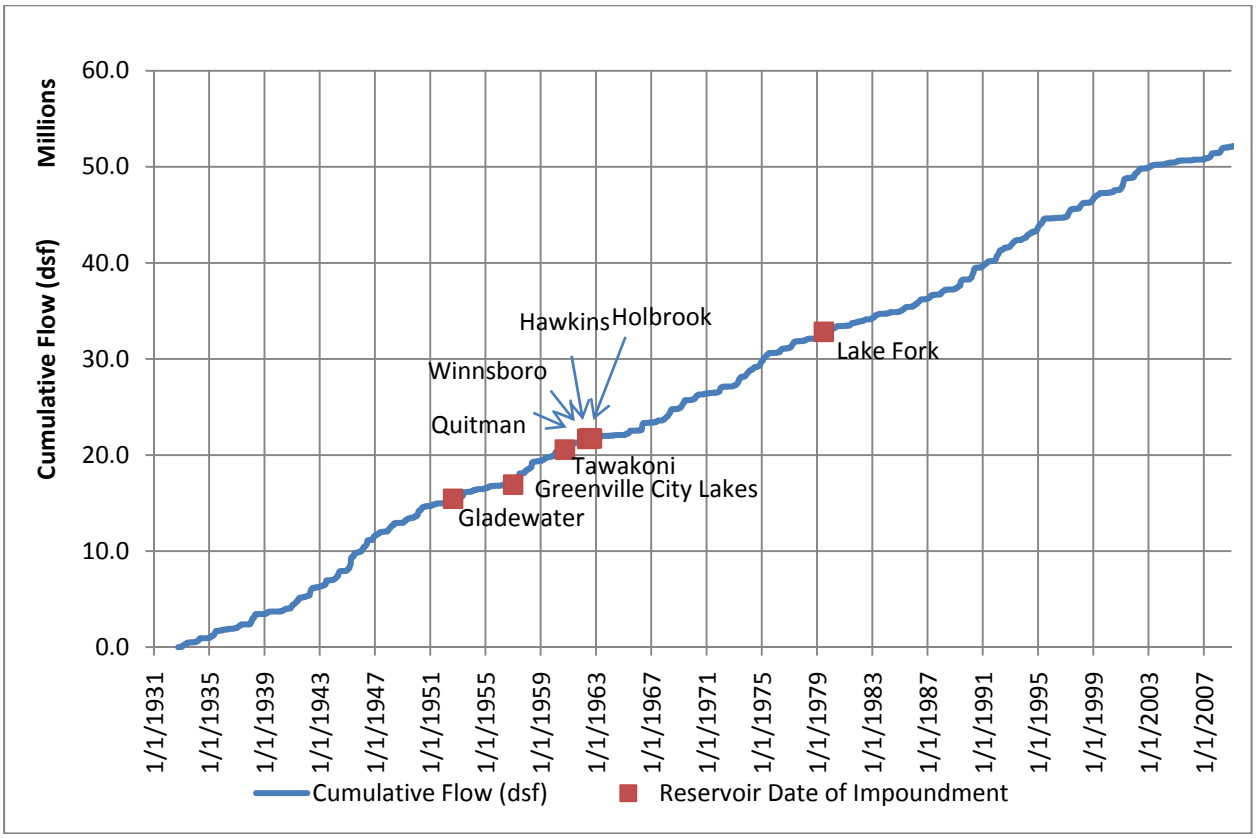


Figure 12: Annual Flows – Sabine River near Gladewater

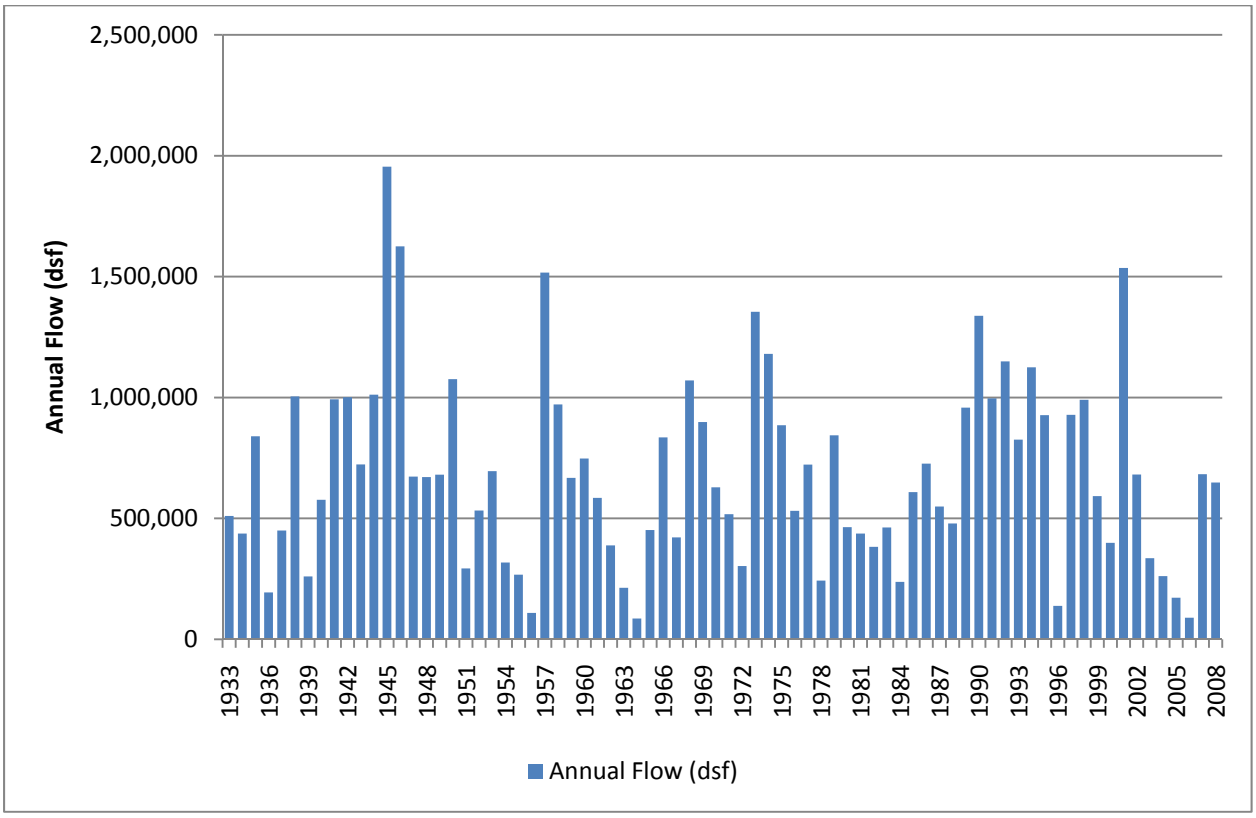


Figure 13: Cumulative Historical Flow – Big Cow Creek near Newton

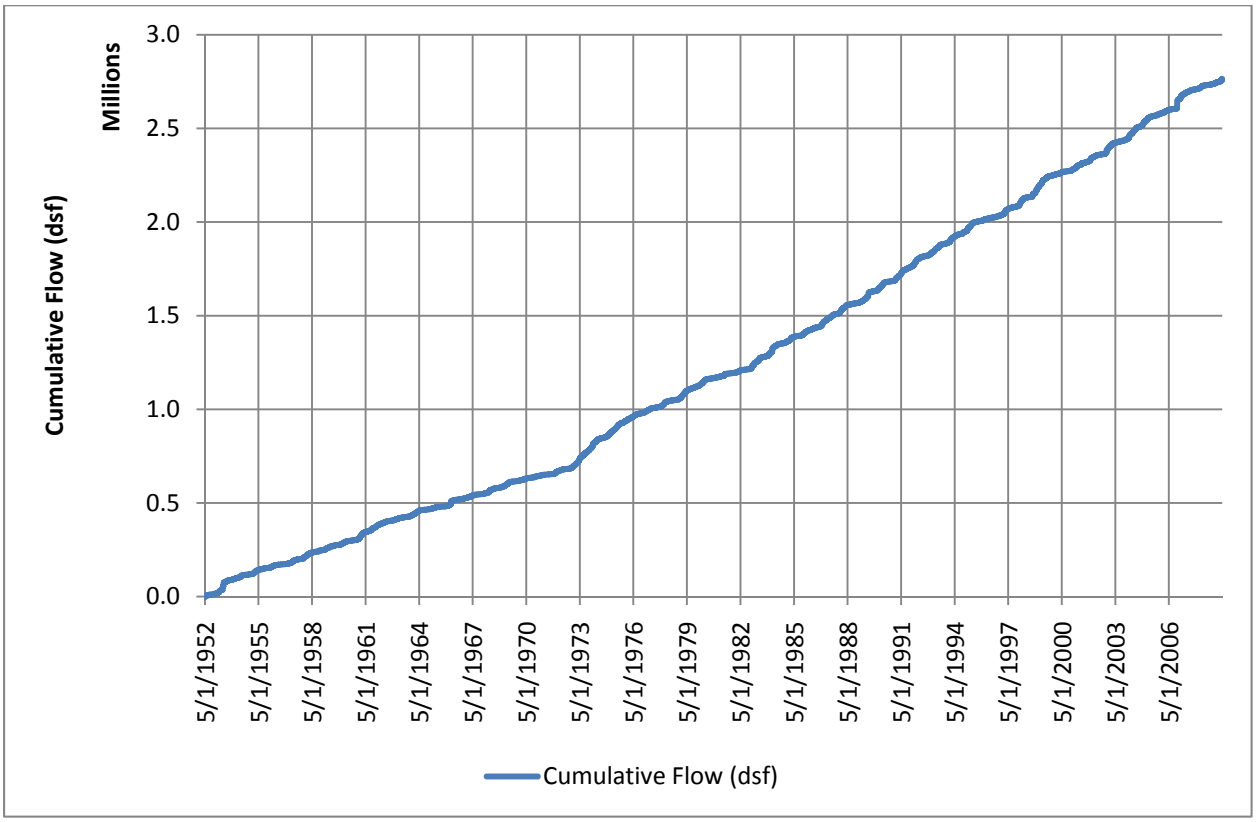


Figure 14: Annual Flows – Big Cow Creek near Newton

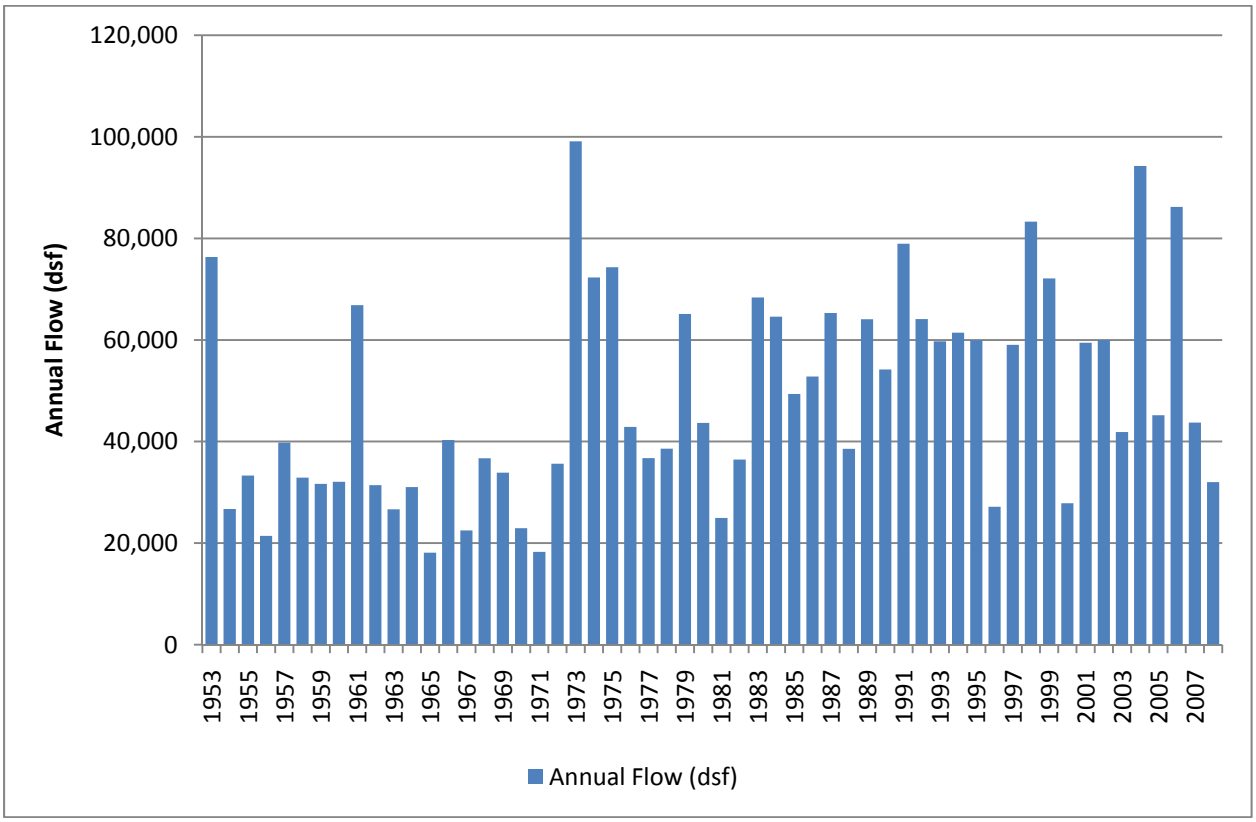
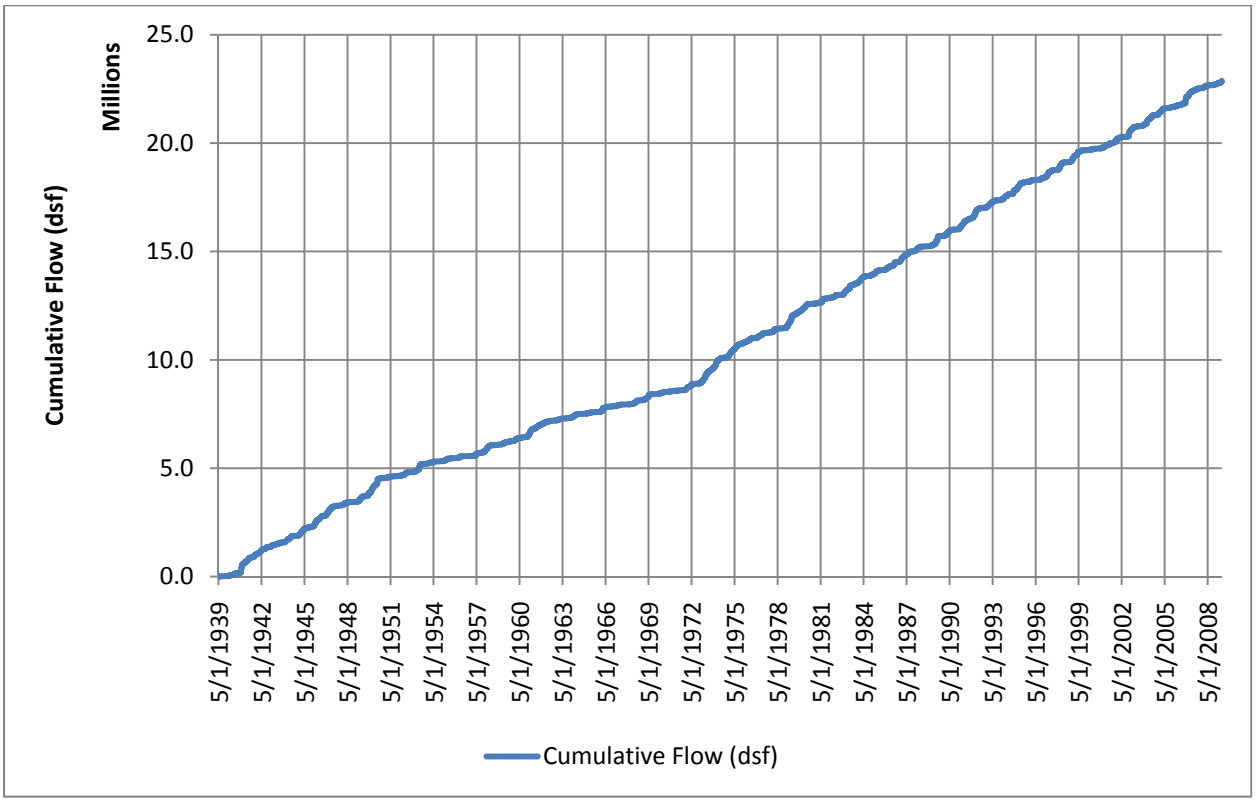


Figure 15: Cumulative Historical Flow – Village Creek near Kountze



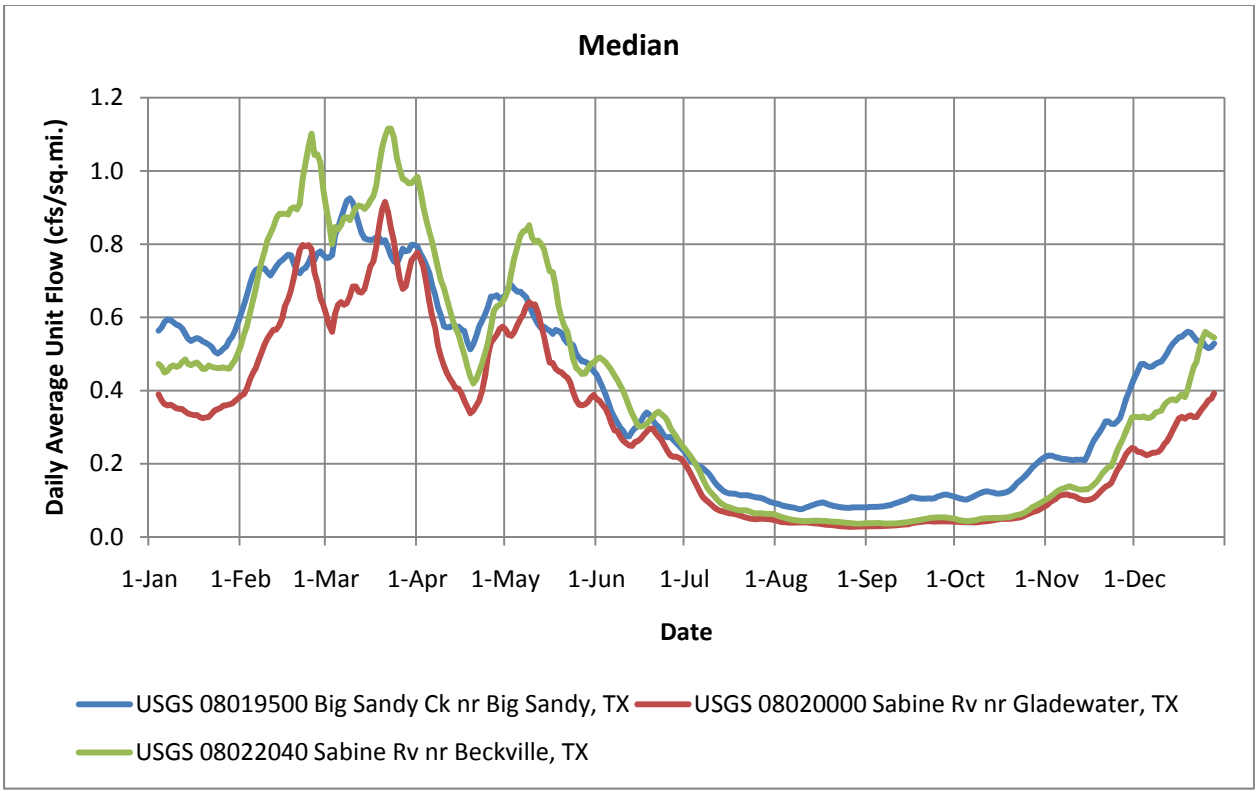
that time. However, it is unclear why lower flow conditions persisted at these gages until the early 1970s. Other gages, such as the Evadale and Gladewater gages may show similar but less pronounced trends. However, the 1960's and 70s was the period when most of the major reservoirs were constructed in these basins, so it is uncertain to what extent this trend is the result of climatic changes or the filling of reservoirs.

Seasonal Streamflow Characteristics of the Selected Gages

Figure 16 and Figure 17 compare median and 25th percentile daily unit flows for the seven selected gages in the upper portions of the Sabine and Neches River Basins, respectively. Data are from USGS Daily Flow Statistics[6]. Figure 18 shows the same data for the two gages in the lower portions of the basins unaffected by hydropower releases. Figure 19 shows the same data for the three gages in the lower portions of the basins affected by hydropower releases.

[6] USGS National Water Center Information Center Web Interface, available on-line at http://waterdata.usgs.gov/tx/nwis/sw

Figure 16: Unit Flows - Upper Sabine River Basin



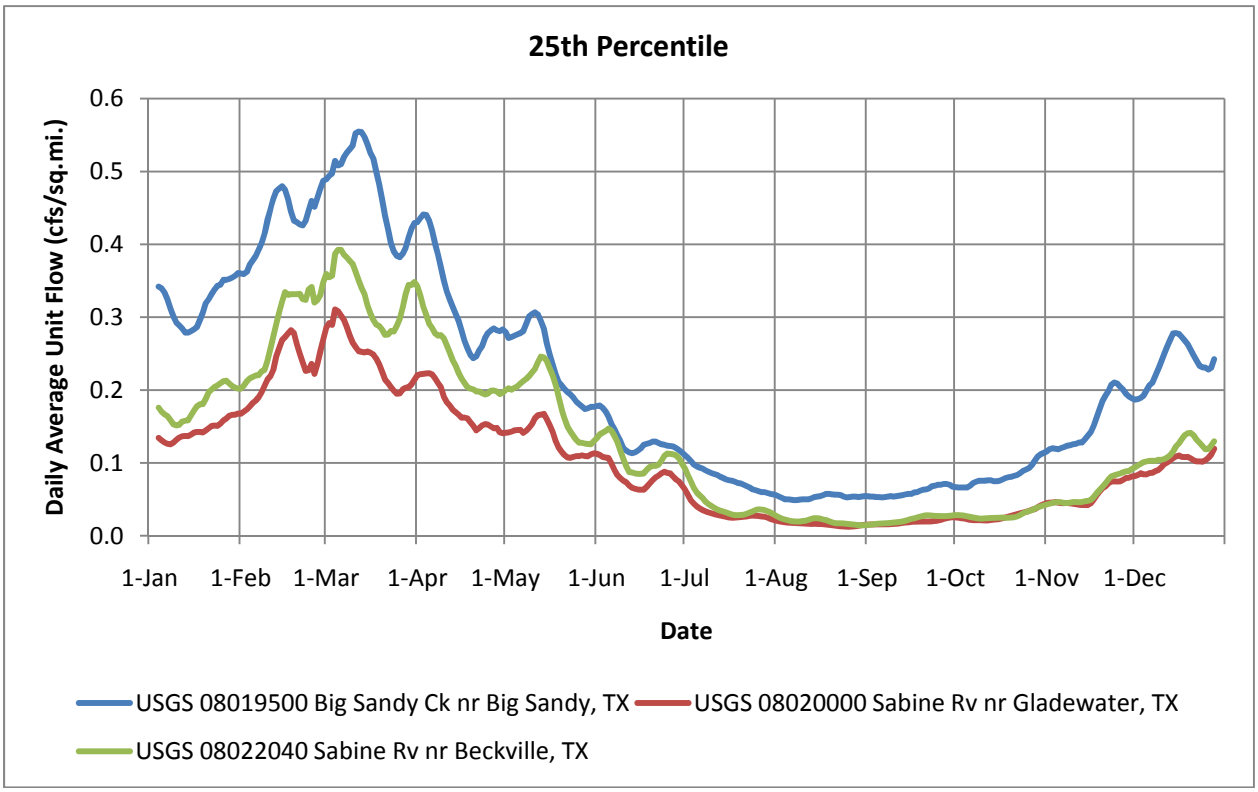
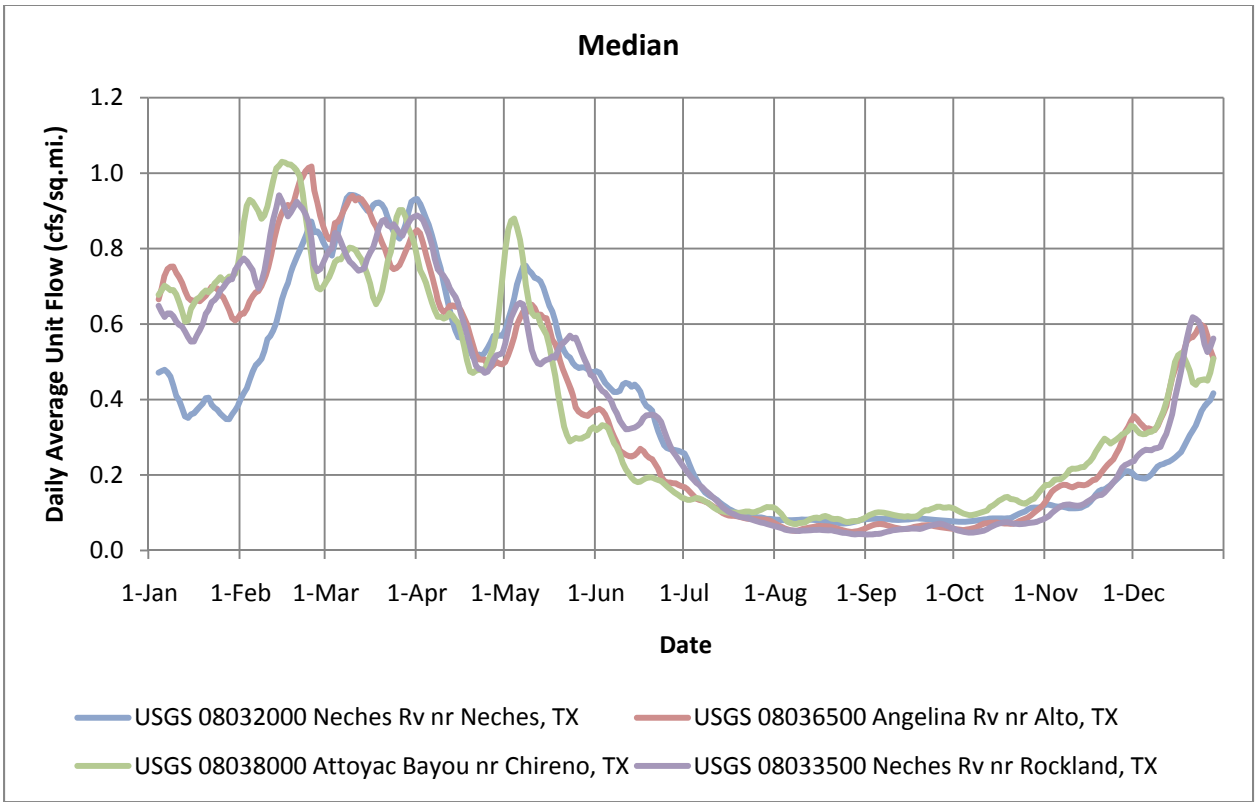


Figure 17: Unit Flows - Upper Neches River Basin



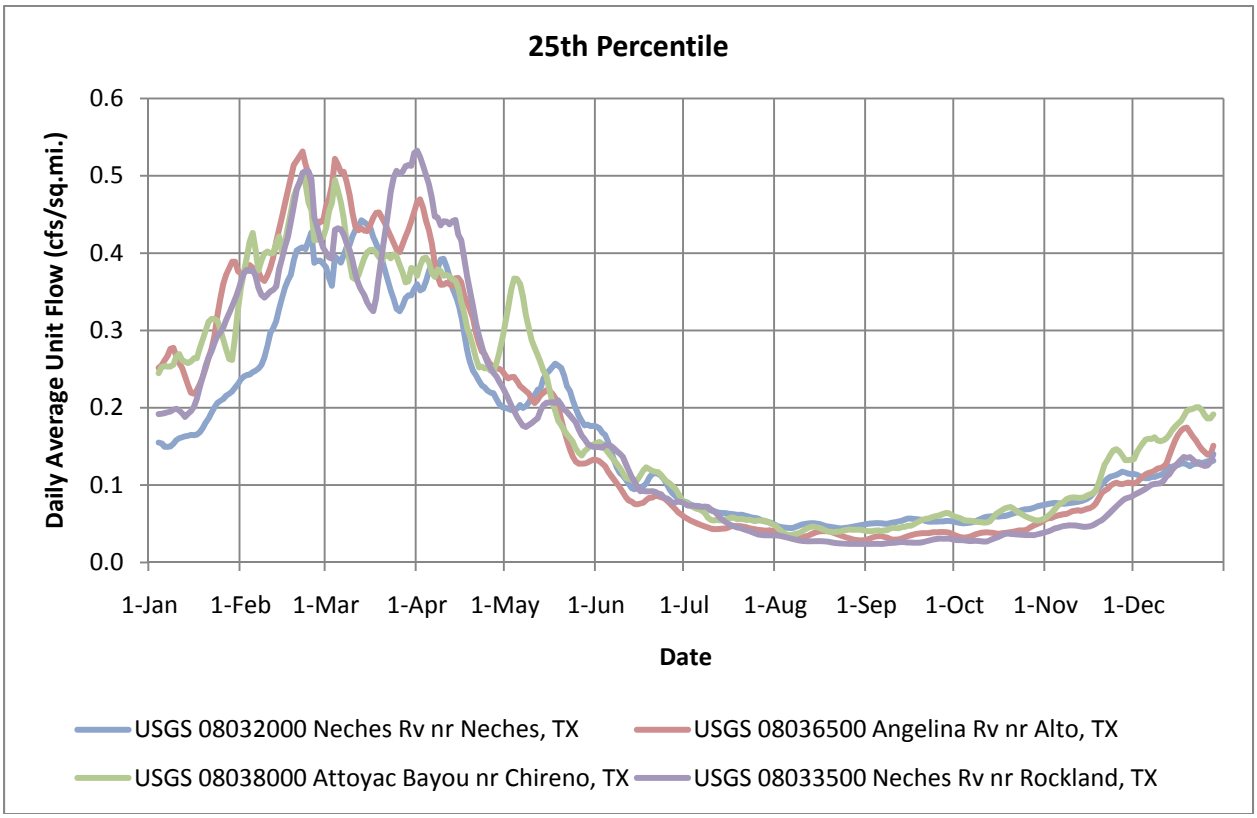
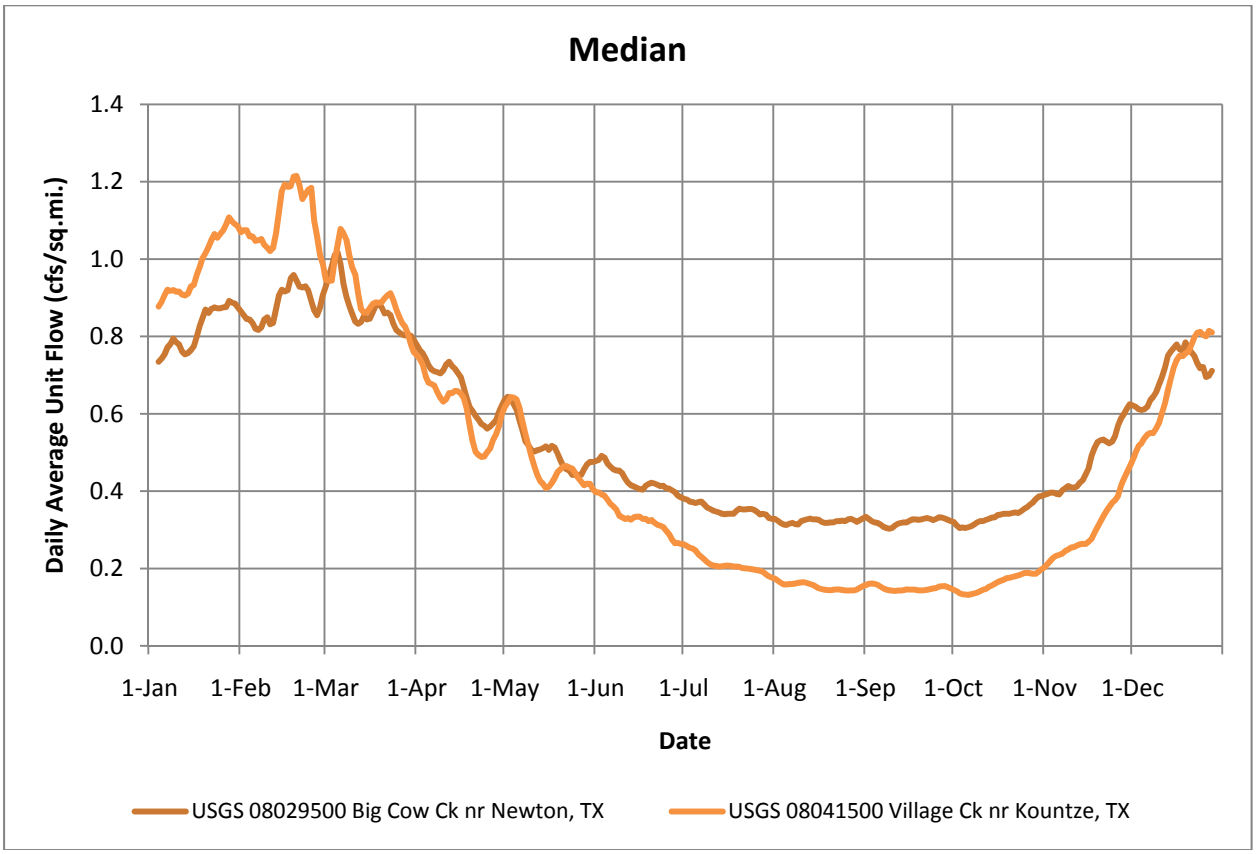


Figure 18: Unit Flows – Lower Basin Gages Unaffected by Hydropower



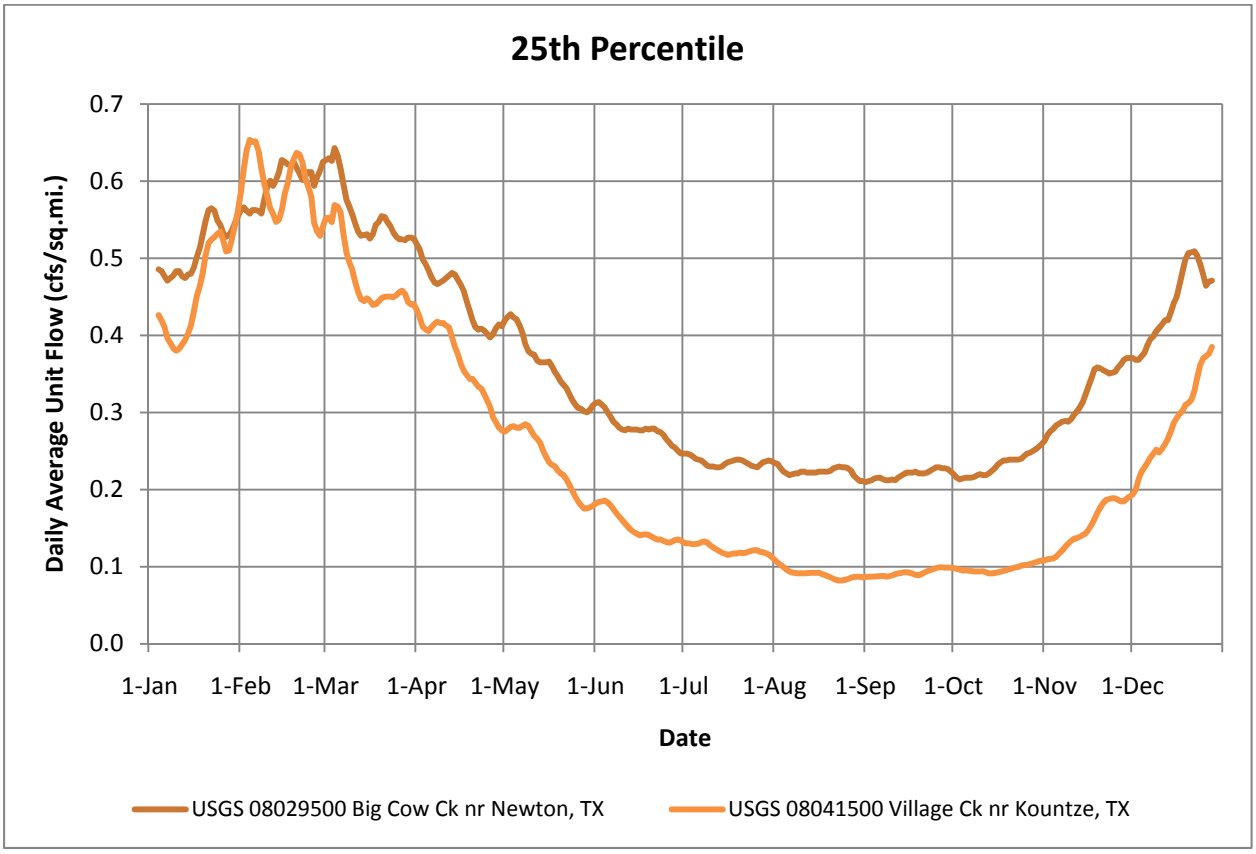
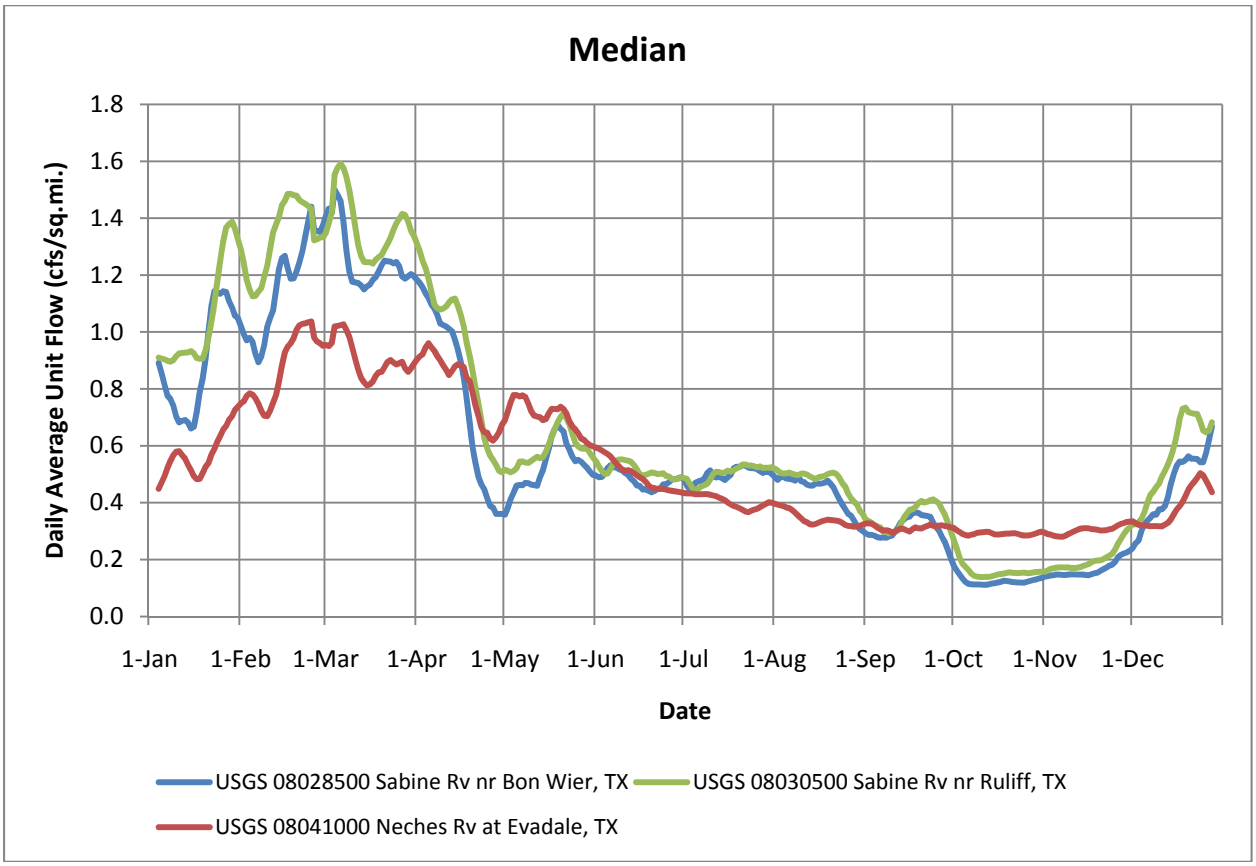


Figure 19: Unit Flows – Lower Basin Gages Affected by Hydropower



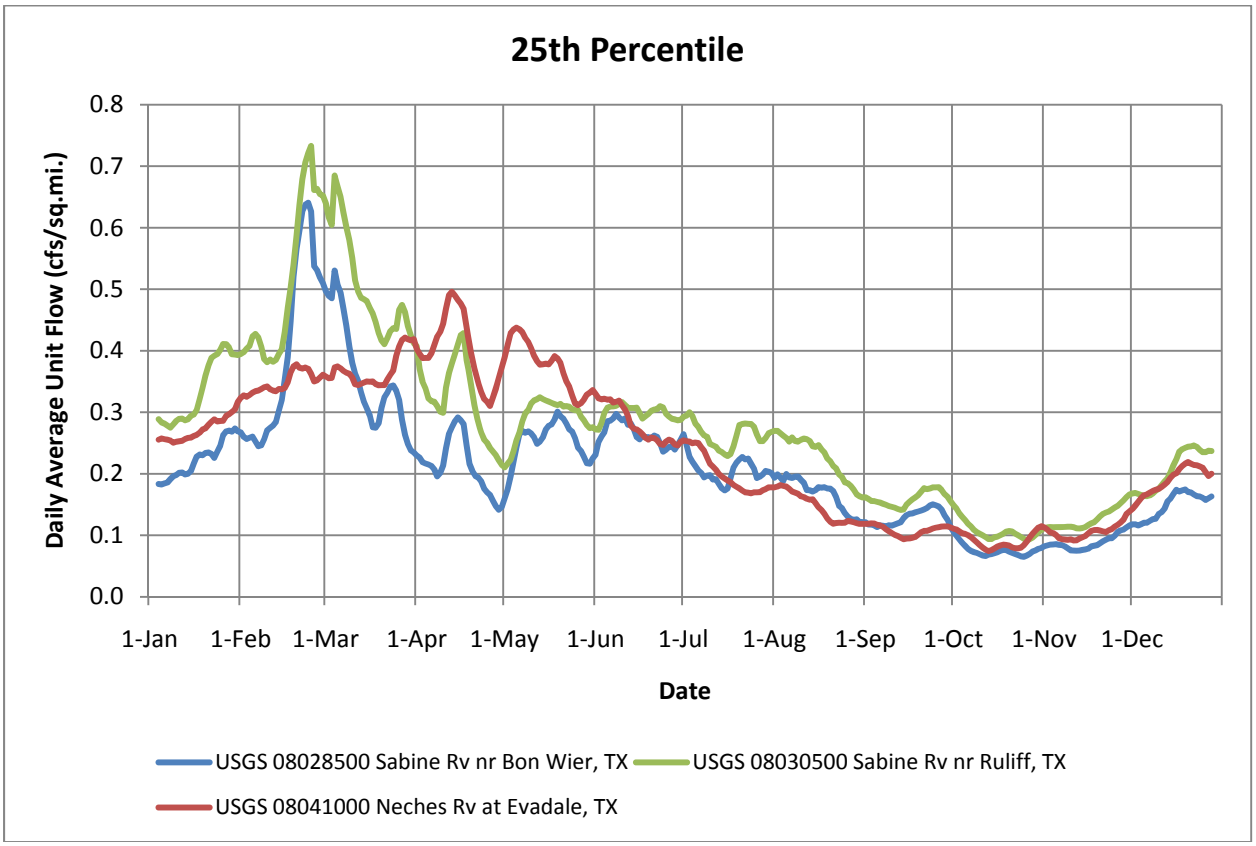


Table 6: Period of Record for USGS Daily Flow Statistics Used in Figures 16 through 18

USGS Gage Name	USGS Gage Number	Start Year	End Year
SABINE BASIN			
Big Sandy Creek nr Big Sandy	8019500	1963	2008
Sabine River nr Gladewater	8020000	1961	2008
Sabine River nr Beckville	8022040	1961	2008
Sabine River nr Bon Weir	8028500	1961	2008
Big Cow Creek nr Newton	8029500	1953	2008
Sabine River nr Ruliff	8030500	1961	2008
NECHES BASIN			
Village Creek nr Kountze	8041500	1940	2008
Neches River at Evadale	8041000	1951	2008
Attoyac Bayou nr Chireno	8038000	1956	1985
Angelina River nr Alto	8036500	1960	2008
Neches River near Rockland	8033500	1962	2008
Neches River at Neches	8032000	1962	2008

Figures 17 through 18 illustrate the typical seasonal flow patterns observed in the two basins. Table 6 shows the period of record for the flow statistics. Most of the statistics cover the period from about 1960 through 2008, although a few gages include data from the 1950s and even the 1940s. The daily medians were divided by the drainage area of each gage to develop unit flows per square mile. Use of unit flows facilitates comparison between gages. A seven-day moving average was applied to smooth the data for easier identification of trends.

Figures 16 and 17, which include gages in the upper portion of the two basins, show a consistent pattern of high flows centered on the months of February and March and low flows from July through October. The medians show a second high-flow peak occurring early in May. This peak is less pronounced in the 25th percentile flows. It is unclear if this second peak is something that occurs consistently or an artifact of the period of record. Flows tend to stay high throughout the spring, with frequent, large magnitude high flow events with little or no base flow dominated periods between events. In the summer, flows are dominated by base flows and low magnitude pulse flows. The pronounced decline in the month of June from the higher flow spring months to the low flow summer months is evident in most of the hydrologic

record.

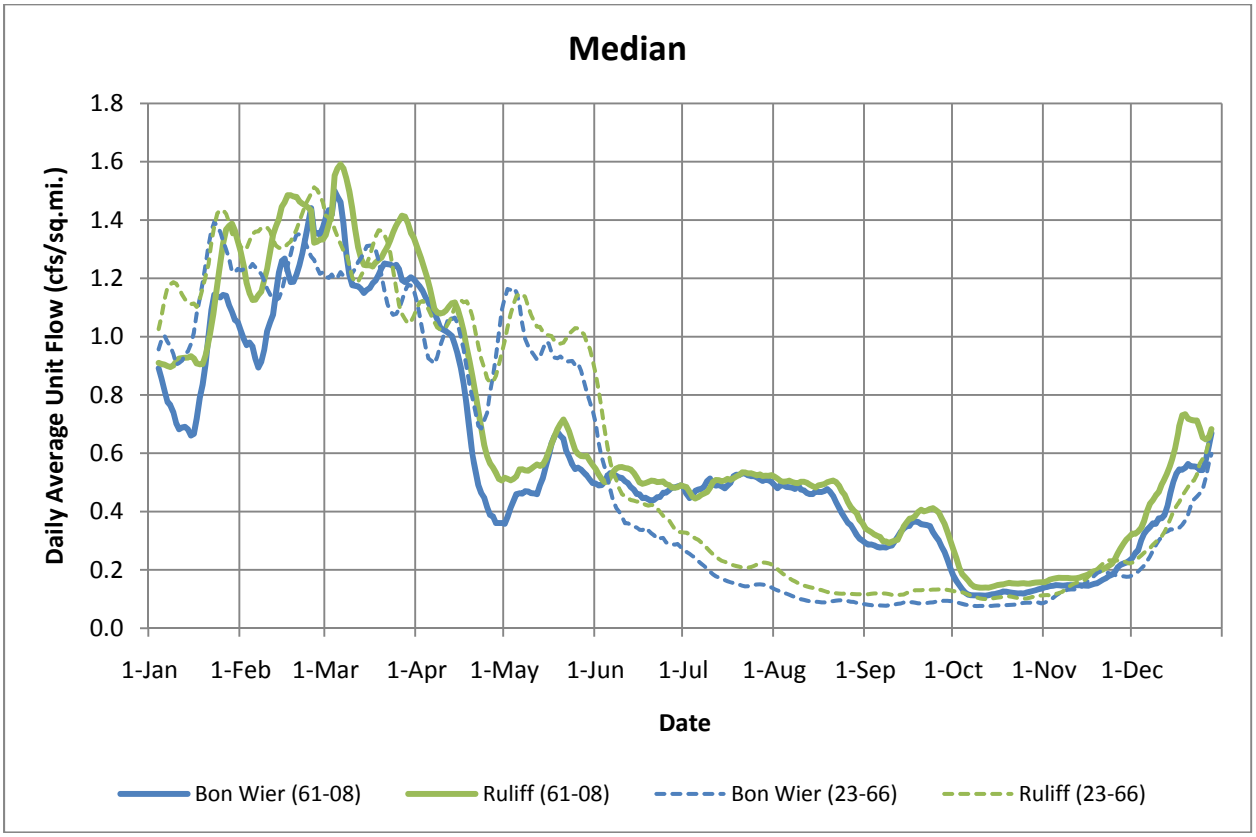
Figure 18 shows the median and 25th percentile flows for Big Cow Creek near Newton and Village Creek near Kountze, the two gages in the lower portions of the basins unaffected by hydropower operations at upstream reservoirs. These two gages show a similar pattern to the upper basin, but with higher unit flows and a slightly more gradual transition between higher spring flows and lower summer flows. The peak spring flow appears to come somewhat earlier, centered in the month of February.

Figure 19 shows the median and 25th percentile flows for the Sabine River near Bon Weir, Sabine River near Ruliff, and the Neches River at Evadale. The Bon Weir and Ruliff gages are downstream of Toledo Bend Reservoir, and the Evadale gage is downstream of the Sam Rayburn/B.A. Steinhagen reservoir system (See Figure 1). Both Toledo Bend and Rayburn/Steinhagen are used for hydropower generation, which affects the flow statistics. These gages show a similar pattern to the upper basin gages, but the difference between spring and summer flows is not as pronounced. Also, a fairly significant drop in flows around the beginning of October is apparent for the two Sabine River gages.

To see how hydropower generation has impacted flow statistics, FNI generated daily flow statistics for pre-reservoir conditions. Figure 20 compares the pre- and post-reservoir statistics for the two Sabine River gages (Ruliff and Bon Weir). Figure 21 compares similar data for the Evadale gage. (The USGS statistics for the Evadale gage begin in 1951, which is the date Lake Steinhagen was constructed. Sam Rayburn Reservoir was not completed until 1965.)

Figure 20 shows how flows have changed with Toledo Bend hydropower operation. Prior to the construction of Toledo Bend, the Bon Weir and Ruliff gages had flow patterns similar to the gages in the upper basin. Hydropower operations result in higher flows during the summer season than occurred prior to reservoir construction. The drop in flows at the beginning of October is probably the result of the end of the summer hydropower generation season at Toledo Bend, with flows returning to pre-dam levels in late October. Also note that the post-dam median flows are less in the month of May, and the 25th percentile flows are less throughout the high flow spring months. The most likely explanation is the retention of higher flows by Toledo Bend Reservoir, although climatic variation may be a factor as well.

Figure 20: Comparison of Pre-Reservoir and Post-Reservoir Statistics for the Bon Weir and Ruliff Gages



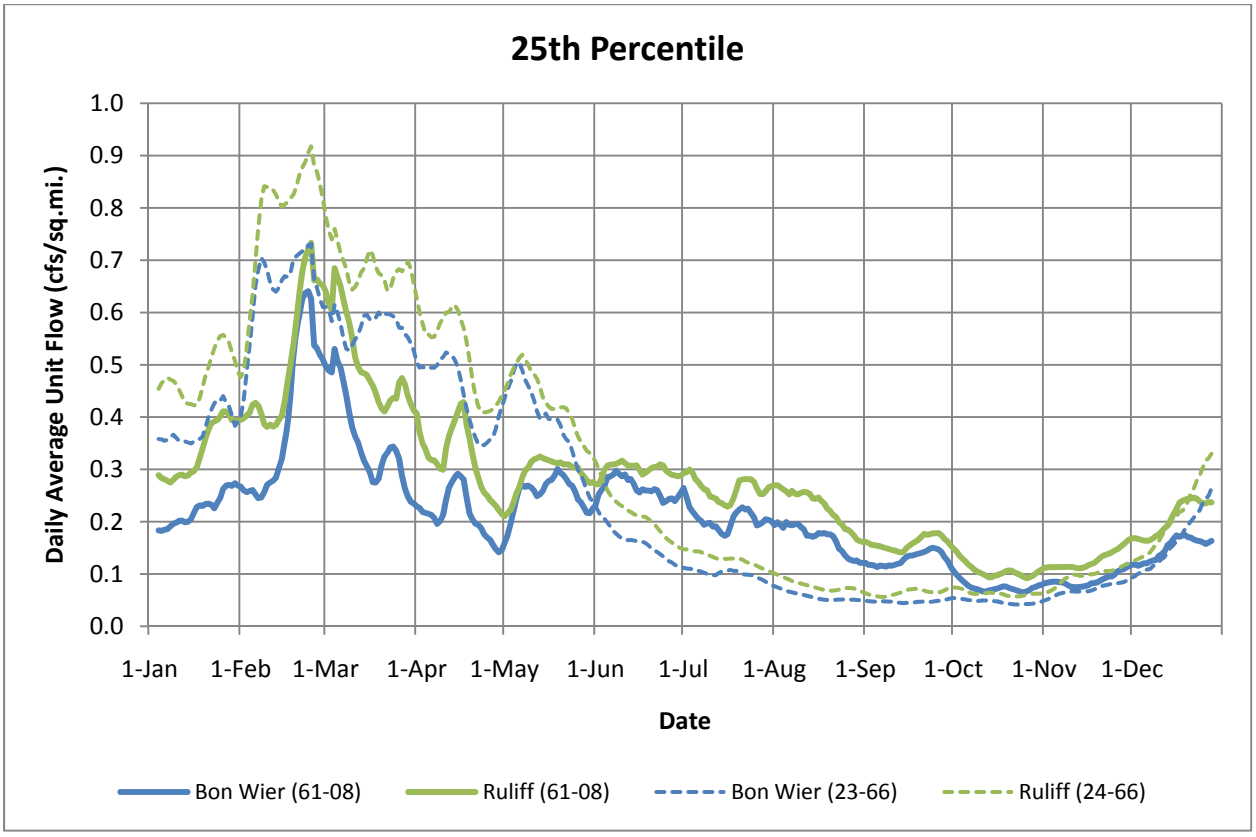
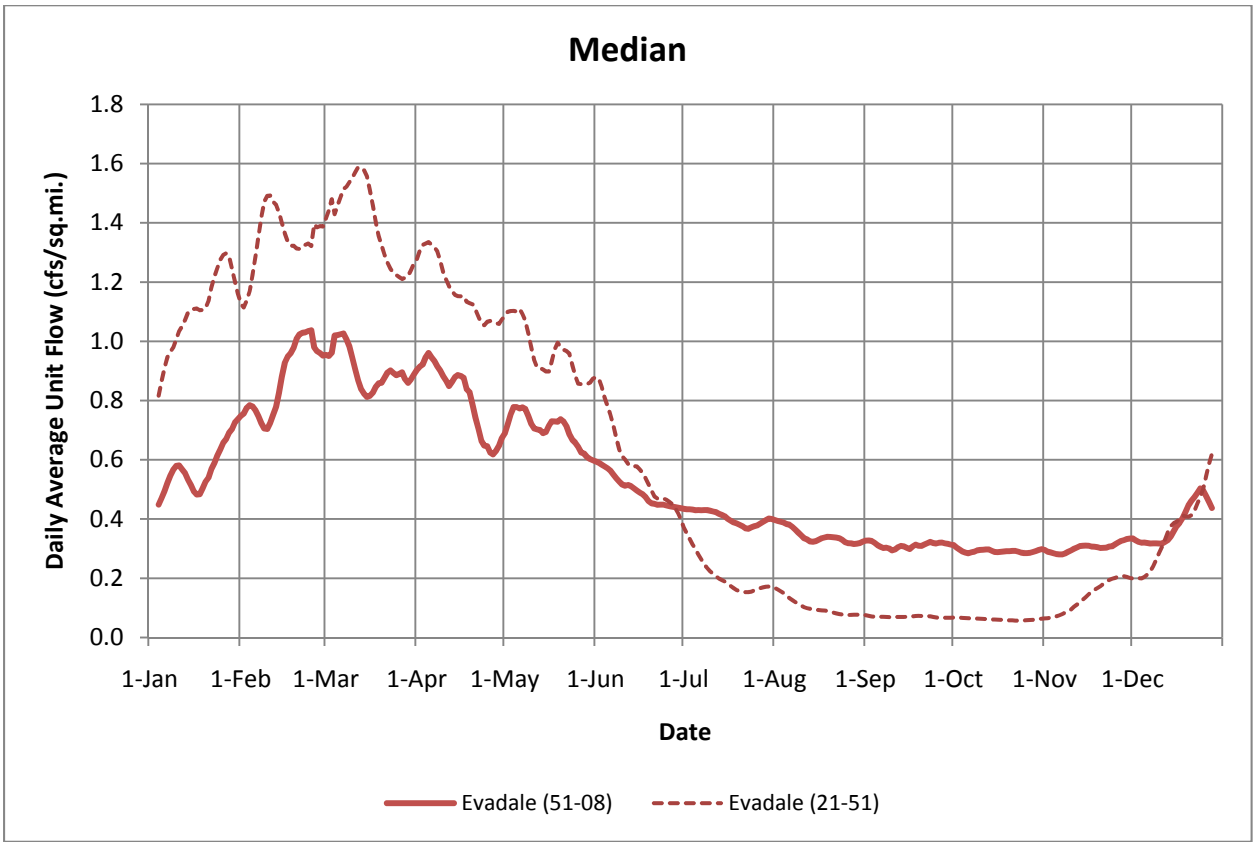
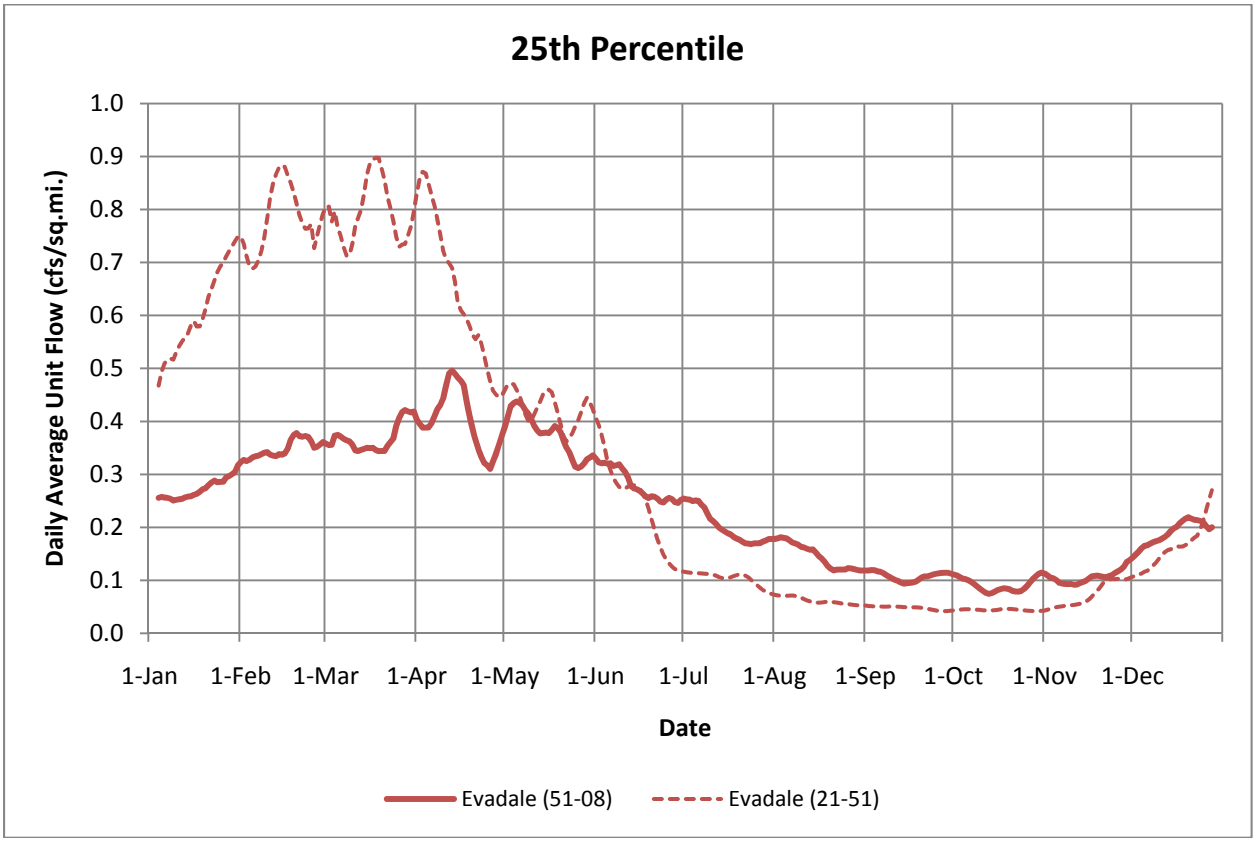


Figure 21: Comparison of Pre-Reservoir and Post-Reservoir Statistics for the Evadale Gage





As with the Sabine gages, Figure 21 shows that pre-dam seasonal flow characteristics at Evadale were closer to the gages in the upper portion of the basin. However, note that the post-dam seasonal flow pattern is somewhat flatter overall than the Sabine gages, with more reduction in flow during the high-flow months in the spring. The most likely explanation for the reduced flows in the spring is the flood operations of Sam Rayburn Reservoir. The reservoir stores potentially flood-producing storm events for gradual release over time. These trends shown in Figure 21 are consistent with the cumulative and annual flow data shown in Figure 8, Figure 9, and Figure 10. The overall volume of water passing the Evadale gage has probably not changed much with construction and operation of the Steinhagen/Rayburn system. However, the seasonal distribution of the flows has changed due to reservoir operations.

Summary and Conclusions

- The BBEST has selected six USGS stream gages in each basin for hydrologic analyses. Table 7 lists the selected gages, and Figure 22 shows the location of these gages. The BBEST gages will serve as the basis for a flow regime developed through the SB3 environmental flows process.

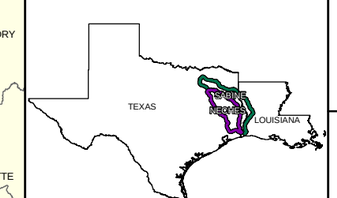
Table 7: USGS Stream Gages Selected by BBEST

USGS Gage Name	USGS Gage Number	HUC	County
SABINE BASIN			
Big Sandy Creek nr Big Sandy	8019500	12010002	Upshur
Sabine River nr Gladewater	8020000	12010002	Gregg
Sabine River nr Beckville	8022040	12010002	Panola
Sabine River nr Bon Weir	8028500	12010005	Newton
Big Cow Creek nr Newton	8029500	12010005	Newton
Sabine River nr Ruliff	8030500	12010005	Newton
NECHES BASIN			
Village Creek nr Kountze	8041500	12020006	Hardin
Neches River at Evadale	8041000	12020003	Jasper
Attoyac Bayou nr Chireno	8038000	12020005	San Augustine
Angelina River nr Alto	8036500	12020004	Cherokee
Neches River near Rockland	8033500	12020003	Tyler
Neches River at Neches	8032000	12020001	Cherokee

Sabine and Neches River Basins

LEGEND

- B — BBEST SELECTED GAGES
- NECHES BASIN
- SABINE BASIN
- RESERVOIR
- RIVER
- COUNTY



0 6.25 12.5 25 Miles

FNI PROJECT NO. TWD09238

FILE H:\WR_PLANNING\WORKING\FINAL\Figure23.mxd

DATUM & COORDINATE SYSTEM NAD83 STATE PLANE TX NORTH CENTRAL (FEET)

DATE AUGUST 2009

PREPARED BY DLB

SABINE AND NECHES RIVER BASINS

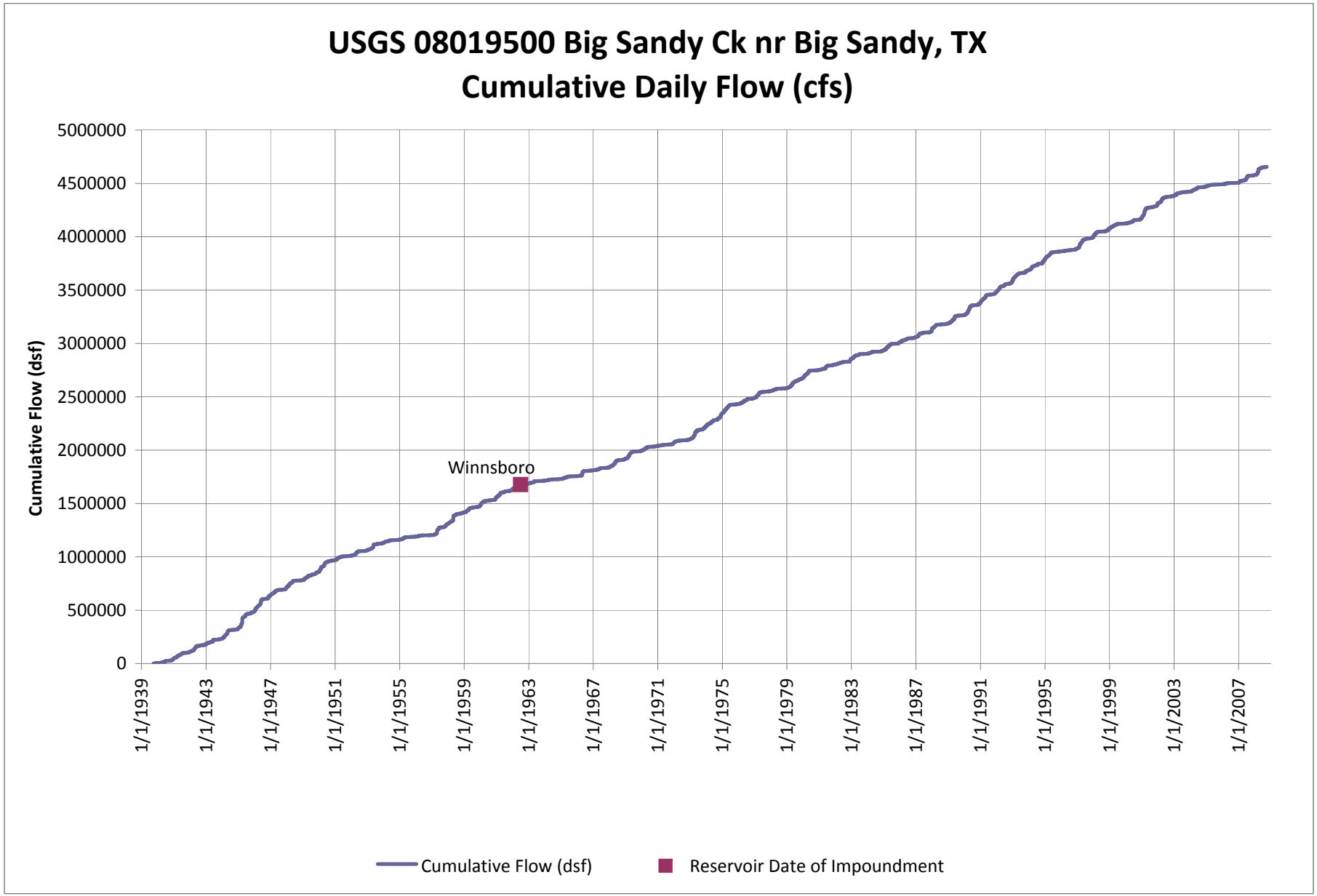
LOCATION MAP

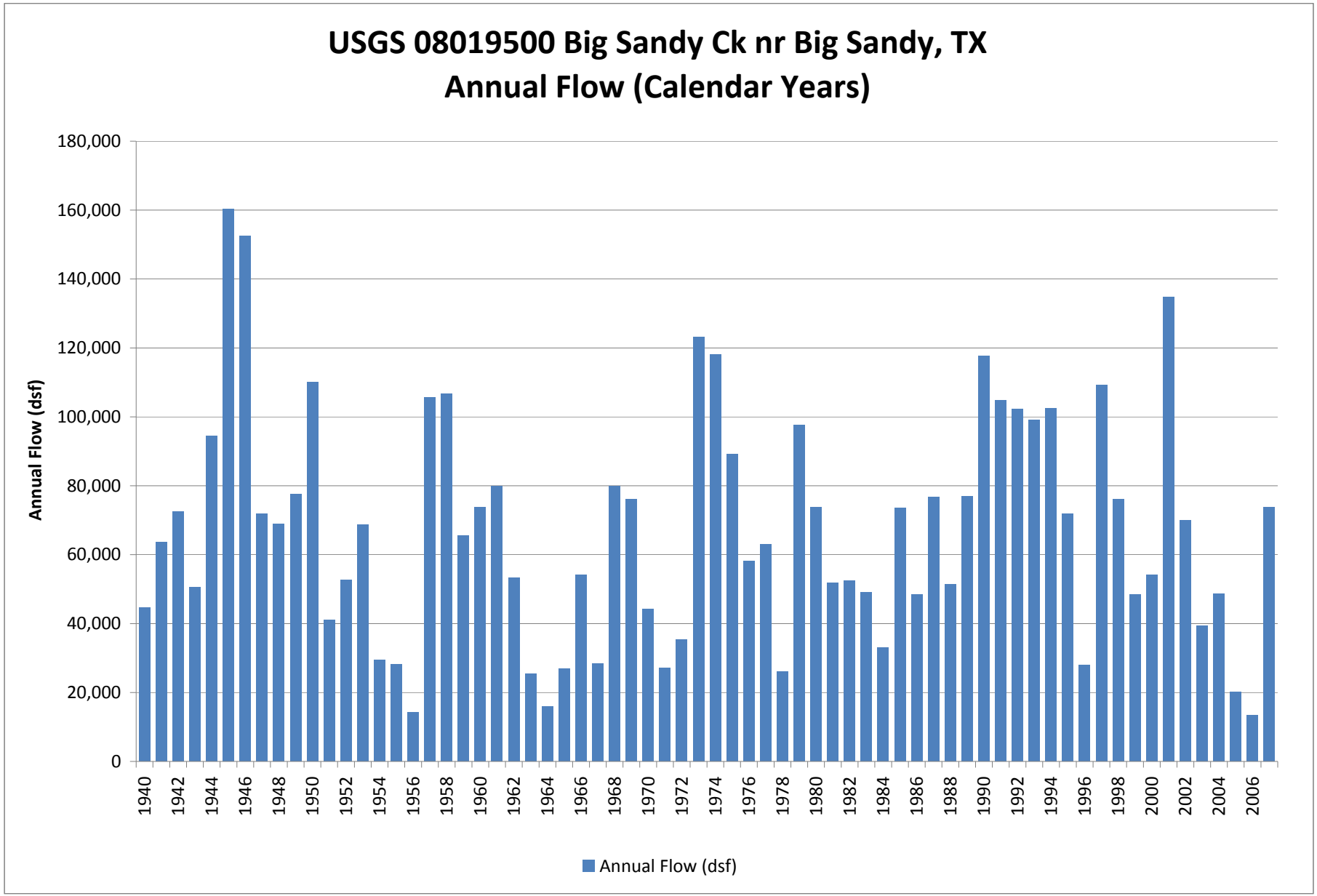
Freese and Nichols
4055 International Plaza, Suite 200
Fort Worth, Texas 76109-4895
817-735-7300

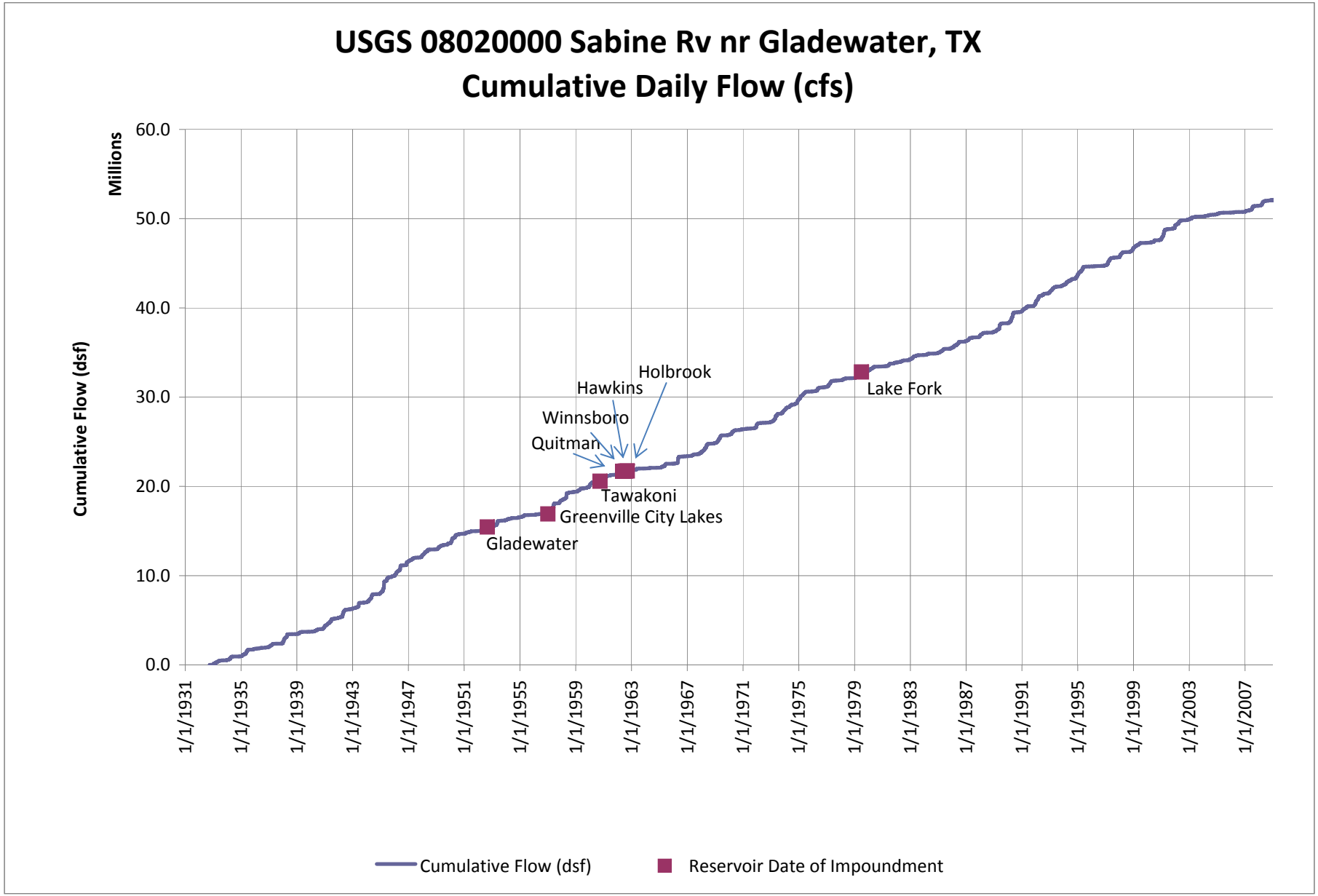
FIGURE 23

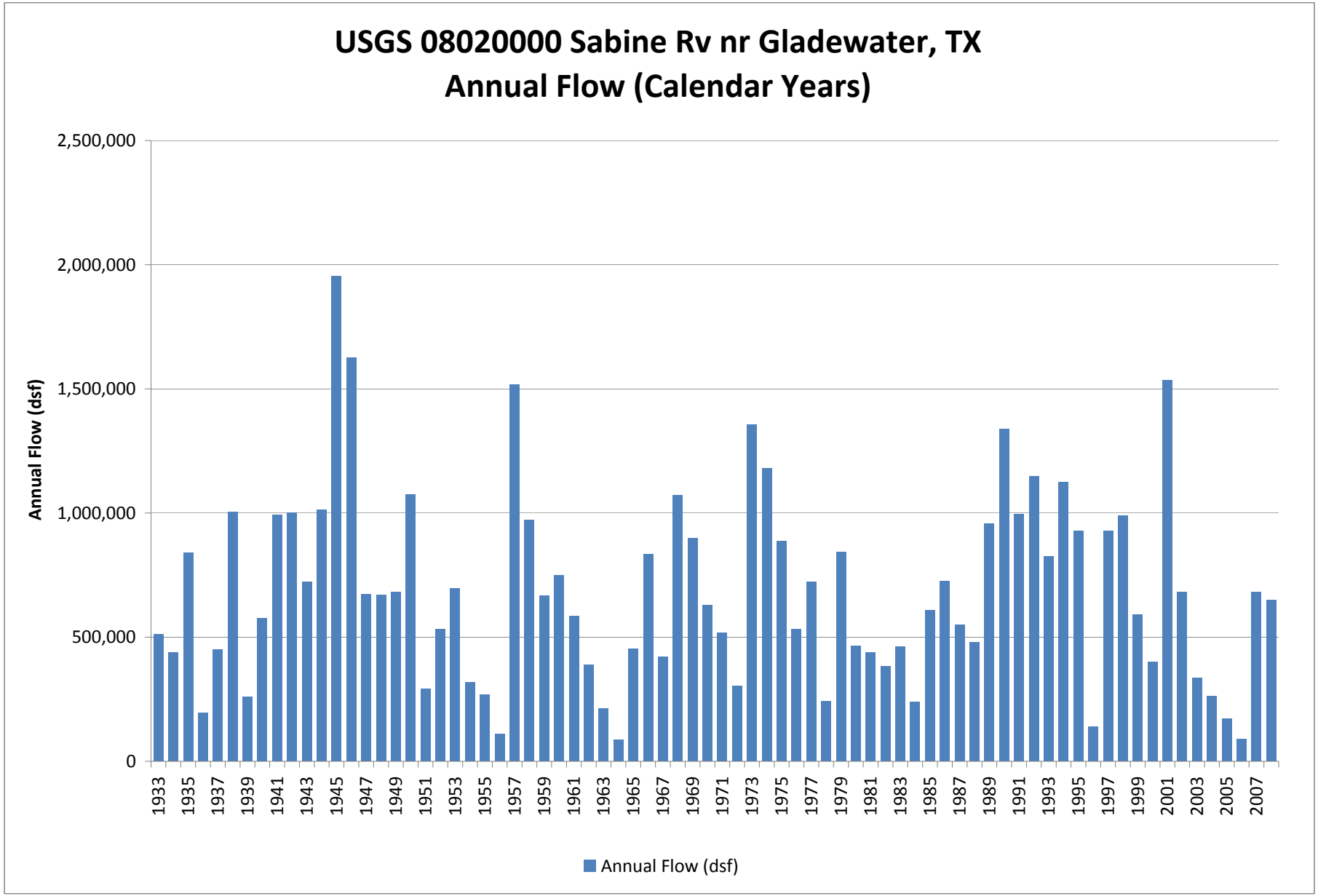
- The geographic coverage of the stream gages was evaluated in light of the process developed by the SAC as outlined in the report entitled *Geographic Scope of Instream Flow Recommendations.* In our opinion, these gages appear to adequately cover both basins geographically.
- The selected gages in the basins exhibit strong seasonal flow patterns, with higher flows concentrated in the spring and persistent low flows during the later part of the summer. It is likely that most species are adapted to this flow pattern making it an important aspect of a flow regime adequate to support a sound ecological environment.
- The historical gage records were analyzed to determine changes to flows over time. The Sabine River near Ruliff, Sabine River near Bon Weir, and the Neches River at Evadale gage show altered seasonal flow patterns because of hydropower and flood operations of upstream reservoirs. Other environmental factors should be examined in these reaches to determine if the altered flow regime has been detrimental to the environment. The overall volume of water passing these three gages does not appear to have been significantly reduced over time.
- At this time, flows at the other gages in the basin appear to be minimally altered by upstream developments in the watersheds. However, most of the larger water supply reservoirs in the basin have not yet been fully used at their authorized water supply potential. WAM analyses performed as part of this study will give an indication of the extent that flows may be changed as these resources are further developed. It is unclear how future water supply development will affect the existing environment.

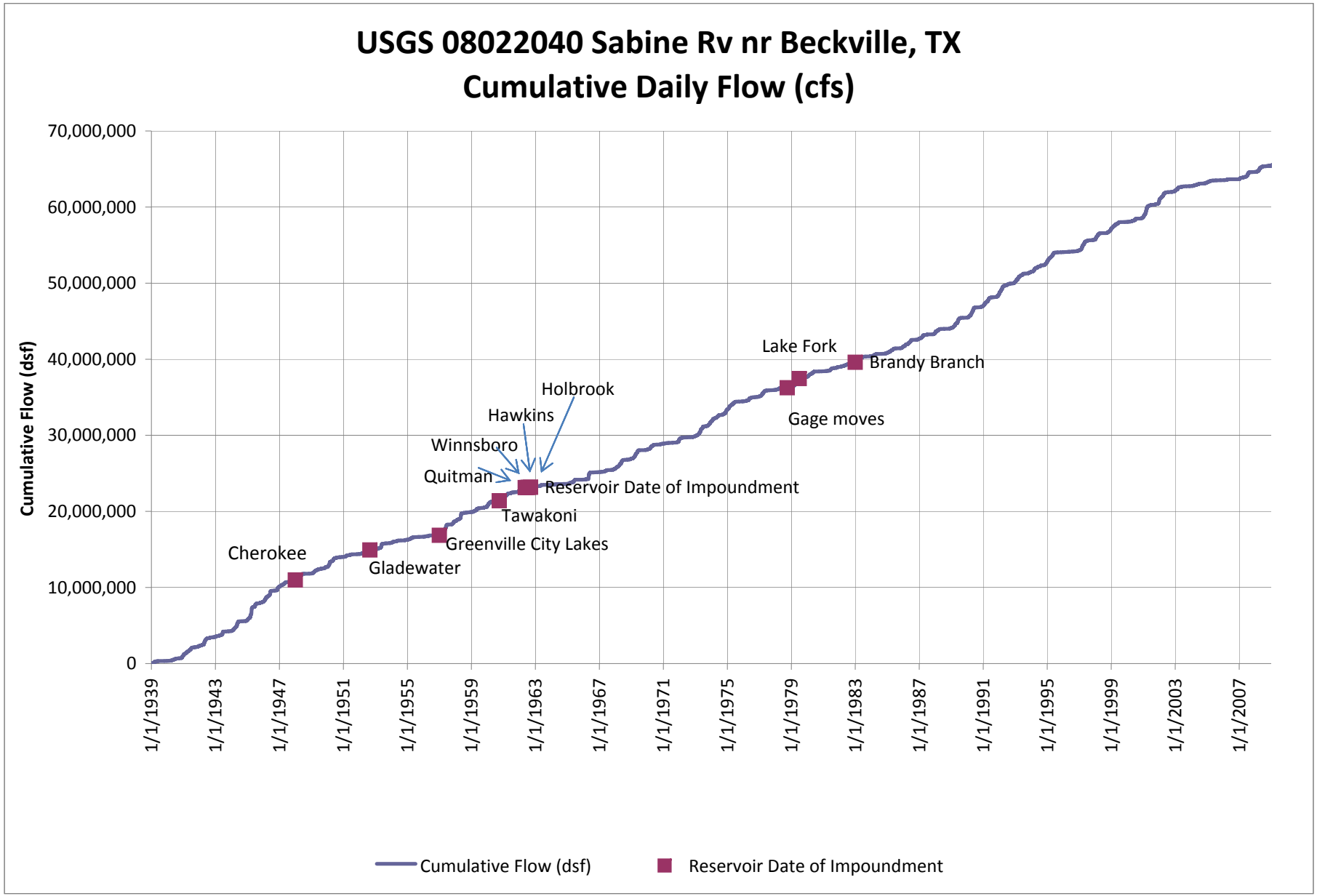
Attachment A
Gage Graphs

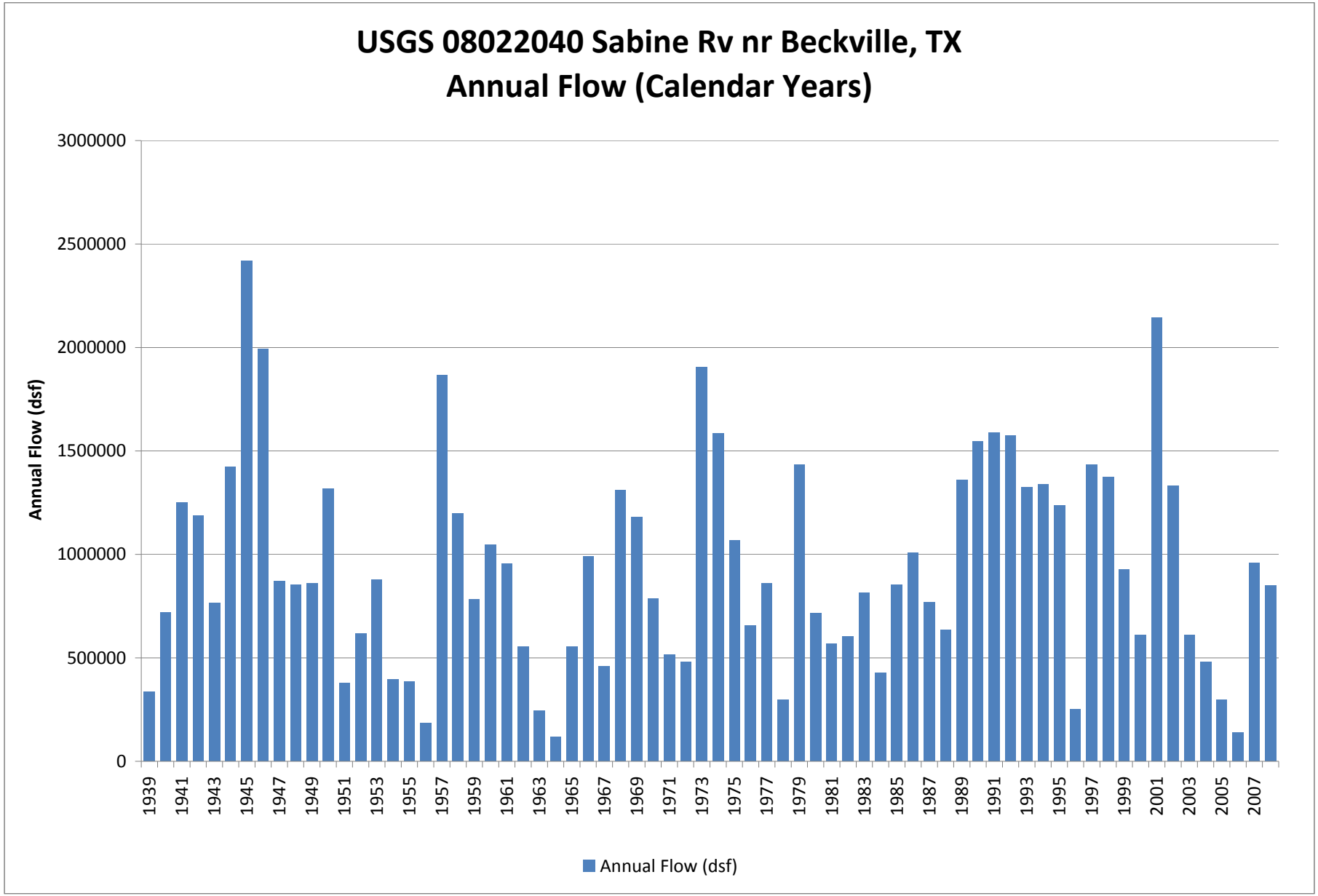

USGS 08019500 Big Sandy Ck nr Big Sandy, TX
Cumulative Daily Flow (cfs)
Cumulative Flow (dsf)
5000000
4500000
4000000
3500000
3000000
2500000
2000000
1500000
1000000
500000
0
Winnsboro
1/1/1939
1/1/1943
1/1/1947
1/1/1951
1/1/1955
1/1/1959
1/1/1963
1/1/1967
1/1/1971
1/1/1975
1/1/1979
1/1/1983
1/1/1987
1/1/1991
1/1/1995
1/1/1999
1/1/2003
1/1/2007
Cumulative Flow (dsf)
Reservoir Date of Impoundment

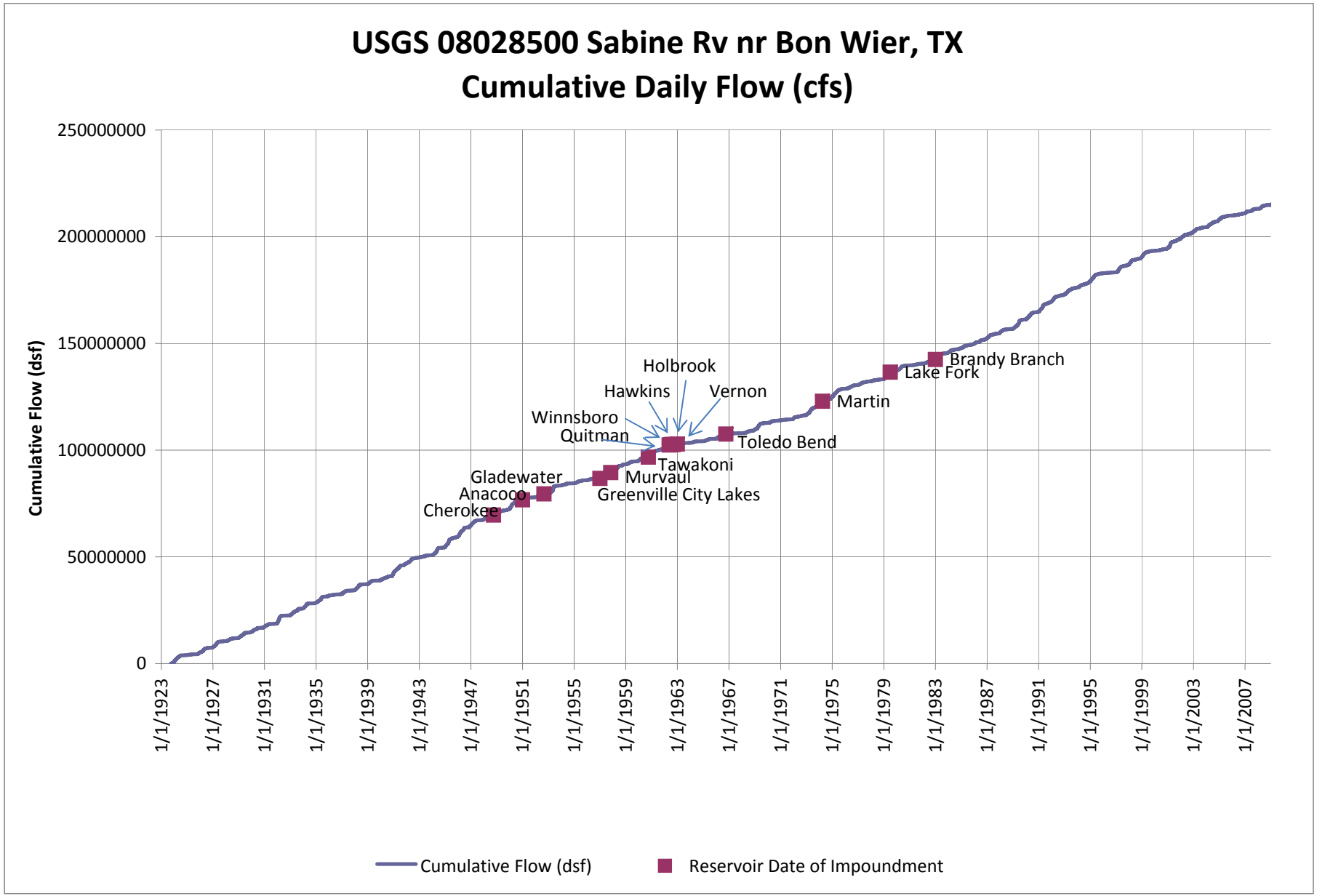

USGS 08019500 Big Sandy Ck nr Big Sandy, TX
Annual Flow (Calendar Years)
Annual Flow (dsf)
180,000
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
1940
1942
1944
1946
1948
1950
1952
1954
1956
1958
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
Annual Flow (dsf)

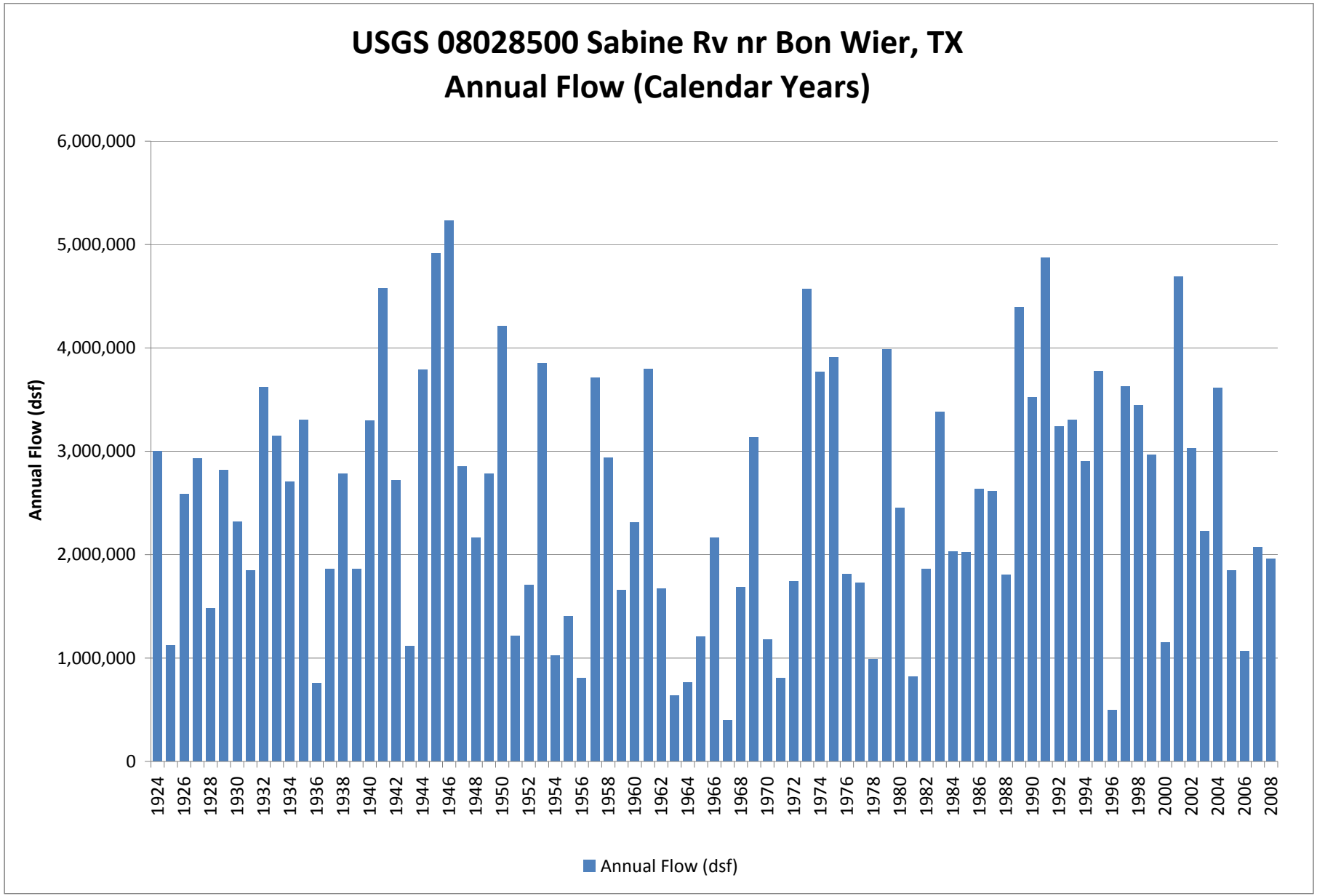

USGS 08020000 Sabine Rv nr Gladewater, TX
Cumulative Daily Flow (cfs)
Millions
Cumulative Flow (dsf)
60.0
50.0
40.0
30.0
20.0
10.0
0.0
1/1/1931
1/1/1935
1/1/1939
1/1/1943
1/1/1947
1/1/1951
1/1/1955
1/1/1959
1/1/1963
1/1/1967
1/1/1971
1/1/1975
1/1/1979
1/1/1983
1/1/1987
1/1/1991
1/1/1995
1/1/1999
1/1/2003
1/1/2007
Holbrook
Hawkins
Winnsboro
Quitman
Lake Fork
Tawakoni
Greenville City Lakes
Gladewater
Cumulative Flow (dsf)
Reservoir Date of Impoundment

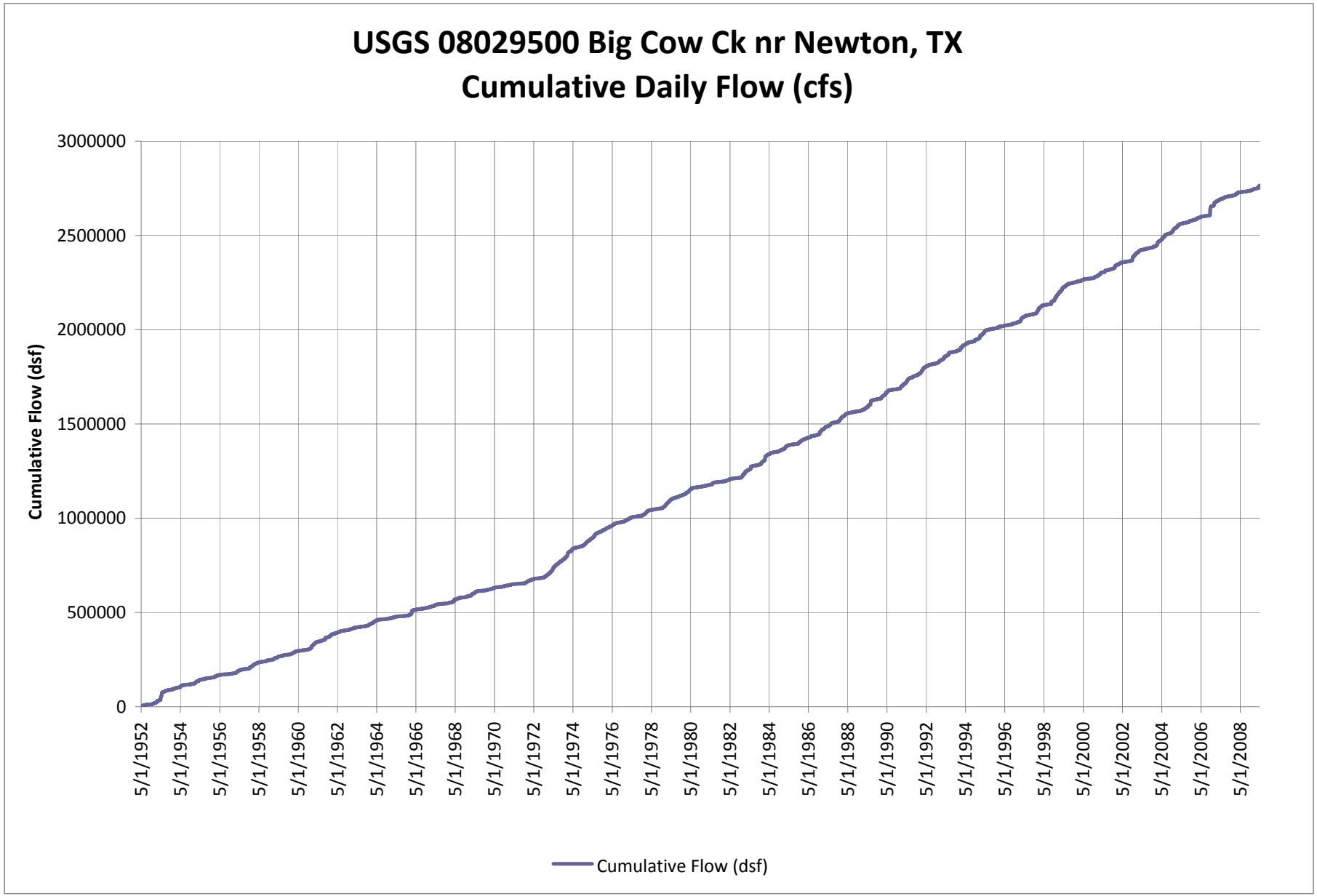

USGS 08020000 Sabine Rv nr Gladewater, TX
Annual Flow (Calendar Years)
Annual Flow (dsf)
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
1933
1935
1937
1939
1941
1943
1945
1947
1949
1951
1953
1955
1957
1959
1961
1963
1965
1967
1969
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
Annual Flow (dsf)

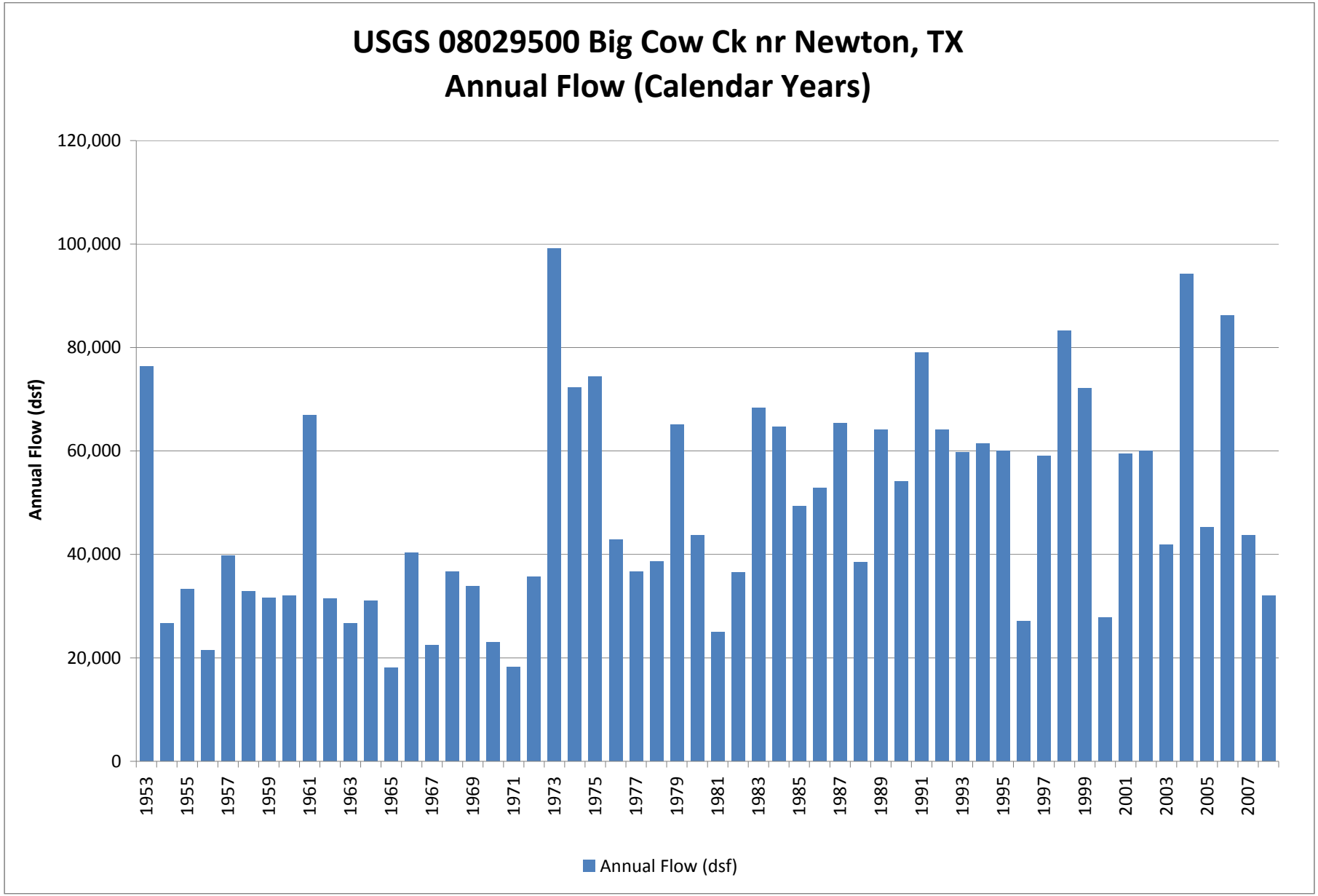

USGS 08022040 Sabine Rv nr Beckville, TX
Cumulative Daily Flow (cfs)
Cumulative Flow (dsf)
70,000,000
60,000,000
50,000,000
40,000,000
30,000,000
20,000,000
10,000,000
0
1/1/1939
1/1/1943
1/1/1947
1/1/1951
1/1/1955
1/1/1959
1/1/1963
1/1/1967
1/1/1971
1/1/1975
1/1/1979
1/1/1983
1/1/1987
1/1/1991
1/1/1995
1/1/1999
1/1/2003
1/1/2007
Cherokee
Gladewater
Greenville City Lakes
Tawakoni
Quitman
Winnsboro
Hawkins
Holbrook
Reservoir Date of Impoundment
Gage moves
Lake Fork
Brandy Branch
Cumulative Flow (dsf)
Reservoir Date of Impoundment

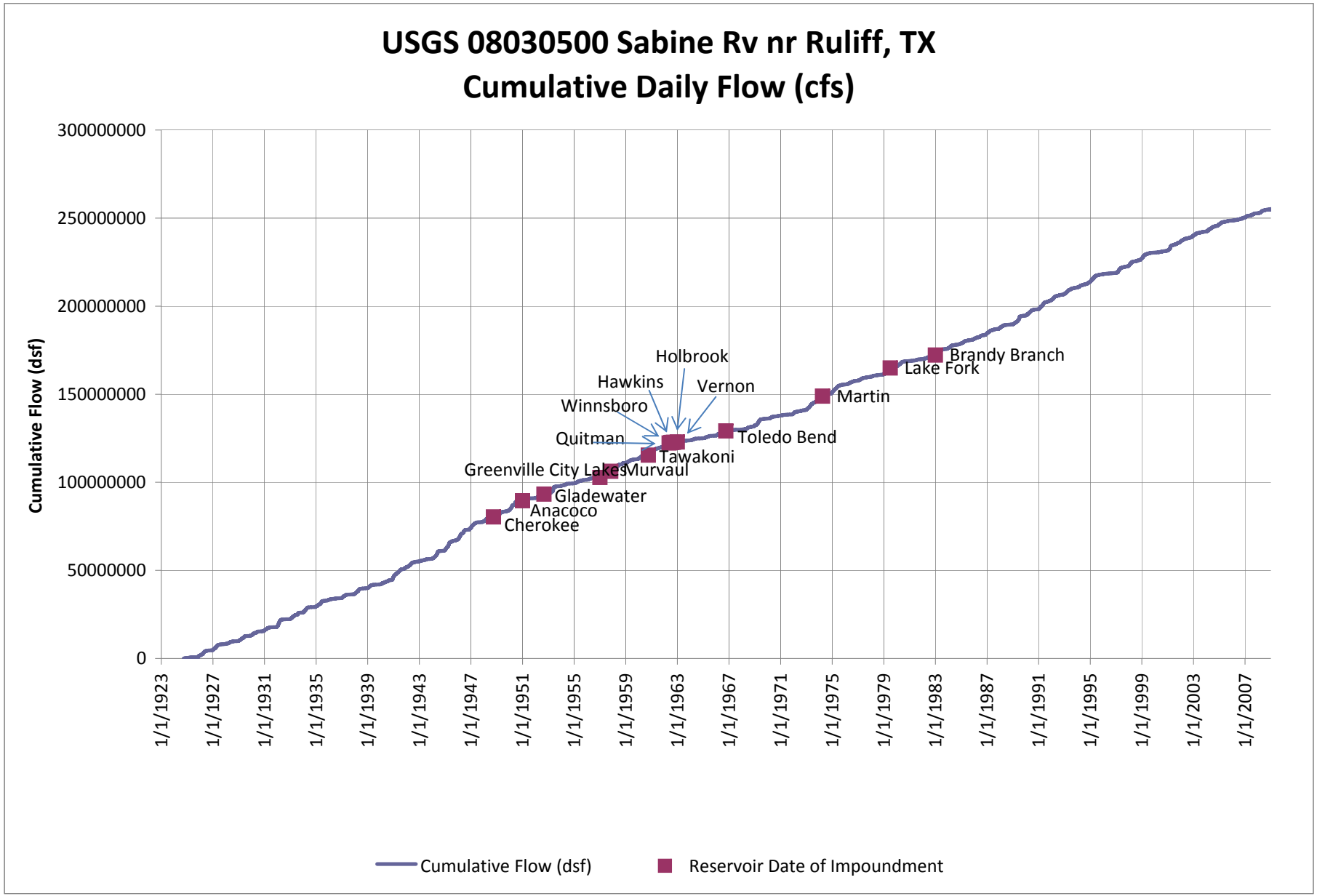

USGS 08022040 Sabine Rv nr Beckville, TX
Annual Flow (Calendar Years)
Annual Flow (dsf)
3000000
2500000
2000000
1500000
1000000
500000
0
1939
1941
1943
1945
1947
1949
1951
1953
1955
1957
1959
1961
1963
1965
1967
1969
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
Annual Flow (dsf)

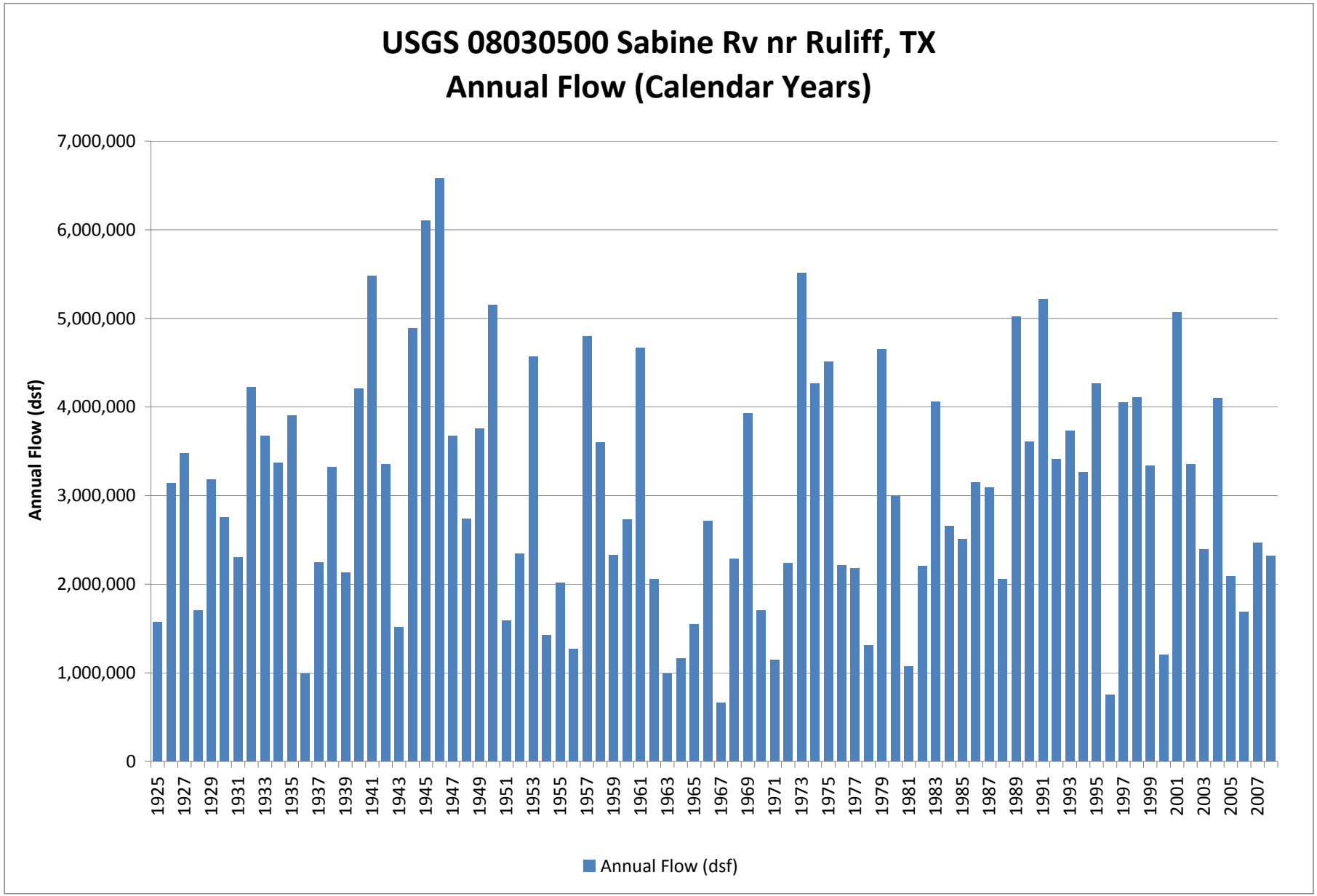

USGS 08028500 Sabine Rv nr Bon Wier, TX
Cumulative Daily Flow (cfs)
Cumulative Flow (dsf)
250000000
200000000
150000000
100000000
50000000
0
1/1/1923
1/1/1927
1/1/1931
1/1/1935
1/1/1939
1/1/1943
1/1/1947
1/1/1951
1/1/1955
1/1/1959
1/1/1963
1/1/1967
1/1/1971
1/1/1975
1/1/1979
1/1/1983
1/1/1987
1/1/1991
1/1/1995
1/1/1999
1/1/2003
1/1/2007
Cherokee
Anacoco
Gladewater
Greenville City Lakes
Murvaul
Tawakoni
Quitman
Winnsboro
Hawkins
Holbrook
Vernon
Toledo Bend
Martin
Lake Fork
Brandy Branch
Cumulative Flow (dsf)
Reservoir Date of Impoundment

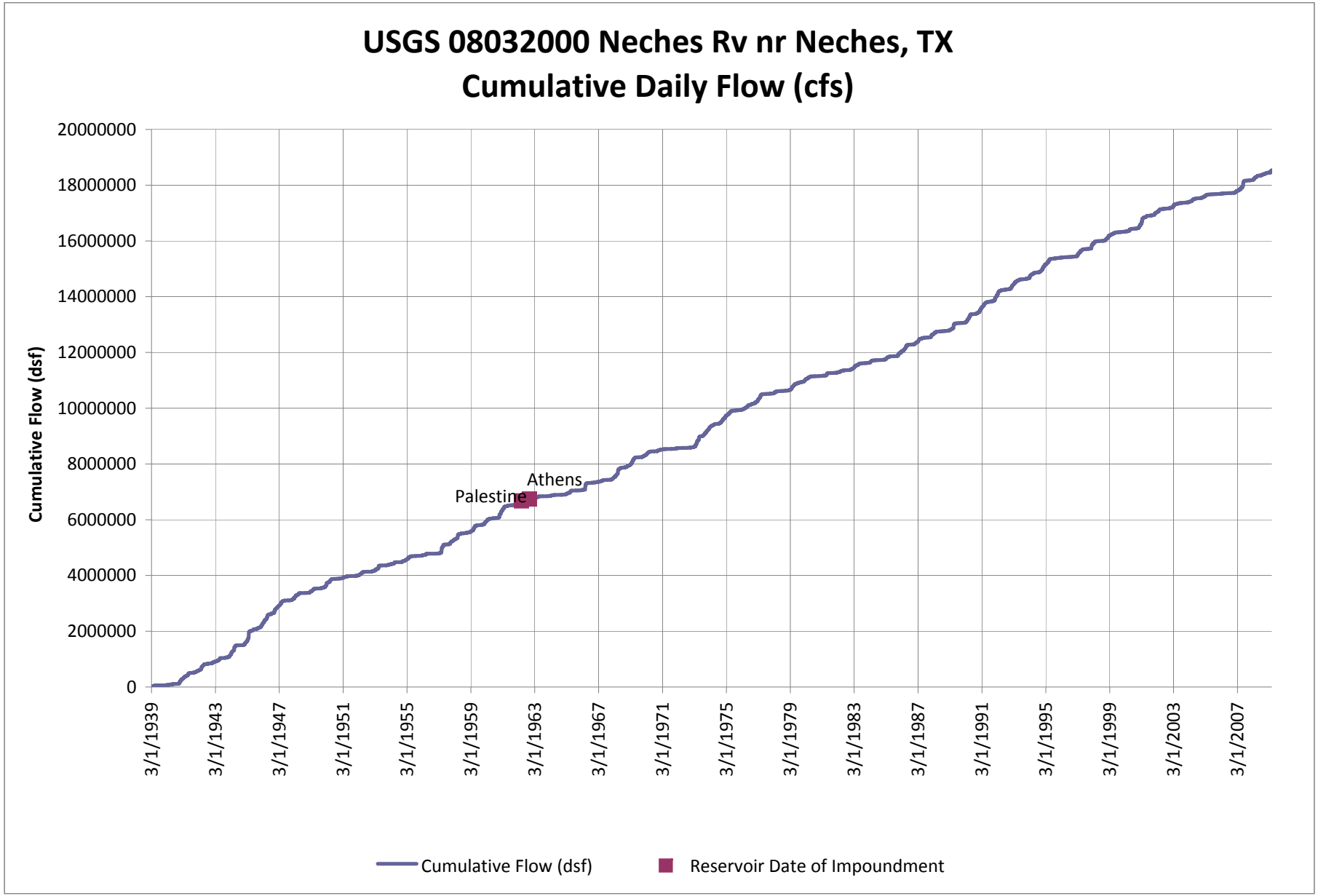

USGS 08028500 Sabine Rv nr Bon Wier, TX
Annual Flow (Calendar Years)
Annual Flow (dsf)
6,000,000
5,000,000
4,000,000
3,000,000
2,000,000
1,000,000
0
1924
1926
1928
1930
1932
1934
1936
1938
1940
1942
1944
1946
1948
1950
1952
1954
1956
1958
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
Annual Flow (dsf)

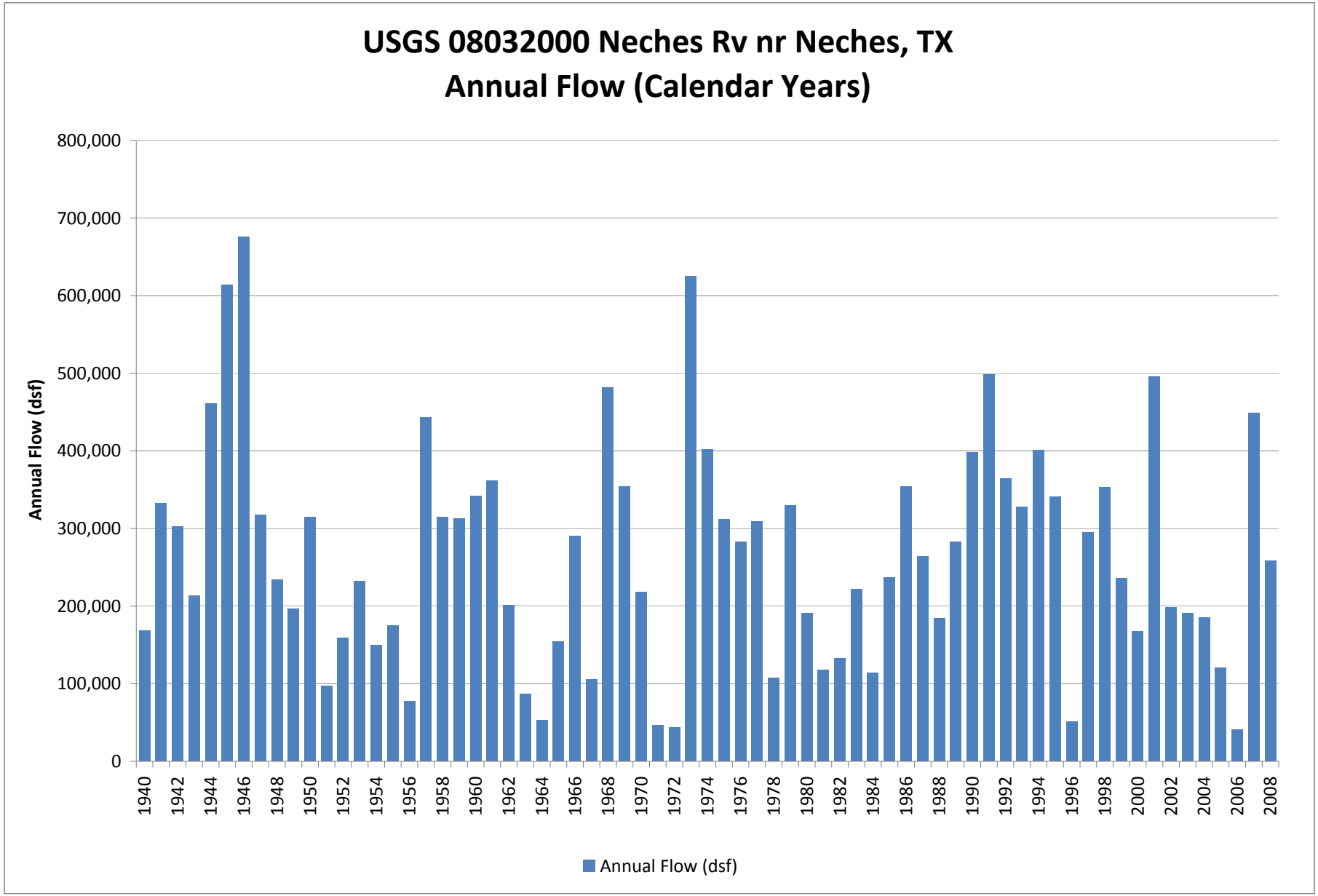

USGS 08029500 Big Cow Ck nr Newton, TX
Cumulative Daily Flow (cfs)
Cumulative Flow (dsf)
3000000
2500000
2000000
1500000
1000000
500000
0
5/1/1952
5/1/1954
5/1/1956
5/1/1958
5/1/1960
5/1/1962
5/1/1964
5/1/1966
5/1/1968
5/1/1970
5/1/1972
5/1/1974
5/1/1976
5/1/1978
5/1/1980
5/1/1982
5/1/1984
5/1/1986
5/1/1988
5/1/1990
5/1/1992
5/1/1994
5/1/1996
5/1/1998
5/1/2000
5/1/2002
5/1/2004
5/1/2006
5/1/2008
Cumulative Flow (dsf)

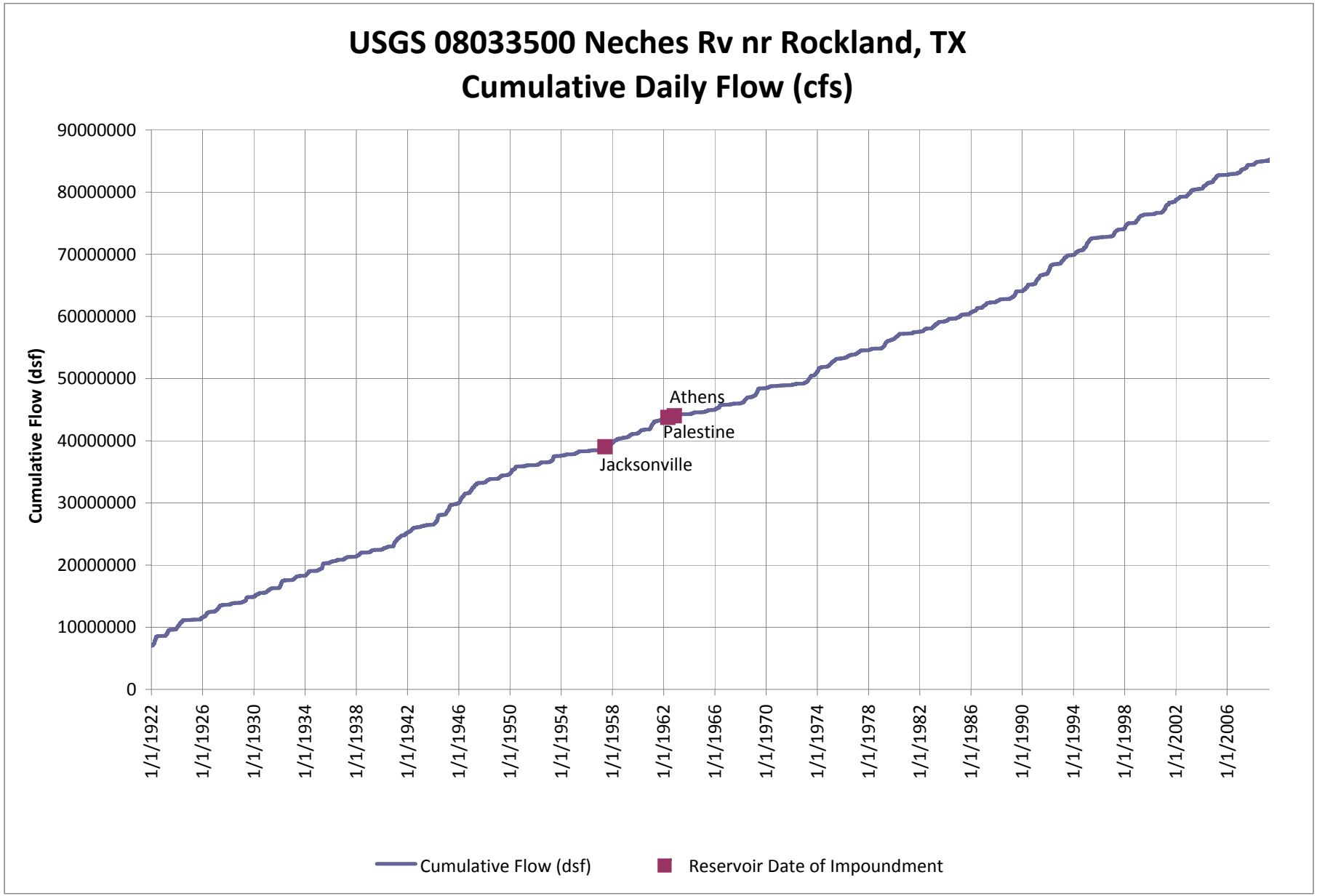

USGS 08029500 Big Cow Ck nr Newton, TX
Annual Flow (Calendar Years)
Annual Flow (dsf)
120,000
100,000
80,000
60,000
40,000
20,000
0
1953
1955
1957
1959
1961
1963
1965
1967
1969
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
Annual Flow (dsf)

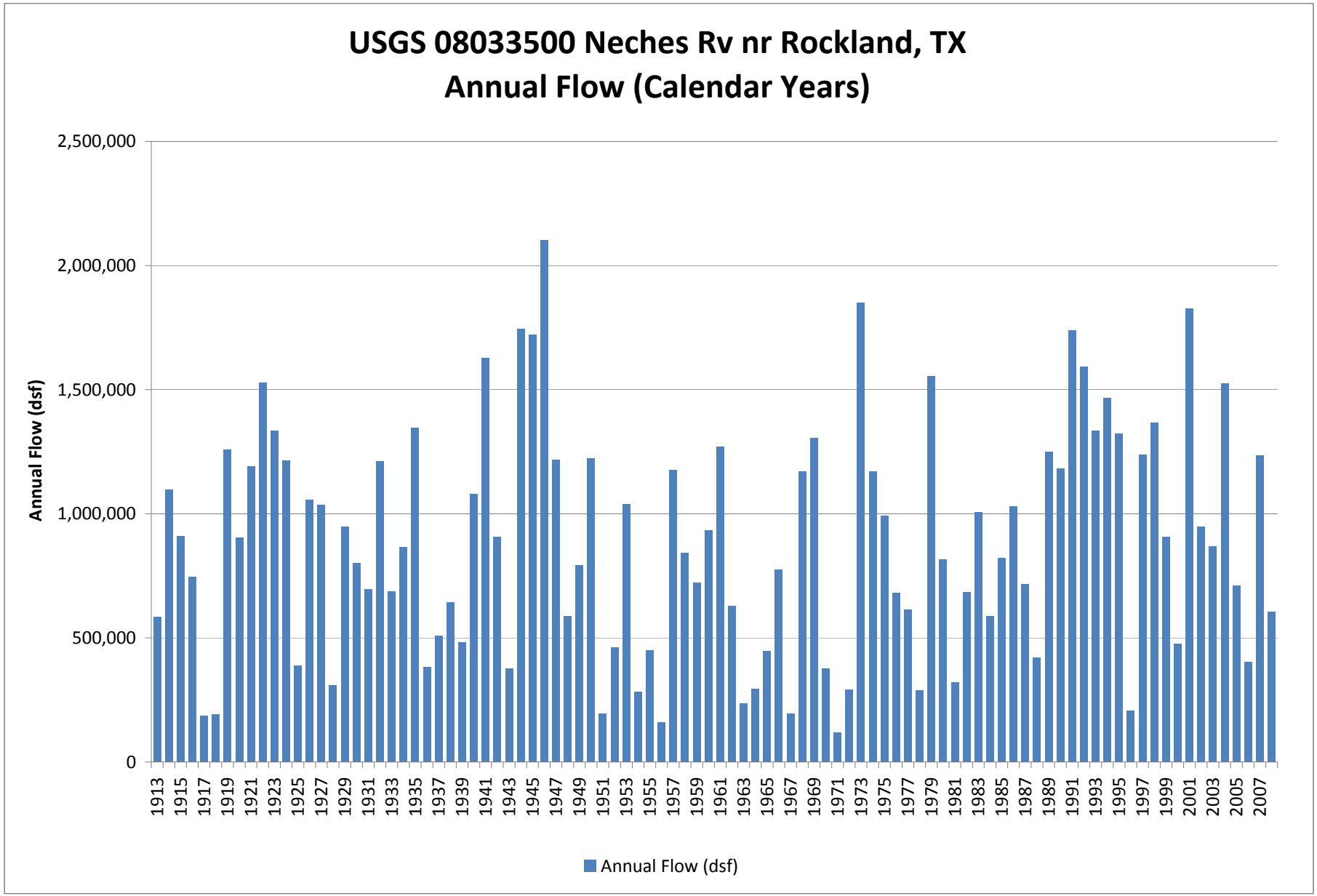

USGS 08030500 Sabine Rv nr Ruliff, TX
Cumulative Daily Flow (cfs)
Cumulative Flow (dsf)
300000000
250000000
200000000
150000000
100000000
50000000
0
1/1/1923
1/1/1927
1/1/1931
1/1/1935
1/1/1939
1/1/1943
1/1/1947
1/1/1951
1/1/1955
1/1/1959
1/1/1963
1/1/1967
1/1/1971
1/1/1975
1/1/1979
1/1/1983
1/1/1987
1/1/1991
1/1/1995
1/1/1999
1/1/2003
1/1/2007
Holbrook
Hawkins
Vernon
Winnsboro
Quitman
Tawakoni
Greenville City Lakes
Murvaul
Gladewater
Anacoco
Cherokee
Toledo Bend
Martin
Lake Fork
Brandy Branch
Cumulative Flow (dsf)
Reservoir Date of Impoundment


USGS 08030500 Sabine Rv nr Ruliff, TX
Annual Flow (Calendar Years)
Annual Flow (dsf)
7,000,000
6,000,000
5,000,000
4,000,000
3,000,000
2,000,000
1,000,000
0
1925
1927
1929
1931
1933
1935
1937
1939
1941
1943
1945
1947
1949
1951
1953
1955
1957
1959
1961
1963
1965
1967
1969
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
Annual Flow (dsf)


USGS 08032000 Neches Rv nr Neches, TX
Cumulative Daily Flow (cfs)
Cumulative Flow (dsf)
20000000
18000000
16000000
14000000
12000000
10000000
8000000
6000000
4000000
2000000
0
Palestine
Athens
3/1/1939
3/1/1943
3/1/1947
3/1/1951
3/1/1955
3/1/1959
3/1/1963
3/1/1967
3/1/1971
3/1/1975
3/1/1979
3/1/1983
3/1/1987
3/1/1991
3/1/1995
3/1/1999
3/1/2003
3/1/2007
Cumulative Flow (dsf)
Reservoir Date of Impoundment


USGS 08032000 Neches Rv nr Neches, TX
Annual Flow (Calendar Years)
Annual Flow (dsf)
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
1940
1942
1944
1946
1948
1950
1952
1954
1956
1958
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
Annual Flow (dsf)


USGS 08033500 Neches Rv nr Rockland, TX
Cumulative Daily Flow (cfs)
Cumulative Flow (dsf)
90000000
80000000
70000000
60000000
50000000
40000000
30000000
20000000
10000000
0
1/1/1922
1/1/1926
1/1/1930
1/1/1934
1/1/1938
1/1/1942
1/1/1946
1/1/1950
1/1/1954
1/1/1958
1/1/1962
1/1/1966
1/1/1970
1/1/1974
1/1/1978
1/1/1982
1/1/1986
1/1/1990
1/1/1994
1/1/1998
1/1/2002
1/1/2006
Athens
Palestine
Jacksonville
Cumulative Flow (dsf)
Reservoir Date of Impoundment


USGS 08033500 Neches Rv nr Rockland, TX
Annual Flow (Calendar Years)
Annual Flow (dsf)
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
1913
1915
1917
1919
1921
1923
1925
1927
1929
1931
1933
1935
1937
1939
1941
1943
1945
1947
1949
1951
1953
1955
1957
1959
1961
1963
1965
1967
1969
1971
1973
1975
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1985
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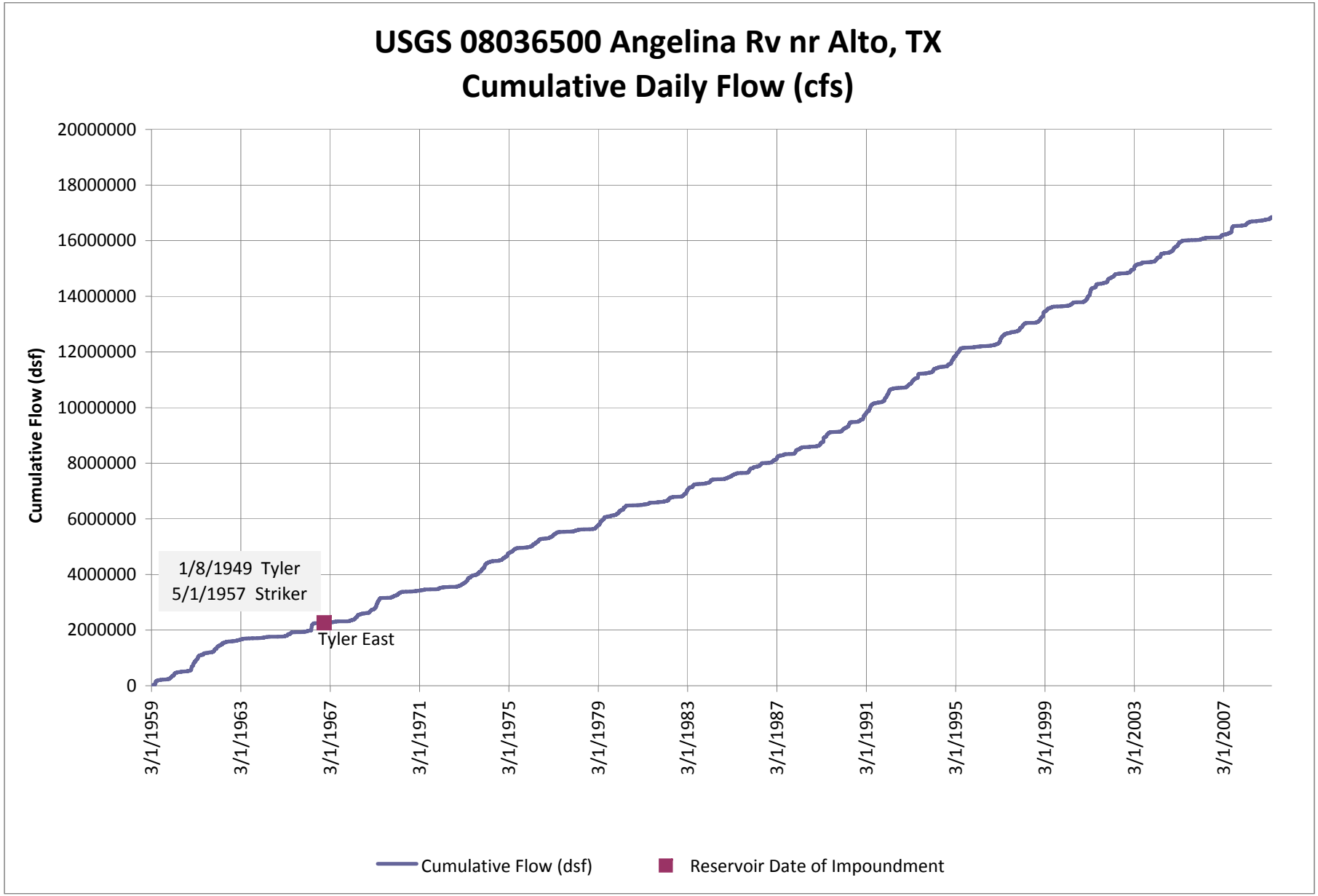
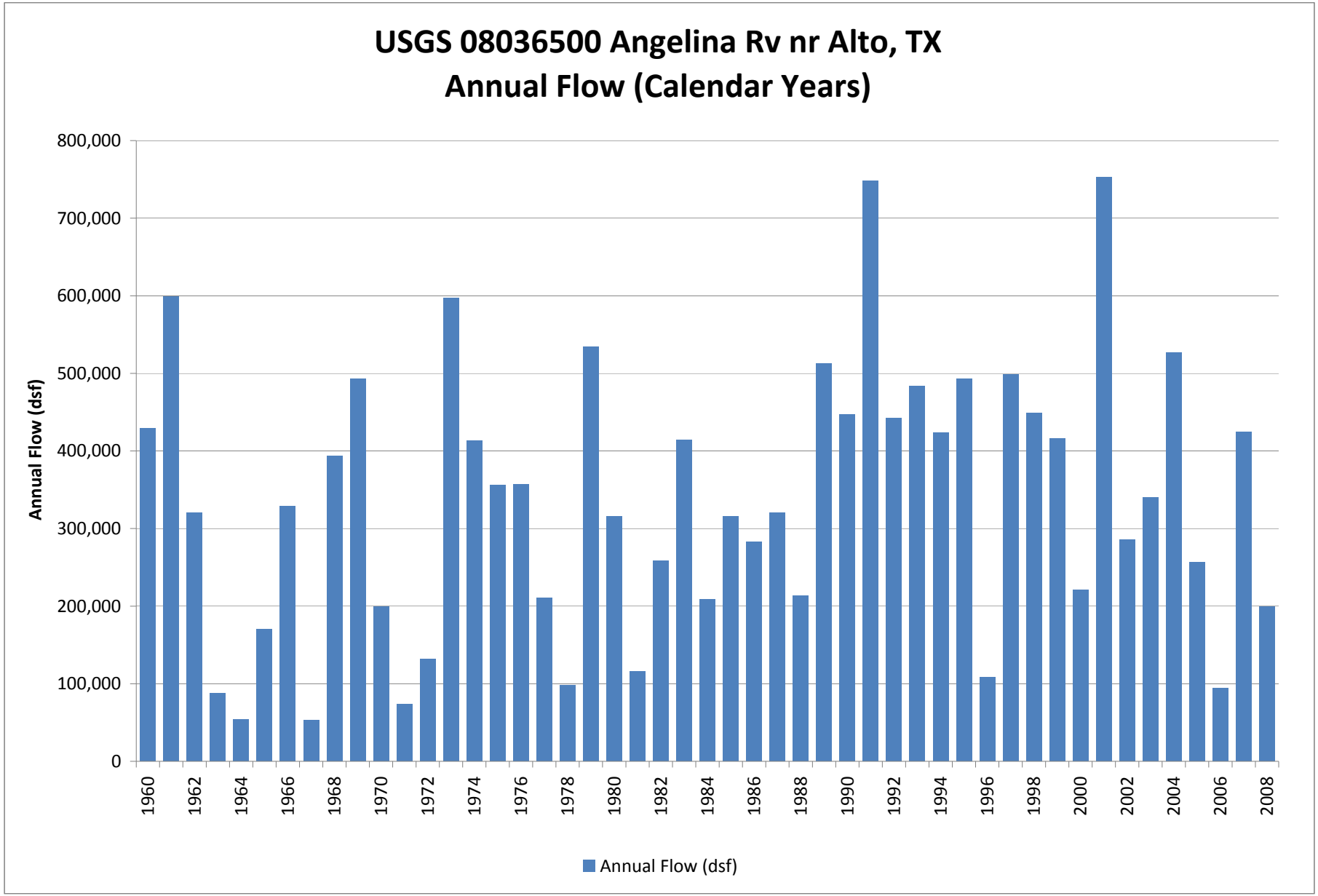
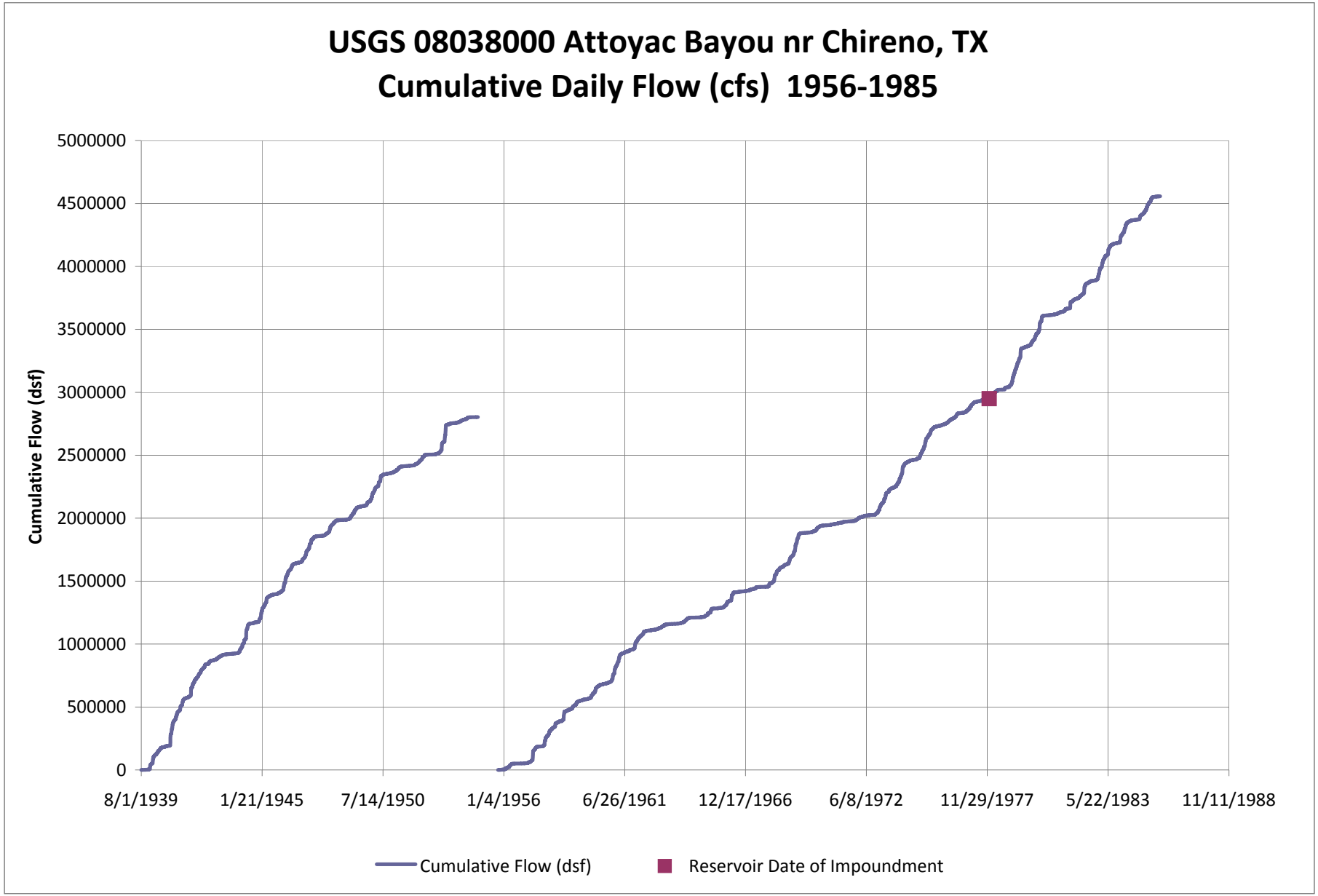
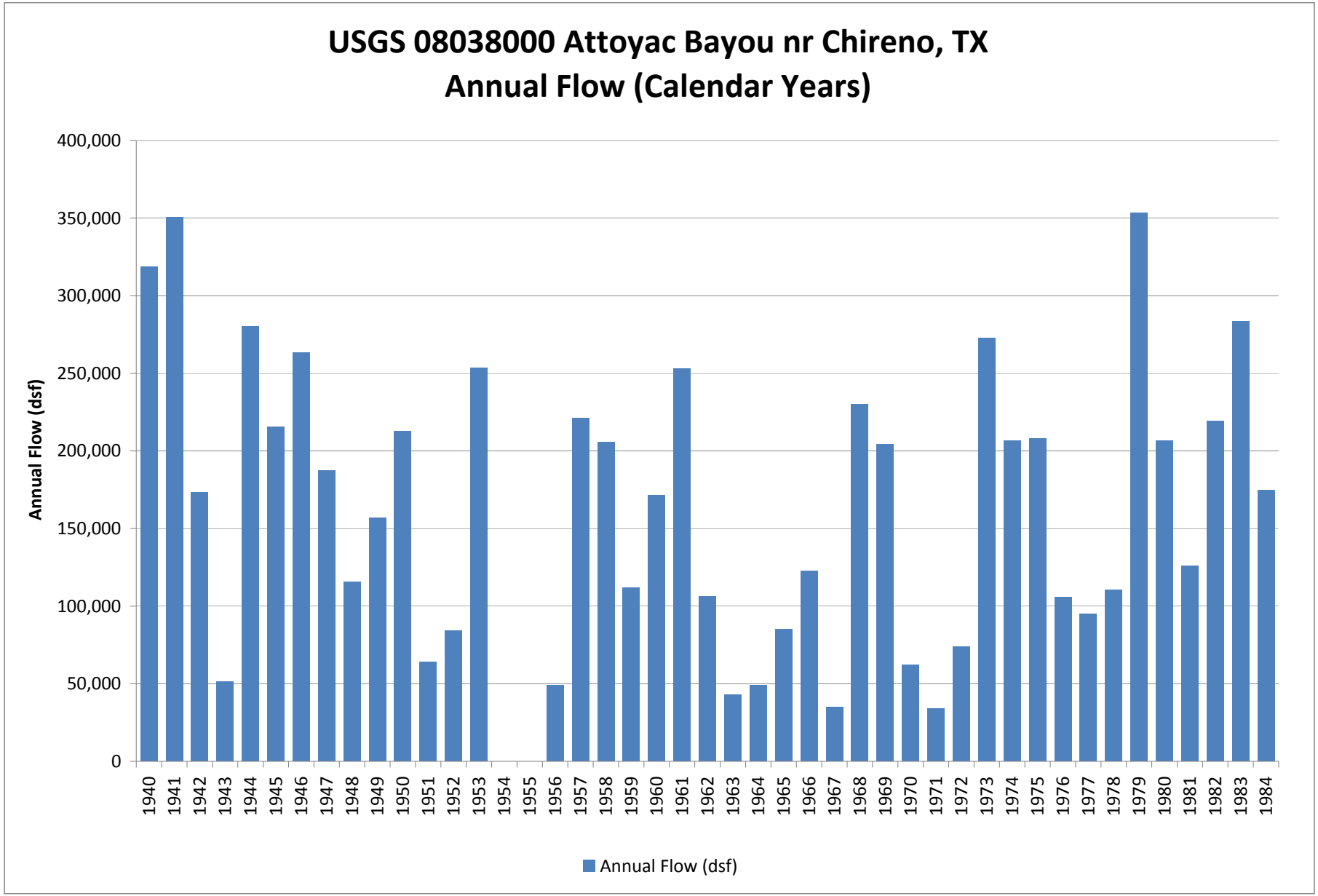
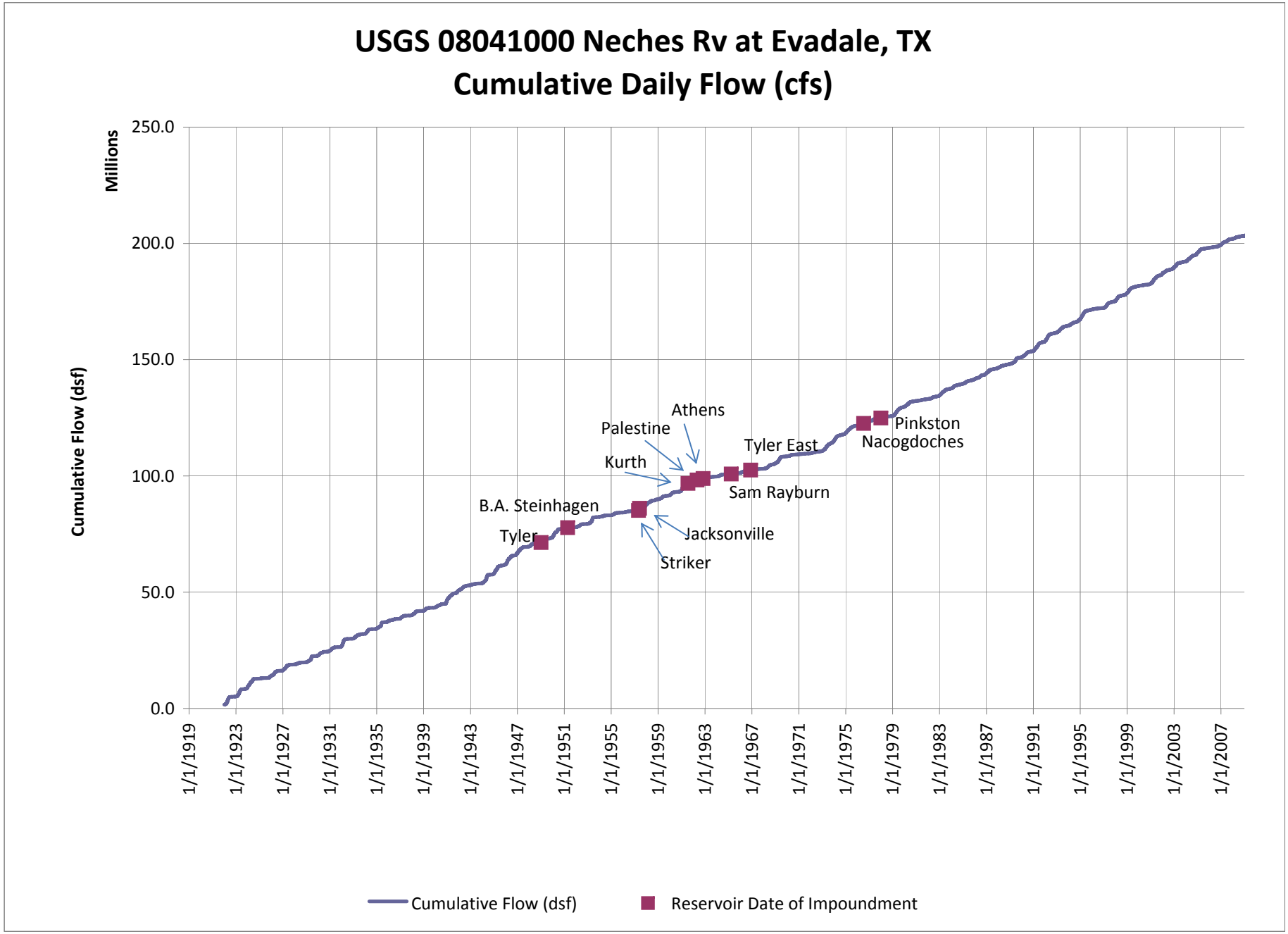
1993
1995
1997
1999
2001
2003
2005
2007
Annual Flow (dsf)

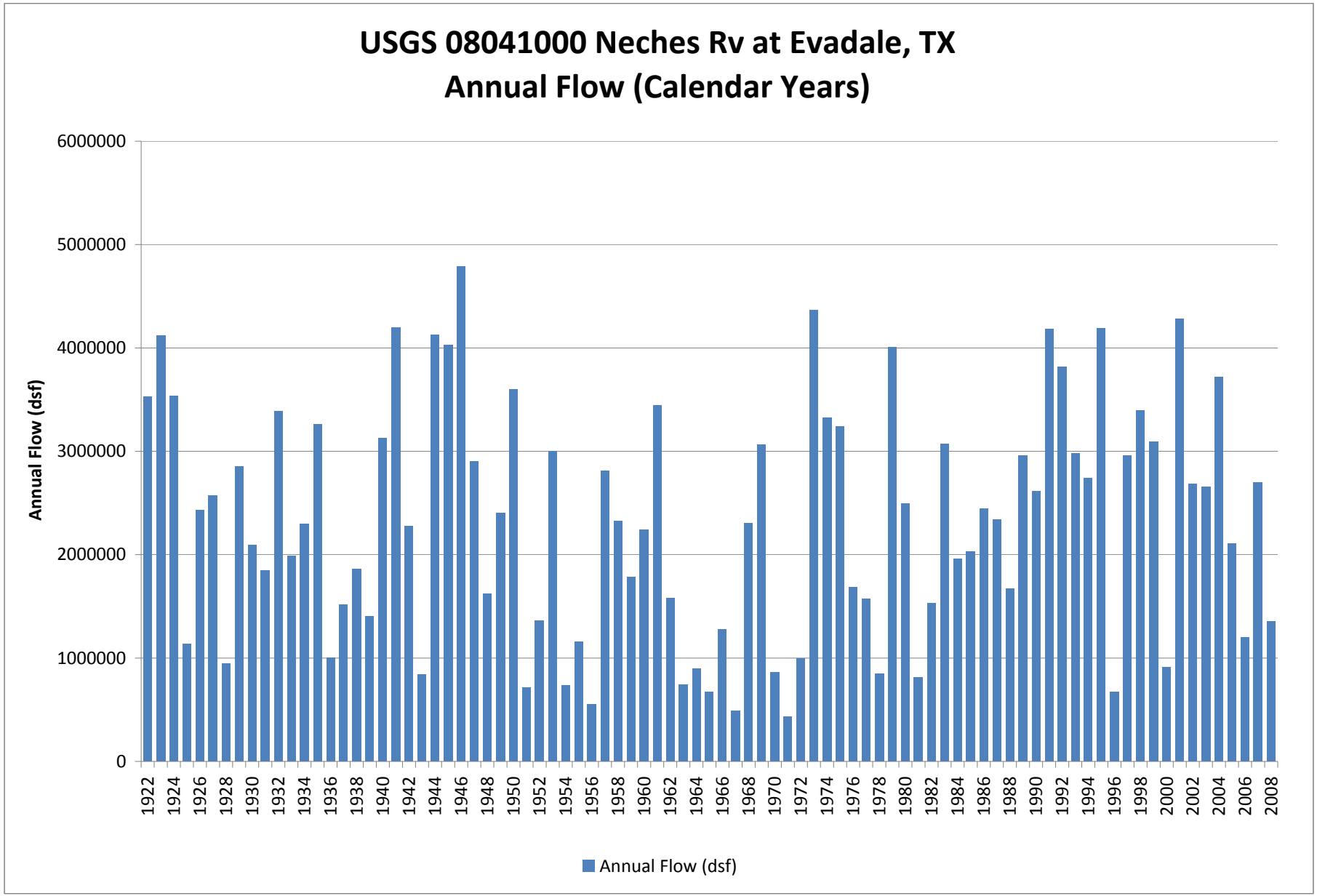

USGS 08036500 Angelina Rv nr Alto, TX
Cumulative Daily Flow (cfs)
Cumulative Flow (dsf)
20000000
18000000
16000000
14000000
12000000
10000000
8000000
6000000
4000000
2000000
0
1/8/1949 Tyler
5/1/1957 Striker
Tyler East
3/1/1959
3/1/1963
3/1/1967
3/1/1971
3/1/1975
3/1/1979
3/1/1983
3/1/1987
3/1/1991
3/1/1995
3/1/1999
3/1/2003
3/1/2007
Cumulative Flow (dsf)
Reservoir Date of Impoundment

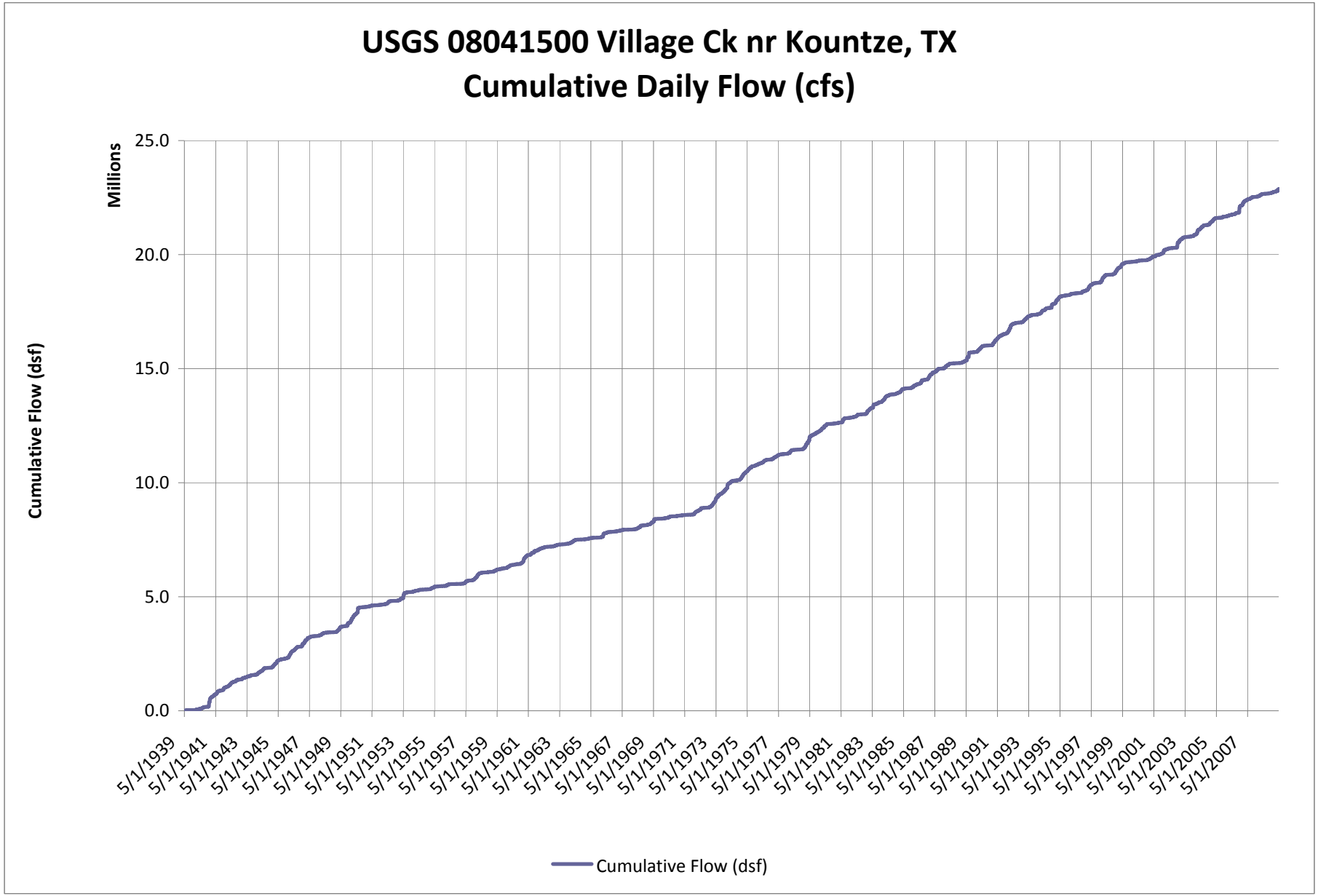

USGS 08036500 Angelina Rv nr Alto, TX
Annual Flow (Calendar Years)
Annual Flow (dsf)
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
Annual Flow (dsf)

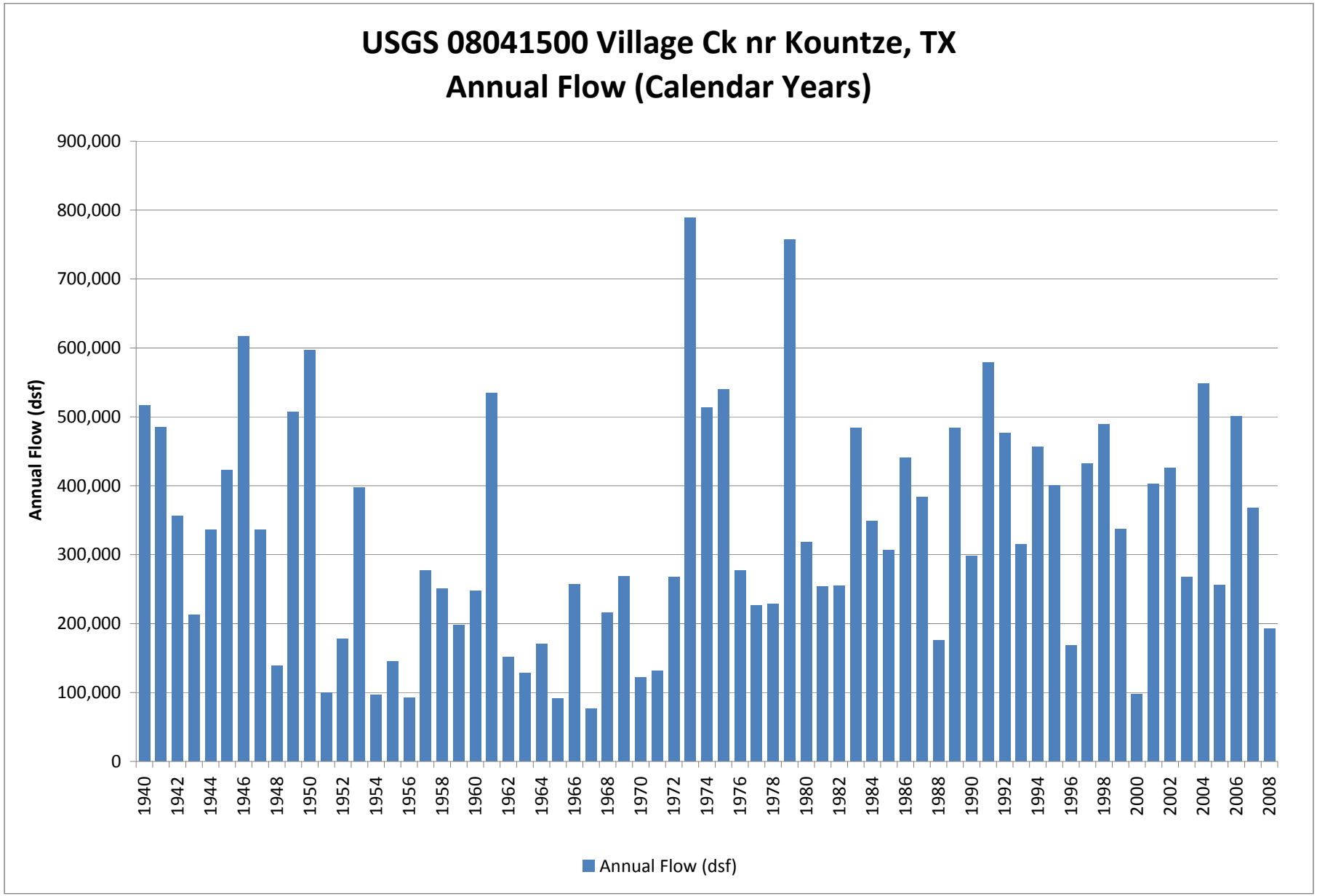

USGS 08038000 Attoyac Bayou nr Chireno, TX
Cumulative Daily Flow (cfs) 1956-1985
Cumulative Flow (dsf)
5000000
4500000
4000000
3500000
3000000
2500000
2000000
1500000
1000000
500000
0
8/1/1939
1/21/1945
7/14/1950
1/4/1956
6/26/1961
12/17/1966
6/8/1972
11/29/1977
5/22/1983
11/11/1988
Cumulative Flow (dsf)
Reservoir Date of Impoundment


USGS 08038000 Attoyac Bayou nr Chireno, TX
Annual Flow (Calendar Years)
Annual Flow (dsf)
400,000
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
1940
1941
1942
1943
1944
1945
1946
1947
1948
1949
1950
1951
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
Annual Flow (dsf)


USGS 08041000 Neches Rv at Evadale, TX
Cumulative Daily Flow (cfs)
Millions
Cumulative Flow (dsf)
250.0
200.0
150.0
100.0
50.0
0.0
1/1/1919
1/1/1923
1/1/1927
1/1/1931
1/1/1935
1/1/1939
1/1/1943
1/1/1947
1/1/1951
1/1/1955
1/1/1959
1/1/1963
1/1/1967
1/1/1971
1/1/1975
1/1/1979
1/1/1983
1/1/1987
1/1/1991
1/1/1995
1/1/1999
1/1/2003
1/1/2007
Athens
Palestine
Kurth
Tyler East
Pinkston
Nacogdoches
Sam Rayburn
B.A. Steinhagen
Tyler
Jacksonville
Striker
Cumulative Flow (dsf)
Reservoir Date of Impoundment


USGS 08041000 Neches Rv at Evadale, TX
Annual Flow (Calendar Years)
Annual Flow (dsf)
6000000
5000000
4000000
3000000
2000000
1000000
0
1922
1924
1926
1928
1930
1932
1934
1936
1938
1940
1942
1944
1946
1948
1950
1952
1954
1956
1958
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
Annual Flow (dsf)


USGS 08041500 Village Ck nr Kountze, TX
Cumulative Daily Flow (cfs)
Millions
Cumulative Flow (dsf)
25.0
20.0
15.0
10.0
5.0
0.0
5/1/1939
5/1/1941
5/1/1943
5/1/1945
5/1/1947
5/1/1949
5/1/1951
5/1/1953
5/1/1955
5/1/1957
5/1/1959
5/1/1961
5/1/1963
5/1/1965
5/1/1967
5/1/1969
5/1/1971
5/1/1973
5/1/1975
5/1/1977
5/1/1979
5/1/1981
5/1/1983
5/1/1985
5/1/1987
5/1/1989
5/1/1991
5/1/1993
5/1/1995
5/1/1997
5/1/1999
5/1/2001
5/1/2003
5/1/2005
5/1/2007
Cumulative Flow (dsf)


USGS 08041500 Village Ck nr Kountze, TX
Annual Flow (Calendar Years)
Annual Flow (dsf)
900,000
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
1940
1942
1944
1946
1948
1950
1952
1954
1956
1958
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
Annual Flow (dsf)

MEMORANDUM

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TO: Sabine-Neches Expert Science Team Technical Committee

FROM: Jon S. Albright, Freese and Nichols, Inc.

SUBJECT: Hydrology-Based Environmental Flow Regime (HEFR) Analyses for Sabine-Neches Bay and Basin Expert Science Team (BBEST)

DATE: September 17, 2009

Introduction

The Senate Bill 3 Science Advisory Committee for Environmental Flows (SAC) developed a draft guidance document *Use of Hydrologic Data in the Development of Instream Flow Recommendations for the Environmental Flows Allocation Process and the Hydrology-Based Environmental Flow Regime (HEFR) Methodology*[1] to guide the basin advisory groups in developing flow recommendations. One of the options in this document is employing the Hydrology-Based Environmental Flow Regime (HEFR) methodology to determine an environmental flow regime based on historical hydrology. The Sabine Neches Bay and Basin Expert Science Team (BBEST) hired Freese and Nichols, Inc. (FNI) to conduct hydrologic analyses at twelve gages in the Sabine and Neches River Basins and inflows into Sabine Lake, including HEFR analyses. Table 1 lists the gages selected by the BBEST.

The HEFR methodology is described in detail in the SAC guidance, so this document contains only a brief description of the method. HEFR is basically a two step process. In the first step, historical daily streamflow data are divided into one of four components or classifications:

- Subsistence flow – minimum streamflow needed during extreme drought conditions
- Base flow – "normal" flow conditions found between storm events
- High flow pulses – short-duration, high flows within the stream channel resulting from a storm event
- Overbank flows –high-flow events that cause flow beyond the riverbanks

Figure 1 is an illustration of the different flow classifications. The flows are displayed using both linear and logarithmic axes in order to illustrate the range of both high and low flows.

[1] Senate Bill 3 Science Advisory Committee for Environmental Flows: *Working Draft: Use of Hydrologic Data in the Development of Instream Flow Recommendations for the Environmental Flows Allocation Process and the Hydrology-Based Environmental Flow Regime (HEFR) Methodology*, April 20, 2009.

Table 1: USGS Stream Gages Selected by the Sabine-Neches BBEST

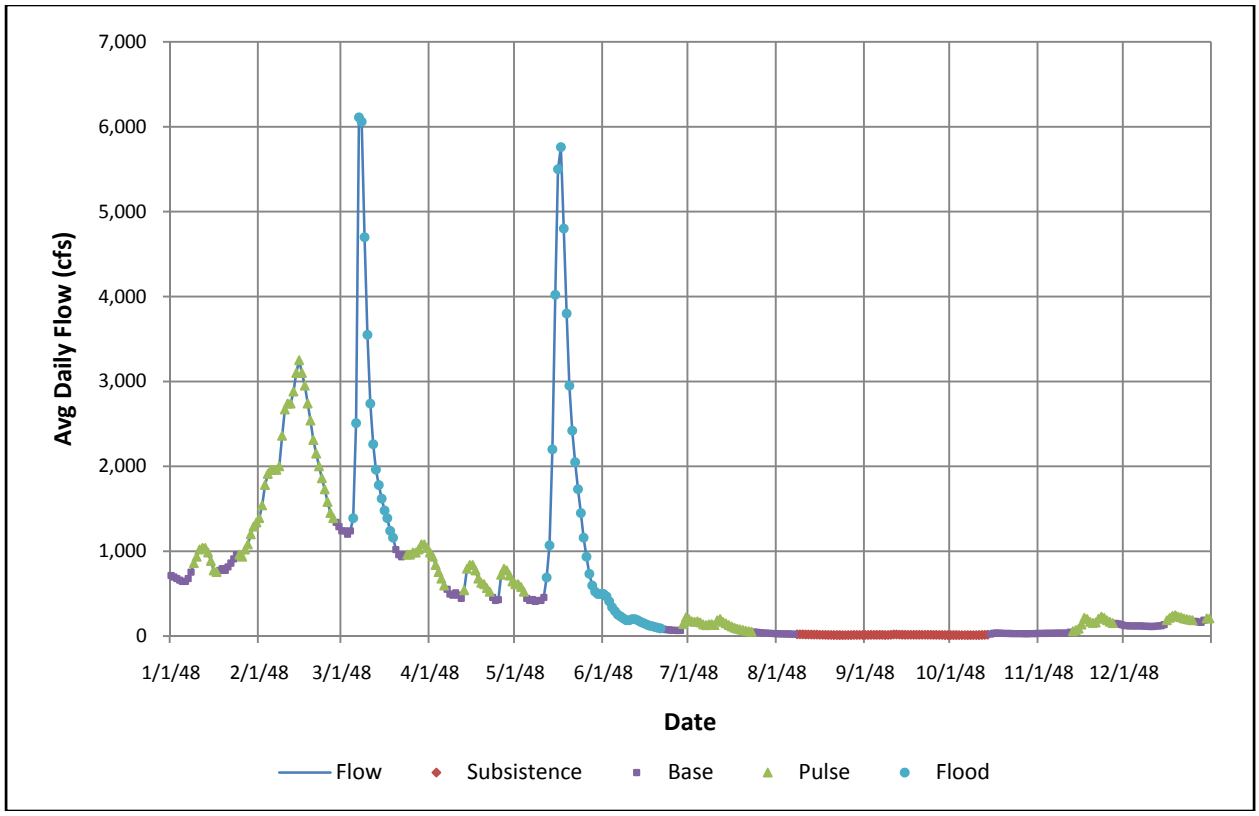
USGS Gage Name	USGS Gage Number	HUC	County
SABINE BASIN			
Big Sandy Creek nr Big Sandy	8019500	12010002	Upshur
Sabine River nr Gladewater	8020000	12010002	Gregg
Sabine River nr Beckville	8022040	12010002	Panola
Sabine River nr Bon Wier	8028500	12010005	Newton
Big Cow Creek nr Newton	8029500	12010005	Newton
Sabine River nr Ruliff	8030500	12010005	Newton
NECHES BASIN			
Village Creek nr Kountze	8041500	12020006	Hardin
Neches River at Evadale	8041000	12020003	Jasper
Attoyac Bayou nr Chireno	8038000	12020005	San Augustine
Angelina River nr Alto	8036500	12020004	Cherokee
Neches River near Rockland	8033500	12020003	Tyler
Neches River at Neches	8032000	12020001	Cherokee

In the second step, the HEFR model performs a series of statistical and regression analyses on the daily flows and associated classifications. The output of this model is a "flow matrix" of values for the various classifications, grouped by wet, average or dry conditions and season. Wet, average and dry conditions are typically associated with the 25th percentile, median and 75th percentile, respectively, of flow, volume, duration and frequency. Figure 2 is an illustration of the default output of the model. The output is explained in more detail later in this memorandum.

The flow matrix method is a useful tool for conceptualizing different parts of the flow regime and thinking about how those parts contribute to environmental health. The matrix method has been employed for developing instream flow goals for Caddo Lake in Texas, as well as in a variety of other situations elsewhere in the United States. A good source of information on the flow classifications and their functions can be found in the *Texas Instream Flow Studies: Technical Overview*[2].

[2] Texas Commission on Environmental Quality, Texas Parks and Wildlife Department and the Texas Water Development Board: *Texas Instream Flow Studies: Technical Overview*, Texas Water Development Board Report 369, May 2008.

Figure 1: Illustration of Flow Components



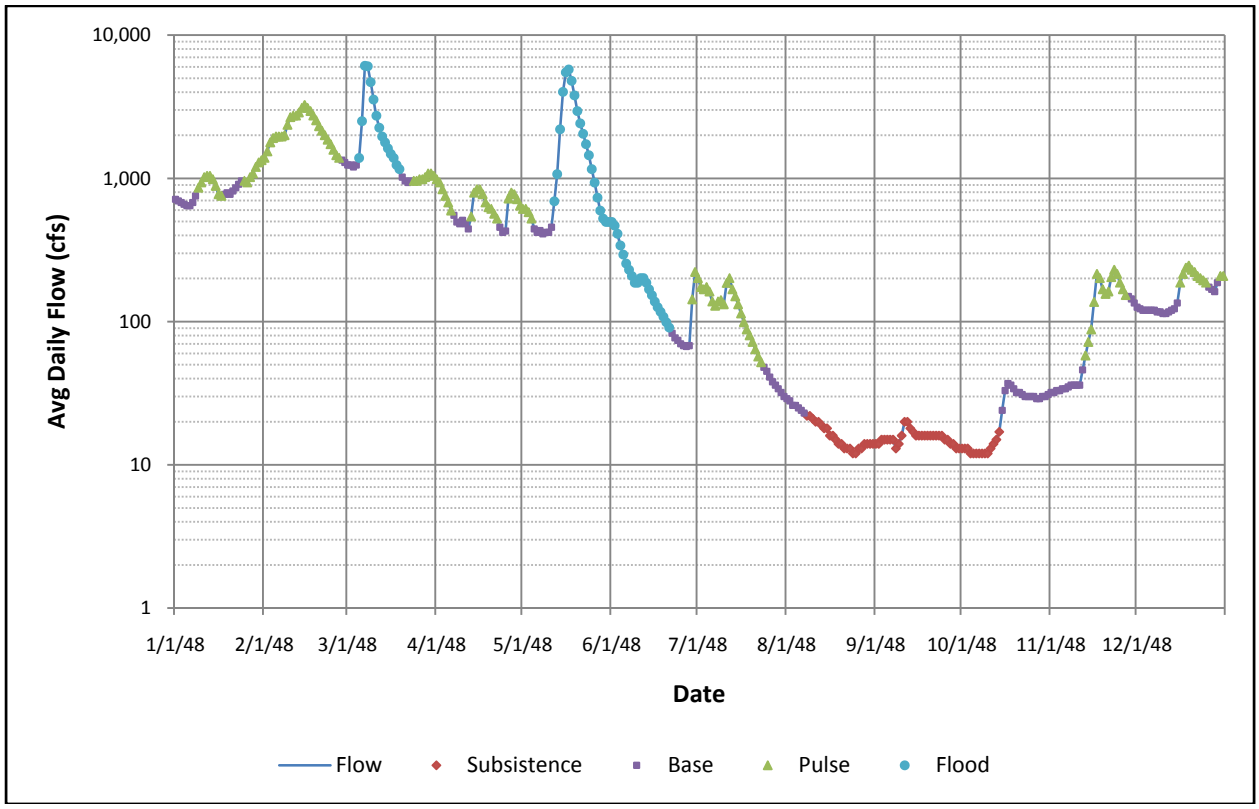


Figure 2: HEFR Output Example

Overbank Flows	Return Period (R) : 1.7 (years)		Duration (D) : 49 (days)	
	Volume (V) : 1068536 (ac-ft)		Peak Flow (Q) : 20800 (cfs)	
High Flow Pulses	F: 0	F: 0	F: 0	F: 1
	D: 31	D: 32	D: 25	D: 22
	Q: 9738	Q: 8205	Q: 3890	Q: 5320
	V: 300873	V: 256900	V: 96100	V: 119033
	F: 1	F: 1	F: 1	F: 1
	D: 18	D: 19	D: 14	D: 16
	Q: 6105	Q: 5580	Q: 2100	Q: 2760
	V: 143799	V: 145101	V: 44625	V: 51194
	F: 2	F: 2	F: 2	F: 2
	D: 8	D: 10	D: 4	D: 4
	Q: 2640	Q: 2973	Q: 1005	Q: 1100
	V: 39010	V: 47462	V: 12647	V: 12686
Base Flows (cfs)	4980	3868	3210	2630
	2590	3070	2140	1280
	1760	1553	471	438
Subsistence Flows (cfs)	135	266	228	204
	Jan, Feb, Mar	Apr, May, Jun	Jul, Aug, Sep	Oct, Nov, Dec
	Winter	Spring	Summer	Fall

Hydrologic Conditions	
	Wet (75th %ile)
	Average (50th %ile)
	Dry (25th %ile)
	Subsistence

High Flow Pulse Characteristics	
	F = Frequency (per season)
	D = Duration (days)
	Q = Peak Flows (cfs)
	V = Volume (ac-ft)

HEFR provides potentially useful information about the statistical distribution of flows. However, the HEFR output by itself is not sufficient to develop a description of a flow regime that defines a sound ecological environment. (The Texas Environmental Flows Advisory Committee defines a sound ecological environment as one that "sustains the full complement of native species in perpetuity, sustains key habitat features required by these species, retains key features of the natural flow regime required by these species to complete their life cycles, and sustains key ecosystem processes and services, such as elemental cycling and the productivity of important plant and animal populations."[3]) When interpreting the matrix, several issues should be kept in mind, including:

- What is the linkage between the statistics in the matrix (i.e. wet, average and dry) and environmental health (biology, geomorphology, water quality, etc.)?

[3] Environmental Flows Advisory Committee: Final Report, prepared for Governor Rick Perry et. al., December, 2006.

- What are the specific goals of the flow matrix? What are we trying to protect? What are the specific functions of the components of the flow matrix?
- How frequently should the flows in the matrix be met to maintain a sound ecological environment?
- Is the flow matrix by itself sufficient to define a flow regime to maintain a sound ecological environment?

HEFR intended to be a starting point for developing environmental flow recommendations. The analyses in this study have been performed using default parameters without regard to site-specific environmental factors that may be important in developing instream flow goals. Other studies commissioned by the BBEST could provide additional insight as to how the flow regime interacts with the environment. The BBEST may wish to rerun HEFR analyses or perform other analyses as other data becomes available.

The remainder of this memorandum describes the analyses performed in this study. The final section includes an evaluation of the result of the study.

Flow Separation

The first step of the HEFR method relies on separation of daily flow into one of the following classifications:

- Subsistence flow – minimum streamflow during extreme drought conditions. According to the Texas Instream Flow Program (TIFP), the primary function of subsistence flows is to maintain water quality.
- Base flow – "normal" flow conditions found between storm events. Primary TIFP functions include maintenance of habitats for the natural community.
- High flow pulses – short-duration, high flows within the stream channel resulting from a storm event. Primary TIFP functions include habitat maintenance and longitudinal connectivity.
- Overbank flows –high-flow events that cause flow beyond the riverbanks Primary TIFP functions include maintenance of riparian areas and lateral connectivity with the active flood plain.

Additional information on the functions of these flow classifications can be found in *Texas Instream Flow Studies: A Technical Overview*[2].

HEFR employs two different methods for flow separation: the Indicators of Hydrologic Alteration Environmental Flow Components (IHA EFC) method developed by the Nature Conservancy, and the Modified Base Flow Index with Threshold (MBFIT) based on a base flow

separation technique developed by the Bureau of Reclamation. Both of these methods parse the daily flow records and classify each day's flows as subsistence, base, high flow pulse or overbank. Each of these methods is described in detail in the SAC hydrologic methods document[1], so only a brief description will be included here.

IHA EFC Method

The IHA EFC method uses a software package developed by the Nature Conservancy to separate flows. (The IHA software does many other things as well, including comparison of two different periods of record to see how flow has changed. The HEFR method only uses the flow separation component of the software.) IHA EFC uses six parameters to classify each day as an overbank event, pulse event, base flow or subsistence flow:

- An *Increase Rate*, expressed as a percentage. If flow on a particular day exceeds the flow in the previous day by this percentage, it signals the beginning of a pulse event. The default value for HEFR is 50% per day.
- A *Decrease Rate*, also expressed as a percentage. If flows during a pulse event decline by less than this percentage, it signals the end of a pulse event. The default value for HEFR is 5 percent per day.
- An *Upper High Flow Pulse Threshold*, expressed as a percentile of flows during the analysis period. If flows on a particular day exceed this value it is always classified as a pulse or overbank event. This parameter is required because pulse events are not always identified by a rise or fall rate. The default value for HEFR is the 75th percentile flow.
- A *Lower High Flow Pulse Threshold*, expressed as a percentile of flows during the analysis period. If flows on a particular day are less than this amount it is always classified as a base flow or subsistence event. This parameter prevents small-magnitude increases in flow during low-flow periods from being classified as initiating a pulse event. The default value for HEFR is the 25th percentile.
- A *Subsistence Flow Threshold*, expressed as a percentile of initially-classified base flows during the analysis period. Base flows below this value are reclassified as subsistence flows. The default value for HEFR is the 10th percentile of base flows during the analysis period.
- An *Overbank Threshold*, expressed as a peak flow with a specific recurrence interval. Once pulse days have been identified, a second pass through the pulse days classifies a pulse event as either a high flow pulse or an overbank event. If flows exceed the overbank threshold level at any time during a pulse event, the entire pulse event is classified as an overbank event. The HEFR default is an overbank event a 1.5 year recurrence interval.

MBFIT Method

The MBFIT method relies on defining daily flows as either "pulse-dominated" or "base-dominated" using three parameters:

- *N* –defining an n-day sliding window of local minima. Must be odd, with a typical value being between 5 and 9.
- *f* –the fraction threshold for a local minimum to be considered a "turning point" and possibly a base-dominated day. Must be between 0 and 1, with a typical value being 0.9.
- *Runoff fraction* – fraction of the flow considered to be runoff for a flow to be classified as a pulse flow. Usually set to 0.2.

Like IHA EFC, another set of threshold parameters can override the initial classification by specifying that flows below a certain level are always classified as a base-dominated and flows above a certain level are always classified as a pulse-dominated. A second step divides the base-dominated days into subsistence or base flows based on a threshold parameter and the pulse-dominated days into either overbank or high flow pulse events based on an overbank threshold parameter. Like the IHA EFC method, an entire event is classified as an overbank event if one or more days during a pulse exceed the overbank threshold. An example of the MBFIT calculation may be found in Attachment A.

For the MBFIT calculations, this study used a spreadsheet method developed by Joe Trungale of Trungale Engineering and Science, which he has graciously made available for use in the Senate Bill 3 studies. FNI modified this spreadsheet to facilitate parameter testing and graphical display of the data.

Evaluation and Selection of Flow Separation Methods

FNI compared the IHA EFC and MBFIT methods using data from the Neches River at Evadale, Neches River near Neches and Sabine River near Ruliff gages. Figure 3 is an example using IHA EFC at the Neches near Neches gage and Figure 4 shows the same data using the MBFIT method. The IHA EFC parameters use the default HEFR values, while the MBFIT parameters use values developed as part of this analysis. In these figures overbank flows are show with light blue circles, pulse flows with green triangles, base flows with purple diamonds and subsistence flows with red squares. The Overbank Threshold value is shown with the solid light blue line. If

Figure 3: Example of IHA EFC Flow Separation

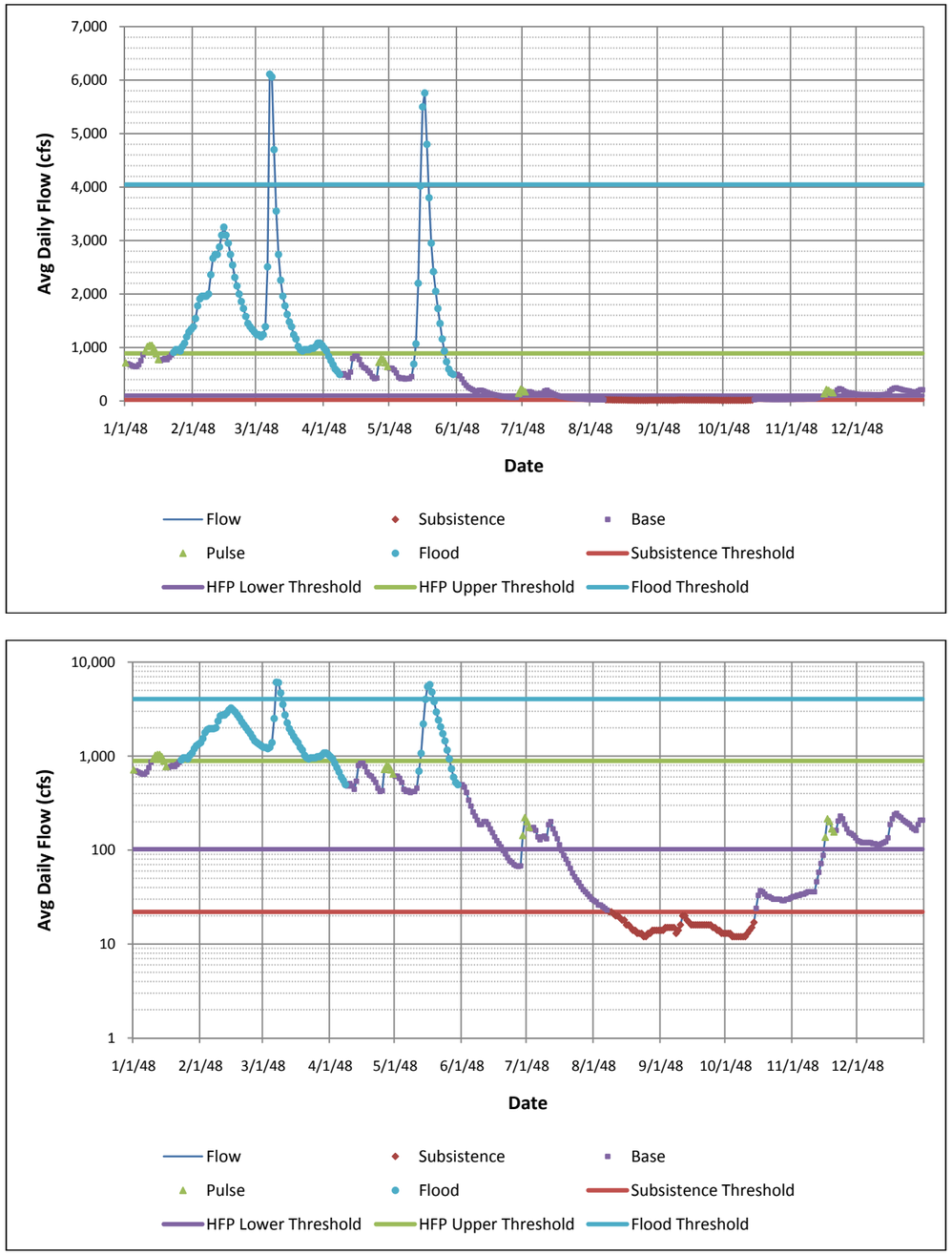
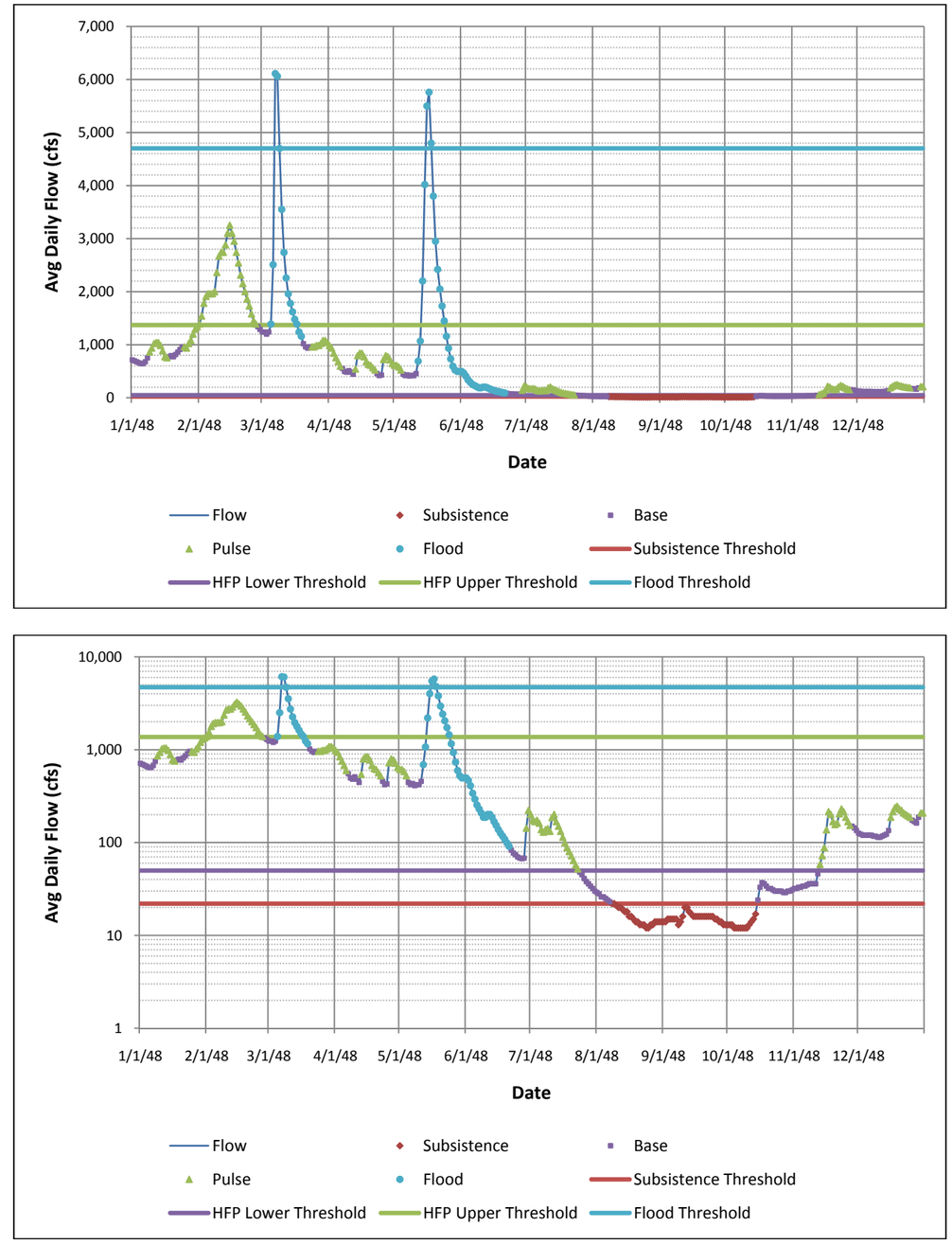


Figure 4: Example of MBFIT Flow Separation



a pulse flow exceeds this threshold at any time during a pulse event, the entire event is classified as an overbank flow. The Upper High Flow Pulse Threshold is shown with a solid green line. If flows are above this value, they are automatically classified as a pulse (or an overbank flow, if the pulse event exceeds the Overbank Threshold). The Lower High Flow Pulse Threshold is shown with the solid purple line. If flows are below this value (but above the Subsistence Threshold), they are always classified as a base flow. The dark red line is the Subsistence Threshold. If flows are below this line, they are automatically classified as subsistence flows. The flow axis is shown at both a linear and logarithmic scale to show both low and high flows.

One of the characteristics of flows in the Sabine and Neches Basins is a season of very high flows from about February through May. Flows during this time are frequently high flow pulses or overbanks flows, with little or no periods of base flow between events. In the example in Figures 3 and 4, there is a fairly large pulse in February followed by an overbank event in March. Note that the IHA EFC method (using this specific parameterization) classifies these two events as one flood event, while the MBFIT method identifies a few days of base flow between the events. Although it is arguable whether these flows really qualify as base flows, one of the benefits of identifying these days as base flows is that the MBFIT method successfully separates the two events into a flood and a pulse event. The IHA EFC method does not separate the two events, classifying the February and March events as a single flood event. The IHA EFC method tends to rely heavily on the Upper High Flow Pulse Threshold to identify pulses, so it can miss higher base flows.

Another characteristic of flows in the Sabine and Neches Basins are persistent low flows beginning around July and continuing through October. Although large pulse events can and do occur during these months, many years are characterized by smaller pulse events that probably serve an important environmental function during these times. The summer flows in Figure 3 and 4 are drier than normal, falling into the subsistence range, so no pulses at all occur from August to October. However, note that the MBFIT method does a better job of identifying the smaller pulses in July and November than IHA EFC method, as well as the two smaller pulses in April and the beginning of May. The IHA EFC method also tends to rely heavily on the Lower High Flow Pulse Threshold to define base flow events, so smaller pulses can be overlooked.

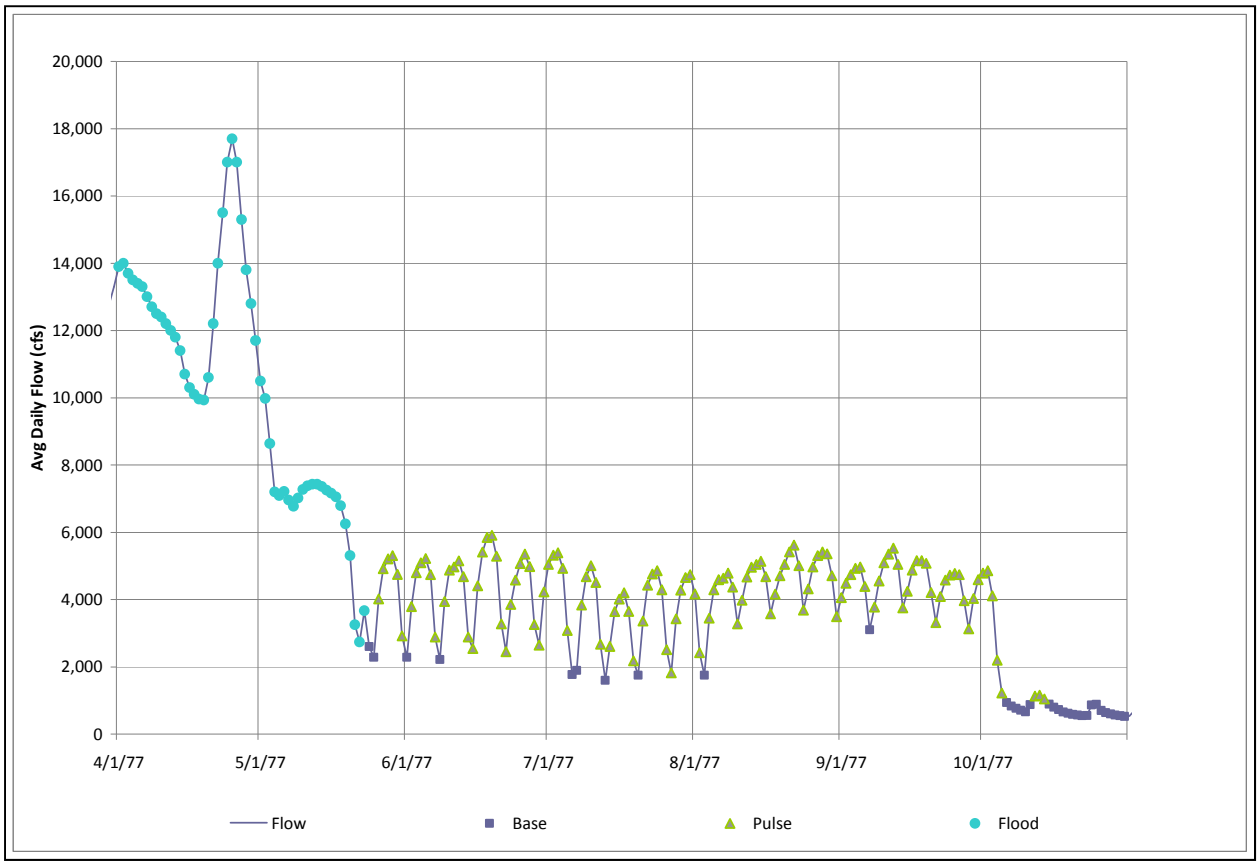
As shown in these examples, the increasing and decreasing rates in the IHA EFC methodology often do not identify the beginning or the end of a pulse event. As a result, the method tends to be sensitive to the upper and lower pulse threshold values when classifying a day as a pulse or base flow. HEFR results tend to be sensitive to the selection of these parameters. The HEFR default is to set these upper and lower thresholds at the 75th and 25th percentiles. Both the IHA EFC and MBFIT tend to have similar results when these parameters are used. However, because MBFIT tends to be more successful at identifying smaller pulse events and larger base flow events, these two thresholds can be set wider, allowing a potentially greater range of flows in each classification. FNI believes that this reduces the tendency of the HEFR results to be influenced by parameter selection.

The flood event in May illustrates another difference between the two methods. The IHA EFC method tends to reclassify the receding limb of a pulse event as a base flow, while the MBFIT method tends to keep these flows as part of the preceding pulse event. It is unclear if inclusion of the receding limb is important to the environmental function of the pulse event.

Although MBFIT works well in this example, it tends to not work well in situations where several short-duration pulse events occur close together. Neither method seems to work well when flow is influenced by hydropower releases, which is the case at the Evadale, Bon Wier and Ruliff gages. Figure 5 shows an example from the Ruliff gage. Note that the summer flows are characterized by small pulse-like events that are induced by hydropower. It is probably not useful to classify all of these cycles as pulse events.

Based on the comparison of the two methods, FNI selected the MBFIT method for the analyses. Table 2 is a summary of the MBFIT parameters used at each gage, as well as the basis used for the threshold parameters. The MBFIT parameters (N, *f* and the Runoff Fraction) were determined by an analysis at each gage. A range of different N values was evaluated at each gage and visually compared for each year of the analysis. Figure 6 is an example of the graphs used for the evaluation. These graphs were created by adding a constant value to the different time series in the graph. The value of N was selected that appeared to most often correctly define separation of pulse and base flows. In most cases, a limited range of *f* values was examined as well. Limited tests of the Runoff Fraction showed that the suggested value of 0.2 was adequate for most situations.

Figure 5: Hydropower-Influenced Flow at the Ruliff Gage



Threshold values for subsistence were all set at the 10th percentile of base flows, a suggested default for this parameter. The lower high flow pulse threshold was set at the 10th percentile of all flows, which is lower than the HEFR default value of the 25th percentile. The lower threshold was selected to preserve smaller pulse events during the summer months. The entire period of the gage was used except for the Bon Wier and Evadale gages. Long periods of repeated flows occur in the record at Bon Wier before 1938, so those were eliminated. The pre-dam period at Evadale was used because the influence of hydropower operation artificially increased the 10th percentile statistic. This effect was not as pronounced on the two Sabine River gages (Ruliff and Bon Wier), so the full period of record was used.

Table 2: Flow Separation Parameter Summary

Basin	Gage Name	USGS Gage Number	Published 7Q2 (cfs)	MBFIT Parameters			Threshold Parameters				Basis for Threshold Parameters			
				N	*f*	Runoff Fraction	Subsistence Threshold (cfs)	Pulse Lower Threshold (cfs)	Pulse Upper Threshold (cfs)	Overbank Threshold (cfs)	Subsistence Threshold	Pulse Lower Threshold	Pulse Upper Threshold	Overbank Threshold
Sabine	Big Sandy Creek nr Big Sandy	8019500	12.4	7	0.90	0.2	10	17	414	1,900	10% of base flows	10% of all flows	90% of all flows	1.5 Year from preliminary analysis
Sabine	Sabine River nr Gladewater	8020000	46.4	9	0.90	0.2	22	54	5,320	10,600	10% of base flows	10% of all flows	90% of all flows	1.5 Year from preliminary analysis
Sabine	Sabine River nr Beckville	8022040	75.9	9	0.90	0.2	31	92	7,230	12,600	10% of base flows	10% of all flows	90% of all flows	NWS flood stage 26 feet
Sabine	Sabine River nr Bon Wier	8028500	703	9	0.90	0.2	306	652	17,800	22,500	10 % of base flows	10th percentile 1938 to 2008	90% of all flows	NWS bankfull 28 feet
Sabine	Big Cow Creek nr Newton	8029500	30	5	0.90	0.2	23	29	230	1,870	10% of base flows	10% of all flows	90% of all flows	No NWS, 1.5 yr from preliminary analysis
Sabine	Sabine River nr Ruliff	8030500	1,121	11	0.90	0.2	450	975	9,880	13,300	10% of base flows	10% of all flows	NWS bankfull 23 feet	NWS flood stage of 24 feet
Neches	Village Creek nr Kountze	8041500	78.9	7	0.90	0.2	51	85	2,070	8,150	10% of base flows	10% of all flows	NWS bankfull 12 feet	1.5 yr from preliminary analysis
Neches	Neches River at Evadale	8041000	1,839	11	0.90	0.2	277	442	8,700	14,200	10% of base flows	10% of 40-60 flows	NWS bankfull 13 feet	Run 1 1.5 year flood 40 to 60
Neches	Attoyac Bayou nr Chireno	8038000	25.6	5	0.90	0.2	13	28	1,200	4,480	10% of base flows	10% of all flows	NWS flood stage 14 ft	1.5 yr from preliminary analysis
Neches	Angelina River nr Alto	8036500	37.7	7	0.90	0.2	20	49	2,340	11,200	10% of base flows	10% of all flows	90% of all flows	NWS flood stage 19 ft
Neches	Neches River near Rockland	8033500	112	11	0.85	0.2	37	94	6,680	19,400	10% of base flows	10% of all flows	90% of all flows	NWS flood stage 26 ft
Neches	Neches River at Neches	8032000	70.7	7	0.90	0.2	22	50	1,370	4,700	10% of base flows	10% of all flows	NWS flood stage 12 ft	1.5 yr from preliminary analysis
	Sabine Lake	N/A	N/A	11	0.90	0.2	1,064	2,759	45,942	115,864	10% of base flows	10% of all flows	90% of all flows	1.5 yr from preliminary analysis

MBFIT Parameters

N – number of days in analysis window

f – fraction of adjacent days to be considered a turning point

Runoff fraction – fraction of runoff for a flow to be considered a base flow

Threshold values

Subsistence – all flows below this value are considered to be subsistence flows

Pulse Lower Threshold – all flows below this value are considered to be a base flow

Pulse Upper Threshold – all flows above this value are considered to be pulse flows

Overbank Threshold – if flows are above this value, the entire pulse event is classified as a flood

NWS = National Weather Service

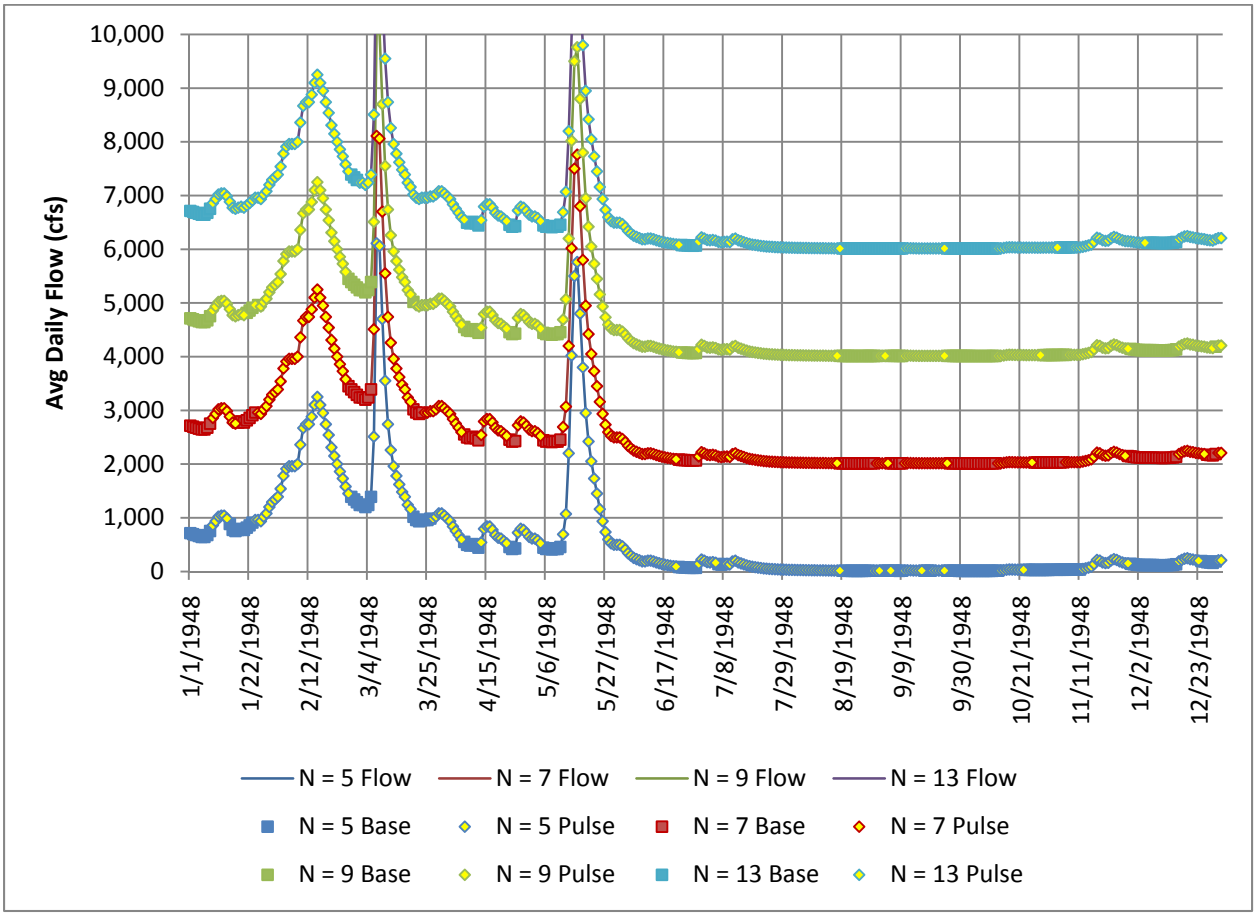
7Q2 data are from the Texas Surface Water Quality Standards

Table 3: National Weather Service Stage Data

River Basin	USGS Stream Gage Name	Flood Categories															Description
		Major Flood Stage			Moderate Flood Stage			Flood Stage			Action Stage			Bankfull Stage			
		Stage (feet)	Flow (kcfs)	Per-centile	Stage (feet)	Flow (kcfs)	Per-centile	Stage (feet)	Flow (kcfs)	Per-centile	Stage (feet)	Flow (kcfs)	Per-centile	Stage (feet)	Flow (kcfs)	Per-centile	
Sabine	Big Sandy Creek n. Big Sandy	21	N/A	N/A	20	N/A	N/A	17	4.8	99.9	16.5	4.22	99.9	N/A	N/A	N/A	17.0 lowlands...along with some secondary roadways...will begin to flood. Ranchers should move livestock and equipment to higher ground.
Sabine	Sabine River n. Gladewater	36	25	99.6	33	13.1	98.3	26	5.72	91.1	25	5.35	90.1	N/A	N/A	N/A	26.0 expect minor lowland flooding with camps and picnic areas near the river suffering some flooding.
Sabine	Sabine River n. Beckville	35	N/A	N/A	30	26.2	99.6	26	12.6	97.6	25.5	12.1	97.1	N/A	N/A	N/A	26.0 expect lowland flooding of the heavily wooded floodplain. In addition...oil field operations in and near the floodplain will be affected and steps should be taken to secure petroleum equipment.
Sabine	Sabine River n. Bon Wier	36	65.2	99.8	33	39.2	99.1	30	28	97.0	30	28	97.0	28	22.5	94.3	30.0 minor lowland flooding will occur along the river between Merryville and Bon Wier. A few roads in southwest Vernon Parish have water over them. 28.0 The river is at its bankfull stage.
Sabine	Big Cow Creek n. Newton	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	No NWS data
Sabine	Sabine River n. Ruliff	28	59.5	99.6	26	29.8	96.1	24	13.3	77.8	23	9.88	70.7	23	9.88	70.7	24.0 minor lowland flooding will occur. Low-lying roads in southwestern Beauregard Parish...including Robert Clark Road will have water over them. 23.0 The river is at bankfull stage.
Neches	Neches River n. Neches	24	N/A	N/A	18	13	99.8	12	1.37	85.6	11.5	1.2	82.8	N/A	N/A	N/A	12.0 expect minor lowland flooding of the heavily wooded floodplain. Ranchers that may have cattle and equipment in the river bottoms should move them to higher ground.
Neches	Neches River n. Rockland	33	41.2	99.9	30	31	99.8	26	19.4	99.2	25	17.8	99.0	N/A	N/A	N/A	28.0 water will begin to flood several secondary roadways especially in the Smith's Ferry community.
Neches	Angelina River n. Alto	23	40.9	99.9	21	25.8	99.9	19	11.2	99.7	18.5	8.8	99.4	N/A	N/A	N/A	19.0 expect lowland flooding of the river bottom. Ranchers that have cattle and equipment near the river should move them to higher ground.
Neches	Attoyac Bayou n. Chireno	26	31.7	> his-torical	22	16.1	99.9	14	1.2	91.0	13.5	1.09	89.8	N/A	N/A	N/A	14.0 expect lowland flooding for the next several days of the heavily wooded floodplain. Ranchers that have cattle and equipment near the river should move them to higher ground.
Neches	Neches River @ Evadale	24	96.6	> his-torical	21	62.5	99.9	19	41.5	99.4	19	41.5	99.4	13	8.7	86.1	19.0 minor lowland flooding. Water enters buildings adjacent to gauge. 13.0 The river is at bankfull stage.
Neches	Village Creek n. Kountze	23	21.1	99.9	21	14.5	99.7	17	6.17	98.5	12	2.07	89.3	12	2.07	89.3	17.0 water covers low spots on Willard Lake Road and Village Creek road near Lumberton. 12.0 The river is at bankfull stage.

Data are from the National Weather Service Western Gulf River Forecast Center
No data available for Big Cow Creek

Figure 6: Example of MBFIT Parameter Analysis



The pulse upper threshold and flood threshold values are based on a comparison of National Weather Service (NWS) stage data and a frequency analysis of historical gage flows[4]. The NWS publishes flood stages and discharges for all BBEST gages except for Big Cow Creek nr Newton and bankfull stages and discharges for the Sabine River near Bon Wier, Sabine River near Ruliff, Neches River at Evadale and Village Creek near Kountze gages. Although the NWS data appear to focus on potential damage to define flood stages, the information does give some potentially useful information about overbanking flows. In particular, it appears that overbanking events occur at Ruliff and Evadale on a fairly regular basis. In most cases the 90th percentile of all flows was used for the pulse upper threshold, and the 1.5 year event from a preliminary HEFR analysis was used for the overbank threshold (the final 1.5 year event may be different because of changed parameters). At Ruliff, the NWS bankfull flow was used as the upper pulse

[4] National Weather Service River Forecast Center, West Gulf RFC, available on-line at http://www.srh.noaa.gov/wgrfc/

threshold and the NWS flood stage for the overbank threshold. These values are the 71st and 78th percentile of all historical flows, respectively, and appear to happen quite regularly. At Kountze, the NWS bankfull flow is about the 90th percentile so it was used as the upper pulse threshold to be consistent with other gages. At Evadale, the NWS bankfull stage is about the 76th percentile, so it was used as the upper pulse threshold. At Chireno the NWS flood stage is very close to the 90th percentile, so the flood stage was used for the upper pulse threshold and the 1.5 year event for an overbank. At the Neches near Neches gage the bankfull flow is about the 90th percentile, so it was used as the upper pulse threshold to be consistent with other analyses.

Although a NWS bankfull flow is available at Bon Wier, the flow is around the around the 95th percentile of all flows. This is very different than the next downstream gage at Ruliff, where the bankfull flow is around the 71st percentile. At Bon Wier the 90th percentile flow was used for the upper pulse threshold and the bankfull flow for the overbank threshold.

HEFR Parameters

The output of the MBFIT flow separation was used as input for the HEFR model. Each location was analyzed using both the original percentile-based approach and the frequency approach for up to three different time periods. This makes a maximum of six runs for each gage plus Sabine Lake. This section discusses the parameters used in the HEFR runs.

Period of Record

The BBEST selected three periods of record for the analysis:

- Full Period – the full period of record for each gage. HEFR must use full years, so partial years at the beginning and the end of the record were dropped. Some gages with data in the 1920s and 1930s had incomplete records or extended periods of repeated daily data, so those years were dropped as well.
- Pre-Dam conditions – the period from 1940 to 1960, prior to the construction of most major reservoirs
- Post-Dam conditions – the period from 1971 to 2008, after the construction of most major reservoirs

A few gages do not have complete records for all analyses. The Big Sandy near Big Sandy gage only has records through 2007, so it is missing the last year of the Post-Dam period. The first full year for Big Cow Creek near Newton is 1953. The Pre-Dam condition from 1953 to 1960

was not included for this gage because it is too short for a meaningful analysis. The first full year for the Angelina River near Alto is 1960, so the Pre-Dam condition is not available. Attoyac Bayou near Chireno has full years of data only from 1940 to 1953 and from 1960 to 1984. Therefore these two periods were substituted for the three conditions used at the other gages. All of these gages have little or no upstream development, so differences in the results are probably the result of climatic variability rather than diversions or return flows.

Seasons

The BBEST divided the year into simple quarters based on historical flow records:

- Winter – January through March
- Spring – April through June
- Summer – July through September
- Fall – October through December

The BBEST considers these seasons as best describing the seasonal flow trends in the Sabine and Neches River Basins.

Use of 7Q2

HEFR provides the option to specify a minimum "water quality protection flow". If this parameter is specified, base or subsistence flow statistics produced by HEFR may never fall below this value. HEFR guidance suggest using a 7Q2 (a historical 7-day average low flow with a 2-year recurrence interval) as this limit. In Texas, a 7Q2 is used as the flow below which water quality standards do not apply. It is also considered when determining stream loading for wastewater discharges. Other states, including Louisiana, use a 7Q10 (a 7-day low flow with a 10-year recurrence interval) for similar purposes. The 7Q2 is also used as a minimum flow limit in other desktop environmental flow methods such as the Lyons or Consensus methods described in the SAC hydrologic methods[1]. Table 4 lists the 7Q2 values for the BBEST gages published in the Texas Surface Water Quality Standards[5].

One of the issues with using a 7Q2 for a minimum discharge is the influence of hydropower at the Ruliff, Bon Wier and Evadale gages. Table 5 compares 7Q2 and 7Q10 values at these three

[5] Texas Administrative Code Chapter 307: Texas Surface Water Quality Standards, available on-line at http://www.sos.state.tx.us/tac/index.shtml

gages calculated using the Environmental Protection Agency's DFLOW model[6]. (7Q10 values are used in the State of Louisiana and are included for comparison purposes.) The periods in this table include the period prior to the construction of Sam Rayburn Reservoir for the Evadale gage and Toledo Bend Reservoir for the Ruliff and Bon Wier gages. Note that the pre-dam 7Q2 values are significantly lower than the published 7Q2 values. The reason for the discrepancy between the published 7Q2 and the DFLOW output for the Ruliff gage is unknown.

Table 4: Published 7Q2 Values

USGS Stream Gage Name	USGS#	7Q2 (cfs)
Big Sandy Creek n. Big Sandy	8019500	12.4
Sabine River n. Gladewater	8020000	46.4
Sabine River n. Beckville	8022040	75.9
Sabine River n. Bon Wier	8028500	703.1
Big Cow Creek n. Newton	8029500	30
Sabine River n. Ruliff	8030500	1,121.3
Neches River n. Neches	8032000	70.7
Neches River n. Rockland	8033500	111.7
Angelina River n. Alto	8036500	37.7
Attoyac Bayou n. Chireno	8038000	25.6
Neches River @ Evadale	8041000	1,838.6
Village Creek n. Kountze	8041500	78.9

Data are from the Texas Surface Water Quality Standards

Table 5: Comparison of Published 7Q2 to DFLOW 7Q2 and 7Q10 for Hydropower Influenced Gages

(Values in cfs)

Gage	Published 7Q2	Period	DFLOW Output								
			Pre-Dam			TCEQ Published Period			Full Period		
			7Q2	7Q10	Period	7Q2	7Q10	Period	7Q2	7Q10	Period
Evadale	1,838.6	'66-'96	308	138	'22-'64	1,839	361	'66-'96	497	167	'22-'08
Ruliff	1,121.3	'68-'96	683	349	'25-'65	1,109	584	'68-'96	895	417	'25-'08
Bon Wier	703.1	'68-'96	399	218	'24-'65	703	371	'68-'96	545	250	'24-'08

[6] U.S. Environmental Protection Agency DFLOW 3.1, available on-line at http://www.epa.gov/waterscience/models/dflow/

Using a 7Q2 as a minimum flow recommendation primarily affects subsistence criteria. Subsistence flows are infrequently occurring low flows during extremely dry periods. However, with a 2-year recurrence interval, a 7Q2 is not a particularly rare occurrence. When considering recommendations for subsistence criteria, the BBEST should balance the function of subsistence flows (the minimum flow to sustain life) and the presence of waste loading in the stream with the natural occurrence of extremely low flows. In the case of hydropower influenced gages, the BBEST should consider how hydropower operations affect biology, as well as the potential for hydropower operations to cease or be reduced in the future.

The BBEST elected not to use a 7Q2 as a limit in the HEFR runs because it can easily be added as a limit later in the process if needed.

HEFR Results

The output matrices of the HEFR runs may be found in Attachment B. Tables 6 through 10 compare the results of the various gages. A maximum of six different matrices was produced for each gage plus Sabine Lake. Each gage was analyzed for three different periods of record: the Full Period of record for the gage, a Pre-Dam period from 1940 to 1960 and a Post-Dam period from 1971 to 2008. (Some gages do not have complete periods of record and only have a subset of the three periods.) Each period was analyzed using both the original percentile-based method and the frequency-based method. In the matrices in Attachment B, the original method results are at the top and the frequency-based results are at the bottom.

The two bottom panels of each matrix in Attachment B contains the subsistence and base flow recommendations for each season and flow condition (wet, average or dry). These flow recommendations are constant throughout the season.

The middle panel of each HEFR matrix in Attachment B describes pulse events, which are episodic and only occur during part of a season. Both statistical methods describe pulses in terms of peak discharge (Q or Qp) in cfs, volume (V) in acre-feet, and duration (D or Duration) of the event in days. The original percentile-based method matrices also contain the frequency for pulse events (F), or the number of times the event is expected to occur during a season. Occasionally the frequency of the event is zero, which indicates that an event meeting these criteria would not be expected to occur every year. The frequency-based method reports these

Table 6: HEFR Overbank Results

Basin	USGS Gage Name	USGS Gage Number	NWS Flood Stage Discharge (cfs)	NWS Bankfull Stage Discharge (cfs)	Flow Statistic	Original			Frequency		
						Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir
Sabine	Big Sandy Creek nr Big Sandy	8019500	4,800	-	Peak Discharge (cfs)	2,875	3,360	2,820	2,930	4,000	2,930
					Volume (Ac-Ft)	32,695	33,461	32,563	35,703	43,877	36,806
					Duration (Days)	23	22	21	30	30	31
					Return Period (Years)	4.9	3.0	4.1	2.0	2.0	2.0
Sabine	Sabine River nr Gladewater	8020000	5,720	-	Peak Discharge (cfs)	18,100	19,400	16,700	18,100	34,600	15,900
					Volume (Ac-Ft)	553,068	456,865	584,547	483,275	703,975	535,070
					Duration (Days)	39	35	44	44	52	44
					Return Period (Years)	4.2	2.6	4.8	2.0	2.0	2.0
Sabine	Sabine River nr Beckville	8022040	12,600	-	Peak Discharge (cfs)	17,300	28,100	15,800	16,100	29,800	15,200
					Volume (Ac-Ft)	773,375	833,246	710,023	541,644	799,357	570,487
					Duration (Days)	42	39	42	45	52	44
					Return Period (Years)	5.4	3.5	4.8	2.0	2.0	2.0
Sabine	Sabine River nr Bon Weir	8028500	28,000	22,500	Peak Discharge (cfs)	29,400	27,900	29,900	36,500	37,500	36,700
					Volume (Ac-Ft)	942,288	989,950	935,207	1,200,452	1,627,017	1,009,374
					Duration (Days)	26	32	23	32	40	28
					Return Period (Years)	1.9	1.4	1.8	2.0	2.0	2.0
Sabine	Big Cow Creek nr Newton	8029500	-	-	Peak Discharge (cfs)	3,150	-	3,000	3,180	-	3,350
					Volume (Ac-Ft)	17,048	-	17,040	18,325	-	19,792
					Duration (Days)	13	-	13	17	-	17
					Return Period (Years)	3.7	-	2.7	2.0	-	2.0
Sabine	Sabine River nr Ruliff	8030500	13,300	9,880	Peak Discharge (cfs)	26,050	26,800	27,250	41,300	52,000	40,600
					Volume (Ac-Ft)	1,209,868	1,017,035	1,358,499	2,581,061	3,530,854	2,511,832
					Duration (Days)	48	46	51	82	90	93
					Return Period (Years)	1.2	0.9	1.4	2.0	2.0	2.0
Neches	Village Creek nr Kountze	8041500	6,170	2,070	Peak Discharge (cfs)	12,100	11,600	11,850	12,400	13,800	13,000
					Volume (Ac-Ft)	175,168	185,347	157,589	170,313	184,922	178,562
					Duration (Days)	22	22	22	29	31	28
					Return Period (Years)	3.8	7.0	2.9	2.0	2.0	2.0
Neches	Neches River at Evadale	8041000	41,500	8,700	Peak Discharge (cfs)	20,800	21,400	21,400	26,800	34,600	25,900
					Volume (Ac-Ft)	1,068,535	1,022,083	1,289,216	1,762,388	2,030,727	2,052,809
					Duration (Days)	49	49	56	46	57	44
					Return Period (Years)	1.7	1.4	1.7	2.0	2.0	2.0
Neches	Attoyac Bayou nr Chireno	8038000	1,200	-	Peak Discharge (cfs)	-	8,130	7,280	-	9,310	7,520
					Volume (Ac-Ft)	-	89,740	85,178	-	110,273	91,536
					Duration (Days)	-	20	23	-	24	27
					Return Period (Years)	-	2.3	2.9	2.0	2.0	2.0
Neches	Angelina River nr Alto	8036500	11,200	-	Peak Discharge (cfs)	13,650	-	13,650	9,690	-	9,690
					Volume (Ac-Ft)	242,645	-	233,432	204,931	-	205,699
					Duration (Days)	28	-	28	29	-	29
					Return Period (Years)	8.2	-	6.3	2.0	2.0	2.0
Neches	Neches River near Rockland	8033500	19,400	-	Peak Discharge (cfs)	26,400	30,550	24,400	18,500	16,000	20,300
					Volume (Ac-Ft)	950,303	1,131,262	788,834	661,717	590,921	706,179
					Duration (Days)	54	45	53	41	38	42
					Return Period (Years)	10.9	7.0	38.0	2.0	2.0	2.0
Neches	Neches River at Neches	8032000	1,370	-	Peak Discharge (cfs)	6,835	7,610	6,650	7,280	10,700	6,650
					Volume (Ac-Ft)	175,539	178,367	174,906	172,590	208,786	185,208
					Duration (Days)	36	34	37	38	40	38
					Return Period (Years)	4.3	3.0	4.2	2.0	2.0	2.0

Full Period analysis not available for Attoyac Bayou nr Chireno
Pre-Reservoir analysis not available for Big Cow Creek nr Newton and Angelina River nr Alto

Table 7a: Winter Pulse Flows (Original Method)

Basin	USGS Gage Name	USGS Gage Number	Flow Statistic	Winter 25th Percentile (Dry)			Winter Median (Average)			Winter 75th Percentile (Wet)		
				Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir
Sabine	Big Sandy Creek nr Big Sandy	8019500	Peak Discharge (cfs)	128	142	136	223	246	240	574	584	591
			Volume (Ac-Ft)	1,513	2,059	1,531	4,143	4,999	4,322	9,546	10,486	9,695
			Duration (Days)	7	9	7	11	12	11	16	17	17
			Frequency (# per Season)	4	4	4	3	2	3	1	1	1
Sabine	Sabine River nr Gladewater	8020000	Peak Discharge (cfs)	741	800	953	2,000	2,520	2,060	5,035	5,290	5,030
			Volume (Ac-Ft)	12,474	13,684	14,224	49,989	54,860	52,092	135,646	129,017	157,924
			Duration (Days)	13	12	13	17	16	18	28	26	27
			Frequency (# per Season)	3	3	3	2	2	2	1	1	1
Sabine	Sabine River nr Beckville	8022040	Peak Discharge (cfs)	1,113	1,185	1,115	3,140	3,720	2,865	6,428	6,083	7,215
			Volume (Ac-Ft)	14,357	20,792	10,849	75,531	89,921	66,081	206,207	201,972	189,248
			Duration (Days)	12	11	11	18	20	17	29	30	25
			Frequency (# per Season)	3	3	3	2	2	2	1	1	1
Sabine	Sabine River nr Bon Weir	8028500	Peak Discharge (cfs)	3,318	6,690	2,690	9,655	10,500	9,680	16,600	15,150	17,300
			Volume (Ac-Ft)	39,069	122,856	30,902	129,081	223,775	94,869	393,099	406,542	394,314
			Duration (Days)	5	8	3	14	15	13	22	23	20
			Frequency (# per Season)	3	3	3	2	2	2	0	0	1
Sabine	Big Cow Creek nr Newton	8029500	Peak Discharge (cfs)	126	-	150	293	-	358	676	-	761
			Volume (Ac-Ft)	828	-	1,014	2,002	-	2,506	4,316	-	5,227
			Duration (Days)	4	-	4	7	-	7	9	-	9
			Frequency (# per Season)	6	-	5	4	-	4	2	-	1
Sabine	Sabine River nr Ruliff	8030500	Peak Discharge (cfs)	1,788	4,570	1,390	4,655	8,020	2,675	8,185	11,400	7,263
			Volume (Ac-Ft)	12,322	58,076	5,217	111,640	199,775	43,676	228,050	512,906	165,342
			Duration (Days)	3	8	2	16	20	12	25	34	24
			Frequency (# per Season)	1	1	2	1	1	1	0	0	0
Neches	Village Creek nr Kountze	8041500	Peak Discharge (cfs)	723	730	776	1,490	1,510	1,650	2,940	2,835	3,620
			Volume (Ac-Ft)	9,203	9,897	9,189	22,885	23,554	26,826	50,836	46,758	67,795
			Duration (Days)	9	9	8	12	12	12	20	19	20
			Frequency (# per Season)	4	5	4	3	3	3	1	1	1
Neches	Neches River at Evadale	8041000	Peak Discharge (cfs)	2,640	2,848	3,220	6,105	5,505	6,480	9,738	10,660	10,750
			Volume (Ac-Ft)	39,010	57,630	22,145	143,799	121,954	143,459	300,873	299,574	308,261
			Duration (Days)	8	14	3	18	18	17	31	34	28
			Frequency (# per Season)	2	2	2	1	1	1	0	1	0
Neches	Attoyac Bayou nr Chireno	8038000	Peak Discharge (cfs)	-	509	245	-	814	598	-	1,800	948
			Volume (Ac-Ft)	-	5,675	2,554	-	13,749	8,180	-	31,016	18,051
			Duration (Days)	-	7	7	-	11	10	-	17	15
			Frequency (# per Season)	-	4	5	-	3	3	-	1	1
Neches	Angelina River nr Alto	8036500	Peak Discharge (cfs)	696	-	834	1,385	-	1,655	3,200	-	3,400
			Volume (Ac-Ft)	10,616	-	13,339	29,002	-	35,381	72,590	-	76,168
			Duration (Days)	10	-	10	14	-	15	22	-	22
			Frequency (# per Season)	4	-	3	2	-	2	1	-	1
Neches	Neches River near Rockland	8033500	Peak Discharge (cfs)	2,040	1,850	2,695	4,280	4,320	4,490	7,605	7,580	8,050
			Volume (Ac-Ft)	22,274	22,770	28,691	104,569	92,172	103,279	257,841	268,031	277,469
			Duration (Days)	8	8	11	18	18	18	35	36	31
			Frequency (# per Season)	3	2	2	2	2	2	1	1	1
Neches	Neches River at Neches	8032000	Peak Discharge (cfs)	378	440	337	705	985	635	1,258	1,680	1,205
			Volume (Ac-Ft)	2,521	8,289	1,687	11,437	18,906	7,517	29,166	43,839	23,767
			Duration (Days)	6	9	2	12	15	10	19	23	18
			Frequency (# per Season)	3	3	3	2	2	2	1	1	1

Full Period analysis not available for Attoyac Bayou nr Chireno

Pre-Reservoir analysis not available for Big Cow Creek nr Newton and Angelina River nr Alto

Table 7b: Spring Pulse Flows (Original Method)

Basin	USGS Gage Name	USGS Gage Number	Flow Statistic	Spring 25th Percentile (Dry)			Spring Median (Average)			Spring 75th Percentile (Wet)		
				Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir
Sabine	Big Sandy Creek nr Big Sandy	8019500	Peak Discharge (cfs)	96	126	98	219	266	212	569	637	465
			Volume (Ac-Ft)	1,270	2,108	1,252	4,255	5,005	3,745	8,592	10,301	7,595
			Duration (Days)	10	10	10	14	14	15	21	22	20
			Frequency (# per Season)	3	3	3	2	2	2	1	1	1
Sabine	Sabine River nr Gladewater	8020000	Peak Discharge (cfs)	649	1,080	643	2,340	2,820	2,500	4,655	4,555	4,655
			Volume (Ac-Ft)	9,579	22,951	10,112	44,846	57,511	44,223	131,931	127,502	140,556
			Duration (Days)	13	13	13	21	22	23	33	29	36
			Frequency (# per Season)	2	2	2	2	1	2	0	1	0
Sabine	Sabine River nr Beckville	8022040	Peak Discharge (cfs)	1,130	1,758	1,105	3,320	3,520	3,840	6,470	6,535	6,893
			Volume (Ac-Ft)	16,913	39,314	17,468	74,880	79,258	82,403	191,107	190,708	192,119
			Duration (Days)	13	13	13	23	21	25	34	33	36
			Frequency (# per Season)	2	2	2	1	1	1	0	0	1
Sabine	Sabine River nr Bon Weir	8028500	Peak Discharge (cfs)	3,240	4,475	3,165	5,730	9,660	4,920	10,700	14,350	8,218
			Volume (Ac-Ft)	34,213	51,937	34,099	90,135	222,387	73,271	256,264	388,398	177,927
			Duration (Days)	6	6	6	13	17	13	23	33	19
			Frequency (# per Season)	3	2	3	2	1	2	1	1	1
Sabine	Big Cow Creek nr Newton	8029500	Peak Discharge (cfs)	68	-	73	123	-	124	356	-	350
			Volume (Ac-Ft)	379	-	409	940	-	956	2,703	-	2,717
			Duration (Days)	3	-	3	5	-	5	9	-	9
			Frequency (# per Season)	6	-	6	4	-	4	2	-	1
Sabine	Sabine River nr Ruliff	8030500	Peak Discharge (cfs)	2,863	4,715	2,960	4,730	6,655	4,380	9,013	10,275	7,520
			Volume (Ac-Ft)	32,326	37,755	35,742	111,352	208,364	100,721	269,445	358,304	236,826
			Duration (Days)	5	7	6	17	26	17	27	40	27
			Frequency (# per Season)	2	1	2	1	0	1	0	0	1
Neches	Village Creek nr Kountze	8041500	Peak Discharge (cfs)	401	434	401	1,040	970	1,145	2,300	2,260	2,455
			Volume (Ac-Ft)	5,345	5,538	5,743	15,632	13,962	18,758	38,144	37,412	41,295
			Duration (Days)	9	9	9	14	14	14	20	20	20
			Frequency (# per Season)	4	4	3	2	2	2	1	1	1
Neches	Neches River at Evadale	8041000	Peak Discharge (cfs)	2,973	3,238	3,458	5,580	7,035	5,575	8,205	9,340	7,740
			Volume (Ac-Ft)	47,461	42,873	43,716	145,101	177,749	118,126	256,899	285,030	212,975
			Duration (Days)	10	11	6	19	20	16	32	32	22
			Frequency (# per Season)	2	2	2	1	1	1	0	0	0
Neches	Attoyac Bayou nr Chireno	8038000	Peak Discharge (cfs)	-	289	204	-	532	491	-	1,225	811
			Volume (Ac-Ft)	-	2,182	2,371	-	7,262	5,754	-	19,164	15,493
			Duration (Days)	-	7	7	-	10	12	-	16	19
			Frequency (# per Season)	-	4	4	-	3	2	-	1	1
Neches	Angelina River nr Alto	8036500	Peak Discharge (cfs)	432	-	431	997	-	1,010	2,410	-	2,365
			Volume (Ac-Ft)	6,060	-	5,812	19,035	-	20,184	59,201	-	59,173
			Duration (Days)	11	-	11	16	-	16	24	-	24
			Frequency (# per Season)	4	-	4	2	-	2	1	-	1
Neches	Neches River near Rockland	8033500	Peak Discharge (cfs)	1,165	1,135	1,150	3,115	2,845	3,440	6,345	6,663	5,780
			Volume (Ac-Ft)	12,357	9,566	10,453	75,472	82,031	65,375	201,424	237,922	187,636
			Duration (Days)	5	4	4	22	21	19	38	36	37
			Frequency (# per Season)	2	3	3	1	2	1	1	1	1
Neches	Neches River at Neches	8032000	Peak Discharge (cfs)	272	524	209	748	794	706	1,398	1,560	1,385
			Volume (Ac-Ft)	3,058	6,240	1,718	13,352	18,054	11,980	35,313	35,806	37,572
			Duration (Days)	6	11	5	14	16	12	24	25	23
			Frequency (# per Season)	3	2	4	2	1	2	1	1	1

Full Period analysis not available for Attoyac Bayou nr Chireno
Pre-Reservoir analysis not available for Big Cow Creek nr Newton and Angelina River nr Alto

Table 7c: Summer Pulse Flows (Original Method)

Basin	USGS Gage Name	USGS Gage Number	Flow Statistic	Summer 25th Percentile (Dry)			Summer Median (Average)			Summer 75th Percentile (Wet)		
				Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir
Sabine	Big Sandy Creek nr Big Sandy	8019500	Peak Discharge (cfs)	25	31	25	40	59	42	112	134	130
			Volume (Ac-Ft)	146	369	144	545	791	587	1,720	2,087	1,906
			Duration (Days)	3	7	3	10	11	10	15	15	16
			Frequency (# per Season)	4	4	4	3	3	3	1	1	1
Sabine	Sabine River nr Gladewater	8020000	Peak Discharge (cfs)	113	174	101	276	492	228	991	1,738	838
			Volume (Ac-Ft)	1,130	2,078	834	5,052	10,213	4,318	17,558	30,198	14,967
			Duration (Days)	6	12	4	14	19	14	22	26	21
			Frequency (# per Season)	3	3	3	2	2	2	1	1	1
Sabine	Sabine River nr Beckville	8022040	Peak Discharge (cfs)	165	250	149	420	735	272	1,270	2,080	1,195
			Volume (Ac-Ft)	775	3,496	630	6,805	15,605	4,588	25,658	40,571	18,612
			Duration (Days)	3	10	2	13	20	12	24	26	20
			Frequency (# per Season)	3	3	4	2	2	2	1	1	1
Sabine	Sabine River nr Bon Weir	8028500	Peak Discharge (cfs)	1,795	1,048	3,968	4,750	2,125	5,860	6,725	5,200	7,115
			Volume (Ac-Ft)	24,947	6,630	44,172	65,117	51,336	72,417	135,699	126,307	144,007
			Duration (Days)	6	2	6	13	16	13	19	24	17
			Frequency (# per Season)	5	3	6	3	2	3	1	1	1
Sabine	Big Cow Creek nr Newton	8029500	Peak Discharge (cfs)	46	-	52	73	-	81	127	-	139
			Volume (Ac-Ft)	228	-	263	559	-	637	1,203	-	1,337
			Duration (Days)	2	-	3	5	-	5	8	-	8
			Frequency (# per Season)	6	-	6	4	-	4	2	-	2
Sabine	Sabine River nr Ruliff	8030500	Peak Discharge (cfs)	1,780	1,595	3,340	4,270	2,920	5,900	6,663	5,215	7,390
			Volume (Ac-Ft)	25,140	9,650	45,144	90,456	85,993	134,420	220,160	157,502	276,555
			Duration (Days)	6	3	6	17	18	18	27	26	28
			Frequency (# per Season)	3	2	3	2	1	2	1	1	1
Neches	Village Creek nr Kountze	8041500	Peak Discharge (cfs)	146	161	143	270	381	263	699	1,113	699
			Volume (Ac-Ft)	1,413	1,397	1,389	3,790	4,492	3,896	10,739	14,117	10,636
			Duration (Days)	5	5	5	10	11	10	17	19	17
			Frequency (# per Season)	4	4	4	3	3	3	1	1	1
Neches	Neches River at Evadale	8041000	Peak Discharge (cfs)	1,005	1,045	3,065	2,100	1,640	3,800	3,890	3,125	4,890
			Volume (Ac-Ft)	12,647	16,589	26,648	44,624	48,754	64,205	96,099	112,188	111,818
			Duration (Days)	4	12	4	14	19	11	25	30	18
			Frequency (# per Season)	2	2	3	1	2	1	0	1	1
Neches	Attoyac Bayou nr Chireno	8038000	Peak Discharge (cfs)	-	66	50	-	108	103	-	235	226
			Volume (Ac-Ft)	-	382	363	-	1,233	1,109	-	2,873	3,052
			Duration (Days)	-	4	4	-	7	7	-	10	13
			Frequency (# per Season)	-	6	6	-	5	4	-	2	2
Neches	Angelina River nr Alto	8036500	Peak Discharge (cfs)	86	-	81	154	-	172	401	-	420
			Volume (Ac-Ft)	1,051	-	1,064	2,598	-	3,099	7,502	-	7,992
			Duration (Days)	6	-	7	12	-	12	18	-	19
			Frequency (# per Season)	4	-	4	3	-	3	1	-	1
Neches	Neches River near Rockland	8033500	Peak Discharge (cfs)	159	181	151	319	344	368	950	1,250	1,050
			Volume (Ac-Ft)	1,081	1,131	758	4,423	5,500	4,881	20,043	24,061	18,493
			Duration (Days)	3	3	3	12	12	12	24	27	23
			Frequency (# per Season)	3	3	3	2	2	2	1	1	1
Neches	Neches River at Neches	8032000	Peak Discharge (cfs)	88	65	99	139	128	150	294	248	386
			Volume (Ac-Ft)	470	329	504	1,581	2,198	1,488	4,590	5,266	4,132
			Duration (Days)	3	3	2	9	11	7	14	18	10
			Frequency (# per Season)	3	3	3	2	2	2	1	1	1

Full Period analysis not available for Attoyac Bayou nr Chireno
Pre-Reservoir analysis not available for Big Cow Creek nr Newton and Angelina River nr Alto

Table 7d: Fall Pulse Flows (Original Method)

Basin	USGS Gage Name	USGS Gage Number	Flow Statistic	Fall 25th Percentile (Dry)			Fall Median (Average)			Fall75th Percentile (Wet)		
				Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir
Sabine	Big Sandy Creek nr Big Sandy	8019500	Peak Discharge (cfs)	47	53	49	94	90	110	239	237	297
			Volume (Ac-Ft)	525	660	511	1,402	1,299	1,809	4,522	5,167	5,076
			Duration (Days)	7	7	7	11	10	11	15	15	16
			Frequency (# per Season)	4	4	4	3	3	3	1	1	1
Sabine	Sabine River nr Gladewater	8020000	Peak Discharge (cfs)	239	288	201	649	730	650	2,540	2,650	2,840
			Volume (Ac-Ft)	3,396	3,731	3,556	10,683	16,677	12,296	54,732	55,666	62,360
			Duration (Days)	12	7	11	17	18	17	24	25	24
			Frequency (# per Season)	3	3	3	2	2	2	1	1	1
Sabine	Sabine River nr Beckville	8022040	Peak Discharge (cfs)	231	429	169	768	885	707	3,235	3,020	3,380
			Volume (Ac-Ft)	2,409	4,776	914	14,418	20,231	13,029	73,518	72,447	82,638
			Duration (Days)	7	8	3	14	16	14	23	22	22
			Frequency (# per Season)	3	3	4	2	2	2	1	1	1
Sabine	Sabine River nr Bon Weir	8028500	Peak Discharge (cfs)	1,085	1,270	1,025	1,720	3,310	1,600	5,160	7,890	4,248
			Volume (Ac-Ft)	5,722	8,430	4,816	17,564	67,736	15,382	90,228	148,683	61,711
			Duration (Days)	3	4	3	6	13	6	17	21	15
			Frequency (# per Season)	4	3	6	3	2	3	1	1	2
Sabine	Big Cow Creek nr Newton	8029500	Peak Discharge (cfs)	82	-	97	162	-	182	412	-	463
			Volume (Ac-Ft)	504	-	575	1,170	-	1,297	3,039	-	3,247
			Duration (Days)	3	-	3	6	-	7	8	-	8
			Frequency (# per Season)	5	-	5	4	-	3	2	-	2
Sabine	Sabine River nr Ruliff	8030500	Peak Discharge (cfs)	1,400	1,250	1,395	2,060	2,770	2,000	4,580	5,595	3,735
			Volume (Ac-Ft)	7,676	7,597	5,484	24,674	52,026	17,812	95,742	184,884	82,463
			Duration (Days)	3	3	2	7	14	6	18	27	16
			Frequency (# per Season)	3	2	4	2	2	3	1	1	1
Neches	Village Creek nr Kountze	8041500	Peak Discharge (cfs)	238	190	325	557	489	693	1,790	1,230	2,080
			Volume (Ac-Ft)	2,724	1,709	3,302	7,449	5,972	8,805	27,057	19,576	36,456
			Duration (Days)	6	4	7	10	10	11	15	15	15
			Frequency (# per Season)	4	4	4	2	2	2	1	1	1
Neches	Neches River at Evadale	8041000	Peak Discharge (cfs)	1,100	767	2,740	2,760	1,880	3,435	5,320	3,890	6,425
			Volume (Ac-Ft)	12,685	11,786	18,347	51,193	51,193	55,547	119,032	110,364	155,395
			Duration (Days)	4	10	3	16	17	11	22	28	19
			Frequency (# per Season)	2	2	2	1	1	1	1	1	1
Neches	Attoyac Bayou nr Chireno	8038000	Peak Discharge (cfs)	-	117	120	-	265	219	-	602	683
			Volume (Ac-Ft)	-	1,163	1,167	-	2,602	2,856	-	8,300	9,313
			Duration (Days)	-	6	6	-	7	8	-	12	13
			Frequency (# per Season)	-	3	5	-	3	3	-	2	1
Neches	Angelina River nr Alto	8036500	Peak Discharge (cfs)	182	-	196	535	-	595	1,440	-	1,505
			Volume (Ac-Ft)	2,408	-	2,463	9,457	-	10,852	31,763	-	32,799
			Duration (Days)	10	-	10	13	-	13	19	-	19
			Frequency (# per Season)	4	-	4	3	-	3	1	-	1
Neches	Neches River near Rockland	8033500	Peak Discharge (cfs)	253	232	287	811	986	1,035	3,000	3,775	3,435
			Volume (Ac-Ft)	2,945	4,278	3,010	13,920	18,207	18,796	70,691	90,086	78,533
			Duration (Days)	5	5	5	16	17	16	26	25	25
			Frequency (# per Season)	3	3	3	2	2	2	1	1	1
Neches	Neches River at Neches	8032000	Peak Discharge (cfs)	162	192	157	310	485	274	647	965	579
			Volume (Ac-Ft)	1,125	2,481	934	4,318	8,820	3,326	11,445	24,343	8,745
			Duration (Days)	4	10	2	10	15	9	16	19	13
			Frequency (# per Season)	4	3	4	3	2	3	1	1	1

Full Period analysis not available for Attoyac Bayou nr Chireno
Pre-Reservoir analysis not available for Big Cow Creek nr Newton and Angelina River nr Alto

Table 8a: Annual Pulse Flows (Frequency Method)

USGS Gage Name	Flow Statistic	1 per 2 Years			1 per Year			2 per 3 Years			2 per Year		
		Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir
Big Sandy Creek nr Big Sandy	Peak Discharge (cfs)	2,930	4,000	2,930	1,920	2,100	2,100	1,420	1,550	1,460	1,170	1,260	1,220
	Volume (Ac-Ft)	35,703	43,877	36,806	24,536	25,150	28,694	18,665	19,224	21,188	15,644	16,008	18,092
	Duration (Days)	30	30	31	26	24	27	23	22	23	21	20	21
Sabine River nr Gladewater	Peak Discharge (cfs)	18,100	34,600	15,900	10,600	17,000	8,800	7,440	10,600	7,150	6,220	8,100	6,220
	Volume (Ac-Ft)	483,275	703,975	535,070	291,042	361,760	305,608	206,844	232,391	248,298	173,829	181,142	215,334
	Duration (Days)	44	52	44	36	39	34	31	33	32	29	30	30
Sabine River nr Beckville	Peak Discharge (cfs)	16,100	29,800	15,200	11,800	12,700	12,300	9,640	10,000	10,600	8,270	8,550	8,650
	Volume (Ac-Ft)	541,644	799,357	570,487	400,063	354,109	471,064	327,118	281,228	409,271	280,219	241,798	335,194
	Duration (Days)	45	52	44	38	35	39	34	31	36	32	29	32
Sabine River nr Bon Weir	Peak Discharge (cfs)	36,500	37,500	36,700	28,700	27,700	30,200	24,300	24,300	25,700	21,600	22,200	22,800
	Volume (Ac-Ft)	1,200,452	1,627,017	1,009,374	931,140	1,151,824	834,847	778,690	989,598	710,449	684,952	890,079	628,732
	Duration (Days)	32	40	28	28	33	25	25	30	23	24	28	21
Big Cow Creek nr Newton	Peak Discharge (cfs)	3,180	-	3,350	1,870	-	2,280	1,480	-	1,680	1,260	-	1,400
	Volume (Ac-Ft)	18,325	-	19,792	11,168	-	13,829	8,975	-	10,387	7,725	-	8,756
	Duration (Days)	17	-	17	14	-	14	13	-	13	12	-	12
Sabine River nr Ruliff	Peak Discharge (cfs)	41,300	52,000	40,600	29,000	33,100	27,900	22,700	27,300	22,000	16,800	21,400	16,000
	Volume (Ac-Ft)	2,581,061	3,530,854	2,511,832	1,760,073	2,175,046	1,692,669	1,337,897	1,751,573	1,304,349	941,501	1,317,231	904,395
	Duration (Days)	82	90	93	60	63	64	49	53	51	37	44	37
Village Creek nr Kountze	Peak Discharge (cfs)	12,400	13,800	13,000	8,150	8,050	9,100	6,180	5,800	6,580	5,050	4,500	5,590
	Volume (Ac-Ft)	170,313	184,922	178,562	118,176	115,871	131,318	92,022	85,981	98,166	76,452	67,975	84,577
	Duration (Days)	29	31	28	25	25	24	22	22	22	21	20	20
Neches River at Evadale	Peak Discharge (cfs)	26,800	34,600	25,900	19,500	22,800	19,200	15,800	19,000	14,800	13,000	15,300	12,700
	Volume (Ac-Ft)	1,762,388	2,030,727	2,052,809	1,242,210	1,314,691	1,288,788	974,359	1,077,767	860,628	769,783	843,682	676,846
	Duration (Days)	46	57	44	38	45	35	33	41	28	30	36	25
Attoyac Bayou nr Chireno	Peak Discharge (cfs)	-	9,310	7,520	-	5,750	4,480	-	4,090	3,260	-	3,240	2,330
	Volume (Ac-Ft)	-	110,273	91,536	-	75,392	61,455	-	56,095	46,734	-	45,467	34,492
	Duration (Days)	-	24	27	-	21	22	-	19	20	-	17	18
Angelina River nr Alto	Peak Discharge (cfs)	9,690	-	9,690	6,900	-	6,930	5,200	-	5,330	3,920	-	4,040
	Volume (Ac-Ft)	204,931	-	205,699	153,429	-	154,659	118,681	-	121,916	90,835	-	93,832
	Duration (Days)	29	-	29	26	-	26	24	-	24	21	-	22
Neches River near Rockland	Peak Discharge (cfs)	18,500	16,000	20,300	13,000	11,900	14,700	9,840	9,500	11,200	7,460	7,270	8,300
	Volume (Ac-Ft)	661,717	590,921	706,179	471,924	436,782	535,721	357,420	345,631	416,254	268,550	260,326	309,730
	Duration (Days)	41	38	42	35	33	36	31	30	32	27	26	27
Neches River at Neches	Peak Discharge (cfs)	7,280	10,700	6,650	4,880	5,760	4,640	3,430	4,220	3,300	2,440	3,340	2,370
	Volume (Ac-Ft)	172,590	208,786	185,208	118,357	116,577	134,806	84,058	86,823	97,411	59,977	69,606	69,675
	Duration (Days)	38	40	38	30	31	30	25	27	25	21	24	20

Full Period analysis not available for Attoyac Bayou nr Chireno

Pre-Reservoir analysis not available for Big Cow Creek nr Newton and Angelina River nr Alto

Table 8b: 1 per Season Pulse Flows (Frequency Method)

USGS Gage Name	Flow Statistic	1 per Season Winter			1 per Season Spring			1 per Season Summer			1 per Season Fall		
		Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir
Big Sandy Creek nr Big Sandy	Peak Discharge (cfs)	942	865	1,080	950	1,120	923	132	140	151	367	376	432
	Volume (Ac-Ft)	14,544	13,378	14,931	12,852	13,838	14,072	2,054	2,175	2,500	6,055	6,387	7,012
	Duration (Days)	16	17	16	19	19	20	11	13	12	14	13	15
Sabine River nr Gladewater	Peak Discharge (cfs)	5,570	5,790	5,470	5,070	8,180	4,600	730	1,410	714	2,240	2,290	2,770
	Volume (Ac-Ft)	194,743	163,437	176,257	140,612	183,526	141,941	13,480	26,786	13,226	66,875	59,491	96,621
	Duration (Days)	24	24	25	25	26	25	17	24	16	21	19	23
Sabine River nr Beckville	Peak Discharge (cfs)	7,200	5,970	8,330	7,030	8,550	6,630	1,120	1,260	1,180	3,250	2,670	4,250
	Volume (Ac-Ft)	302,174	210,126	378,918	220,513	234,879	237,367	19,863	30,776	19,886	100,717	85,995	132,399
	Duration (Days)	24	21	26	27	26	27	16	19	16	21	19	23
Sabine River nr Bon Weir	Peak Discharge (cfs)	20,600	18,000	22,800	16,500	18,500	15,500	7,360	4,700	7,800	8,960	7,900	10,300
	Volume (Ac-Ft)	690,800	536,946	659,704	483,992	687,013	418,139	175,009	148,553	183,207	249,617	84,084	251,422
	Duration (Days)	17	21	15	21	24	17	14	16	14	17	15	18
Big Cow Creek nr Newton	Peak Discharge (cfs)	1,080	-	1,300	862	-	1,010	191	-	223	790	-	1,040
	Volume (Ac-Ft)	7,387	-	8,761	6,075	-	7,588	1,447	-	1,650	5,038	-	6,527
	Duration (Days)	10	-	10	10	-	10	7	-	8	9	-	10
Sabine River nr Ruliff	Peak Discharge (cfs)	14,800	16,200	12,000	10,600	14,200	9,060	6,600	3,980	7,560	6,030	4,680	7,510
	Volume (Ac-Ft)	923,041	672,419	891,358	489,092	683,919	281,109	182,343	123,614	234,720	161,358	113,910	221,092
	Duration (Days)	32	32	29	23	30	19	19	13	20	15	13	17
Village Creek nr Kountze	Peak Discharge (cfs)	4,170	3,330	5,000	3,250	3,150	3,860	804	1,240	841	2,400	1,780	2,830
	Volume (Ac-Ft)	78,857	62,045	89,150	46,002	44,156	56,506	11,418	19,272	12,263	35,862	25,582	41,595
	Duration (Days)	18	17	19	18	18	18	13	16	13	14	12	14
Neches River at Evadale	Peak Discharge (cfs)	10,900	11,800	10,700	9,500	13,800	8,090	3,390	1,860	4,440	3,820	3,520	6,480
	Volume (Ac-Ft)	617,583	544,871	419,772	456,832	652,700	193,548	73,933	59,057	103,201	90,628	98,061	169,349
	Duration (Days)	27	28	26	24	30	17	13	14	10	13	18	12
Attoyac Bayou nr Chireno	Peak Discharge (cfs)	-	2,790	1,850	-	2,350	1,550	-	322	390	-	854	898
	Volume (Ac-Ft)	-	46,539	29,620	-	30,739	23,048	-	4,098	5,384	-	12,064	16,133
	Duration (Days)	-	18	14	-	14	17	-	10	12	-	11	12
Angelina River nr Alto	Peak Discharge (cfs)	3,530	-	3,770	2,760	-	2,760	397	-	420	1,500	-	1,640
	Volume (Ac-Ft)	89,332	-	97,268	59,278	-	59,755	7,129	-	7,597	34,291	-	37,070
	Duration (Days)	18	-	18	20	-	19	13	-	13	16	-	16
Neches River near Rockland	Peak Discharge (cfs)	6,910	5,920	7,430	5,600	6,580	5,570	615	622	857	2,240	2,050	3,050
	Volume (Ac-Ft)	256,523	235,673	234,661	167,866	209,493	165,766	13,365	16,535	22,183	72,600	47,704	100,255
	Duration (Days)	22	19	24	23	25	20	11	11	13	17	16	17
Neches River at Neches	Peak Discharge (cfs)	1,750	2,220	1,750	1,830	3,610	1,660	248	222	279	782	865	771
	Volume (Ac-Ft)	53,526	63,336	53,209	41,351	68,399	46,632	4,029	4,164	4,171	19,996	23,985	17,551
	Duration (Days)	15	18	14	18	23	18	7	9	6	12	15	11

Full Period analysis not available for Attoyac Bayou nr Chireno

Pre-Reservoir analysis not available for Big Cow Creek nr Newton and Angelina River nr Alto

Table 8c: 2 per Season Pulse Flows (Frequency Method)

USGS Gage Name	Flow Statistic	2 per Season Winter			2 per Season Spring			2 per Season Summer			2 per Season Fall		
		Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir
Big Sandy Creek nr Big Sandy	Peak Discharge (cfs)	358	339	484	313	376	301	50	70	54	130	128	171
	Volume (Ac-Ft)	5,932	6,525	7,055	5,062	6,155	4,905	671	1,081	623	2,189	2,233	2,812
	Duration (Days)	10	11	11	13	14	13	6	9	6	9	9	10
Sabine River nr Gladewater	Peak Discharge (cfs)	1,880	2,260	1,770	1,580	2,820	1,390	168	238	172	380	422	517
	Volume (Ac-Ft)	48,599	61,528	43,834	51,150	81,030	33,802	2,752	4,070	2,908	1,098	7,920	2,902
	Duration (Days)	15	16	15	16	17	15	7	8	7	11	10	12
Sabine River nr Beckville	Peak Discharge (cfs)	2,900	3,530	3,020	2,160	2,720	1,890	285	492	272	628	615	886
	Volume (Ac-Ft)	84,998	111,620	89,502	72,092	90,188	34,297	5,436	8,732	4,031	7,245	8,617	15,286
	Duration (Days)	15	16	14	15	14	15	6	10	5	9	9	9
Sabine River nr Bon Weir	Peak Discharge (cfs)	13,800	11,600	17,100	6,700	7,360	6,660	5,880	1,440	6,900	2,590	2,350	3,300
	Volume (Ac-Ft)	421,966	253,913	472,075	151,163	143,294	145,449	132,571	15,323	155,752	40,957	45,713	66,672
	Duration (Days)	14	16	13	12	12	11	13	6	13	7	6	8
Big Cow Creek nr Newton	Peak Discharge (cfs)	693	-	799	350	-	393	109	-	127	322	-	405
	Volume (Ac-Ft)	4,911	-	5,615	2,545	-	3,017	873	-	1,022	2,232	-	2,777
	Duration (Days)	8	-	8	7	-	7	5	-	5	7	-	7
Sabine River nr Ruliff	Peak Discharge (cfs)	1,600	2,390	1,460	3,250	#N/A	3,530	3,380	1,610	6,010	2,020	1,220	2,250
	Volume (Ac-Ft)	#N/A	#N/A	#N/A	#N/A	#N/A	79,096	108,505	8,950	187,343	33,993	38,612	40,386
	Duration (Days)	3	7	3	8	#N/A	9	11	6	16	5	4	5
Village Creek nr Kountze	Peak Discharge (cfs)	2,010	2,010	2,540	1,380	1,110	1,630	341	394	393	712	568	1,020
	Volume (Ac-Ft)	36,927	35,379	45,535	23,093	19,584	26,496	6,159	5,384	7,135	11,426	9,262	16,312
	Duration (Days)	13	13	14	13	12	14	8	8	8	9	8	10
Neches River at Evadale	Peak Discharge (cfs)	2,000	2,240	1,290	3,440	4,500	4,110	1,190	1,000	3,380	1,150	550	3,030
	Volume (Ac-Ft)	#N/A	#N/A	5,754	#N/A	36,118	68,584	28,078	20,901	58,511	4,918	42,738	44,291
	Duration (Days)	6	9	2	12	13	10	8	9	9	6	6	7
Attoyac Bayou nr Chireno	Peak Discharge (cfs)	-	1,140	837	-	840	690	-	204	146	-	446	405
	Volume (Ac-Ft)	-	19,313	13,871	-	12,241	10,618	-	2,483	1,888	-	6,722	6,353
	Duration (Days)	-	11	10	-	11	13	-	8	7	-	9	9
Angelina River nr Alto	Peak Discharge (cfs)	1,620	-	1,930	1,100	-	1,270	146	-	177	588	-	645
	Volume (Ac-Ft)	37,114	-	45,570	24,117	-	27,812	2,632	-	3,250	12,038	-	12,923
	Duration (Days)	13	-	14	14	-	14	8	-	8	12	-	12
Neches River near Rockland	Peak Discharge (cfs)	3,080	2,740	3,420	1,720	2,500	2,200	195	228	287	515	448	800
	Volume (Ac-Ft)	82,195	74,886	85,689	39,935	67,562	48,282	#N/A	548	191	649	13,921	13,668
	Duration (Days)	14	13	15	12	12	13	5	5	6	8	8	9
Neches River at Neches	Peak Discharge (cfs)	833	990	800	820	890	820	113	90	136	345	338	365
	Volume (Ac-Ft)	19,104	25,161	17,618	20,405	20,370	19,781	1,339	1,085	1,019	5,391	3,704	5,900
	Duration (Days)	10	12	8	12	13	11	4	5	4	8	10	7

Full Period analysis not available for Attoyac Bayou nr Chireno

Pre-Reservoir analysis not available for Big Cow Creek nr Newton and Angelina River nr Alto

2 per season regression failed for Spring season for pre-reservoir conditions at the Sabine River near Ruliff

Table 9a: Base Flows (Winter)

(Values in cfs)

Basin	USGS Gage Name	USGS Gage Number	Winter 25th Percentile (Dry)			Winter Median (Average)			Winter 75th Percentile (Wet)		
			Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir
Sabine	Big Sandy Creek nr Big Sandy	8019500	66	72	71	106	113	116	163	165	166
Sabine	Sabine River nr Gladewater	8020000	277	274	266	472	422	525	836	770	939
Sabine	Sabine River nr Beckville	8022040	438	448	511	807	766	923	1,580	1,580	1,710
Sabine	Sabine River nr Bon Weir	8028500	1,460	1,890	1,210	5,870	3,615	10,200	15,400	9,275	16,200
Sabine	Big Cow Creek nr Newton	8029500	56	-	66	78	-	91	106	-	119
Sabine	Sabine River nr Ruliff	8030500	1,520	2,350	1,303	2,565	2,890	1,685	5,063	4,600	3,618
Neches	Village Creek nr Kountze	8041500	240	205	315	424	344	521	672	666	717
Neches	Neches River at Evadale	8041000	1,760	1,840	1,750	2,590	2,420	2,505	4,980	5,160	3,070
Neches	Attoyac Bayou nr Chireno	8038000	-	195	107	-	348	188	-	516	339
Neches	Angelina River nr Alto	8036500	252	72	259	581	-	610	971	-	955
Neches	Neches River near Rockland	8033500	548	503	422	1,390	1,070	1,365	2,500	2,860	2,335
Neches	Neches River at Neches	8032000	178	240	165	408	438	351	814	762	700

Table 9b: Base Flows (Spring)

Basin	USGS Gage Name	USGS Gage Number	Spring 25th Percentile (Dry)			Spring Median (Average)			Spring 75th Percentile (Wet)		
			Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir
Sabine	Big Sandy Creek nr Big Sandy	8019500	30	38	26	51	75	51	111	127	106
Sabine	Sabine River nr Gladewater	8020000	119	198	100	283	332	325	664	616	910
Sabine	Sabine River nr Beckville	8022040	232	326	197	526	598	589	1,260	1,220	1,533
Sabine	Sabine River nr Bon Weir	8028500	856	1,440	755	1,590	3,210	1,195	6,680	6,980	8,808
Sabine	Big Cow Creek nr Newton	8029500	38	-	43	52	-	60	74	-	82
Sabine	Sabine River nr Ruliff	8030500	1,208	2,018	1,130	1,795	2,860	1,480	3,035	4,488	2,250
Neches	Village Creek nr Kountze	8041500	106	101	121	189	177	229	335	285	382
Neches	Neches River at Evadale	8041000	1,553	1,380	2,940	3,070	2,480	3,410	3,868	5,000	3,968
Neches	Attoyac Bayou nr Chireno	8038000	-	96	49	-	189	96	-	276	178
Neches	Angelina River nr Alto	8036500	82	-	85	206	-	231	518	-	520
Neches	Neches River near Rockland	8033500	382	738	349	1,020	1,260	837	2,160	2,473	2,225
Neches	Neches River at Neches	8032000	87	122	80	194	262	134	524	520	463

Full Period analysis not available for Attoyac Bayou nr Chireno

Pre-Reservoir analysis not available for Big Cow Creek nr Newton and Angelina River nr Alto

Table 9c: Base Flows (Summer)

(Values in cfs)

Basin	USGS Gage Name	USGS Gage Number	Summer 25th Percentile (Dry)			Summer Median (Average)			Summer 75th Percentile (Wet)		
			Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir
Sabine	Big Sandy Creek nr Big Sandy	8019500	14	16	13	18	21	16	26	29	26
Sabine	Sabine River nr Gladewater	8020000	34	36	36	46	49	49	78	85	96
Sabine	Sabine River nr Beckville	8022040	51	61	52	74	88	76	122	160	128
Sabine	Sabine River nr Bon Weir	8028500	478	440	712	656	615	990	1,120	1,060	2,395
Sabine	Big Cow Creek nr Newton	8029500	28	-	31	36	-	40	48	-	50
Sabine	Sabine River nr Ruliff	8030500	670	688	1,080	870	950	1,600	1,430	1,633	3,485
Neches	Village Creek nr Kountze	8041500	70	70	78	91	95	105	135	141	143
Neches	Neches River at Evadale	8041000	471	392	2,693	2,140	610	3,140	3,210	994	3,478
Neches	Attoyac Bayou nr Chireno	8038000	-	26	20	-	45	28	-	66	48
Neches	Angelina River nr Alto	8036500	36	-	37	48	-	49	69	-	71
Neches	Neches River near Rockland	8033500	61	64	80	88	106	109	151	181	196
Neches	Neches River at Neches	8032000	42	30	63	73	38	88	108	47	120

Table 9d: Base Flows (Fall)

Basin	USGS Gage Name	USGS Gage Number	Fall 25th Percentile (Dry)			Fall Median (Average)			Fall 75th Percentile (Wet)		
			Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir
Sabine	Big Sandy Creek nr Big Sandy	8019500	20	23	19	36	39	36	63	70	66
Sabine	Sabine River nr Gladewater	8020000	49	47	74	105	155	110	232	265	223
Sabine	Sabine River nr Beckville	8022040	75	74	90	141	206	140	356	424	372
Sabine	Sabine River nr Bon Weir	8028500	478	471	522	615	640	648	1,110	1,160	1,160
Sabine	Big Cow Creek nr Newton	8029500	36	-	41	46	-	51	64	-	72
Sabine	Sabine River nr Ruliff	8030500	735	840	883	970	1,030	1,130	1,400	1,700	1,460
Neches	Village Creek nr Kountze	8041500	89	86	100	138	122	170	236	200	295
Neches	Neches River at Evadale	8041000	438	400	1,990	1,280	543	2,620	2,630	1,240	3,050
Neches	Attoyac Bayou nr Chireno	8038000	-	37	34	-	78	65	-	139	122
Neches	Angelina River nr Alto	8036500	47	-	50	92	-	101	175	-	238
Neches	Neches River near Rockland	8033500	82	71	124	168	220	220	381	484	455
Neches	Neches River at Neches	8032000	73	42	80	104	136	103	172	238	158

Full Period analysis not available for Attoyac Bayou nr Chireno

Pre-Reservoir analysis not available for Big Cow Creek nr Newton and Angelina River nr Alto

Table 10: Subsistence Flows

(Values in cfs)

Basin	USGS Gage Name	USGS Gage Number	7Q2	Winter			Spring			Summer			Fall		
				Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir	Full Period	Pre-Reservoir	Post Reservoir
Sabine	Big Sandy Creek nr Big Sandy	8019500	12.4	#N/A	#N/A	#N/A	9	10	9	8	8	7	8	8	7
Sabine	Sabine River nr Gladewater	8020000	46.4	#N/A	#N/A	#N/A	22	22	22	14	12	18	17	18	22
Sabine	Sabine River nr Beckville	8022040	75.9	#N/A	#N/A	#N/A	28	#N/A	28	20	16	22	19	23	25
Sabine	Sabine River nr Bon Weir	8028500	703.1	#N/A	#N/A	#N/A	279	#N/A	#N/A	241	223	#N/A	234	236	#N/A
Sabine	Big Cow Creek nr Newton	8029500	30	#N/A	-	#N/A	20	-	20	20	-	18	20	-	20
Sabine	Sabine River nr Ruliff	8030500	1121.3	#N/A	#N/A	#N/A	436	#N/A	#N/A	396	360	#N/A	362	350	425
Neches	Village Creek nr Kountze	8041500	78.9	#N/A	#N/A	#N/A	49	46	49	41	42	37	41	43	46
Neches	Neches River at Evadale	8041000	1838.6	135	132	256	266	#N/A	#N/A	228	238	234	204	171	240
Neches	Attoyac Bayou nr Chireno	8038000	25.6	-	#N/A	#N/A	-	#N/A	0	-	12	9	-	11	7
Neches	Angelina River nr Alto	8036500	37.7	#N/A	-	#N/A	18	-	18	11	-	11	16	-	16
Neches	Neches River near Rockland	8033500	111.7	#N/A	#N/A	#N/A	29	#N/A	#N/A	21	16	26	21	9	#N/A
Neches	Neches River at Neches	8032000	70.7	#N/A	#N/A	#N/A	21	18	21	12	9	19	13	12	#N/A

n/a indicates that a subsistence flow does not occur during this season in the historical record

7Q2 values are from the Texas Surface Water Quality Standards

Full Period analysis not available for Attoyac Bayou nr Chireno

Pre-Reservoir analysis not available for Big Cow Creek nr Newton and Angelina River nr Alto

values somewhat differently. Instead of specifying the number of times an event is expected to occur in a season, the pulse events are given a "recurrence interval", which is the frequency at which these types of events could be expected to occur over time. These events can be expressed either in terms of years or seasons. The recurrence interval does not mean that these types of events are expected to occur in any particular year. For example, if a pulse event is observed that has a two-year recurrence interval it does not mean that this type of event will not occur until two years later. A similar event could occur later in the same year, or may not occur again for several years. What it does mean is that over relatively long periods of time, these types of events should occur about once every two years. Also notice in the frequency-based results that a single value is reported for discharge (Qp), but a range of values is specified for volume and duration, with a central tendency value reported in parenthesis. The frequency-based method used regression techniques to identify a typical range of values for volume and duration associated with the historical discharges. Occasionally these regressions produce negative values, and these are reported at #N/A in the output matrix. This seems to occur most often in the volume regressions. Before implementation of the flow regime, all regressions should be examined to evaluate their utility at the recommended flow magnitudes. A reduction in the significance value for the prediction intervals in the regressions could eliminate some of these, but it will also reduce the range of values reported in the matrix.

Looking at the overbank flows in Table 6, it appears that most of the HEFR overbank events exceed the NWS Flood Stage flows, with some even exceeding the Moderate Stage. (See Table 3 for additional NWS data.) The implications of recommending a relatively large flood flow as part of an environmental flow regime are uncertain. The BBEST may wish to refine their definition of overbank flows as additional information becomes available.

It is difficult to discern any general trends in the pulse and base flow data in Tables 7, 8 and 9. In many (but not all) cases the Pre-Dam values are higher than the Full Period and Post-Dam values. FNI recommends caution before making any definite conclusions based on this trend. The Pre-Dam analysis period of 21 years is relatively short compared to the Full Period (variable, but typically at least 70 years) or the Post-Dam period (38 years). The shorter record makes the analysis more easily influenced by individual storm events. Reservoirs typically reduce the number of pulse events and can reduce base flow events, depending on mode of

operation (hydropower typically increases base flows). However, most of the reservoirs in the Sabine and Neches Basins are either relatively small or have not been used to their fullest capacity. The flow records may be examined to see if the analysis could have been influenced by individual storms and verify the Pre-Dam HEFR results.

The gages with the most significant discrepancies are the Sabine River near Bon Wier and the Sabine River near Ruliff. The Bon Wier gage is located about 59 river miles downstream of Toledo Bend Reservoir. The Ruliff is about 58 river miles downstream of Bon Wier and about 40 river miles upstream of Sabine Lake[7]. In most cases, we would expect the downstream gage to have higher values than the upstream gage. However, the HEFR values for Bon Wier are almost always significantly higher than Ruliff. The reason for this discrepancy appears to be the result of using the NWS bankfull and flood stage discharges for the upper pulse threshold and overbank thresholds. The NWS discharges are significantly higher at Bon Wier than at Ruliff. A preliminary test using threshold parameters at Bon Wier that are closer to the Ruliff parameters removes the discrepancy. It is unclear at this time if lower values for the upper pulse and overbank thresholds at Bon Wier are warranted, if higher values at Ruliff should be used, or the results should be left as they are because the environment needs more water at Bon Wier than at Ruliff. Additional information from the current FERC relicensing in this reach may shed light on this issue.

Table 10 compares the HEFR subsistence values to the published 7Q2s for each gage. The subsistence values are uniformly lower than the 7Q2 values except for at the Neches River near Neches gage, where they are higher in the spring and fall for the pre-reservoir condition. Not surprisingly the most significant differences are at the three hydropower-influenced gages: Bon Wier, Ruliff and Evadale.

The HEFR matrices in Attachment B use of the terms “wet, “average” and “dry” to classify flow conditions. In general, HEFR associates these terms with the 75th percentile, median and 25th percentile of the parameters in the flow matrix. The method does not directly link the results to observed climatic conditions. Figure 7 illustrates how HEFR applies these terms. This particular year is interesting because it includes two overbank events, subsistence flows and

[7] United State Geological Survey National Water Information System, Surface-Water Data for Texas, available on-line at http://waterdata.usgs.gov/tx/nwis/sw.

Figure 7a: Example of Pulse Classification by Climatic Condition

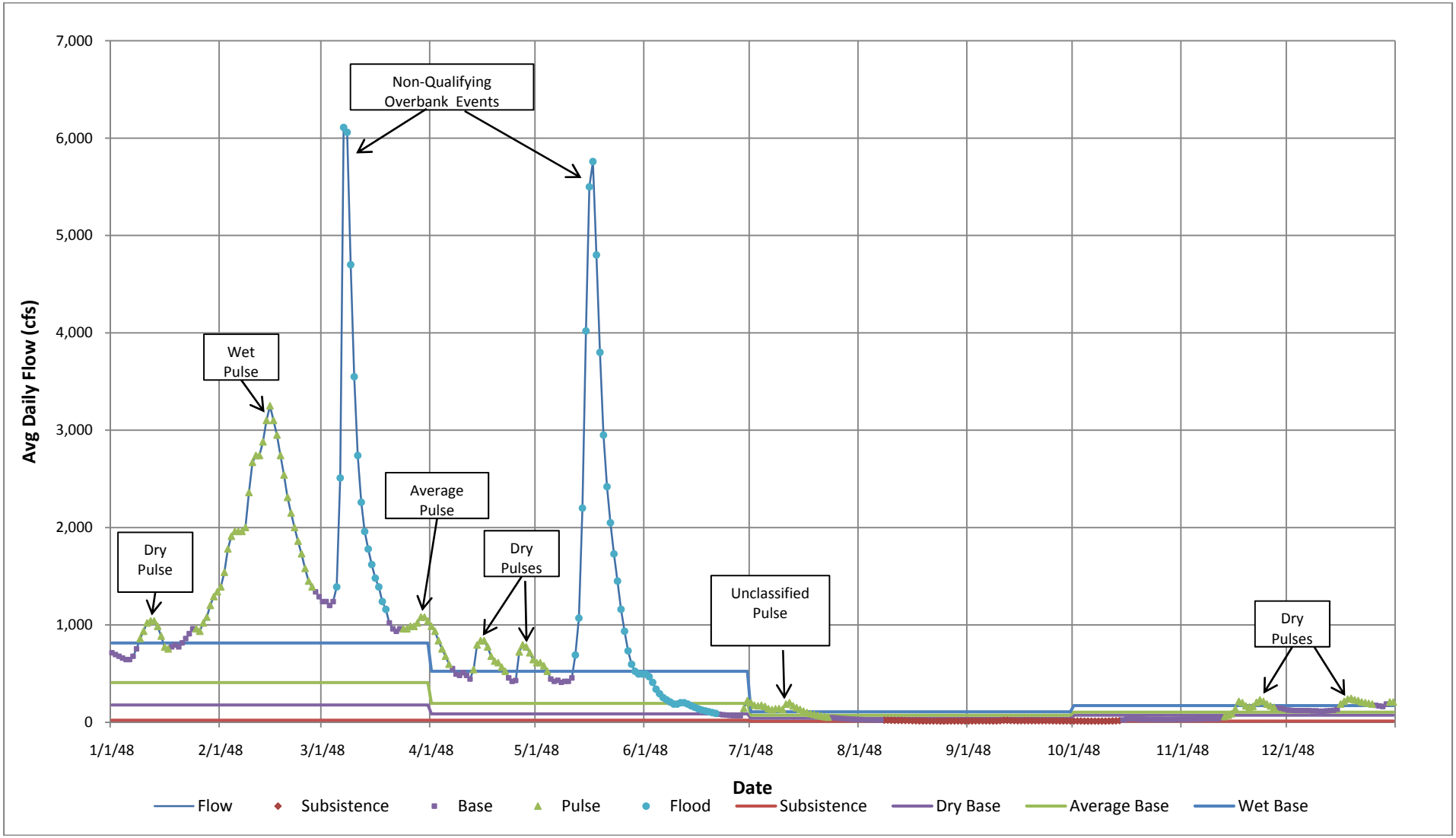
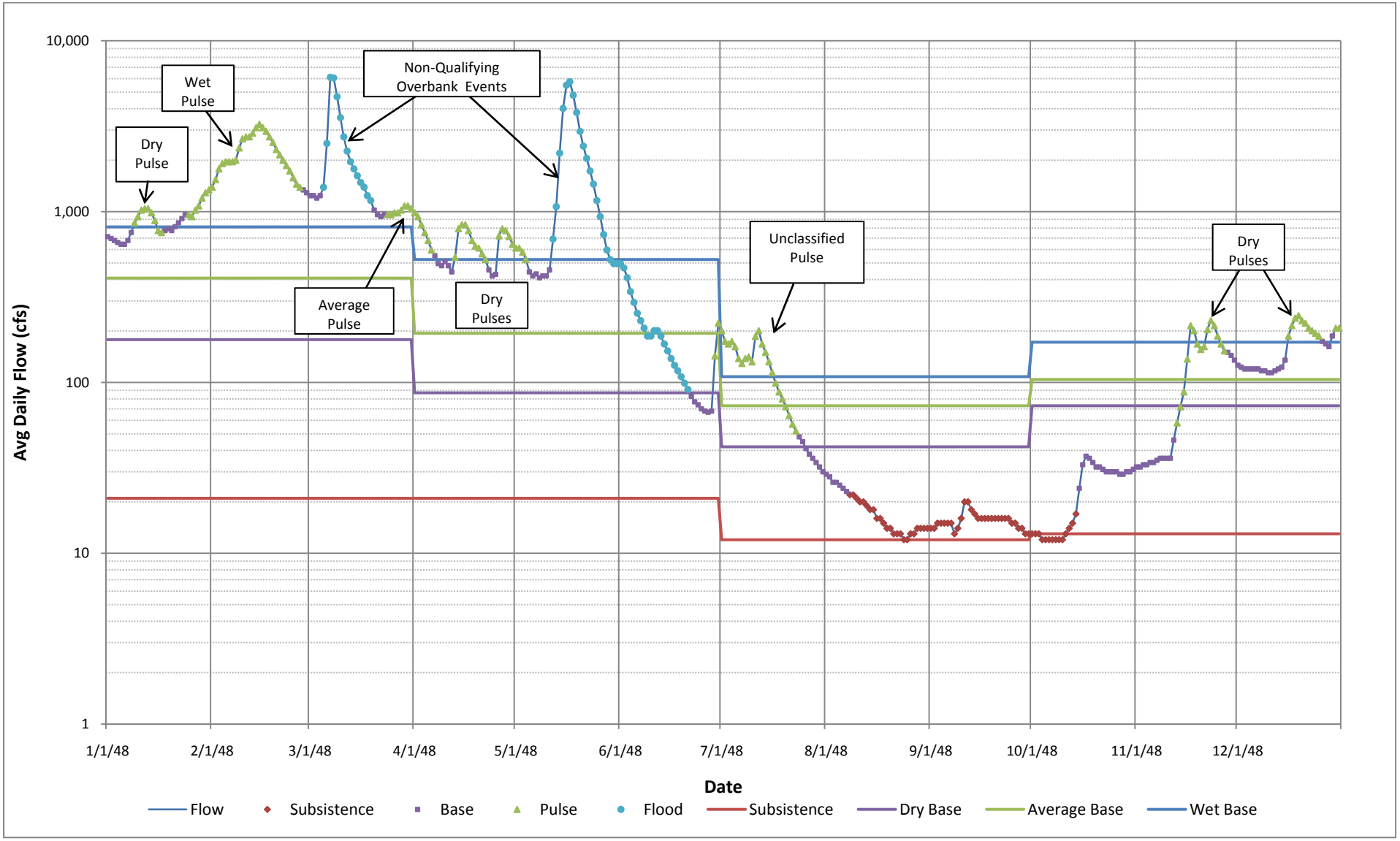


Figure 7b: Example of Pulse Classification by Climatic Condition



several sizes of pulse events. The total flow for this year is slightly below the annual median, so the year could be considered an "average" year. Seasonally, the winter, spring and fall would probably be classified as average while the summer would be classified as dry.

The pulse flow events in Table 6 have been marked with the designation of wet, average or dry found in a table generated by HEFR. The model did not give any particular designation to the pulse at the beginning of July, so it is marked as an "unclassified pulse". The two overbank flows do not meet the HEFR criteria for overbank events because the peak discharge is lower than the matrix criteria, so they have been marked as "non-qualifying overbank events". Also plotted on the graph are the subsistence and wet, dry and average base flow criteria from the matrix. Note that the winter and spring seasons have a mixture of average, dry, wet and overbank events. Also note that the magnitude of "dry" pulses varies significantly depending on the season. The winter and spring dry pulses are quite a bit larger than the fall dry pulse.

Figure 7 illustrates that even though an event qualifies as "dry" or "wet", it does not necessarily mean that you would be observing dry or wet conditions. The HEFR statistics are generated without regard to climatic condition, so the use of these terms to describe the statistics can be somewhat misleading. To address this issue, FNI recommends that the BBEST report HEFR results in terms of the statistics as well as the assumed condition. In other words, replace "dry" with the term "25th Percentile (dry)" and so forth. We believe that this will help clarify the statistical nature of the analysis.

Comparison of HEFR results to State Methodology for Sabine Lake

In addition to the HEFR analyses for the twelve stream gages, a HEFR analysis was performed on inflows into Sabine Lake. The flow data consists of historical daily flows from BBEST gages Village Creek near Kountze, Neches River at Evadale and Sabine River near Ruliff, plus the USGS gages Pine Island Bayou near Sour Lake (08041700) and Cow Bayou near Mauriceville (08031000). The historical daily gage flows were added to estimated ungaged inflows obtained from the Texas Water Development Board (TWDB). The ungaged flows consist of monthly data for the period from 1941 to 2005. These flows were distributed to daily using historical flow patterns from the Kountze gage. TWDB also has monthly estimates of diversions and return flows for the ungaged data. These data were distributed evenly throughout the each month and the diversions were subtracted and the return flows added to the daily flows. TWDB also

has historical monthly precipitation and evaporation estimates for Sabine Lake. These data were not included in the inflows. The median net precipitation on Sabine Lake (precipitation – evaporation) for the 1941 to 2005 period averages about 49,000 acre-feet per year, which is less than 1 percent of the average annual flow into the Sabine Lake.

Table 11 compares the annual volume from the HEFR runs using the percentile-based approach for Sabine Lake to the annual volume for MinQ, MaxC and MaxQ[8] from the State Methodology for bay and estuary inflows. HEFR matrix volumes for each flow condition (25th percentile, median or 75th percentile) are shown for base flows only, base plus pulse flows and with the entire HEFR overbank event added to each condition. (Overbank flows may not occur in any given year.) Subsistence flows have not historically occurred during the winter and spring months. In these months the fall HEFR result was used to calculated volumes.

Comparing HEFR to the State Methodology shows that the HEFR 25th percentile (dry) conditions are less than the MinQ unless an overbank event occurs during the year. Base plus pulse flows for median (average) conditions are less than MinQ for the Full Period and Pre-Dam time periods, but are more than MinQ for the Post-Dam period. MaxC values are only exceeded for the median (average) condition if an overbank event occurs during the year. The 75th percentile (wet) condition is relatively close to the MaxQ even without the occurrence of an overbank flow.

Also note that for the HEFR results in Table 11 most of the volume entering the Lake is included in the base flow component. The base flow by itself is about 70% of the Base + Pulse volume in the 25th percentile (dry) conditions and over 90% for 75th percentile (wet) condition. Also, note that the Post-Dam HEFR results have higher volumes than the Full Period or Pre-Dam results.

Figure 8 compares the seasonal distribution of the HEFR volumes to the seasonal distribution using the State Methodology. (The monthly State Methodology values were summed by the same seasons used in the HEFR analysis.) Note that the distribution for the HEFR volumes without overbank flows is similar to the State Methodology, with the highest flows occurring during the winter months and the lowest during the summer months. The occurrence of an

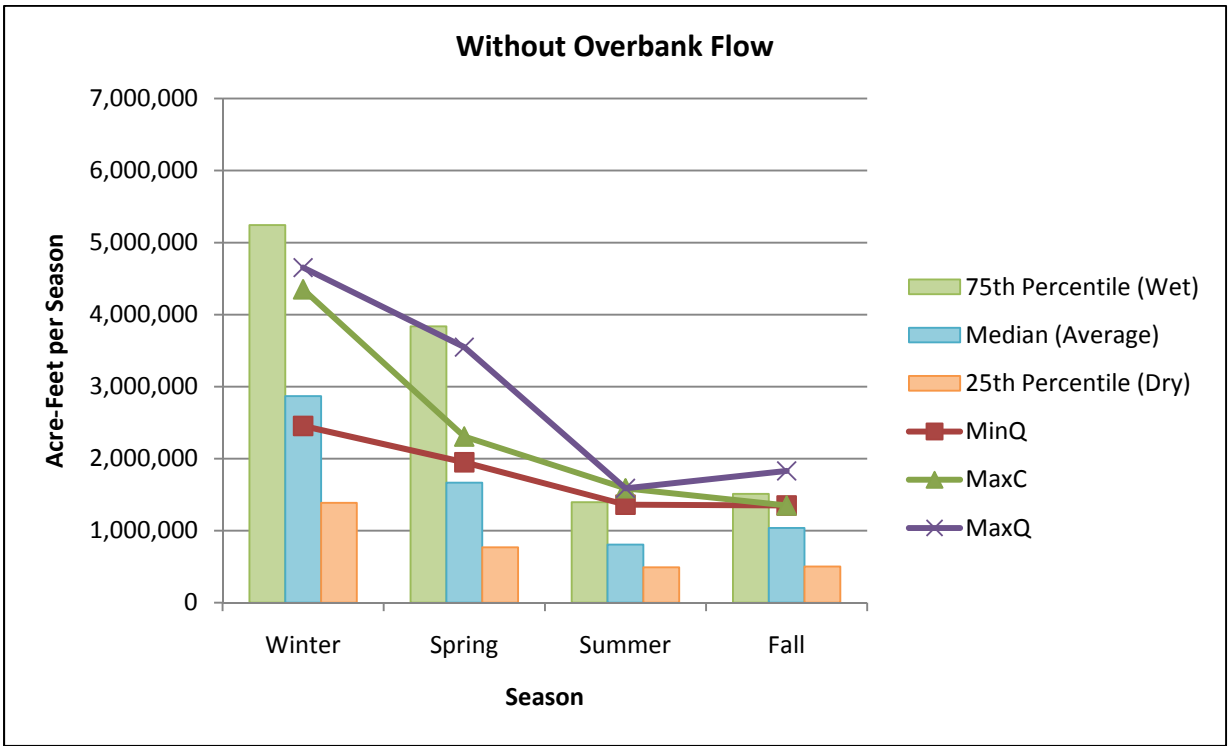
[8] Texas Parks and Wildlife Department: Freshwater Inflow Recommendation for the Sabine Lake Estuary of Texas and Louisiana, March 2005.

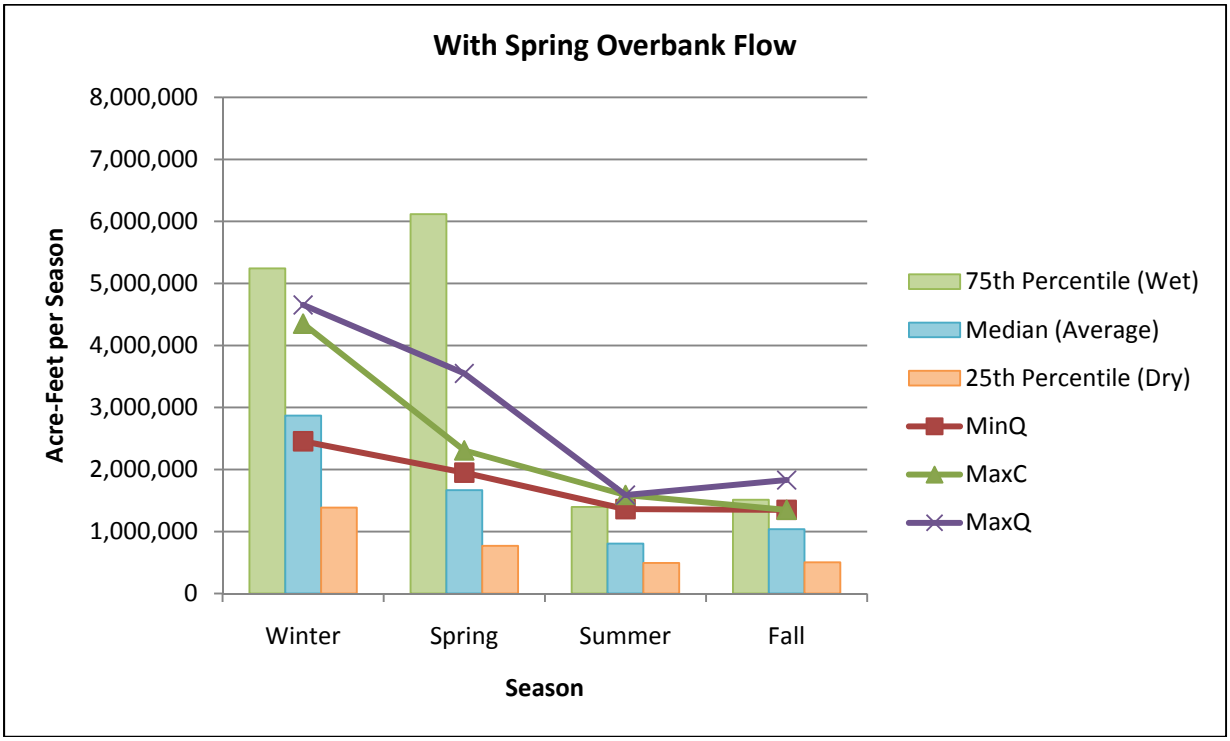
overbank flow can significantly alter the distribution, however. The HEFR volumes are for the Full Period of record. The Pre-Dam and Post-Dam periods have similar results.

Table 11: Comparison of HEFR Annual Volumes to State Methodology for Sabine Lake
(Values in Acre-Feet per Year)

HEFR Annual Volumes	Full Period (41-05)	Pre-Dam (41-60)	Post-Dam (71-05)
Subsistence	549,757	535,467	680,223
25th Percentile (Dry) Condition			
Base Only	2,243,997	2,316,804	3,306,215
Base + Pulse	3,150,508	3,643,588	4,114,963
Base + Pulse + Overbank	6,451,892	8,646,629	7,316,168
Median (Average) Condition			
Base Only	5,018,915	5,013,258	7,240,502
Base + Pulse	6,380,477	6,325,716	8,234,125
Base + Pulse + Overbank	9,467,182	10,719,867	11,271,050
75th Percentile (Wet) Condition			
Base Only	11,076,875	10,520,563	13,694,250
Base + Pulse	11,986,199	11,300,553	14,298,506
Base + Pulse + Overbank	14,266,063	14,416,682	16,359,393
State Methodology			
MinQ	7,114,000		
MaxC	9,596,600		
MaxQ	11,619,300		

Figure 8: Comparison of Seasonal Flow Volumes for Full Period HEFR and State Methodology for Sabine Lake, with and without Overbank Flow





Summary and Conclusions

FNI has performed a series of HEFR analyses for twelve stream gages in the Sabine and Neches Basins and for inflows into Sabine Lake. Where data were available, each gage was evaluated for three different time periods: the Full Period of record for the gage, a Pre-Dam period from 1940 to 1961, and a Post-Dam period from 1971 to 2008. Each period was analyzed using both the original percentile-based approach and frequency based approach available in HEFR. In general these analyses did not stray significantly from default values suggested in the SAC guidance for application of HEFR[1]. Major differences from the SAC defaults are the use of NWS stage data to define overbank flows, allowance for a wider range of flow values in pulse and base flow classifications. Subsistence and base flows were not limited to the published 7Q2 in the HEFR analysis. If desired by the BBEST, this limitation can easily be applied to the results. The output flow matrices from the HEFR analyses can be found in Attachment B. Tables 6 through 10 compare the results for the different gages.

The HEFR results for Sabine Lake were compared to the State Methodology MinQ, MaxC and MaxQ values. Table 11 compares the annual volumes. The HEFR 25th percentile (dry) conditions are less than the MinQ unless an overbank event occurs during the year. Base plus pulse flows for median (average) conditions are less than MinQ for the Full Period and Pre-Dam time periods, but are more than MinQ for the Post-Dam period. MaxC values are only exceeded for the median (average) condition if an overbank event occurs during the year. The 75th percentile (wet) condition is relatively close to the MaxQ even without the occurrence of an overbank flow. Most of the flow volume into Sabine Lake in the HEFR matrix occurs as base flows or overbank flows.

HEFR is a “desktop method” for developing streamflow recommendations. Other desktop methods commonly used in Texas are the Lyons Method and Consensus Criteria for Environmental Flow Needs (CCEFN). Both of these methods are described in the SAC guidance[1]. Both the Lyons Method and CCEFN have been used to develop minimum bypass flows in water rights permits and for regional water planning for many years. These methods share some of the concerns associated with the HEFR method, chiefly the lack of a clear link between the recommended flows and environmental health. They have also been employed in a somewhat different fashion than the flow regime that will be recommended by the BBEST. The Lyons and

CCEFN methods have been used to determine permit conditions that define a specific lower limit to diversion or impoundment by the water right. They do not specify a flow regime. The flow regime is the result of the interaction of these low-flow conditions with other boundaries such as storage capacity, diversion rates, annual diversion limits and diversions by other water rights, as well as the water provided by nature.

The Legislature has tasked the BBEST with defining a flow regime that defines a sound ecological environment. In FNI's opinion, this assignment has a larger scope than developing boundary conditions that are appropriate for permits. It is likely that a flow regime defining a sound ecological environment will be so complex that permit conditions for new water rights will not be readily apparent from the results. Future permit conditions will need to be developed based on site-specific interactions of existing water rights and the future water rights, taking into consideration flow goals established by the BBEST.

FNI does not believe that the flow matrix, by itself, is sufficient to define a flow regime. Other information that the BBEST should consider as part of its recommendation include a list of the functions of each flow component (for example protection of a specific species or habitat), the frequency with which the different recommendations are expected to be met (at all times, in one of every five years, etc.), and guidance for defining the meaning of the wet, average and dry flow statistics. One potentially misleading aspect of the flow matrix is the specificity of the HEFR output. Often these are reported as a single number, implying that only that flow level is protective of the environment. The precision of the numbers is not justified by the method. The values in the matrix will change depending on the parameters used in the analysis and the period selected, even in cases where the historical flows describe basically natural conditions. In reality, a range of discharges, volumes and duration are not only adequate but probably necessary to maintaining ecological health. Therefore FNI recommends that the BBEST consider a range of values rather than specific numbers in their final recommendations.

The chief limitation of this analysis is the lack of a link between environmental processes and the statistical output generated by the HEFR method. Although it is reasonable to assume that streamflow is linked to the ecological health of a river, it is unclear what part specific statistics play in maintaining a sound ecological environment. For example, it is not clear that the environment will benefit from using the 75th percentile of peak flows as a basis for a pulse flow

recommendation during a wet cycle. Although this may be a reasonable assumption as a starting point, there is no theoretical basis for doing so, and there is no empirical evidence that doing so is effective. Without reference to other environmental factors (biology, water quality and geomorphology for example) it is difficult to have confidence that the tables produced by the HEFR method have any meaning. The SAC is in the process of developing several "overlays" that should help in refining the linkage between HEFR and other environmental factors. Most of these guidance documents are in draft form and should be used by the BBEST to refine the results of these analyses. The HEFR analyses are only the first step in the process.

Because of the lack of linkage to environmental factors, there is no clear recommendation for adopting any particular HEFR analysis based on hydrology alone. FNI recommends the following:

- The BBEST select one or more of the analysis periods and matrix methods as a hypothesis that can be tested as additional data become available. Additional HEFR runs could be made if needed.
- The frequency-based approach is probably more effective in describing an environmental flow regime because of its greater flexibility. The frequency method is not as specific as the percentile-based method and potentially leaves room for more variability. The frequency matrix includes a range of volumes and durations, and using the recurrence interval implies additional variability that is missing from listing a specific number of occurrences in a particular season. The recurrence interval method is similar to the "design flows" used in a variety of other water-oriented applications. FNI is unaware of another application of the percentile approach.
- If the gage location currently has a sound ecological environment, the use of the Post-Dam analysis period may be appropriate. However, because the Post-Dam period includes only 38 years of record it may not effectively describe the full range of flows that can be expected. The Full Period analysis may be more indicative of long-term trends for the gages unimpacted by hydropower. For the gages impacted by hydropower (Ruliff, Bon Wier and Evadale), the flow separation and analyses during periods of hydropower generation is suspect. Therefore for those gages the Pre-Dam period is suggested as a starting point.

These recommendations are not strong recommendations. The BBEST may have other good reasons for adoption of different periods of methods.

In the event that the additional data does not lead to a clear path forward, FNI recommends that the BBEST develop a statement that expresses a relatively low level of confidence in the flow regime provided by the HEFR analysis until such time as the results are verified by other site-specific studies.

Attachment A: MBFIT Calculations

Attachment A: MBFIT Calculation Method

Parameters Input by User

N –defining an n-day sliding window of local minima. Must be odd, with a typical value being between 5 and 9.

f –the fraction threshold for a local minimum to be considered a "turning point" and possibly a base-dominated day. Must be between 0 and 1, with a typical value being 0.9.

Runoff fraction – fraction of the flow considered to be runoff for a flow to be classified as a pulse flow. Usually set to 0.2.

Calculation steps

1. Determine the minimum flow in a sliding N-day window (user input). Assign the minimum flow to the day at the center of the window.
2. Multiply the minimum N-day flow by the value of *f*. Determine if this value is less than the flow N days before and N days after the current day. If this is true, the day is considered to be a "turning point" and may be a base flow day.
3. If the day is not a turning point, then the day is a pulse-dominated day.
4. If the day is a turning point, determine if the difference between the current day's flow and the minimum flow in the N-day window. If this value is less than the Runoff Fraction multiplied by the minimum flow, then the day is classified as base-flow dominated. Otherwise the day is considered a pulse-flow dominated day.
5. Base-flow dominated days are further split into base flow days or subsistence flow days based on the subsistence threshold.
6. Days that are less than the lower pulse flow threshold will always be classified as base flow days. Similarly, days that are higher than the upper pulse flow threshold will always be classified as pulse flow days.
7. Pulse flow days that are higher than the overbank threshold will cause an entire pulse event to be reclassified as an overbank event.

Attachment B
HEFR Output Matrices

USGS 08019500 Big Sandy Ck nr Big Sandy, TX

Full Period

Overbank Flows	Return Period (R) : 4.9 (years)		Duration (D) : 23 (days)	
	Volume (V) : 32695 (ac-ft)		Peak Flow (Q) : 2875 (cfs)	
High Flow Pulses	F: 1	F: 1	F: 1	F: 1
	D: 17	D: 21	D: 15	D: 15
	Q: 575	Q: 569	Q: 112	Q: 239
	V: 9547	V: 8593	V: 1720	V: 4523
	F: 3	F: 2	F: 3	F: 3
	D: 11	D: 14	D: 10	D: 11
	Q: 223	Q: 219	Q: 40	Q: 94
	V: 4144	V: 4255	V: 546	V: 1403
	F: 4	F: 3	F: 4	F: 4
	D: 7	D: 10	D: 3	D: 7
	Q: 128	Q: 96	Q: 25	Q: 47
	V: 1514	V: 1271	V: 146	V: 525
Base Flows (cfs)	163	111	26	63
	106	51	18	36
	66	30	14	20
Subsistence Flows (cfs)	N/A	9	8	8
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 2,930 cfs with Frequency 1 per 2 years Volume is 31,375 to 40,032 (35,703) Duration is 14 to 66 (30)			
High Flow Pulses	Qp: 1,920 cfs with Frequency 1 per year Volume is 20,214 to 28,858 (24,536) Duration is 12 to 56 (26)			
	Qp: 1,420 cfs with Frequency 2 per 3 years Volume is 14,345 to 22,984 (18,665) Duration is 10 to 49 (23)			
	Qp: 1,170 cfs with Frequency 2 per year Volume is 11,325 to 19,962 (15,644) Duration is 10 to 45 (21)			
	Qp: 942 cfs with Frequency 1 per season Volume is 9,133 to 19,954 (14,544) Duration is 7 to 36 (16)	Qp: 950 cfs with Frequency 1 per season Volume is 7,699 to 18,004 (12,852) Duration is 9 to 40 (19)	Qp: 132 cfs with Frequency 1 per season Volume is #N/A to 4,110 (2,054) Duration is 5 to 24 (11)	Qp: 367 cfs with Frequency 1 per season Volume is 3,811 to 8,299 (6,055) Duration is 6 to 29 (14)
	Qp: 358 cfs with Frequency 2 per season Volume is 521 to 11,342 (5,932) Duration is 5 to 23 (10)	Qp: 313 cfs with Frequency 2 per season Volume is #N/A to 10,215 (5,062) Duration is 6 to 27 (13)	Qp: 50 cfs with Frequency 2 per season Volume is #N/A to 2,727 (671) Duration is 3 to 13 (6)	Qp: 130 cfs with Frequency 2 per season Volume is #N/A to 4,433 (2,189) Duration is 4 to 19 (9)
Base Flows (cfs)	163	111	26	63
	106	51	18	36
	66	30	14	20
Subsistence Flows (cfs)	N/A	9	8	8
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

1940 to 1960

Overbank Flows	Return Period (R) : 3 (years)		Duration (D) : 22 (days)	
	Volume (V) : 33462 (ac-ft)		Peak Flow (Q) : 3360 (cfs)	
High Flow Pulses	F: 1	F: 1	F: 1	F: 1
	D: 17	D: 22	D: 15	D: 15
	Q: 584	Q: 637	Q: 134	Q: 237
	V: 10487	V: 10301	V: 2087	V: 5167
	F: 2	F: 2	F: 3	F: 3
	D: 12	D: 14	D: 11	D: 10
	Q: 246	Q: 266	Q: 59	Q: 90
	V: 5000	V: 5006	V: 792	V: 1300
	F: 4	F: 3	F: 4	F: 4
	D: 9	D: 10	D: 7	D: 7
	Q: 142	Q: 126	Q: 31	Q: 53
	V: 2060	V: 2109	V: 369	V: 661
Base Flows (cfs)	165	127	29	70
	113	75	21	39
	73	38	16	23
Subsistence Flows (cfs)	N/A	10	9	9
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 4,000 cfs with Frequency 1 per 2 years Volume is 39,033 to 48,722 (43,877) Duration is 15 to 61 (30)			
High Flow Pulses	Qp: 2,100 cfs with Frequency 1 per year Volume is 20,336 to 29,964 (25,150) Duration is 12 to 49 (24)			
	Qp: 1,550 cfs with Frequency 2 per 3 years Volume is 14,415 to 24,033 (19,224) Duration is 11 to 44 (22)			
	Qp: 1,260 cfs with Frequency 2 per year Volume is 11,200 to 20,816 (16,008) Duration is 10 to 41 (20)			
	Qp: 865 cfs with Frequency 1 per season Volume is 7,631 to 19,125 (13,378) Duration is 8 to 35 (17)	Qp: 1,120 cfs with Frequency 1 per season Volume is 7,102 to 20,575 (13,838) Duration is 10 to 36 (19)	Qp: 140 cfs with Frequency 1 per season Volume is 1,377 to 2,974 (2,175) Duration is 7 to 23 (13)	Qp: 376 cfs with Frequency 1 per season Volume is 3,797 to 8,977 (6,387) Duration is 6 to 27 (13)
	Qp: 339 cfs with Frequency 2 per season Volume is 777 to 12,274 (6,525) Duration is 5 to 23 (11)	Qp: 376 cfs with Frequency 2 per season Volume is #N/A to 12,898 (6,155) Duration is 7 to 26 (14)	Qp: 70 cfs with Frequency 2 per season Volume is 282 to 1,880 (1,081) Duration is 5 to 16 (9)	Qp: 128 cfs with Frequency 2 per season Volume is #N/A to 4,825 (2,233) Duration is 4 to 18 (9)
Base Flows (cfs)	165	127	29	70
	113	75	21	39
	73	38	16	23
Subsistence Flows (cfs)	N/A	10	9	9
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

1971 to 2007

Overbank Flows	Return Period (R) : 4.1 (years)		Duration (D) : 21 (days)	
	Volume (V) : 32563 (ac-ft)		Peak Flow (Q) : 2820 (cfs)	
High Flow Pulses	F: 1	F: 1	F: 1	F: 1
	D: 17	D: 20	D: 16	D: 16
	Q: 591	Q: 465	Q: 131	Q: 297
	V: 9696	V: 7595	V: 1907	V: 5076
	F: 3	F: 2	F: 3	F: 3
	D: 11	D: 15	D: 10	D: 11
	Q: 240	Q: 212	Q: 42	Q: 110
	V: 4322	V: 3745	V: 588	V: 1809
	F: 4	F: 3	F: 4	F: 4
	D: 7	D: 10	D: 3	D: 7
	Q: 136	Q: 98	Q: 25	Q: 49
	V: 1532	V: 1252	V: 145	V: 511
Base Flows (cfs)	166	106	26	66
	116	51	16	36
	71	26	13	19
Subsistence Flows (cfs)	N/A	9	8	8
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 2,930 cfs with Frequency 1 per 2 years Volume is 32,686 to 40,925 (36,806) Duration is 14 to 69 (31)			
High Flow Pulses	Qp: 2,100 cfs with Frequency 1 per year Volume is 24,590 to 32,799 (28,694) Duration is 12 to 60 (27)			
	Qp: 1,460 cfs with Frequency 2 per 3 years Volume is 17,091 to 25,285 (21,188) Duration is 10 to 51 (23)			
	Qp: 1,220 cfs with Frequency 2 per year Volume is 13,997 to 22,188 (18,092) Duration is 10 to 47 (21)			
	Qp: 1,080 cfs with Frequency 1 per season Volume is 9,581 to 20,281 (14,931) Duration is 7 to 38 (16)	Qp: 923 cfs with Frequency 1 per season Volume is 10,478 to 17,665 (14,072) Duration is 9 to 43 (20)	Qp: 151 cfs with Frequency 1 per season Volume is 72 to 4,928 (2,500) Duration is 6 to 26 (12)	Qp: 432 cfs with Frequency 1 per season Volume is 4,711 to 9,312 (7,012) Duration is 7 to 30 (15)
	Qp: 484 cfs with Frequency 2 per season Volume is 1,709 to 12,401 (7,055) Duration is 5 to 26 (11)	Qp: 301 cfs with Frequency 2 per season Volume is 1,311 to 8,499 (4,905) Duration is 6 to 27 (13)	Qp: 54 cfs with Frequency 2 per season Volume is #N/A to 3,052 (623) Duration is 3 to 13 (6)	Qp: 171 cfs with Frequency 2 per season Volume is 511 to 5,113 (2,812) Duration is 5 to 21 (10)
Base Flows (cfs)	166	106	26	66
	116	51	16	36
	71	26	13	19
Subsistence Flows (cfs)	N/A	9	8	8
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

USGS 08020000 Sabine Rv nr Gladewater, TX

Full Period

Overbank Flows	Return Period (R) : 4.2		Duration (D) : 39 (days)	
	Volume (V) : 553069 (ac-ft)		Peak Flow (Q) : 18100 (cfs)	
High Flow Pulses	F: 1	F: 0	F: 1	F: 1
	D: 28	D: 33	D: 22	D: 24
	Q: 5035	Q: 4655	Q: 991	Q: 2540
	V: 135647	V: 131931	V: 17558	V: 54732
	F: 2	F: 2	F: 2	F: 2
	D: 17	D: 21	D: 14	D: 17
	Q: 2000	Q: 2340	Q: 276	Q: 649
	V: 49990	V: 44847	V: 5052	V: 10683
	F: 3	F: 2	F: 3	F: 3
	D: 13	D: 13	D: 6	D: 12
	Q: 741	Q: 649	Q: 113	Q: 239
	V: 12474	V: 9580	V: 1130	V: 3396
Base Flows (cfs)	836	664	78	232
	472	283	46	105
	277	119	34	49
Subsistence Flows (cfs)	N/A	22	14	17
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 18,100 cfs with Frequency 1 per 2 years Volume is 404,867 to 561,682 (483,275) Duration is 21 to 94 (44)			
High Flow Pulses	Qp: 10,600 cfs with Frequency 1 per year Volume is 212,733 to 369,351 (291,042) Duration is 17 to 76 (36)			
	Qp: 7,440 cfs with Frequency 2 per 3 years Volume is 128,555 to 285,133 (206,844) Duration is 15 to 66 (31)			
	Qp: 6,220 cfs with Frequency 2 per year Volume is 95,545 to 252,113 (173,829) Duration is 14 to 62 (29)			
	Qp: 5,570 cfs with Frequency 1 per season Volume is 109,352 to 280,134 (194,743) Duration is 12 to 49 (24)	Qp: 5,070 cfs with Frequency 1 per season Volume is 31,414 to 249,809 (140,612) Duration is 11 to 57 (25)	Qp: 730 cfs with Frequency 1 per season Volume is #N/A to 27,594 (13,480) Duration is 8 to 34 (17)	Qp: 2,240 cfs with Frequency 1 per season Volume is 25,212 to 108,539 (66,875) Duration is 10 to 42 (21)
	Qp: 1,880 cfs with Frequency 2 per season Volume is #N/A to 134,021 (48,599) Duration is 8 to 31 (15)	Qp: 1,580 cfs with Frequency 2 per season Volume is #N/A to 160,380 (51,150) Duration is 7 to 35 (16)	Qp: 168 cfs with Frequency 2 per season Volume is #N/A to 16,871 (2,752) Duration is 3 to 14 (7)	Qp: 380 cfs with Frequency 2 per season Volume is #N/A to 42,775 (1,098) Duration is 5 to 22 (11)
Base Flows (cfs)	836	664	78	232
	472	283	46	105
	277	119	34	49
Subsistence Flows (cfs)	N/A	22	14	17
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

1940 to 1960

Overbank Flows	Return Period (R) : 2.6		Duration (D) : 35 (days)	
	Volume (V) : 456865 (ac-ft)		Peak Flow (Q) : 19400 (cfs)	
High Flow Pulses	F: 1	F: 1	F: 1	F: 1
	D: 26	D: 29	D: 27	D: 25
	Q: 5290	Q: 4555	Q: 1738	Q: 2650
	V: 129018	V: 127503	V: 30199	V: 55667
	F: 2	F: 1	F: 2	F: 2
	D: 16	D: 22	D: 19	D: 18
	Q: 2520	Q: 2820	Q: 492	Q: 730
	V: 54860	V: 57511	V: 10213	V: 16678
	F: 3	F: 2	F: 3	F: 3
	D: 12	D: 13	D: 12	D: 7
	Q: 800	Q: 1080	Q: 174	Q: 288
	V: 13684	V: 22951	V: 2078	V: 3731
Base Flows (cfs)	770	616	85	265
	422	332	49	155
	274	198	36	47
Subsistence Flows (cfs)	N/A	22	12	18
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 34,600 cfs with Frequency 1 per 2 years Volume is 643,638 to 764,312 (703,975) Duration is 25 to 108 (52)			
High Flow Pulses	Qp: 17,000 cfs with Frequency 1 per year Volume is 301,947 to 421,573 (361,760) Duration is 19 to 82 (39)			
	Qp: 10,600 cfs with Frequency 2 per 3 years Volume is 172,656 to 292,126 (232,391) Duration is 16 to 68 (33)			
	Qp: 8,100 cfs with Frequency 2 per year Volume is 121,422 to 240,863 (181,142) Duration is 14 to 61 (30)			
	Qp: 5,790 cfs with Frequency 1 per season Volume is 121,491 to 205,383 (163,437) Duration is 13 to 45 (24)	Qp: 8,180 cfs with Frequency 1 per season Volume is 85,407 to 281,645 (183,526) Duration is 13 to 52 (26)	Qp: 1,410 cfs with Frequency 1 per season Volume is 14,371 to 39,200 (26,786) Duration is 12 to 47 (24)	Qp: 2,290 cfs with Frequency 1 per season Volume is 34,832 to 84,151 (59,491) Duration is 8 to 42 (19)
	Qp: 2,260 cfs with Frequency 2 per season Volume is 19,545 to 103,510 (61,528) Duration is 8 to 29 (16)	Qp: 2,820 cfs with Frequency 2 per season Volume is #N/A to 179,267 (81,030) Duration is 9 to 35 (17)	Qp: 238 cfs with Frequency 2 per season Volume is #N/A to 16,518 (4,070) Duration is 4 to 16 (8)	Qp: 422 cfs with Frequency 2 per season Volume is #N/A to 32,613 (7,920) Duration is 5 to 23 (10)
Base Flows (cfs)	770	616	85	265
	422	332	49	155
	274	198	36	47
Subsistence Flows (cfs)	N/A	22	12	18
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

1971 to 2007

Overbank Flows	Return Period (R) : 4.8		Duration (D) : 44 (days)	
	Volume (V) : 584547 (ac-ft)		Peak Flow (Q) : 16700 (cfs)	
High Flow Pulses	F: 1	F: 1	F: 1	F: 1
	D: 27	D: 36	D: 21	D: 24
	Q: 5030	Q: 4655	Q: 838	Q: 2840
	V: 157924	V: 140556	V: 14968	V: 62361
	F: 2	F: 2	F: 2	F: 2
	D: 18	D: 23	D: 14	D: 17
	Q: 2060	Q: 2500	Q: 228	Q: 650
	V: 52092	V: 44224	V: 4319	V: 12296
	F: 3	F: 3	F: 3	F: 3
	D: 13	D: 13	D: 4	D: 11
	Q: 953	Q: 643	Q: 102	Q: 201
	V: 14225	V: 10112	V: 835	V: 3557
Base Flows (cfs)	940	910	96	223
	525	325	49	110
	267	100	36	74
Subsistence Flows (cfs)	N/A	22	18	22
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 15,900 cfs with Frequency 1 per 2 years Volume is 460,220 to 609,920 (535,070) Duration is 20 to 95 (44)			
High Flow Pulses	Qp: 8,800 cfs with Frequency 1 per year Volume is 231,084 to 380,132 (305,608) Duration is 16 to 75 (34)			
	Qp: 7,150 cfs with Frequency 2 per 3 years Volume is 173,814 to 322,783 (248,298) Duration is 15 to 69 (32)			
	Qp: 6,220 cfs with Frequency 2 per year Volume is 140,866 to 289,802 (215,334) Duration is 14 to 65 (30)			
	Qp: 5,470 cfs with Frequency 1 per season Volume is 91,075 to 261,439 (176,257) Duration is 12 to 51 (25)	Qp: 4,600 cfs with Frequency 1 per season Volume is 47,950 to 235,931 (141,941) Duration is 10 to 64 (25)	Qp: 714 cfs with Frequency 1 per season Volume is #N/A to 28,963 (13,226) Duration is 8 to 33 (16)	Qp: 2,770 cfs with Frequency 1 per season Volume is 50,535 to 142,706 (96,621) Duration is 11 to 46 (23)
	Qp: 1,770 cfs with Frequency 2 per season Volume is #N/A to 129,107 (43,834) Duration is 8 to 31 (15)	Qp: 1,390 cfs with Frequency 2 per season Volume is #N/A to 127,871 (33,802) Duration is 6 to 38 (15)	Qp: 172 cfs with Frequency 2 per season Volume is #N/A to 18,653 (2,908) Duration is 4 to 15 (7)	Qp: 517 cfs with Frequency 2 per season Volume is #N/A to 49,014 (2,902) Duration is 6 to 25 (12)
Base Flows (cfs)	940	910	96	223
	525	325	49	110
	267	100	36	74
Subsistence Flows (cfs)	N/A	22	18	22
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

USGS 08022040 Sabine Rv nr Beckville, TX

Full Period

Overbank Flows	Return Period (R) : 5.4		Duration (D) : 42 (days)	
	Volume (V) : 773376 (ac-ft)		Peak Flow (Q) : 17300 (cfs)	
High Flow Pulses	F: 1	F: 0	F: 1	F: 1
	D: 29	D: 34	D: 24	D: 23
	Q: 6428	Q: 6470	Q: 1270	Q: 3235
	V: 206207	V: 191108	V: 25659	V: 73519
	F: 2	F: 1	F: 2	F: 2
	D: 18	D: 23	D: 13	D: 14
	Q: 3140	Q: 3320	Q: 420	Q: 768
	V: 75531	V: 74880	V: 6806	V: 14418
	F: 3	F: 2	F: 3	F: 3
	D: 12	D: 13	D: 3	D: 7
	Q: 1113	Q: 1130	Q: 165	Q: 231
	V: 14358	V: 16914	V: 775	V: 2410
Base Flows (cfs)	1580	1260	122	356
	807	526	74	141
	438	232	51	75
Subsistence Flows (cfs)	N/A	28	20	19
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 16,100 cfs with Frequency 1 per 2 years Volume is 433,485 to 649,804 (541,644) Duration is 19 to 103 (45)			
High Flow Pulses	Qp: 11,800 cfs with Frequency 1 per year Volume is 291,988 to 508,138 (400,063) Duration is 17 to 88 (38)			
	Qp: 9,640 cfs with Frequency 2 per 3 years Volume is 219,072 to 435,164 (327,118) Duration is 15 to 79 (34)			
	Qp: 8,270 cfs with Frequency 2 per year Volume is 172,186 to 388,252 (280,219) Duration is 14 to 73 (32)			
	Qp: 7,200 cfs with Frequency 1 per season Volume is 167,780 to 436,567 (302,174) Duration is 10 to 56 (24)	Qp: 7,030 cfs with Frequency 1 per season Volume is 73,413 to 367,613 (220,513) Duration is 12 to 63 (27)	Qp: 1,120 cfs with Frequency 1 per season Volume is #N/A to 42,586 (19,863) Duration is 7 to 36 (16)	Qp: 3,250 cfs with Frequency 1 per season Volume is 41,400 to 160,034 (100,717) Duration is 10 to 46 (21)
	Qp: 2,900 cfs with Frequency 2 per season Volume is #N/A to 219,395 (84,998) Duration is 6 to 34 (15)	Qp: 2,160 cfs with Frequency 2 per season Volume is #N/A to 219,264 (72,092) Duration is 7 to 35 (15)	Qp: 285 cfs with Frequency 2 per season Volume is #N/A to 28,168 (5,436) Duration is 3 to 13 (6)	Qp: 628 cfs with Frequency 2 per season Volume is #N/A to 66,586 (7,245) Duration is 4 to 19 (9)
Base Flows (cfs)	1580	1260	122	356
	807	526	74	141
	438	232	51	75
Subsistence Flows (cfs)	N/A	28	20	19
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

1940 to 1960

Overbank Flows	Return Period (R) : 3.5		Duration (D) : 39 (days)	
	Volume (V) : 833247 (ac-ft)		Peak Flow (Q) : 28100 (cfs)	
High Flow Pulses	F: 1	F: 0	F: 1	F: 1
	D: 30	D: 34	D: 26	D: 22
	Q: 6083	Q: 6535	Q: 2080	Q: 3020
	V: 201972	V: 190709	V: 40571	V: 72448
	F: 2	F: 1	F: 2	F: 2
	D: 20	D: 21	D: 20	D: 16
	Q: 3720	Q: 3520	Q: 735	Q: 885
	V: 89921	V: 79258	V: 15605	V: 20232
	F: 3	F: 2	F: 3	F: 3
	D: 12	D: 13	D: 10	D: 8
	Q: 1185	Q: 1758	Q: 251	Q: 430
	V: 20793	V: 39315	V: 3496	V: 4777
Base Flows (cfs)	1580	1220	160	424
	766	598	88	206
	448	326	61	74
Subsistence Flows (cfs)	N/A	N/A	16	23
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 29,800 cfs with Frequency 1 per 2 years Volume is 723,687 to 875,027 (799,357) Duration is 23 to 117 (52)			
High Flow Pulses	Qp: 12,700 cfs with Frequency 1 per year Volume is 279,027 to 429,190 (354,109) Duration is 16 to 79 (35)			
	Qp: 10,000 cfs with Frequency 2 per 3 years Volume is 206,181 to 356,274 (281,228) Duration is 14 to 71 (31)			
	Qp: 8,550 cfs with Frequency 2 per year Volume is 166,763 to 316,832 (241,798) Duration is 13 to 66 (29)			
	Qp: 5,970 cfs with Frequency 1 per season Volume is 154,487 to 265,765 (210,126) Duration is 9 to 50 (21)	Qp: 8,550 cfs with Frequency 1 per season Volume is 109,671 to 360,087 (234,879) Duration is 11 to 58 (26)	Qp: 1,260 cfs with Frequency 1 per season Volume is 11,550 to 50,002 (30,776) Duration is 9 to 40 (19)	Qp: 2,670 cfs with Frequency 1 per season Volume is 43,553 to 128,437 (85,995) Duration is 9 to 40 (19)
	Qp: 3,530 cfs with Frequency 2 per season Volume is 55,977 to 167,262 (111,620) Duration is 7 to 37 (16)	Qp: 2,720 cfs with Frequency 2 per season Volume is #N/A to 215,600 (90,188) Duration is 6 to 32 (14)	Qp: 492 cfs with Frequency 2 per season Volume is #N/A to 27,990 (8,732) Duration is 5 to 21 (10)	Qp: 615 cfs with Frequency 2 per season Volume is #N/A to 51,130 (8,617) Duration is 5 to 19 (9)
Base Flows (cfs)	1580	1220	160	424
	766	598	88	206
	448	326	61	74
Subsistence Flows (cfs)	N/A	N/A	16	23
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

1971 to 2007

Overbank Flows	Return Period (R) : 4.8		Duration (D) : 42 (days)	
	Volume (V) : 710024 (ac-ft)		Peak Flow (Q) : 15800 (cfs)	
High Flow Pulses	F: 1	F: 1	F: 1	F: 1
	D: 26	D: 36	D: 20	D: 22
	Q: 7215	Q: 6893	Q: 1195	Q: 3380
	V: 189248	V: 192120	V: 18612	V: 82639
	F: 2	F: 1	F: 3	F: 2
	D: 17	D: 25	D: 12	D: 14
	Q: 2865	Q: 3840	Q: 272	Q: 707
	V: 66082	V: 82404	V: 4588	V: 13030
	F: 3	F: 2	F: 4	F: 4
	D: 11	D: 13	D: 2	D: 3
	Q: 1115	Q: 1105	Q: 149	Q: 169
	V: 10850	V: 17469	V: 630	V: 915
Base Flows (cfs)	1710	1533	128	372
	923	589	76	140
	511	198	52	90
Subsistence Flows (cfs)	N/A	28	22	25
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 15,200 cfs with Frequency 1 per 2 years Volume is 451,307 to 689,667 (570,487) Duration is 19 to 104 (44)			
High Flow Pulses	Qp: 12,300 cfs with Frequency 1 per year Volume is 352,107 to 590,022 (471,064) Duration is 17 to 92 (39)			
	Qp: 10,600 cfs with Frequency 2 per 3 years Volume is 290,414 to 528,128 (409,271) Duration is 15 to 85 (36)			
	Qp: 8,650 cfs with Frequency 2 per year Volume is 216,425 to 453,964 (335,194) Duration is 14 to 76 (32)			
	Qp: 8,330 cfs with Frequency 1 per season Volume is 210,292 to 547,543 (378,918) Duration is 11 to 61 (26)	Qp: 6,630 cfs with Frequency 1 per season Volume is 94,947 to 379,788 (237,367) Duration is 11 to 63 (27)	Qp: 1,180 cfs with Frequency 1 per season Volume is #N/A to 115,610 (19,886) Duration is 7 to 36 (16)	Qp: 4,250 cfs with Frequency 1 per season Volume is #N/A to 331,474 (132,399) Duration is 2 to 314 (23)
	Qp: 3,020 cfs with Frequency 2 per season Volume is #N/A to 469,303 (89,502) Duration is 1 to 254 (14)	Qp: 1,890 cfs with Frequency 2 per season Volume is #N/A to 351,599 (34,297) Duration is 1 to 366 (15)	Qp: 272 cfs with Frequency 2 per season Volume is #N/A to 99,810 (4,031) Duration is 0 to 57 (5)	Qp: 886 cfs with Frequency 2 per season Volume is #N/A to 214,412 (15,286) Duration is 1 to 125 (9)
Base Flows (cfs)	1710	1533	128	372
	923	589	76	140
	511	198	52	90
Subsistence Flows (cfs)	N/A	28	22	25
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

USGS 08028500 Sabine Rv nr Bon Wier, TX

Full Period

Overbank Flows	Return Period (R) : 1.9		Duration (D) : 26 (days)	
	Volume (V) : 942288 (ac-ft)		Peak Flow (Q) : 29400 (cfs)	
High Flow Pulses	F: 0	F: 1	F: 1	F: 1
	D: 22	D: 23	D: 19	D: 17
	Q: 16600	Q: 10700	Q: 6725	Q: 5160
	V: 393100	V: 256265	V: 135700	V: 90229
	F: 2	F: 2	F: 3	F: 3
	D: 14	D: 13	D: 13	D: 6
	Q: 9655	Q: 5730	Q: 4750	Q: 1720
	V: 129082	V: 90135	V: 65118	V: 17564
	F: 3	F: 3	F: 5	F: 4
	D: 6	D: 6	D: 6	D: 3
	Q: 3318	Q: 3240	Q: 1795	Q: 1085
	V: 39070	V: 34213	V: 24948	V: 5723
Base Flows (cfs)	15400	6680	1120	1110
	5870	1590	656	615
	1460	857	478	478
Subsistence Flows (cfs)	N/A	279	241	234
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 36,500 cfs with Frequency 1 per 2 years Volume is 933,492 to 1,467,413 (1,200,452) Duration is 14 to 74 (32)			
High Flow Pulses	Qp: 28,700 cfs with Frequency 1 per year Volume is 664,470 to 1,197,810 (931,140) Duration is 12 to 64 (28)			
	Qp: 24,300 cfs with Frequency 2 per 3 years Volume is 512,142 to 1,045,239 (778,690) Duration is 11 to 58 (25)			
	Qp: 21,600 cfs with Frequency 2 per year Volume is 418,463 to 951,441 (684,952) Duration is 10 to 54 (24)			
	Qp: 20,600 cfs with Frequency 1 per season Volume is 310,344 to 1,071,255 (690,800) Duration is 7 to 45 (17)	Qp: 16,500 cfs with Frequency 1 per season Volume is 175,190 to 792,794 (483,992) Duration is 10 to 45 (21)	Qp: 7,360 cfs with Frequency 1 per season Volume is 71,346 to 278,672 (175,009) Duration is 7 to 31 (14)	Qp: 8,960 cfs with Frequency 1 per season Volume is 40,996 to 458,238 (249,617) Duration is 8 to 36 (17)
	Qp: 13,800 cfs with Frequency 2 per season Volume is 41,664 to 802,267 (421,966) Duration is 6 to 38 (14)	Qp: 6,700 cfs with Frequency 2 per season Volume is #N/A to 460,013 (151,163) Duration is 5 to 25 (12)	Qp: 5,880 cfs with Frequency 2 per season Volume is 28,916 to 236,225 (132,571) Duration is 6 to 27 (13)	Qp: 2,590 cfs with Frequency 2 per season Volume is #N/A to 249,559 (40,957) Duration is 3 to 14 (7)
Base Flows (cfs)	15400	6680	1120	1110
	5870	1590	656	615
	1460	857	478	478
Subsistence Flows (cfs)	N/A	279	241	234
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

1940 to 1960

Overbank Flows	Return Period (R) : 1.4		Duration (D) : 32 (days)	
	Volume (V) : 989951 (ac-ft)		Peak Flow (Q) : 27900 (cfs)	
High Flow Pulses	F: 0	F: 1	F: 1	F: 1
	D: 23	D: 33	D: 24	D: 21
	Q: 15150	Q: 14350	Q: 5200	Q: 7890
	V: 406543	V: 388399	V: 126308	V: 148683
	F: 2	F: 1	F: 2	F: 2
	D: 15	D: 17	D: 16	D: 13
	Q: 10500	Q: 9660	Q: 2125	Q: 3310
	V: 223776	V: 222387	V: 51337	V: 67736
	F: 3	F: 2	F: 3	F: 3
	D: 8	D: 6	D: 3	D: 4
	Q: 6690	Q: 4475	Q: 1048	Q: 1270
	V: 122857	V: 51938	V: 6630	V: 8430
Base Flows (cfs)	9275	6980	1060	1160
	3615	3210	615	640
	1890	1440	440	471
Subsistence Flows (cfs)	N/A	N/A	223	236
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 37,500 cfs with Frequency 1 per 2 years Volume is 1,269,811 to 1,984,223 (1,627,017) Duration is 16 to 97 (40)			
High Flow Pulses	Qp: 27,700 cfs with Frequency 1 per year Volume is 796,229 to 1,507,418 (1,151,824) Duration is 14 to 80 (33)			
	Qp: 24,300 cfs with Frequency 2 per 3 years Volume is 634,391 to 1,344,806 (989,598) Duration is 12 to 73 (30)			
	Qp: 22,200 cfs with Frequency 2 per year Volume is 535,066 to 1,245,092 (890,079) Duration is 12 to 69 (28)			
	Qp: 18,000 cfs with Frequency 1 per season Volume is 229,397 to 844,494 (536,946) Duration is 9 to 49 (21)	Qp: 18,500 cfs with Frequency 1 per season Volume is 248,877 to 1,125,150 (687,013) Duration is 10 to 56 (24)	Qp: 4,700 cfs with Frequency 1 per season Volume is #N/A to 315,225 (148,553) Duration is 6 to 42 (16)	Qp: 7,900 cfs with Frequency 1 per season Volume is #N/A to 201,903 (84,084) Duration is 7 to 36 (15)
	Qp: 11,600 cfs with Frequency 2 per season Volume is #N/A to 561,460 (253,913) Duration is 7 to 37 (16)	Qp: 7,360 cfs with Frequency 2 per season Volume is #N/A to 582,539 (143,294) Duration is 5 to 28 (12)	Qp: 1,440 cfs with Frequency 2 per season Volume is #N/A to 182,352 (15,323) Duration is 2 to 16 (6)	Qp: 2,350 cfs with Frequency 2 per season Volume is #N/A to 163,760 (45,713) Duration is 3 to 15 (6)
Base Flows (cfs)	9275	6980	1060	1160
	3615	3210	615	640
	1890	1440	440	471
Subsistence Flows (cfs)	N/A	N/A	223	236
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

1971 to 2007

Overbank Flows	Return Period (R) : 1.8		Duration (D) : 23 (days)	
	Volume (V) : 935207 (ac-ft)		Peak Flow (Q) : 29900 (cfs)	
High Flow Pulses	F: 1	F: 1	F: 1	F: 2
	D: 20	D: 20	D: 17	D: 16
	Q: 17300	Q: 8218	Q: 7115	Q: 4248
	V: 394315	V: 177928	V: 144008	V: 61711
	F: 2	F: 2	F: 3	F: 4
	D: 13	D: 13	D: 13	D: 6
	Q: 9680	Q: 4920	Q: 5860	Q: 1600
	V: 94870	V: 73272	V: 72417	V: 15382
	F: 3	F: 3	F: 6	F: 6
	D: 3	D: 6	D: 6	D: 3
	Q: 2690	Q: 3165	Q: 3968	Q: 1025
	V: 30903	V: 34100	V: 44172	V: 4817
Base Flows (cfs)	16200	8808	2395	1160
	10200	1195	990	648
	1210	756	712	522
Subsistence Flows (cfs)	N/A	N/A	N/A	N/A
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 36,700 cfs with Frequency 1 per 2 years Volume is 816,628 to 1,202,121 (1,009,374) Duration is 13 to 62 (28)			
High Flow Pulses	Qp: 30,200 cfs with Frequency 1 per year Volume is 642,396 to 1,027,298 (834,847) Duration is 11 to 55 (25)			
	Qp: 25,700 cfs with Frequency 2 per 3 years Volume is 518,157 to 902,740 (710,449) Duration is 10 to 51 (23)			
	Qp: 22,800 cfs with Frequency 2 per year Volume is 436,523 to 820,941 (628,732) Duration is 10 to 47 (21)			
	Qp: 22,800 cfs with Frequency 1 per season Volume is 326,963 to 992,445 (659,704) Duration is 6 to 40 (15)	Qp: 15,500 cfs with Frequency 1 per season Volume is 234,326 to 601,952 (418,139) Duration is 8 to 36 (17)	Qp: 7,800 cfs with Frequency 1 per season Volume is 97,477 to 268,937 (183,207) Duration is 7 to 26 (14)	Qp: 10,300 cfs with Frequency 1 per season Volume is 149,038 to 353,806 (251,422) Duration is 8 to 38 (18)
	Qp: 17,100 cfs with Frequency 2 per season Volume is 139,625 to 804,525 (472,075) Duration is 5 to 35 (13)	Qp: 6,660 cfs with Frequency 2 per season Volume is #N/A to 329,250 (145,449) Duration is 5 to 23 (11)	Qp: 6,900 cfs with Frequency 2 per season Volume is 70,029 to 241,474 (155,752) Duration is 7 to 24 (13)	Qp: 3,300 cfs with Frequency 2 per season Volume is #N/A to 168,995 (66,672) Duration is 3 to 16 (8)
Base Flows (cfs)	16200	8808	2395	1160
	10200	1195	990	648
	1210	756	712	522
Subsistence Flows (cfs)	N/A	N/A	N/A	N/A
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

USGS 08029500 Big Cow Ck nr Newton, TX

Full Period

Overbank Flows	Return Period (R) : 3.7		Duration (D) : 13 (days)	
	Volume (V) : 17048 (ac-ft)		Peak Flow (Q) : 3150 (cfs)	
High Flow Pulses	F: 2	F: 2	F: 2	F: 2
	D: 9	D: 9	D: 8	D: 8
	Q: 676	Q: 356	Q: 127	Q: 412
	V: 4316	V: 2704	V: 1203	V: 3039
	F: 4	F: 4	F: 4	F: 4
	D: 7	D: 5	D: 5	D: 6
	Q: 293	Q: 123	Q: 73	Q: 162
	V: 2003	V: 941	V: 560	V: 1171
	F: 6	F: 6	F: 6	F: 5
	D: 4	D: 3	D: 2	D: 3
	Q: 126	Q: 68	Q: 46	Q: 82
	V: 828	V: 379	V: 229	V: 504
Base Flows (cfs)	106	74	48	64
	78	52	36	46
	56	38	28	36
Subsistence Flows (cfs)	N/A	20	20	20
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 3,180 cfs with Frequency 1 per 2 years Volume is 16,621 to 20,029 (18,325) Duration is 9 to 32 (17)			
High Flow Pulses	Qp: 1,870 cfs with Frequency 1 per year Volume is 9,467 to 12,869 (11,168) Duration is 8 to 26 (14)			
	Qp: 1,480 cfs with Frequency 2 per 3 years Volume is 7,275 to 10,675 (8,975) Duration is 7 to 23 (13)			
	Qp: 1,260 cfs with Frequency 2 per year Volume is 6,025 to 9,424 (7,725) Duration is 6 to 22 (12)			
	Qp: 1,080 cfs with Frequency 1 per season Volume is 5,617 to 9,158 (7,387) Duration is 6 to 18 (10)	Qp: 862 cfs with Frequency 1 per season Volume is 4,109 to 8,041 (6,075) Duration is 5 to 19 (10)	Qp: 191 cfs with Frequency 1 per season Volume is 726 to 2,168 (1,447) Duration is 4 to 13 (7)	Qp: 790 cfs with Frequency 1 per season Volume is 3,544 to 6,533 (5,038) Duration is 6 to 16 (9)
	Qp: 693 cfs with Frequency 2 per season Volume is 3,140 to 6,681 (4,911) Duration is 5 to 15 (8)	Qp: 350 cfs with Frequency 2 per season Volume is 580 to 4,511 (2,545) Duration is 4 to 13 (7)	Qp: 109 cfs with Frequency 2 per season Volume is 151 to 1,594 (873) Duration is 3 to 10 (5)	Qp: 322 cfs with Frequency 2 per season Volume is 738 to 3,727 (2,232) Duration is 4 to 11 (7)
Base Flows (cfs)	106	74	48	64
	78	52	36	46
	56	38	28	36
Subsistence Flows (cfs)	N/A	20	20	20
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

1971 to 2007

Overbank Flows	Return Period (R) : 2.7		Duration (D) : 13 (days)	
	Volume (V) : 17040 (ac-ft)		Peak Flow (Q) : 3000 (cfs)	
High Flow Pulses	F: 1	F: 1	F: 2	F: 2
	D: 9	D: 9	D: 8	D: 8
	Q: 762	Q: 350	Q: 139	Q: 463
	V: 5227	V: 2718	V: 1337	V: 3247
	F: 4	F: 4	F: 4	F: 3
	D: 7	D: 5	D: 5	D: 7
	Q: 358	Q: 124	Q: 81	Q: 182
	V: 2507	V: 957	V: 637	V: 1298
	F: 5	F: 6	F: 6	F: 5
	D: 4	D: 3	D: 3	D: 3
	Q: 150	Q: 73	Q: 52	Q: 97
	V: 1014	V: 409	V: 263	V: 576
Base Flows (cfs)	119	82	50	72
	91	60	40	51
	66	43	31	41
Subsistence Flows (cfs)	N/A	20	18	20
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 3,350 cfs with Frequency 1 per 2 years Volume is 17,923 to 21,660 (19,792) Duration is 9 to 31 (17)			
High Flow Pulses	Qp: 2,280 cfs with Frequency 1 per year Volume is 11,964 to 15,693 (13,829) Duration is 8 to 26 (14)			
	Qp: 1,680 cfs with Frequency 2 per 3 years Volume is 8,524 to 12,250 (10,387) Duration is 7 to 23 (13)			
	Qp: 1,400 cfs with Frequency 2 per year Volume is 6,894 to 10,619 (8,756) Duration is 6 to 21 (12)			
	Qp: 1,300 cfs with Frequency 1 per season Volume is 6,771 to 10,752 (8,761) Duration is 6 to 18 (10)	Qp: 1,010 cfs with Frequency 1 per season Volume is 1,527 to 13,649 (7,588) Duration is 2 to 63 (10)	Qp: 223 cfs with Frequency 1 per season Volume is #N/A to 4,408 (1,650) Duration is 1 to 43 (8)	Qp: 1,040 cfs with Frequency 1 per season Volume is #N/A to 15,325 (6,527) Duration is 2 to 67 (10)
	Qp: 799 cfs with Frequency 2 per season Volume is #N/A to 12,532 (5,615) Duration is 1 to 59 (8)	Qp: 393 cfs with Frequency 2 per season Volume is #N/A to 9,071 (3,017) Duration is 1 to 42 (7)	Qp: 127 cfs with Frequency 2 per season Volume is 295 to 1,749 (1,022) Duration is 3 to 10 (5)	Qp: 405 cfs with Frequency 2 per season Volume is 1,092 to 4,461 (2,777) Duration is 4 to 12 (7)
Base Flows (cfs)	119	82	50	72
	91	60	40	51
	66	43	31	41
Subsistence Flows (cfs)	N/A	20	18	20
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

USGS 08030500 Sabine Rv nr Ruliff, TX

Full Period

Overbank Flows	Return Period (R) : 1.2		Duration (D) : 48 (days)	
	Volume (V) : 1209868 (ac-ft)		Peak Flow (Q) : 26050 (cfs)	
High Flow Pulses	F: 0	F: 0	F: 1	F: 1
	D: 25	D: 27	D: 28	D: 18
	Q: 8185	Q: 9013	Q: 6663	Q: 4580
	V: 228050	V: 269445	V: 220161	V: 95743
	F: 1	F: 1	F: 2	F: 2
	D: 16	D: 17	D: 17	D: 7
	Q: 4655	Q: 4730	Q: 4270	Q: 2060
	V: 111640	V: 111353	V: 90457	V: 24675
	F: 1	F: 2	F: 3	F: 3
	D: 4	D: 5	D: 6	D: 3
	Q: 1788	Q: 2863	Q: 1780	Q: 1400
	V: 12323	V: 32326	V: 25141	V: 7677
Base Flows (cfs)	5063	3035	1430	1400
	2565	1795	870	970
	1520	1208	670	735
Subsistence Flows (cfs)	N/A	436	396	362
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 41,300 cfs with Frequency 1 per 2 years Volume is 1,993,647 to 3,168,474 (2,581,061) Duration is 39 to 176 (82)			
High Flow Pulses	Qp: 29,000 cfs with Frequency 1 per year Volume is 1,173,583 to 2,346,562 (1,760,073) Duration is 28 to 128 (60)			
	Qp: 22,700 cfs with Frequency 2 per 3 years Volume is 751,704 to 1,924,090 (1,337,897) Duration is 23 to 103 (49)			
	Qp: 16,800 cfs with Frequency 2 per year Volume is 355,478 to 1,527,524 (941,501) Duration is 17 to 79 (37)			
	Qp: 14,800 cfs with Frequency 1 per season Volume is 43,787 to 1,802,294 (923,041) Duration is 17 to 63 (32)	Qp: 10,600 cfs with Frequency 1 per season Volume is #N/A to 1,195,749 (489,092) Duration is 11 to 49 (23)	Qp: 6,600 cfs with Frequency 1 per season Volume is 24,785 to 339,902 (182,343) Duration is 9 to 41 (19)	Qp: 6,030 cfs with Frequency 1 per season Volume is #N/A to 412,168 (161,358) Duration is 7 to 31 (15)
	Qp: 1,600 cfs with Frequency 2 per season Volume is #N/A to 619,714 (#N/A) Duration is 2 to 7 (3)	Qp: 3,250 cfs with Frequency 2 per season Volume is #N/A to 652,171 (#N/A) Duration is 4 to 18 (8)	Qp: 3,380 cfs with Frequency 2 per season Volume is #N/A to 266,091 (108,505) Duration is 5 to 23 (11)	Qp: 2,020 cfs with Frequency 2 per season Volume is #N/A to 284,879 (33,993) Duration is 2 to 11 (5)
Base Flows (cfs)	5063	3035	1430	1400
	2565	1795	870	970
	1520	1208	670	735
Subsistence Flows (cfs)	N/A	436	396	362
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

1940 to 1960

Overbank Flows	Return Period (R) : 0.9		Duration (D) : 46 (days)	
	Volume (V) : 1017035 (ac-ft)		Peak Flow (Q) : 26800 (cfs)	
High Flow Pulses	F: 0	F: 0	F: 1	F: 1
	D: 34	D: 40	D: 26	D: 27
	Q: 11400	Q: 10275	Q: 5215	Q: 5595
	V: 512906	V: 358305	V: 157503	V: 184885
	F: 1	F: 0	F: 1	F: 2
	D: 20	D: 26	D: 18	D: 14
	Q: 8020	Q: 6655	Q: 2920	Q: 2770
	V: 199776	V: 208364	V: 85994	V: 52027
	F: 1	F: 1	F: 2	F: 2
	D: 8	D: 7	D: 4	D: 3
	Q: 4570	Q: 4715	Q: 1595	Q: 1250
	V: 58077	V: 37756	V: 9650	V: 7597
Base Flows (cfs)	4600	4488	1633	1700
	2890	2860	950	1030
	2350	2018	688	840
Subsistence Flows (cfs)	N/A	N/A	360	350
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 52,000 cfs with Frequency 1 per 2 years Volume is 2,795,335 to 4,266,373 (3,530,854) Duration is 40 to 202 (90)			
High Flow Pulses	Qp: 33,100 cfs with Frequency 1 per year Volume is 1,446,172 to 2,903,921 (2,175,046) Duration is 28 to 139 (63)			
	Qp: 27,300 cfs with Frequency 2 per 3 years Volume is 1,023,859 to 2,479,288 (1,751,573) Duration is 24 to 119 (53)			
	Qp: 21,400 cfs with Frequency 2 per year Volume is 590,268 to 2,044,195 (1,317,231) Duration is 20 to 97 (44)			
	Qp: 16,200 cfs with Frequency 1 per season Volume is 15,245 to 1,329,592 (672,419) Duration is 18 to 58 (32)	Qp: 14,200 cfs with Frequency 1 per season Volume is #N/A to 1,807,833 (683,919) Duration is 13 to 69 (30)	Qp: 3,980 cfs with Frequency 1 per season Volume is #N/A to 260,323 (123,614) Duration is 5 to 33 (13)	Qp: 4,680 cfs with Frequency 1 per season Volume is #N/A to 254,208 (113,910) Duration is 6 to 28 (13)
	Qp: 2,390 cfs with Frequency 2 per season Volume is #N/A to 405,534 (#N/A) Duration is 3 to 13 (7)	*None Calculated*	Qp: 1,610 cfs with Frequency 2 per season Volume is #N/A to 145,902 (8,950) Duration is 2 to 15 (6)	Qp: 1,220 cfs with Frequency 2 per season Volume is #N/A to 179,227 (38,612) Duration is 2 to 9 (4)
Base Flows (cfs)	4600	4488	1633	1700
	2890	2860	950	1030
	2350	2018	688	840
Subsistence Flows (cfs)	N/A	N/A	360	350
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

1971 to 2007

Overbank Flows	Return Period (R) : 1.4		Duration (D) : 51 (days)	
	Volume (V) : 1358500 (ac-ft)		Peak Flow (Q) : 27250 (cfs)	
High Flow Pulses	F: 0	F: 1	F: 1	F: 2
	D: 24	D: 27	D: 28	D: 16
	Q: 7263	Q: 7520	Q: 7390	Q: 3735
	V: 165343	V: 236827	V: 276556	V: 82463
	F: 1	F: 1	F: 2	F: 3
	D: 12	D: 17	D: 18	D: 6
	Q: 2675	Q: 4380	Q: 5900	Q: 2000
	V: 43677	V: 100721	V: 134420	V: 17812
	F: 2	F: 3	F: 4	F: 4
	D: 2	D: 6	D: 6	D: 2
	Q: 1390	Q: 2960	Q: 3340	Q: 1395
	V: 5217	V: 35743	V: 45144	V: 5485
Base Flows (cfs)	3618	2250	3485	1460
	1685	1480	1600	1130
	1303	1130	1080	883
Subsistence Flows (cfs)	N/A	N/A	N/A	425
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 40,600 cfs with Frequency 1 per 2 years Volume is 2,008,891 to 3,014,773 (2,511,832) Duration is 44 to 195 (93)			
High Flow Pulses	Qp: 27,900 cfs with Frequency 1 per year Volume is 1,191,500 to 2,193,838 (1,692,669) Duration is 30 to 136 (64)			
	Qp: 22,000 cfs with Frequency 2 per 3 years Volume is 803,700 to 1,804,997 (1,304,349) Duration is 24 to 108 (51)			
	Qp: 16,000 cfs with Frequency 2 per year Volume is 404,078 to 1,404,713 (904,395) Duration is 18 to 79 (37)			
	Qp: 12,000 cfs with Frequency 1 per season Volume is 108,441 to 1,674,274 (891,358) Duration is 15 to 56 (29)	Qp: 9,060 cfs with Frequency 1 per season Volume is #N/A to 757,537 (281,109) Duration is 9 to 42 (19)	Qp: 7,560 cfs with Frequency 1 per season Volume is 77,284 to 392,156 (234,720) Duration is 10 to 41 (20)	Qp: 7,510 cfs with Frequency 1 per season Volume is #N/A to 472,414 (221,092) Duration is 8 to 36 (17)
	Qp: 1,460 cfs with Frequency 2 per season Volume is #N/A to 518,491 (#N/A) Duration is 1 to 6 (3)	Qp: 3,530 cfs with Frequency 2 per season Volume is #N/A to 556,252 (79,096) Duration is 4 to 20 (9)	Qp: 6,010 cfs with Frequency 2 per season Volume is 29,905 to 344,782 (187,343) Duration is 8 to 33 (16)	Qp: 2,250 cfs with Frequency 2 per season Volume is #N/A to 291,793 (40,386) Duration is 2 to 11 (5)
Base Flows (cfs)	3618	2250	3485	1460
	1685	1480	1600	1130
	1303	1130	1080	883
Subsistence Flows (cfs)	N/A	N/A	N/A	425
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

USGS 08041500 Village Ck nr Kountze, TX

Full Period

Overbank Flows	Return Period (R) : 3.8		Duration (D) : 22 (days)	
	Volume (V) : 175169 (ac-ft)		Peak Flow (Q) : 12100 (cfs)	
High Flow Pulses	F: 1	F: 1	F: 1	F: 1
	D: 20	D: 20	D: 17	D: 15
	Q: 2940	Q: 2300	Q: 699	Q: 1790
	V: 50837	V: 38145	V: 10739	V: 27058
	F: 3	F: 2	F: 3	F: 2
	D: 12	D: 14	D: 10	D: 10
	Q: 1490	Q: 1040	Q: 270	Q: 557
	V: 22886	V: 15632	V: 3791	V: 7449
	F: 4	F: 4	F: 4	F: 4
	D: 9	D: 9	D: 5	D: 6
	Q: 723	Q: 401	Q: 146	Q: 238
	V: 9204	V: 5346	V: 1414	V: 2724
Base Flows (cfs)	672	335	135	236
	424	189	91	138
	240	106	70	89
Subsistence Flows (cfs)	N/A	49	41	41
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall
Overbank Flows	Qp: 12,400 cfs with Frequency 1 per 2 years Volume is 148,832 to 191,794 (170,313) Duration is 15 to 58 (29)			
High Flow Pulses	Qp: 8,150 cfs with Frequency 1 per year Volume is 53,173 to 183,180 (118,176) Duration is 2 to 307 (25)			
	Qp: 6,180 cfs with Frequency 2 per 3 years Volume is 70,572 to 113,472 (92,022) Duration is 11 to 44 (22)			
	Qp: 5,050 cfs with Frequency 2 per year Volume is 55,004 to 97,899 (76,452) Duration is 11 to 41 (21)			
	Qp: 4,170 cfs with Frequency 1 per season Volume is 54,290 to 103,424 (78,857) Duration is 10 to 35 (18)	Qp: 3,250 cfs with Frequency 1 per season Volume is 27,361 to 64,644 (46,002) Duration is 9 to 33 (18)	Qp: 804 cfs with Frequency 1 per season Volume is 1,263 to 21,573 (11,418) Duration is 6 to 26 (13)	Qp: 2,400 cfs with Frequency 1 per season Volume is 15,979 to 55,745 (35,862) Duration is 7 to 27 (14)
	Qp: 2,010 cfs with Frequency 2 per season Volume is 12,365 to 61,489 (36,927) Duration is 7 to 25 (13)	Qp: 1,380 cfs with Frequency 2 per season Volume is 4,449 to 41,736 (23,093) Duration is 7 to 25 (13)	Qp: 341 cfs with Frequency 2 per season Volume is #N/A to 16,315 (6,159) Duration is 4 to 16 (8)	Qp: 712 cfs with Frequency 2 per season Volume is #N/A to 31,312 (11,426) Duration is 5 to 17 (9)
Base Flows (cfs)	672	335	135	236
	424	189	91	138
	240	106	70	89
Subsistence Flows (cfs)	N/A	49	41	41
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

1940 to 1960

	Return Period (R) : 7		Duration (D) : 22 (days)	
	Volume (V) : 185348 (ac-ft)		Peak Flow (Q) : 11600 (cfs)	
	F: 1	F: 1	F: 1	F: 1
	D: 19	D: 20	D: 19	D: 15
	Q: 2835	Q: 2260	Q: 1113	Q: 1230
	V: 46759	V: 37413	V: 14117	V: 19577
	F: 3	F: 2	F: 3	F: 2
	D: 12	D: 14	D: 11	D: 10
	Q: 1510	Q: 970	Q: 381	Q: 489
	V: 23554	V: 13962	V: 4492	V: 5973
	F: 5	F: 4	F: 4	F: 4
	D: 9	D: 9	D: 5	D: 4
	Q: 730	Q: 434	Q: 161	Q: 191
	V: 9897	V: 5538	V: 1397	V: 1709
	666	285	141	200
	344	177	95	122
	205	101	70	86
	N/A	46	42	43
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall
	Qp: 13,800 cfs with Frequency 1 per 2 years Volume is 165,896 to 203,948 (184,922) Duration is 16 to 62 (31)			
	Qp: 8,050 cfs with Frequency 1 per year Volume is 96,923 to 134,819 (115,871) Duration is 13 to 50 (25)			
	Qp: 5,800 cfs with Frequency 2 per 3 years Volume is 67,049 to 104,912 (85,981) Duration is 11 to 44 (22)			
	Qp: 4,500 cfs with Frequency 2 per year Volume is 49,049 to 86,901 (67,975) Duration is 10 to 39 (20)			
	Qp: 3,330 cfs with Frequency 1 per season Volume is 43,222 to 80,867 (62,045) Duration is 8 to 34 (17)	Qp: 3,150 cfs with Frequency 1 per season Volume is 23,411 to 64,900 (44,156) Duration is 10 to 32 (18)	Qp: 1,240 cfs with Frequency 1 per season Volume is 12,897 to 25,646 (19,272) Duration is 8 to 33 (16)	Qp: 1,780 cfs with Frequency 1 per season Volume is 10,823 to 40,341 (25,582) Duration is 6 to 24 (12)
	Qp: 2,010 cfs with Frequency 2 per season Volume is 16,567 to 54,190 (35,379) Duration is 7 to 27 (13)	Qp: 1,110 cfs with Frequency 2 per season Volume is #N/A to 40,338 (19,584) Duration is 7 to 23 (12)	Qp: 394 cfs with Frequency 2 per season Volume is #N/A to 11,762 (5,384) Duration is 4 to 17 (8)	Qp: 568 cfs with Frequency 2 per season Volume is #N/A to 24,027 (9,262) Duration is 4 to 15 (8)
	666	285	141	200
	344	177	95	122
	205	101	70	86
	N/A	46	42	43
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

1971 to 2007

	Return Period (R) : 2.9		Duration (D) : 22 (days)	
	Volume (V) : 157589 (ac-ft)		Peak Flow (Q) : 11850 (cfs)	
	F: 1	F: 1	F: 1	F: 1
	D: 20	D: 20	D: 17	D: 15
	Q: 3620	Q: 2455	Q: 699	Q: 2080
	V: 67796	V: 41296	V: 10637	V: 36457
	F: 3	F: 2	F: 3	F: 2
	D: 12	D: 14	D: 10	D: 11
	Q: 1650	Q: 1145	Q: 263	Q: 693
	V: 26827	V: 18758	V: 3896	V: 8805
	F: 4	F: 3	F: 4	F: 4
	D: 8	D: 10	D: 5	D: 7
	Q: 776	Q: 402	Q: 143	Q: 325
	V: 9190	V: 5743	V: 1390	V: 3303
	717	382	143	296
	521	229	105	170
	315	121	78	100
	N/A	49	37	46
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall
	Qp: 13,000 cfs with Frequency 1 per 2 years Volume is 154,796 to 202,328 (178,562) Duration is 14 to 56 (28)			
	Qp: 9,100 cfs with Frequency 1 per year Volume is 107,600 to 155,037 (131,318) Duration is 12 to 49 (24)			
	Qp: 6,580 cfs with Frequency 2 per 3 years Volume is 74,466 to 121,865 (98,166) Duration is 11 to 43 (22)			
	Qp: 5,590 cfs with Frequency 2 per year Volume is 60,883 to 108,272 (84,577) Duration is 10 to 40 (20)			
	Qp: 5,000 cfs with Frequency 1 per season Volume is 60,766 to 117,533 (89,150) Duration is 10 to 36 (19)	Qp: 3,860 cfs with Frequency 1 per season Volume is 38,615 to 74,397 (56,506) Duration is 9 to 33 (18)	Qp: 841 cfs with Frequency 1 per season Volume is 1,331 to 23,196 (12,263) Duration is 6 to 27 (13)	Qp: 2,830 cfs with Frequency 1 per season Volume is 19,312 to 63,878 (41,595) Duration is 7 to 27 (14)
	Qp: 2,540 cfs with Frequency 2 per season Volume is 17,173 to 73,898 (45,535) Duration is 7 to 25 (14)	Qp: 1,630 cfs with Frequency 2 per season Volume is 8,601 to 44,390 (26,496) Duration is 7 to 26 (14)	Qp: 393 cfs with Frequency 2 per season Volume is #N/A to 45,846 (7,135) Duration is 1 to 90 (8)	Qp: 1,020 cfs with Frequency 2 per season Volume is #N/A to 93,397 (16,312) Duration is 1 to 114 (10)
	717	382	143	296
	521	229	105	170
	315	121	78	100
	N/A	49	37	46
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

USGS 08041000 Neches Rv at Evadale, TX

Full Period

Overbank Flows	Return Period (R) : 1.7		Duration (D) : 49 (days)	
	Volume (V) : 1068536 (ac-ft)		Peak Flow (Q) : 20800 (cfs)	
High Flow Pulses	F: 0	F: 0	F: 0	F: 1
	D: 31	D: 32	D: 25	D: 22
	Q: 9738	Q: 8205	Q: 3890	Q: 5320
	V: 300873	V: 256900	V: 96100	V: 119033
	F: 1	F: 1	F: 1	F: 1
	D: 18	D: 19	D: 14	D: 16
	Q: 6105	Q: 5580	Q: 2100	Q: 2760
	V: 143799	V: 145101	V: 44625	V: 51194
	F: 2	F: 2	F: 2	F: 2
	D: 8	D: 10	D: 4	D: 4
	Q: 2640	Q: 2973	Q: 1005	Q: 1100
	V: 39010	V: 47462	V: 12647	V: 12686
Base Flows (cfs)	4980	3868	3210	2630
	2590	3070	2140	1280
	1760	1553	471	438
Subsistence Flows (cfs)	135	266	228	204
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 26,800 cfs with Frequency 1 per 2 years Volume is 1,251,746 to 2,273,029 (1,762,388) Duration is 18 to 116 (46)			
High Flow Pulses	Qp: 19,500 cfs with Frequency 1 per year Volume is 732,189 to 1,752,232 (1,242,210) Duration is 15 to 95 (38)			
	Qp: 15,800 cfs with Frequency 2 per 3 years Volume is 464,537 to 1,484,182 (974,359) Duration is 13 to 84 (33)			
	Qp: 13,000 cfs with Frequency 2 per year Volume is 260,060 to 1,279,507 (769,783) Duration is 12 to 74 (30)			
	Qp: 10,900 cfs with Frequency 1 per season Volume is #N/A to 1,318,757 (617,583) Duration is 11 to 65 (27)	Qp: 9,500 cfs with Frequency 1 per season Volume is #N/A to 1,008,117 (456,832) Duration is 11 to 56 (24)	Qp: 3,390 cfs with Frequency 1 per season Volume is 3,713 to 144,152 (73,933) Duration is 5 to 37 (13)	Qp: 3,820 cfs with Frequency 1 per season Volume is #N/A to 414,139 (90,628) Duration is 5 to 33 (13)
	Qp: 2,000 cfs with Frequency 2 per season Volume is #N/A to 486,188 (#N/A) Duration is 3 to 16 (6)	Qp: 3,440 cfs with Frequency 2 per season Volume is #N/A to 530,675 (#N/A) Duration is 5 to 28 (12)	Qp: 1,190 cfs with Frequency 2 per season Volume is #N/A to 98,341 (28,078) Duration is 3 to 22 (8)	Qp: 1,150 cfs with Frequency 2 per season Volume is #N/A to 328,642 (4,918) Duration is 3 to 16 (6)
Base Flows (cfs)	4980	3868	3210	2630
	2590	3070	2140	1280
	1760	1553	471	438
Subsistence Flows (cfs)	135	266	228	204
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

1940 to 1960

	Return Period (R) : 1.9		Duration (D) : 44 (days)	
	Volume (V) : 885700 (ac-ft)		Peak Flow (Q) : 19200 (cfs)	
High Flow Pulses	F: 0	F: 0	F: 1	F: 1
	D: 26	D: 33	D: 24	D: 21
	Q: 9495	Q: 7400	Q: 4120	Q: 4165
	V: 260896	V: 234030	V: 98097	V: 94622
	F: 1	F: 1	F: 2	F: 2
	D: 18	D: 20	D: 16	D: 16
	Q: 6220	Q: 5340	Q: 2180	Q: 2605
	V: 156233	V: 144516	V: 46071	V: 53146
	F: 3	F: 3	F: 3	F: 3
	D: 8	D: 13	D: 5	D: 3
	Q: 2070	Q: 2420	Q: 1490	Q: 1275
	V: 27898	V: 62956	V: 18968	V: 9993
Base Flows (cfs)	2980	3820	3280	2210
	1710	2340	2095	1120
	1160	1320	712	438
Subsistence Flows (cfs)	N/A	N/A	227	210
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 21,300 cfs with Frequency 1 per 2 years Volume is 1,122,636 to 1,823,324 (1,472,980) Duration is 16 to 93 (38)			
High Flow Pulses	Qp: 16,800 cfs with Frequency 1 per year Volume is 503,961 to 1,201,129 (852,545) Duration is 14 to 81 (33)			
	Qp: 14,200 cfs with Frequency 2 per 3 years Volume is 226,996 to 922,691 (574,843) Duration is 12 to 73 (30)			
	Qp: 11,100 cfs with Frequency 2 per year Volume is #N/A to 668,293 (321,053) Duration is 11 to 63 (26)			
	Qp: 9,700 cfs with Frequency 1 per season Volume is #N/A to 771,357 (259,250) Duration is 11 to 55 (24)	Qp: 8,560 cfs with Frequency 1 per season Volume is #N/A to 689,067 (187,491) Duration is 10 to 58 (25)	Qp: 4,060 cfs with Frequency 1 per season Volume is 16,956 to 180,605 (98,781) Duration is 5 to 35 (14)	Qp: 4,150 cfs with Frequency 1 per season Volume is 43,181 to 159,471 (101,326) Duration is 5 to 34 (14)
	Qp: 2,210 cfs with Frequency 2 per season Volume is #N/A to 570,457 (54,993) Duration is 3 to 17 (8)	Qp: 3,690 cfs with Frequency 2 per season Volume is #N/A to 605,103 (101,884) Duration is 7 to 40 (17)	Qp: 2,000 cfs with Frequency 2 per season Volume is #N/A to 125,213 (43,256) Duration is 4 to 27 (11)	Qp: 2,400 cfs with Frequency 2 per season Volume is #N/A to 107,196 (48,975) Duration is 4 to 23 (9)
Base Flows (cfs)	2980	3820	3280	2210
	1710	2340	2095	1120
	1160	1320	712	438
Subsistence Flows (cfs)	N/A	N/A	227	210
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

1971 to 2007

	Return Period (R) : 1.7		Duration (D) : 56 (days)	
	Volume (V) : 1289217 (ac-ft)		Peak Flow (Q) : 21400 (cfs)	
High Flow Pulses	F: 0	F: 0	F: 1	F: 1
	D: 28	D: 22	D: 18	D: 19
	Q: 10750	Q: 7740	Q: 4890	Q: 6425
	V: 308262	V: 212976	V: 111819	V: 155395
	F: 1	F: 1	F: 1	F: 2
	D: 17	D: 16	D: 11	D: 11
	Q: 6480	Q: 5575	Q: 3800	Q: 3435
	V: 143459	V: 118126	V: 64205	V: 55548
	F: 2	F: 2	F: 3	F: 2
	D: 3	D: 6	D: 4	D: 3
	Q: 3220	Q: 3458	Q: 3065	Q: 2740
	V: 22146	V: 43716	V: 26648	V: 18348
Base Flows (cfs)	3070	3968	3478	3050
	2505	3410	3140	2620
	1750	2940	2693	1990
Subsistence Flows (cfs)	256	N/A	234	240
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 25,900 cfs with Frequency 1 per 2 years Volume is 1,539,446 to 2,566,173 (2,052,809) Duration is 17 to 115 (44)			
High Flow Pulses	Qp: 19,200 cfs with Frequency 1 per year Volume is 777,660 to 1,799,916 (1,288,788) Duration is 13 to 90 (35)			
	Qp: 14,800 cfs with Frequency 2 per 3 years Volume is 350,419 to 1,370,838 (860,628) Duration is 11 to 72 (28)			
	Qp: 12,700 cfs with Frequency 2 per year Volume is 166,920 to 1,186,771 (676,846) Duration is 10 to 64 (25)			
	Qp: 10,700 cfs with Frequency 1 per season Volume is #N/A to 981,558 (419,772) Duration is 11 to 62 (26)	Qp: 8,090 cfs with Frequency 1 per season Volume is #N/A to 605,128 (193,548) Duration is 7 to 43 (17)	Qp: 4,440 cfs with Frequency 1 per season Volume is #N/A to 241,545 (103,201) Duration is 4 to 29 (10)	Qp: 6,480 cfs with Frequency 1 per season Volume is 14,145 to 324,554 (1,103,139,987) Duration is 5 to 31 (12)
	Qp: 1,290 cfs with Frequency 2 per season Volume is #N/A to 572,251 (5,754) Duration is 1 to 5 (2)	Qp: 4,110 cfs with Frequency 2 per season Volume is #N/A to 480,992 (68,584) Duration is 4 to 26 (10)	Qp: 3,380 cfs with Frequency 2 per season Volume is #N/A to 196,922 (58,511) Duration is 3 to 24 (9)	Qp: 3,030 cfs with Frequency 2 per season Volume is #N/A to 199,664 (132,670,206) Duration is 3 to 19 (7)
Base Flows (cfs)	3070	3968	3478	3050
	2505	3410	3140	2620
	1750	2940	2693	1990
Subsistence Flows (cfs)	256	N/A	234	240
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

USGS 08038000 Attoyac Bayou nr Chireno, TX

1940-1953

Overbank Flows	Return Period (R) : 2.3		Duration (D) : 20 (days)	
	Volume (V) : 89741 (ac-ft)		Peak Flow (Q) : 8130 (cfs)	
High Flow Pulses	F: 2	F: 1	F: 2	F: 2
	D: 17	D: 16	D: 10	D: 12
	Q: 1800	Q: 1225	Q: 235	Q: 602
	V: 31016	V: 19164	V: 2873	V: 8301
	F: 3	F: 3	F: 5	F: 4
	D: 11	D: 10	D: 7	D: 7
	Q: 814	Q: 532	Q: 108	Q: 265
	V: 13750	V: 7263	V: 1233	V: 2603
	F: 4	F: 4	F: 7	F: 4
	D: 7	D: 7	D: 4	D: 6
	Q: 509	Q: 290	Q: 66	Q: 117
	V: 5675	V: 2183	V: 382	V: 1164
Base Flows (cfs)	516	276	66	139
	348	189	45	78
	195	96	26	37
Subsistence Flows (cfs)	N/A	N/A	12	11
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 9,310 cfs with Frequency 1 per 2 years Volume is 102,535 to 118,011 (110,273) Duration is 13 to 45 (24)			
High Flow Pulses	Qp: 5,750 cfs with Frequency 1 per year Volume is 67,720 to 83,064 (75,392) Duration is 11 to 38 (21)			
	Qp: 4,090 cfs with Frequency 2 per 3 years Volume is 48,442 to 63,748 (56,095) Duration is 10 to 34 (19)			
	Qp: 3,240 cfs with Frequency 2 per year Volume is 37,820 to 53,115 (45,467) Duration is 9 to 31 (17)			
	Qp: 2,790 cfs with Frequency 1 per season Volume is 36,211 to 56,868 (46,539) Duration is 11 to 29 (18)	Qp: 2,350 cfs with Frequency 1 per season Volume is 22,267 to 39,212 (30,739) Duration is 7 to 29 (14)	Qp: 322 cfs with Frequency 1 per season Volume is 2,756 to 5,440 (4,098) Duration is 5 to 19 (10)	Qp: 854 cfs with Frequency 1 per season Volume is 5,574 to 18,554 (12,064) Duration is 6 to 18 (11)
	Qp: 1,140 cfs with Frequency 2 per season Volume is 8,990 to 29,636 (19,313) Duration is 7 to 18 (11)	Qp: 840 cfs with Frequency 2 per season Volume is 3,763 to 20,719 (12,241) Duration is 6 to 22 (11)	Qp: 204 cfs with Frequency 2 per season Volume is 1,143 to 3,824 (2,483) Duration is 4 to 15 (8)	Qp: 446 cfs with Frequency 2 per season Volume is 231 to 13,213 (6,722) Duration is 5 to 15 (9)
Base Flows (cfs)	516	276	66	139
	348	189	45	78
	195	96	26	37
Subsistence Flows (cfs)	N/A	N/A	12	11
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

1956 to 1984

Overbank Flows	Return Period (R) : 2.9		Duration (D) : 23 (days)	
	Volume (V) : 85179 (ac-ft)		Peak Flow (Q) : 7280 (cfs)	
High Flow Pulses	F: 1	F: 1	F: 2	F: 1
	D: 15	D: 19	D: 13	D: 13
	Q: 948	Q: 811	Q: 226	Q: 684
	V: 18051	V: 15493	V: 3052	V: 9314
	F: 3	F: 2	F: 4	F: 3
	D: 10	D: 12	D: 7	D: 8
	Q: 598	Q: 491	Q: 103	Q: 219
	V: 8180	V: 5755	V: 1109	V: 2857
	F: 5	F: 4	F: 6	F: 5
	D: 7	D: 7	D: 4	D: 6
	Q: 245	Q: 204	Q: 50	Q: 120
	V: 2554	V: 2372	V: 363	V: 1167
Base Flows (cfs)	339	178	48	122
	188	96	28	65
	107	49	20	34
Subsistence Flows (cfs)	N/A	0	10	8
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 7,520 cfs with Frequency 1 per 2 years Volume is 85,054 to 98,019 (91,536) Duration is 14 to 49 (27)			
High Flow Pulses	Qp: 4,480 cfs with Frequency 1 per year Volume is 55,014 to 67,896 (61,455) Duration is 12 to 41 (22)			
	Qp: 3,260 cfs with Frequency 2 per 3 years Volume is 40,302 to 53,165 (46,734) Duration is 11 to 36 (20)			
	Qp: 2,330 cfs with Frequency 2 per year Volume is 28,065 to 40,918 (34,492) Duration is 10 to 32 (18)			
	Qp: 1,850 cfs with Frequency 1 per season Volume is 21,966 to 37,273 (29,620) Duration is 8 to 25 (14)	Qp: 1,550 cfs with Frequency 1 per season Volume is 15,515 to 30,581 (23,048) Duration is 10 to 29 (17)	Qp: 390 cfs with Frequency 1 per season Volume is 2,687 to 8,081 (5,384) Duration is 6 to 23 (12)	Qp: 898 cfs with Frequency 1 per season Volume is 11,481 to 20,786 (16,133) Duration is 7 to 21 (12)
	Qp: 837 cfs with Frequency 2 per season Volume is 6,221 to 21,522 (13,871) Duration is 6 to 18 (10)	Qp: 690 cfs with Frequency 2 per season Volume is 3,082 to 18,153 (10,618) Duration is 8 to 23 (13)	Qp: 146 cfs with Frequency 2 per season Volume is #N/A to 4,585 (1,888) Duration is 4 to 14 (7)	Qp: 405 cfs with Frequency 2 per season Volume is 1,700 to 11,007 (6,353) Duration is 5 to 16 (9)
Base Flows (cfs)	339	178	48	122
	188	96	28	65
	107	49	20	34
Subsistence Flows (cfs)	N/A	0	10	8
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

USGS 08036500 Angelina Rv nr Alto, TX

Full Period

Overbank Flows	Return Period (R) : 8.2		Duration (D) : 28 (days)	
	Volume (V) : 242645 (ac-ft)		Peak Flow (Q) : 13650 (cfs)	
High Flow Pulses	F: 1	F: 1	F: 1	F: 1
	D: 22	D: 24	D: 18	D: 19
	Q: 3200	Q: 2410	Q: 401	Q: 1440
	V: 72591	V: 59201	V: 7502	V: 31763
	F: 2	F: 2	F: 3	F: 3
	D: 14	D: 16	D: 12	D: 13
	Q: 1385	Q: 997	Q: 154	Q: 535
	V: 29003	V: 19036	V: 2599	V: 9458
	F: 4	F: 4	F: 4	F: 4
	D: 10	D: 11	D: 6	D: 10
	Q: 697	Q: 432	Q: 86	Q: 182
	V: 10617	V: 6060	V: 1051	V: 2409
Base Flows (cfs)	971	518	69	176
	581	206	48	92
	252	82	36	47
Subsistence Flows (cfs)	N/A	18	11	16
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 9,690 cfs with Frequency 1 per 2 years Volume is 132,233 to 277,628 (204,931) Duration is 2 to 411 (29)			
High Flow Pulses	Qp: 6,900 cfs with Frequency 1 per year Volume is 80,876 to 225,982 (153,429) Duration is 2 to 366 (26)			
	Qp: 5,200 cfs with Frequency 2 per 3 years Volume is 46,186 to 191,176 (118,681) Duration is 2 to 332 (24)			
	Qp: 3,920 cfs with Frequency 2 per year Volume is 18,368 to 163,303 (90,835) Duration is 2 to 302 (21)			
	Qp: 3,530 cfs with Frequency 1 per season Volume is #N/A to 192,302 (89,332) Duration is 1 to 272 (18)	Qp: 2,760 cfs with Frequency 1 per season Volume is #N/A to 138,530 (59,278) Duration is 1 to 331 (20)	Qp: 397 cfs with Frequency 1 per season Volume is #N/A to 39,843 (7,129) Duration is 1 to 153 (13)	Qp: 1,500 cfs with Frequency 1 per season Volume is #N/A to 89,321 (34,291) Duration is 1 to 221 (16)
	Qp: 1,620 cfs with Frequency 2 per season Volume is #N/A to 140,101 (37,114) Duration is 1 to 200 (13)	Qp: 1,100 cfs with Frequency 2 per season Volume is #N/A to 103,391 (24,117) Duration is 1 to 232 (14)	Qp: 146 cfs with Frequency 2 per season Volume is #N/A to 35,348 (2,632) Duration is 1 to 90 (8)	Qp: 588 cfs with Frequency 2 per season Volume is #N/A to 67,083 (12,038) Duration is 1 to 163 (12)
Base Flows (cfs)	971	518	69	176
	581	206	48	92
	252	82	36	47
Subsistence Flows (cfs)	N/A	18	11	16
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

1971 to 2008

Overbank Flows	Return Period (R) : 6.3		Duration (D) : 28 (days)	
	Volume (V) : 233432 (ac-ft)		Peak Flow (Q) : 13650 (cfs)	
High Flow Pulses	F: 1	F: 1	F: 1	F: 1
	D: 22	D: 24	D: 19	D: 19
	Q: 3400	Q: 2365	Q: 420	Q: 1505
	V: 76169	V: 59173	V: 7993	V: 32799
	F: 2	F: 2	F: 3	F: 3
	D: 15	D: 16	D: 12	D: 13
	Q: 1655	Q: 1010	Q: 172	Q: 595
	V: 35382	V: 20184	V: 3100	V: 10852
	F: 4	F: 4	F: 4	F: 4
	D: 10	D: 11	D: 7	D: 10
	Q: 834	Q: 431	Q: 81	Q: 196
	V: 13339	V: 5812	V: 1065	V: 2464
Base Flows (cfs)	955	520	72	238
	610	231	49	101
	260	85	37	50
Subsistence Flows (cfs)	N/A	18	11	16
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 9,690 cfs with Frequency 1 per 2 years Volume is 183,785 to 227,613 (205,699) Duration is 14 to 62 (29)			
High Flow Pulses	Qp: 6,930 cfs with Frequency 1 per year Volume is 132,798 to 176,519 (154,659) Duration is 12 to 55 (26)			
	Qp: 5,330 cfs with Frequency 2 per 3 years Volume is 100,077 to 143,756 (121,916) Duration is 11 to 50 (24)			
	Qp: 4,040 cfs with Frequency 2 per year Volume is 72,004 to 115,661 (93,832) Duration is 10 to 46 (22)			
	Qp: 3,770 cfs with Frequency 1 per season Volume is 62,714 to 131,822 (97,268) Duration is 9 to 37 (18)	Qp: 2,760 cfs with Frequency 1 per season Volume is 43,109 to 76,401 (59,755) Duration is 8 to 43 (19)	Qp: 420 cfs with Frequency 1 per season Volume is 3,538 to 11,655 (7,597) Duration is 6 to 28 (13)	Qp: 1,640 cfs with Frequency 1 per season Volume is 25,546 to 48,593 (37,070) Duration is 8 to 32 (16)
	Qp: 1,930 cfs with Frequency 2 per season Volume is 11,010 to 80,129 (45,570) Duration is 7 to 28 (14)	Qp: 1,270 cfs with Frequency 2 per season Volume is #N/A to 101,383 (27,812) Duration is 1 to 228 (14)	Qp: 177 cfs with Frequency 2 per season Volume is #N/A to 39,649 (3,250) Duration is 1 to 102 (8)	Qp: 645 cfs with Frequency 2 per season Volume is #N/A to 67,700 (12,923) Duration is 1 to 157 (12)
Base Flows (cfs)	955	520	72	238
	610	231	49	101
	260	85	37	50
Subsistence Flows (cfs)	N/A	18	11	16
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

USGS 08033500 Neches Rv nr Rockland, TX

Full Period

Overbank Flows	Return Period (R) : 10.9		Duration (D) : 54 (days)	
	Volume (V) : 950303 (ac-ft)		Peak Flow (Q) : 26400 (cfs)	
High Flow Pulses	F: 1	F: 1	F: 1	F: 1
	D: 35	D: 38	D: 24	D: 26
	Q: 7605	Q: 6345	Q: 950	Q: 3000
	V: 257842	V: 201425	V: 20043	V: 70691
	F: 2	F: 1	F: 2	F: 2
	D: 18	D: 22	D: 12	D: 16
	Q: 4280	Q: 3115	Q: 319	Q: 811
	V: 104569	V: 75473	V: 4424	V: 13920
	F: 3	F: 2	F: 3	F: 3
	D: 8	D: 6	D: 3	D: 5
	Q: 2040	Q: 1165	Q: 159	Q: 253
	V: 22275	V: 12358	V: 1082	V: 2946
Base Flows (cfs)	2500	2160	151	381
	1390	1020	88	168
	548	382	61	82
Subsistence Flows (cfs)	N/A	29	21	21
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 18,500 cfs with Frequency 1 per 2 years Volume is 550,505 to 772,928 (661,717) Duration is 16 to 109 (41)			
High Flow Pulses	Qp: 13,000 cfs with Frequency 1 per year Volume is 360,876 to 582,971 (471,924) Duration is 13 to 93 (35)			
	Qp: 9,840 cfs with Frequency 2 per 3 years Volume is 246,431 to 468,409 (357,420) Duration is 12 to 81 (31)			
	Qp: 7,460 cfs with Frequency 2 per year Volume is 157,589 to 379,512 (268,550) Duration is 10 to 71 (27)			
	Qp: 6,910 cfs with Frequency 1 per season Volume is 97,598 to 415,449 (256,523) Duration is 8 to 58 (22)	Qp: 5,600 cfs with Frequency 1 per season Volume is 76,297 to 259,435 (167,866) Duration is 8 to 65 (23)	Qp: 615 cfs with Frequency 1 per season Volume is #N/A to 42,351 (13,365) Duration is 5 to 25 (11)	Qp: 2,240 cfs with Frequency 1 per season Volume is #N/A to 163,127 (72,600) Duration is 6 to 42 (17)
	Qp: 3,080 cfs with Frequency 2 per season Volume is #N/A to 241,202 (82,195) Duration is 5 to 36 (14)	Qp: 1,720 cfs with Frequency 2 per season Volume is #N/A to 131,559 (39,935) Duration is 4 to 34 (12)	Qp: 195 cfs with Frequency 2 per season Volume is #N/A to 28,952 (#N/A) Duration is 2 to 11 (5)	Qp: 515 cfs with Frequency 2 per season Volume is #N/A to 91,208 (649) Duration is 3 to 21 (8)
Base Flows (cfs)	2500	2160	151	381
	1390	1020	88	168
	548	382	61	82
Subsistence Flows (cfs)	N/A	29	21	21
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

1940 to 1960

	Return Period (R) : 7		Duration (D) : 45 (days)	
	Volume (V) : 1131262 (ac-ft)		Peak Flow (Q) : 30550 (cfs)	
High Flow Pulses	F: 1	F: 1	F: 1	F: 1
	D: 36	D: 36	D: 27	D: 25
	Q: 7580	Q: 6663	Q: 1250	Q: 3775
	V: 268032	V: 237923	V: 24062	V: 90087
	F: 2	F: 2	F: 2	F: 2
	D: 18	D: 21	D: 12	D: 17
	Q: 4320	Q: 2845	Q: 344	Q: 986
	V: 92172	V: 82032	V: 5501	V: 18208
	F: 2	F: 3	F: 3	F: 3
	D: 8	D: 5	D: 3	D: 5
	Q: 1850	Q: 1135	Q: 181	Q: 232
	V: 22771	V: 9567	V: 1131	V: 4278
Base Flows (cfs)	2860	2473	181	484
	1070	1260	106	220
	503	738	65	71
Subsistence Flows (cfs)	N/A	N/A	16	9
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 16,000 cfs with Frequency 1 per 2 years Volume is 492,489 to 689,354 (590,921) Duration is 14 to 101 (38)			
High Flow Pulses	Qp: 11,900 cfs with Frequency 1 per year Volume is 338,721 to 534,843 (436,782) Duration is 12 to 88 (33)			
	Qp: 9,500 cfs with Frequency 2 per 3 years Volume is 247,715 to 443,546 (345,631) Duration is 11 to 78 (30)			
	Qp: 7,270 cfs with Frequency 2 per year Volume is 162,498 to 358,153 (260,326) Duration is 10 to 69 (26)			
	Qp: 5,920 cfs with Frequency 1 per season Volume is 120,617 to 350,730 (235,673) Duration is 7 to 52 (19)	Qp: 6,580 cfs with Frequency 1 per season Volume is 144,574 to 274,413 (209,493) Duration is 10 to 64 (25)	Qp: 622 cfs with Frequency 1 per season Volume is 2,525 to 30,545 (16,535) Duration is 5 to 26 (11)	Qp: 2,050 cfs with Frequency 1 per season Volume is #N/A to 168,924 (47,704) Duration is 6 to 42 (16)
	Qp: 2,740 cfs with Frequency 2 per season Volume is #N/A to 190,188 (74,886) Duration is 5 to 37 (13)	Qp: 2,500 cfs with Frequency 2 per season Volume is 2,552 to 132,571 (67,562) Duration is 5 to 31 (12)	Qp: 228 cfs with Frequency 2 per season Volume is #N/A to 14,581 (548) Duration is 2 to 12 (5)	Qp: 448 cfs with Frequency 2 per season Volume is #N/A to 135,358 (13,921) Duration is 3 to 20 (8)
Base Flows (cfs)	2860	2473	181	484
	1070	1260	106	220
	503	738	65	71
Subsistence Flows (cfs)	N/A	N/A	16	9
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

1971 to 2007

	Return Period (R) : 38		Duration (D) : 53 (days)	
	Volume (V) : 788835 (ac-ft)		Peak Flow (Q) : 24400 (cfs)	
High Flow Pulses	F: 1	F: 1	F: 1	F: 1
	D: 31	D: 37	D: 23	D: 25
	Q: 8050	Q: 5780	Q: 1050	Q: 3435
	V: 277469	V: 187637	V: 18493	V: 78533
	F: 2	F: 1	F: 2	F: 2
	D: 18	D: 19	D: 12	D: 16
	Q: 4490	Q: 3440	Q: 368	Q: 1035
	V: 103280	V: 65376	V: 4882	V: 18797
	F: 2	F: 3	F: 3	F: 3
	D: 11	D: 4	D: 3	D: 5
	Q: 2695	Q: 1150	Q: 151	Q: 288
	V: 28691	V: 10453	V: 758	V: 3010
Base Flows (cfs)	2335	2225	196	455
	1365	837	109	220
	422	349	80	124
Subsistence Flows (cfs)	N/A	N/A	26	N/A
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 20,300 cfs with Frequency 1 per 2 years Volume is 573,488 to 838,870 (706,179) Duration is 16 to 110 (42)			
High Flow Pulses	Qp: 14,700 cfs with Frequency 1 per year Volume is 403,548 to 667,895 (535,721) Duration is 14 to 94 (36)			
	Qp: 11,200 cfs with Frequency 2 per 3 years Volume is 284,292 to 548,215 (416,254) Duration is 12 to 83 (32)			
	Qp: 8,300 cfs with Frequency 2 per year Volume is 177,880 to 441,580 (309,730) Duration is 11 to 72 (27)			
	Qp: 7,430 cfs with Frequency 1 per season Volume is 47,515 to 421,808 (234,661) Duration is 10 to 59 (24)	Qp: 5,570 cfs with Frequency 1 per season Volume is 66,634 to 264,898 (165,766) Duration is 7 to 60 (20)	Qp: 857 cfs with Frequency 1 per season Volume is #N/A to 53,324 (22,183) Duration is 5 to 30 (13)	Qp: 3,050 cfs with Frequency 1 per season Volume is 28,251 to 172,259 (100,255) Duration is 7 to 44 (17)
	Qp: 3,420 cfs with Frequency 2 per season Volume is #N/A to 273,104 (85,689) Duration is 6 to 37 (15)	Qp: 2,200 cfs with Frequency 2 per season Volume is #N/A to 147,552 (48,282) Duration is 4 to 38 (13)	Qp: 287 cfs with Frequency 2 per season Volume is #N/A to 31,339 (191) Duration is 3 to 14 (6)	Qp: 800 cfs with Frequency 2 per season Volume is #N/A to 85,723 (13,668) Duration is 4 to 23 (9)
Base Flows (cfs)	2335	2225	196	455
	1365	837	109	220
	422	349	80	124
Subsistence Flows (cfs)	N/A	N/A	26	N/A
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

USGS 08032000 Neches Rv nr Neches, TX

Full Period

Overbank Flows	Return Period (R) : 4.3		Duration (D) : 36 (days)	
	Volume (V) : 175540 (ac-ft)		Peak Flow (Q) : 6835 (cfs)	
High Flow Pulses	F: 1	F: 1	F: 1	F: 1
	D: 19	D: 24	D: 14	D: 16
	Q: 1258	Q: 1398	Q: 294	Q: 647
	V: 29167	V: 35313	V: 4590	V: 11445
	F: 2	F: 2	F: 2	F: 3
	D: 12	D: 14	D: 9	D: 10
	Q: 705	Q: 748	Q: 139	Q: 310
	V: 11437	V: 13352	V: 1581	V: 4319
	F: 3	F: 3	F: 3	F: 4
	D: 6	D: 6	D: 3	D: 4
	Q: 378	Q: 273	Q: 88	Q: 162
	V: 2521	V: 3059	V: 471	V: 1125
Base Flows (cfs)	814	524	108	172
	408	194	73	104
	178	87	42	73
Subsistence Flows (cfs)	N/A	21	12	13
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 7,280 cfs with Frequency 1 per 2 years Volume is 147,606 to 197,573 (172,590) Duration is 16 to 90 (38)
High Flow Pulses	Qp: 4,880 cfs with Frequency 1 per year Volume is 93,407 to 143,307 (118,357) Duration is 13 to 72 (30)
	Qp: 3,430 cfs with Frequency 2 per 3 years Volume is 59,120 to 108,996 (84,058) Duration is 10 to 60 (25)
	Qp: 2,440 cfs with Frequency 2 per year Volume is 35,044 to 84,911 (59,977) Duration is 9 to 50 (21)
	Qp: 1,750 cfs with Frequency 1 per season Volume is 22,303 to 84,748 (53,526) Duration is 6 to 38 (15)
	Qp: 1,830 cfs with Frequency 1 per season Volume is 12,212 to 70,489 (41,351) Duration is 7 to 44 (18)
	Qp: 248 cfs with Frequency 1 per season Volume is #N/A to 8,343 (4,029) Duration is 3 to 16 (7)
	Qp: 782 cfs with Frequency 1 per season Volume is 7,746 to 32,246 (19,996) Duration is 5 to 28 (12)
	Qp: 833 cfs with Frequency 2 per season Volume is #N/A to 50,333 (19,104) Duration is 4 to 25 (10)
	Qp: 820 cfs with Frequency 2 per season Volume is #N/A to 49,550 (20,405) Duration is 5 to 29 (12)
	Qp: 113 cfs with Frequency 2 per season Volume is #N/A to 5,654 (1,339) Duration is 2 to 10 (4)
	Qp: 345 cfs with Frequency 2 per season Volume is #N/A to 17,643 (5,391) Duration is 3 to 17 (8)

1940 to 1960

	Return Period (R) : 3		Duration (D) : 34 (days)	
	Volume (V) : 178367 (ac-ft)		Peak Flow (Q) : 7610 (cfs)	
	F: 1	F: 1	F: 1	F: 1
	D: 23	D: 25	D: 18	D: 19
	Q: 1680	Q: 1560	Q: 248	Q: 965
	V: 43839	V: 35806	V: 5267	V: 24344
	F: 2	F: 1	F: 2	F: 2
	D: 15	D: 16	D: 11	D: 15
	Q: 985	Q: 794	Q: 128	Q: 485
	V: 18907	V: 18054	V: 2198	V: 8821
	F: 3	F: 2	F: 3	F: 3
	D: 9	D: 11	D: 3	D: 10
	Q: 440	Q: 524	Q: 65	Q: 192
	V: 8289	V: 6240	V: 330	V: 2482
	1290	1300	150	416
	724	631	50	215
	370	313	18	95
	N/A	102	60	286
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

	Qp: 10,700 cfs with Frequency 1 per 2 years Volume is 184,401 to 233,170 (208,786) Duration is 17 to 94 (40)
	Qp: 5,760 cfs with Frequency 1 per year Volume is 92,365 to 140,789 (116,577) Duration is 13 to 71 (31)
	Qp: 4,220 cfs with Frequency 2 per 3 years Volume is 62,638 to 111,009 (86,823) Duration is 12 to 62 (27)
	Qp: 3,340 cfs with Frequency 2 per year Volume is 45,430 to 93,782 (69,606) Duration is 10 to 56 (24)
	Qp: 2,220 cfs with Frequency 1 per season Volume is 37,828 to 88,843 (63,336) Duration is 8 to 42 (18)
	Qp: 3,610 cfs with Frequency 1 per season Volume is 41,317 to 95,482 (68,399) Duration is 10 to 55 (23)
	Qp: 222 cfs with Frequency 1 per season Volume is 1,018 to 7,310 (4,164) Duration is 4 to 19 (9)
	Qp: 865 cfs with Frequency 1 per season Volume is 7,696 to 40,274 (23,985) Duration is 6 to 35 (15)
	Qp: 990 cfs with Frequency 2 per season Volume is #N/A to 50,687 (25,161) Duration is 5 to 28 (12)
	Qp: 890 cfs with Frequency 2 per season Volume is #N/A to 47,484 (20,370) Duration is 6 to 32 (13)
	Qp: 90 cfs with Frequency 2 per season Volume is #N/A to 4,234 (1,085) Duration is 2 to 10 (5)
	Qp: 338 cfs with Frequency 2 per season Volume is #N/A to 20,006 (3,704) Duration is 4 to 24 (10)

1971 to 2007

	Return Period (R) : 4.2		Duration (D) : 37 (days)	
	Volume (V) : 174907 (ac-ft)		Peak Flow (Q) : 6650 (cfs)	
	F: 1	F: 1	F: 1	F: 1
	D: 18	D: 23	D: 10	D: 13
	Q: 1205	Q: 1385	Q: 386	Q: 579
	V: 23767	V: 37572	V: 4132	V: 8746
	F: 2	F: 2	F: 2	F: 3
	D: 10	D: 12	D: 7	D: 9
	Q: 635	Q: 706	Q: 150	Q: 274
	V: 7518	V: 11981	V: 1488	V: 3327
	F: 4	F: 4	F: 4	F: 4
	D: 2	D: 5	D: 2	D: 2
	Q: 337	Q: 209	Q: 99	Q: 157
	V: 1687	V: 1718	V: 504	V: 935
	700	463	120	158
	351	134	88	103
	165	80	63	80
	N/A	21	19	N/A
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

	Qp: 6,650 cfs with Frequency 1 per 2 years Volume is 163,036 to 207,381 (185,208) Duration is 16 to 91 (38)
	Qp: 4,640 cfs with Frequency 1 per year Volume is 112,704 to 156,907 (134,806) Duration is 13 to 73 (30)
	Qp: 3,300 cfs with Frequency 2 per 3 years Volume is 75,340 to 119,483 (97,411) Duration is 10 to 59 (25)
	Qp: 2,370 cfs with Frequency 2 per year Volume is 47,616 to 91,734 (69,675) Duration is 8 to 49 (20)
	Qp: 1,750 cfs with Frequency 1 per season Volume is 20,819 to 85,599 (53,209) Duration is 5 to 38 (14)
	Qp: 1,660 cfs with Frequency 1 per season Volume is 22,939 to 70,325 (46,632) Duration is 7 to 44 (18)
	Qp: 279 cfs with Frequency 1 per season Volume is #N/A to 8,676 (4,171) Duration is 3 to 14 (6)
	Qp: 771 cfs with Frequency 1 per season Volume is 6,964 to 28,137 (17,551) Duration is 5 to 24 (11)
	Qp: 800 cfs with Frequency 2 per season Volume is #N/A to 50,018 (17,618) Duration is 3 to 22 (8)
	Qp: 820 cfs with Frequency 2 per season Volume is #N/A to 43,482 (19,781) Duration is 5 to 28 (11)
	Qp: 136 cfs with Frequency 2 per season Volume is #N/A to 5,523 (1,019) Duration is 2 to 9 (4)
	Qp: 365 cfs with Frequency 2 per season Volume is #N/A to 16,489 (5,900) Duration is 3 to 15 (7)

Sabine Lake

Full Period

Overbank Flows	Return Period (R) : 9.3 (years)		Duration (D) : 31 (days)	
	Volume (V) : 3507146 (ac-ft)		Peak Flow (Q) : 158589 (cfs)	
High Flow Pulses	F: 1	F: 1	F: 1	F: 1
	D: 33	D: 29	D: 25	D: 24
	Q: 55502	Q: 47840	Q: 18305	Q: 31971
	V: 1822645	V: 1382141	V: 583358	V: 778743
	F: 1	F: 2	F: 2	F: 2
	D: 20	D: 17	D: 15	D: 16
	Q: 32604	Q: 21822	Q: 10416	Q: 12040
	V: 886252	V: 447195	V: 234460	V: 278635
	F: 3	F: 3	F: 3	F: 3
	D: 12	D: 5	D: 5	D: 6
	Q: 13317	Q: 8440	Q: 6667	Q: 6091
	V: 277887	V: 88241	V: 68411	V: 66318
Base Flows (cfs)	29977	19955	6107	5435
	14221	6836	2744	4041
	5134	3346	1880	2069
Subsistence Flows (cfs)	N/A	N/A	618	806
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 115,864 cfs with Frequency 1 per 2 years Volume is 2,662,582 to 4,249,022 (3,455,802) Duration is 17 to 93 (40)			
High Flow Pulses	Qp: 85,161 cfs with Frequency 1 per year Volume is 1,901,214 to 3,484,928 (2,693,071) Duration is 14 to 77 (33)			
	Qp: 73,486 cfs with Frequency 2 per 3 years Volume is 1,572,807 to 3,155,804 (2,364,305) Duration is 13 to 71 (30)			
	Qp: 61,627 cfs with Frequency 2 per year Volume is 1,217,286 to 2,799,734 (2,008,510) Duration is 11 to 64 (27)			
	Qp: 52,636 cfs with Frequency 1 per season Volume is 832,543 to 2,729,934 (1,781,238) Duration is 11 to 57 (25)	Qp: 48,255 cfs with Frequency 1 per season Volume is 656,308 to 2,449,977 (1,553,142) Duration is 8 to 49 (20)	Qp: 17,337 cfs with Frequency 1 per season Volume is 193,636 to 735,815 (464,726) Duration is 6 to 33 (14)	Qp: 27,414 cfs with Frequency 1 per season Volume is 292,929 to 1,220,262 (756,596) Duration is 7 to 40 (17)
	Qp: 25,635 cfs with Frequency 2 per season Volume is #N/A to 1,693,541 (744,678) Duration is 7 to 36 (16)	Qp: 18,925 cfs with Frequency 2 per season Volume is #N/A to 1,391,885 (494,689) Duration is 5 to 28 (12)	Qp: 10,045 cfs with Frequency 2 per season Volume is #N/A to 523,185 (252,026) Duration is 4 to 24 (10)	Qp: 7,635 cfs with Frequency 2 per season Volume is #N/A to 612,994 (149,042) Duration is 3 to 17 (7)
Base Flows (cfs)	29977	19955	6107	5435
	14221	6836	2744	4041
	5134	3346	1880	2069
Subsistence Flows (cfs)	N/A	N/A	618	806
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

1941 to 1960

Overbank Flows	Return Period (R) : 6.7 (years)		Duration (D) : 47 (days)	
	Volume (V) : 5349924 (ac-ft)		Peak Flow (Q) : 144103 (cfs)	
High Flow Pulses	F: 1	F: 1	F: 1	F: 0
	D: 38	D: 34	D: 35	D: 30
	Q: 61265	Q: 48142	Q: 35984	Q: 37201
	V: 2352705	V: 1844017	V: 672030	V: 1027343
	F: 2	F: 1	F: 1	F: 1
	D: 23	D: 23	D: 20	D: 23
	Q: 35389	Q: 31036	Q: 11884	Q: 15196
	V: 847385	V: 799361	V: 328888	V: 397760
	F: 2	F: 2	F: 2	F: 2
	D: 15	D: 4	D: 14	D: 12
	Q: 16643	Q: 18231	Q: 6354	Q: 6812
	V: 368571	V: 296272	V: 129120	V: 156465
Base Flows (cfs)	27166	24213	3134	3906
	12864	10360	2252	2347
	5744	3760	1703	1636
Subsistence Flows (cfs)	N/A	N/A	561	799
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 118,692 cfs with Frequency 1 per 2 years Volume is 3,331,742 to 5,440,184 (4,385,963) Duration is 15 to 91 (37)			
High Flow Pulses	Qp: 84,805 cfs with Frequency 1 per year Volume is 2,043,498 to 4,136,170 (3,089,834) Duration is 13 to 78 (31)			
	Qp: 72,879 cfs with Frequency 2 per 3 years Volume is 1,584,629 to 3,673,752 (2,629,190) Duration is 12 to 72 (29)			
	Qp: 62,138 cfs with Frequency 2 per year Volume is 1,168,904 to 3,255,729 (2,212,316) Duration is 11 to 67 (27)			
	Qp: 46,503 cfs with Frequency 1 per season Volume is 655,318 to 2,617,371 (1,636,345) Duration is 12 to 62 (27)	Qp: 51,583 cfs with Frequency 1 per season Volume is 909,023 to 2,296,583 (1,602,803) Duration is 8 to 58 (22)	Qp: 24,833 cfs with Frequency 1 per season Volume is #N/A to 1,472,681 (732,254) Duration is 7 to 53 (19)	Qp: 11,090 cfs with Frequency 1 per season Volume is #N/A to 949,436 (274,203) Duration is 6 to 29 (13)
	Qp: 15,196 cfs with Frequency 2 per season Volume is #N/A to 1,329,416 (342,070) Duration is 7 to 37 (16)	Qp: 29,866 cfs with Frequency 2 per season Volume is 96,487 to 1,485,862 (791,175) Duration is 6 to 40 (15)	Qp: 3,500 cfs with Frequency 2 per season Volume is #N/A to 800,438 (55,854) Duration is 3 to 23 (8)	Qp: 2,983 cfs with Frequency 2 per season Volume is #N/A to 654,717 (#N/A) Duration is 3 to 16 (7)
Base Flows (cfs)	17668	31172	4175	2740
	5724	15826	2444	2087
	2910	9059	1844	1578
Subsistence Flows (cfs)	N/A	N/A	620	715
	Dec Jan Feb	Mar Apr May	Jun Jul Aug	Sep Oct Nov
	Winter	Spring	Summer	Fall

1971 to 2005

Overbank Flows	Return Period (R) : 11.7 (years)		Duration (D) : 28 (days)	
	Volume (V) : 3427220 (ac-ft)		Peak Flow (Q) : 156575 (cfs)	
High Flow Pulses	F: 1	F: 1	F: 1	F: 1
	D: 28	D: 24	D: 23	D: 21
	Q: 56217	Q: 48255	Q: 16804	Q: 32042
	V: 1836286	V: 1265935	V: 586770	V: 739311
	F: 2	F: 2	F: 2	F: 2
	D: 19	D: 15	D: 15	D: 16
	Q: 38160	Q: 15027	Q: 10794	Q: 12040
	V: 1058454	V: 317646	V: 278593	V: 220166
	F: 3	F: 3	F: 4	F: 3
	D: 10	D: 5	D: 5	D: 5
	Q: 16391	Q: 7250	Q: 8151	Q: 6365
	V: 281667	V: 72404	V: 77921	V: 59138
Base Flows (cfs)	35503	25043	8935	6493
	21809	7154	6262	4936
	5600	4143	4476	4048
Subsistence Flows (cfs)	N/A	N/A	1012	914
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Overbank Flows	Qp: 118,201 cfs with Frequency 1 per 2 years Volume is 2,531,046 to 3,778,927 (3,154,986) Duration is 16 to 86 (37)			
High Flow Pulses	Qp: 88,180 cfs with Frequency 1 per year Volume is 1,889,762 to 3,134,177 (2,511,970) Duration is 13 to 72 (31)			
	Qp: 75,965 cfs with Frequency 2 per 3 years Volume is 1,591,137 to 2,834,554 (2,212,846) Duration is 12 to 66 (28)			
	Qp: 66,379 cfs with Frequency 2 per year Volume is 1,341,514 to 2,584,314 (1,962,914) Duration is 11 to 61 (26)			
	Qp: 54,464 cfs with Frequency 1 per season Volume is 900,133 to 2,696,776 (1,798,455) Duration is 9 to 54 (22)	Qp: 52,166 cfs with Frequency 1 per season Volume is 849,838 to 2,185,940 (1,517,889) Duration is 9 to 46 (20)	Qp: 20,193 cfs with Frequency 1 per season Volume is 331,488 to 824,008 (577,748) Duration is 7 to 35 (15)	Qp: 33,551 cfs with Frequency 1 per season Volume is 534,995 to 1,217,308 (876,152) Duration is 8 to 40 (17)
	Qp: 33,998 cfs with Frequency 2 per season Volume is 154,711 to 1,950,796 (1,052,754) Duration is 7 to 40 (16)	Qp: 15,343 cfs with Frequency 2 per season Volume is #N/A to 1,066,619 (398,242) Duration is 4 to 23 (10)	Qp: 11,620 cfs with Frequency 2 per season Volume is 55,130 to 547,804 (301,467) Duration is 5 to 24 (11)	Qp: 12,042 cfs with Frequency 2 per season Volume is #N/A to 601,445 (260,122) Duration is 4 to 19 (9)
Base Flows (cfs)	35503	25043	8935	6493
	21809	7154	6262	4936
	5600	4143	4476	4048
Subsistence Flows (cfs)	N/A	N/A	1012	914
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

MEMORANDUM

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TO: Sabine-Neches Expert Science Team Technical Committee

FROM: Jon S. Albright, Freese and Nichols, Inc.

SUBJECT: Water Availability Analyses for Sabine-Neches Bay and Basin Expert Science Team (BBEST)

DATE: September 17, 2009

Introduction

This memorandum describes an analysis of water available for environmental flows performed by Freese and Nichols, Inc., (FNI) for the Sabine & Neches Rivers and Sabine Lake Bay and Basin Expert Science Team (BBEST). These analyses employed the Texas Commission on Environmental Quality (TCEQ) Water Availability Models (WAM) for the Sabine and Neches River Basins, as modified for use by the Region I Water Planning Group. The analyses include assessments of:

- Unappropriated and regulated flows at 11 of the 12 stream gages selected by the BBEST (there are no WAM control points on Big Cow Creek). Table 1 shows the BBEST gages and the associated WAM control points.
- Frequency of compliance with preliminary Hydrology-Based Environmental Flow Regime matrices by both naturalized and regulated flows.

The WAM analyses include use of both the Current Conditions (Run 8) and Full Authorization (Run 3) scenarios.

Water Availability Models for the Sabine and Neches Basin

TCEQ has developed water availability models for every basin in the State of Texas. Each model includes all water rights in the basin. TCEQ developed the WAM models primarily to analyze new water rights, although the models have been used for other purposes such as regional water planning and evaluation of environmental flows. TCEQ maintains two versions of the model for each basin:

Table 1: USGS Stream Gages and WAM Control Points Selected by the Sabine-Neches BBEST

USGS Gage Name	USGS Gage Number	County	WAM Control Point
SABINE BASIN			
Big Sandy Creek nr Big Sandy	8019500	Upshur	BSBS
Sabine River nr Gladewater	8020000	Gregg	SRGW
Sabine River nr Beckville	8022040	Panola	SRBE
Sabine River nr Bon Wier	8028500	Newton	SRBW
Big Cow Creek nr Newton	8029500	Newton	N/A
Sabine River nr Ruliff	8030500	Newton	SRRL
NECHES BASIN			
Neches River nr Neches	8032000	Cherokee	NENE
Neches River nr Rockland	8033500	Tyler	NERO
Angelina River nr Alto	8036500	Cherokee	ANAL
Attoyac Bayou nr Chireno	8038000	San Augustine	ATCH
Neches River at Evadale	8041000	Jasper	NEEV
Village Creek nr Kountze	8041500	Hardin	VIKO

- *Current Conditions (Run 8)* used by TCEQ to process term water rights applications. Run 8 assumes year 2000 storage condition in reservoirs and diversion levels and return flows from the 1990s. It also includes temporary or term permits. Although the diversion levels are over a decade old, Run 8 is still relatively close to what is currently seen in the basin.
- *Full Authorization (Run 3)* used by TCEQ to analyze permanent water rights. Run 3 assumes full diversion and storage for every permanent water right and no return flows unless required by the permit. Run 3 does not include term permits. Full authorized diversion is assumed even if the source cannot reliably support that level of diversion, and full authorized storage is assumed even if some of that storage has been lost to sedimentation. Run 3 can be thought of as a "worst case" scenario, since it is unlikely that all water rights will all be fully exercised at once, reservoirs will be dredged to restore lost capacity, or that return flows will not be present at some level.

The WAMS used in this study have been modified for use by the Region I Water Planning Group. Modifications to the Neches WAM include adding hydropower from Sam Rayburn

Reservoir and Lake Steinhagen and improving the subordination modeling of the Rayburn/Steinhagen water right (which cannot make a priority call on certain water rights in the upper Neches Basin). Modifications to the Sabine WAM include reduction of the Lake Cherokee storage to its actual storage capacity and increases in diversions by the State of Louisiana reflecting authorizations in the Sabine River Compact.

The WAMs assume a strict application of the priority rights system used in the State of Texas. The model assumes that senior water rights continuously make priority calls on junior water rights to pass water. At this time, priority calls are rare and the priority system is seldom enforced outside of areas governed by a Watermaster. However, as water supplies become fully utilized, it is reasonable to assume that priority calls will be made on a more frequent basis.

The WAMs use a monthly timestep and "naturalized" flow data. Naturalized flows are monthly historical gage flows that have been adjusted to remove the effects of major reservoirs, diversions, and return flows. Naturalized flows are not corrected for smaller impoundments or changes in flows due to urbanization or other modifications in land use, groundwater interaction, or other situations that may modify flows over time. The flow data for the Neches WAM covers the period from 1940 to 1996. The Sabine WAM covers the period from 1940 to 1998.

This analysis uses two of the outputs from the WAM:

- *Unappropriated Flow* – which is the flow after all water rights have diverted or stored water that has not been claimed by any water rights. Unappropriated flow is potentially available for appropriation by future water rights or for environmental flow purposes.
- *Regulated Flow* – which is the actual flow remaining in the stream after all water rights have diverted and stored water. Regulated flow includes flow being passed downstream for water rights, water reserved for existing instream flow requirements, and unappropriated flow. Regulated flow can be thought of as naturalized flow less the net depletions that are the result of upstream water rights.

Even though regulated flow includes water that has already been claimed for a water right, it can be used for environmental purposes in the portions of the river upstream of the diversion. However, at some point, the appropriated portion of the regulated flow will be claimed by a water right somewhere on the river.

TCEQ publishes water availability maps for all of the basins in the state based on unappropriated water. Figure 1 shows spatial availability for term permits from Run 8 and for permanent water rights from Run 3 for the Sabine Basin. Figure 2 shows the same information for the Neches Basin. In general, if water is available more than 75 percent of the time it is likely that new water rights could be obtained without a storage reservoir. If water is available less than 25 percent of the time it would be very difficult to obtain any new water rights even with storage.

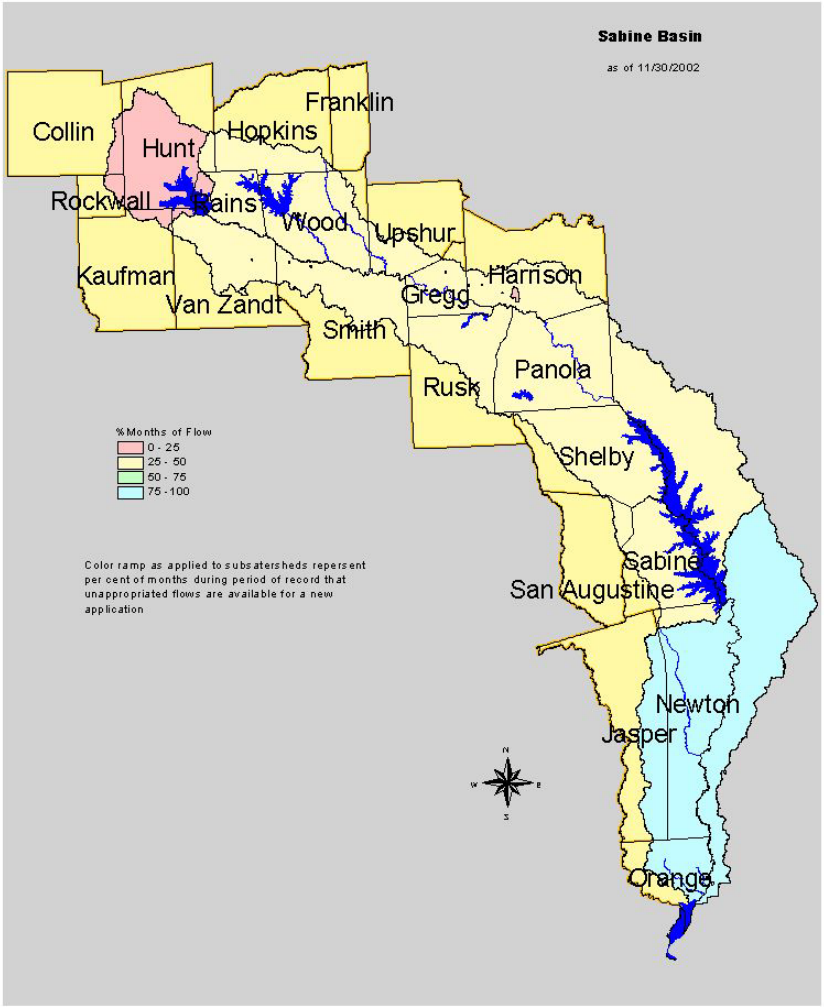
Table 2 is a summary of statistics for naturalized flows, unappropriated flows, and regulated flows from Run 3 and Run 8 for the 11 BBEST gages. (Data for Big Cow Creek near Newton gage are not available from the WAM.) Figure 3 compares annual historical, naturalized, and regulated flows from Run 3 and 8 for an upper basin gage, Big Sandy Creek near Big Sandy. In this graph, historical gage flows are shown as a purple line. The unappropriated flows appear as blue bars. The difference between unappropriated flows and regulated flows is shown as red bars labeled "Flow Passed Downstream". This represents the water that is being passed for downstream water rights or instream flow requirements. The difference between regulated flows and naturalized flows is shown as clear bars labeled "Flow Appropriated Upstream". Note that there is very little difference between historical flows and naturalized flows, and that very little of the flow is used upstream of the gage. Also note that, between Run 8 and Run 3, a significant portion of the unappropriated flow becomes classified as flow passed downstream. This is because as demand increases more of the Run 8 unappropriated water is claimed by downstream water rights. The flow in the Run 8 example is not really unappropriated in the legal sense - some of the flow has already been appropriated by existing water rights. As you can see from this figure, there are several years where no unappropriated water is available for new water rights.

Figure 4 compares the same information for a lower basin gage, Neches River at Evadale. In this figure, Run 8 shows very little difference between naturalized flows and regulated flows. As demand increases, more water is taken upstream reducing the amount of regulated flow at the gage. However, even with full use of water rights, there remains a significant amount of water passing the gage, and much of it is unappropriated.

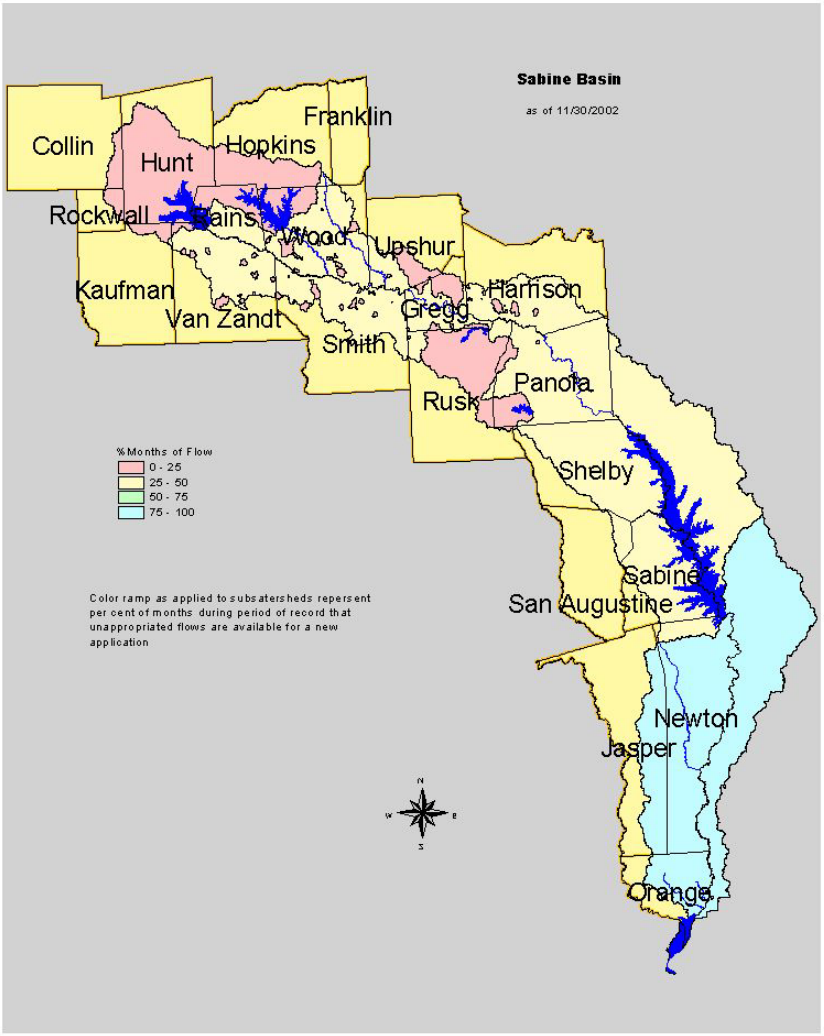
The same information for the other gages may be found in Attachment A.

Figure 1: Available Water in the Sabine Basin

Water Availability Evaluation for Term Rights

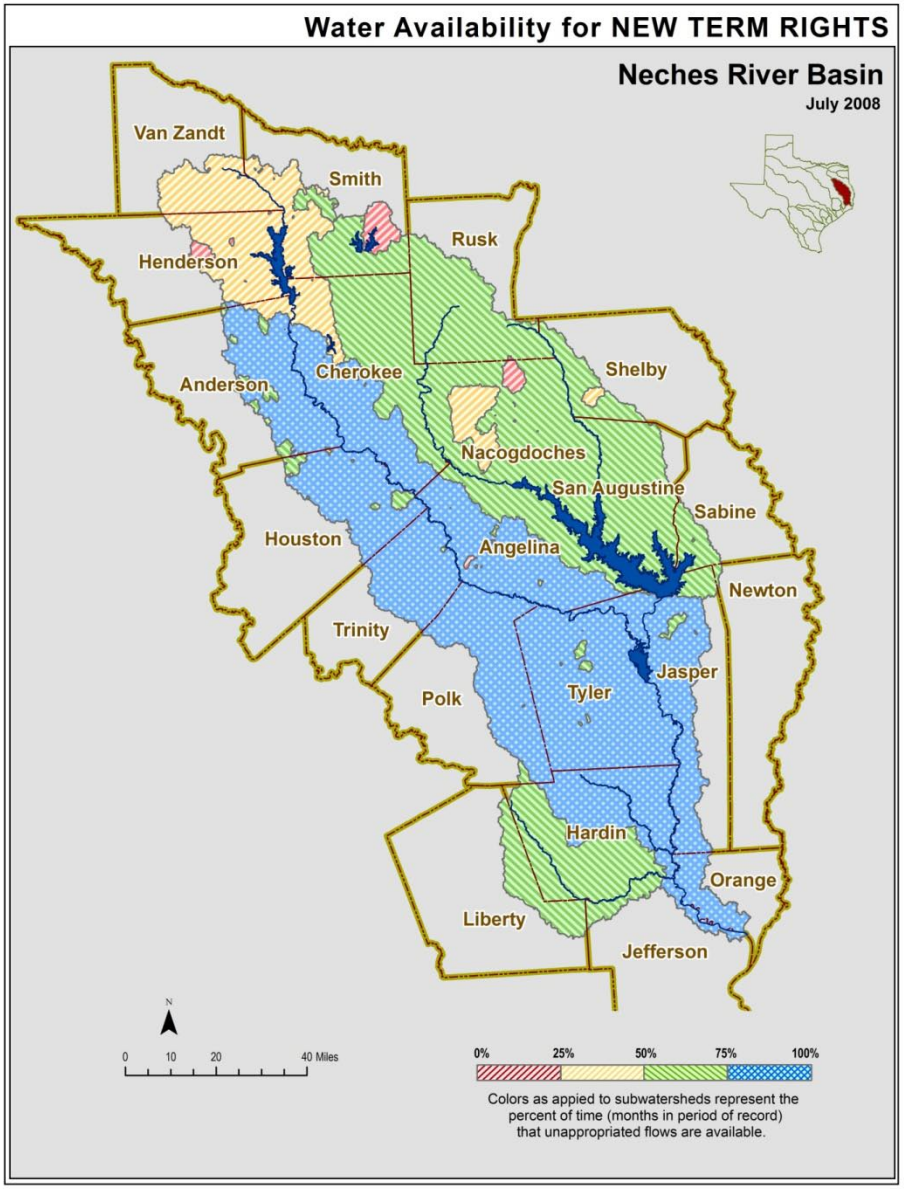


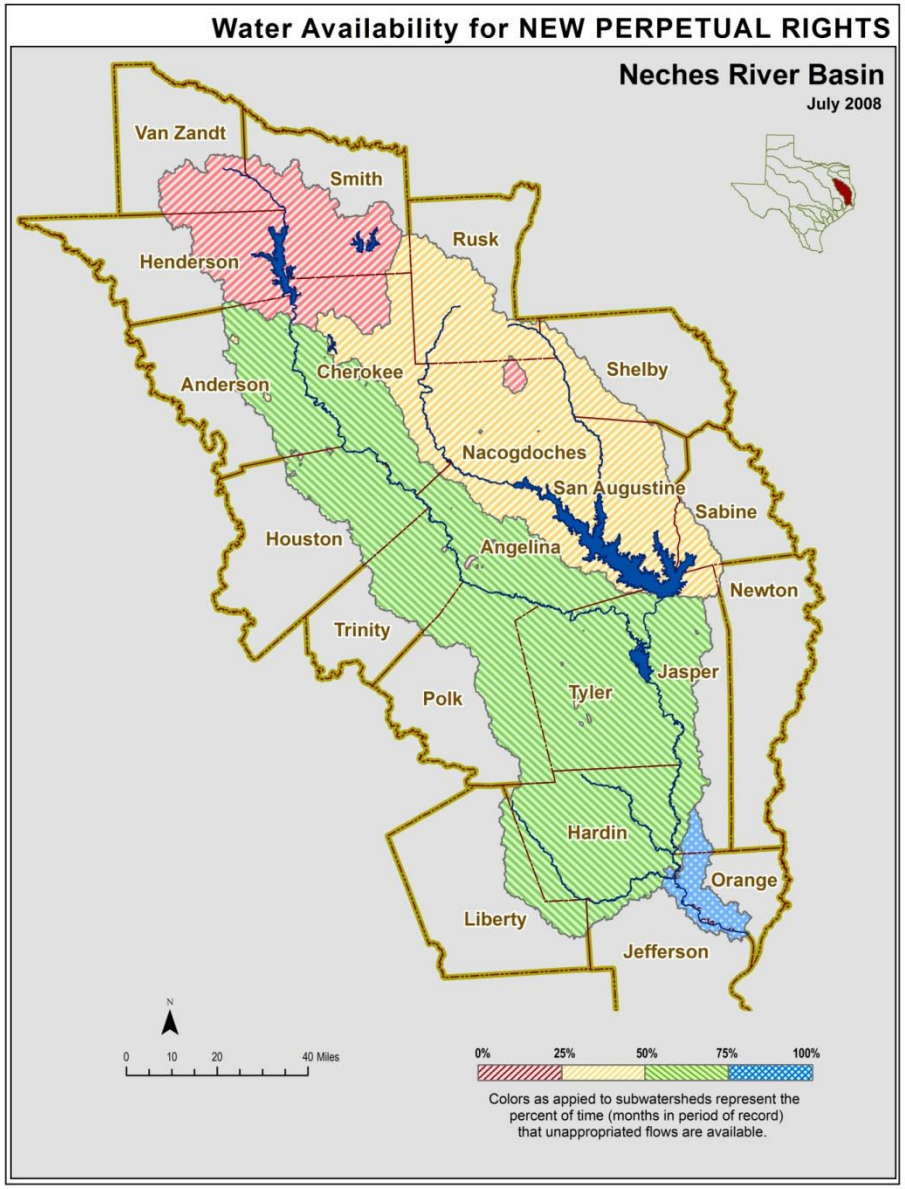
Water Availability Evaluation for New Perpetual Rights



Maps are from the Texas Commission on Environmental Quality

Figure 2: Available Water for the Neches Basin





Maps are from the Texas Commission on Environmental Quality

Table 2a: WAM Flow Statistics for the Neches Basin

(Values in Acre-Feet per Year)

Statistic	Angelina River nr Alto				Attoyac Bayou nr Chireno				Neches River at Neches			
	Naturalized Flows	Un-appropriated Flows	Run 8 Regulated Flows	Run 3 Regulated Flows	Naturalized Flows	Un-appropriated Flows	Run 8 Regulated Flows	Run 3 Regulated Flows	Naturalized Flows	Un-appropriated Flows	Run 8 Regulated Flows	Run 3 Regulated Flows
Min	126,621	0	106,431	64,280	67,212	0	64,502	64,502	118,476	11,123	53,744	46,746
25%	370,566	68,074	335,363	214,963	167,871	51,842	162,747	162,747	322,583	84,720	269,789	116,030
Median	666,113	431,973	622,809	528,888	355,927	251,013	351,045	351,045	591,632	234,188	530,742	259,730
75%	940,277	632,781	908,633	740,923	447,533	380,006	437,697	437,697	710,776	431,245	664,899	467,005
Max	1,492,728	1,270,315	1,469,446	1,296,088	703,382	663,666	691,508	691,508	1,346,137	1,047,750	1,310,436	1,081,900
Average	684,709	417,965	657,365	516,509	332,719	251,191	326,818	326,818	558,775	277,185	507,542	309,495

Statistic	Neches River nr Rockland				Neches River at Evadale				Village Creek nr Kountze			
	Naturalized Flows	Un-appropriated Flows	Run 8 Regulated Flows	Run 3 Regulated Flows	Naturalized Flows	Un-appropriated Flows	Run 8 Regulated Flows	Run 3 Regulated Flows	Naturalized Flows	Un-appropriated Flows	Run 8 Regulated Flows	Run 3 Regulated Flows
Min	311,455	81,528	257,104	195,580	996,302	194,482	785,692	1,084,438	151,549	102,786	152,115	151,446
25%	851,024	481,460	800,048	628,682	2,276,899	1,062,669	2,058,268	1,719,232	349,749	284,281	350,105	349,405
Median	1,681,037	1,324,262	1,631,033	1,398,276	4,477,779	3,161,216	4,366,359	3,745,308	548,719	500,102	549,144	548,167
75%	2,460,687	2,140,805	2,429,595	2,194,981	6,285,660	5,174,397	6,202,975	5,692,114	924,731	876,733	924,935	924,141
Max	4,164,838	3,824,706	4,138,387	3,870,954	9,462,832	8,849,035	9,586,470	9,069,560	1,564,617	1,564,482	1,565,326	1,564,482
Average	1,774,488	1,418,444	1,725,985	1,488,554	4,576,251	3,415,218	4,450,035	3,982,884	639,756	591,950	640,220	639,436

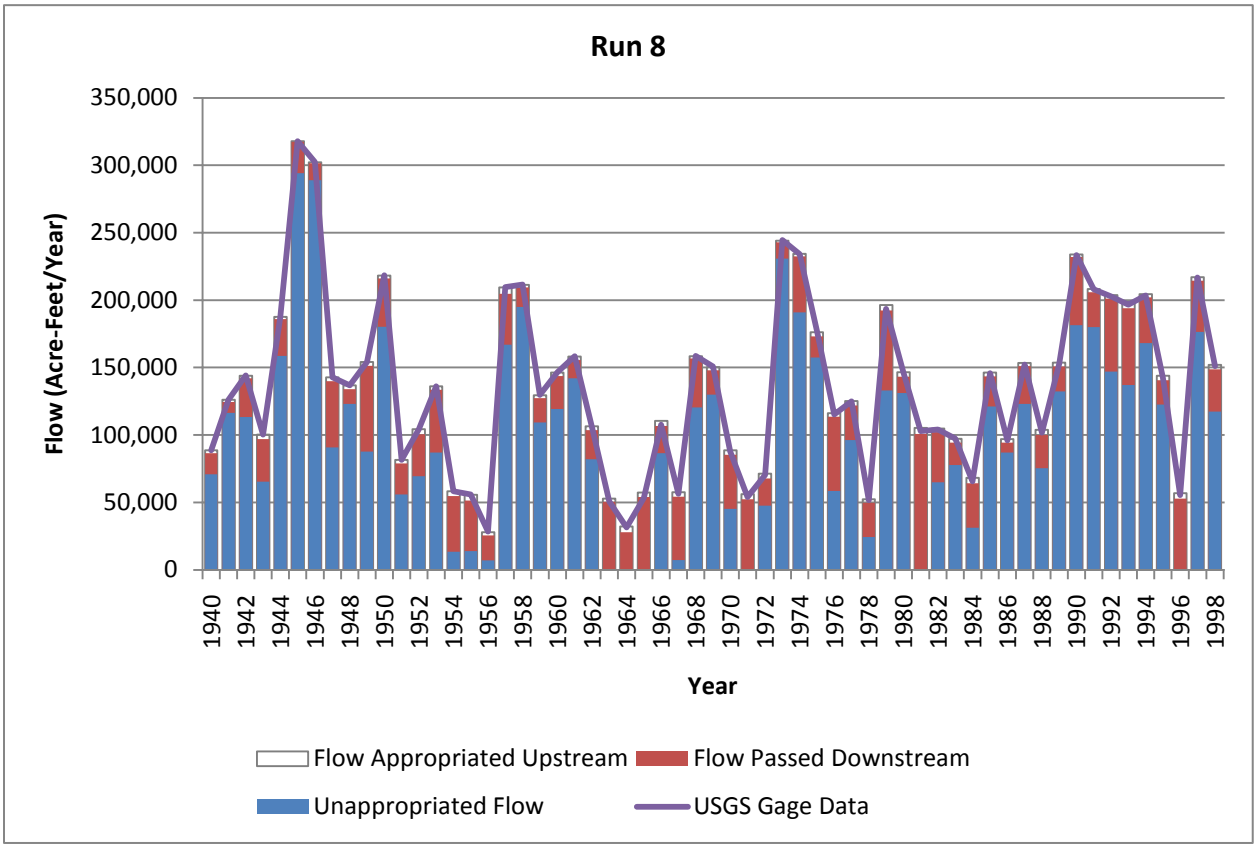
Table 2b: WAM Flow Statistics for the Sabine Basin

(Values in Acre-Feet per Year)

Statistic	Big Sandy Creek nr Big Sandy				Sabine River nr Gladewater				Sabine River nr Beckville			
	Naturalized Flows	Un-appropriated Flows	Run 8 Regulated Flows	Run 3 Regulated Flows	Naturalized Flows	Un-appropriated Flows	Run 8 Regulated Flows	Run 3 Regulated Flows	Naturalized Flows	Un-appropriated Flows	Run 8 Regulated Flows	Run 3 Regulated Flows
Min	27,990	0	25,643	24,451	220,658	0	119,617	115,407	380,029	0	257,623	207,490
25%	88,684	0	86,561	85,931	1,043,163	0	727,251	551,497	1,421,811	0	906,798	710,939
Median	136,768	66,107	133,869	133,741	1,435,302	444,622	1,222,333	920,736	1,794,569	592,561	1,595,424	1,208,779
75%	187,582	107,695	185,889	185,236	2,008,557	1,068,942	1,776,733	1,433,251	2,885,648	1,478,761	2,530,632	2,096,614
Max	317,852	279,485	317,285	316,655	3,878,064	2,587,110	3,647,580	3,314,325	4,928,299	3,093,602	4,679,228	4,233,841
Average	137,594	67,063	134,750	134,135	1,570,927	578,948	1,279,503	1,025,113	2,077,932	790,791	1,767,612	1,424,551

Statistic	Sabine River nr Bon Weir				Sabine River nr Ruliff			
	Naturalized Flows	Un-appropriated Flows	Run 8 Regulated Flows	Run 3 Regulated Flows	Naturalized Flows	Un-appropriated Flows	Run 8 Regulated Flows	Run 3 Regulated Flows
Min	1,489,739	222,549	1,356,509	304,875	2,191,564	307,367	1,852,629	851,978
25%	3,324,211	800,184	2,894,278	976,761	4,293,504	988,040	3,769,220	1,957,509
Median	5,289,135	1,677,503	4,913,793	2,576,453	6,309,082	2,007,513	6,500,623	3,740,235
75%	7,372,119	3,104,274	6,921,711	4,754,677	8,540,700	3,177,403	8,268,729	6,287,261
Max	10,367,157	5,438,457	10,323,305	8,230,689	13,051,062	5,599,088	13,008,548	10,914,689
Average	5,354,106	2,029,196	4,961,195	3,107,424	6,485,355	2,154,053	6,091,900	4,233,295

Figure 3: Comparison of Annual Flows for Big Sandy Creek near Big Sandy



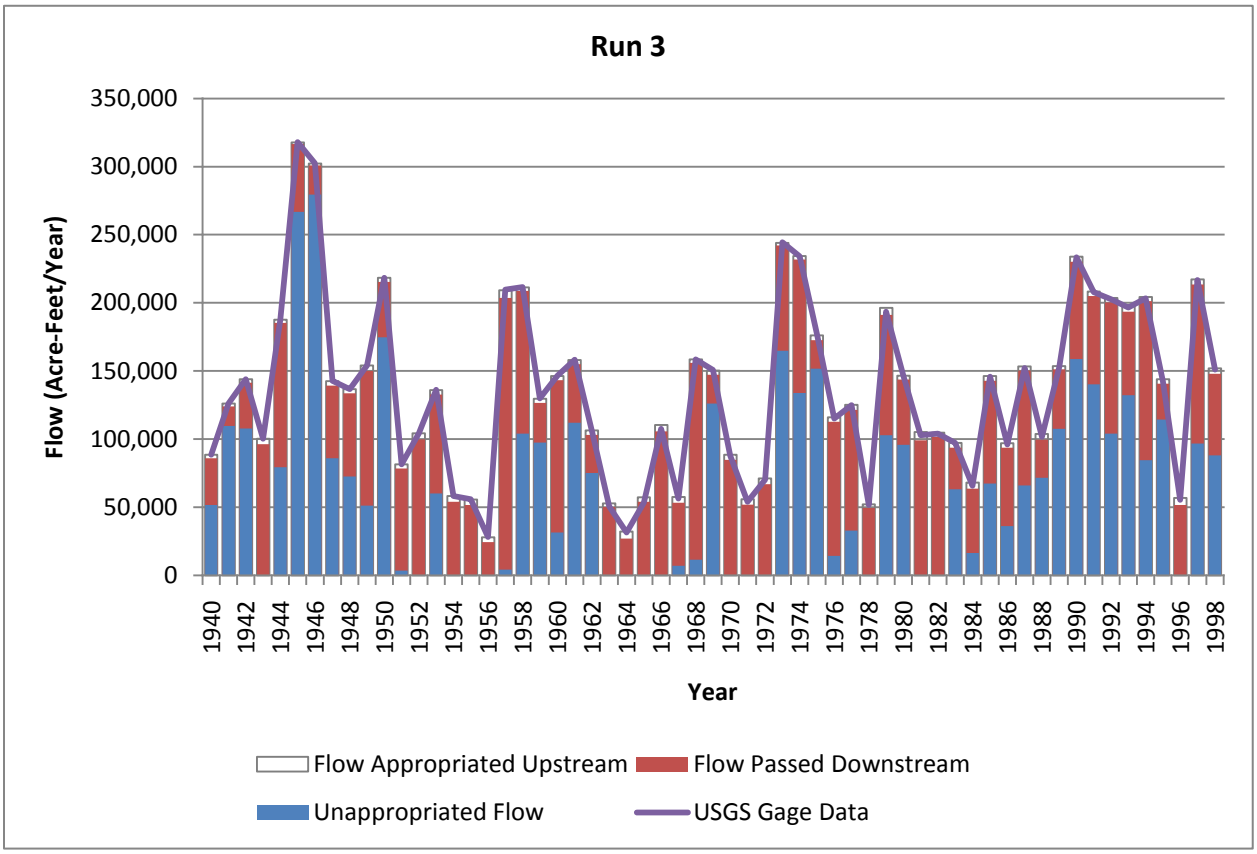
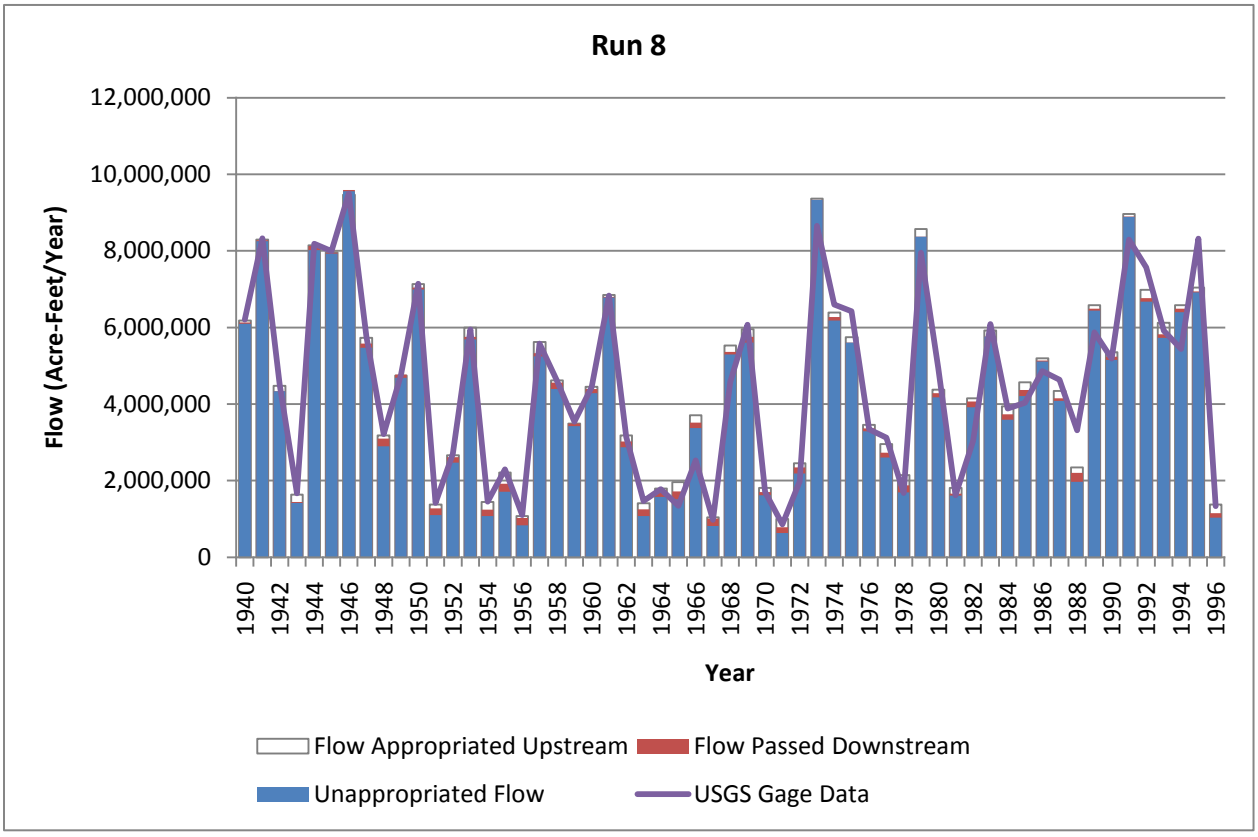
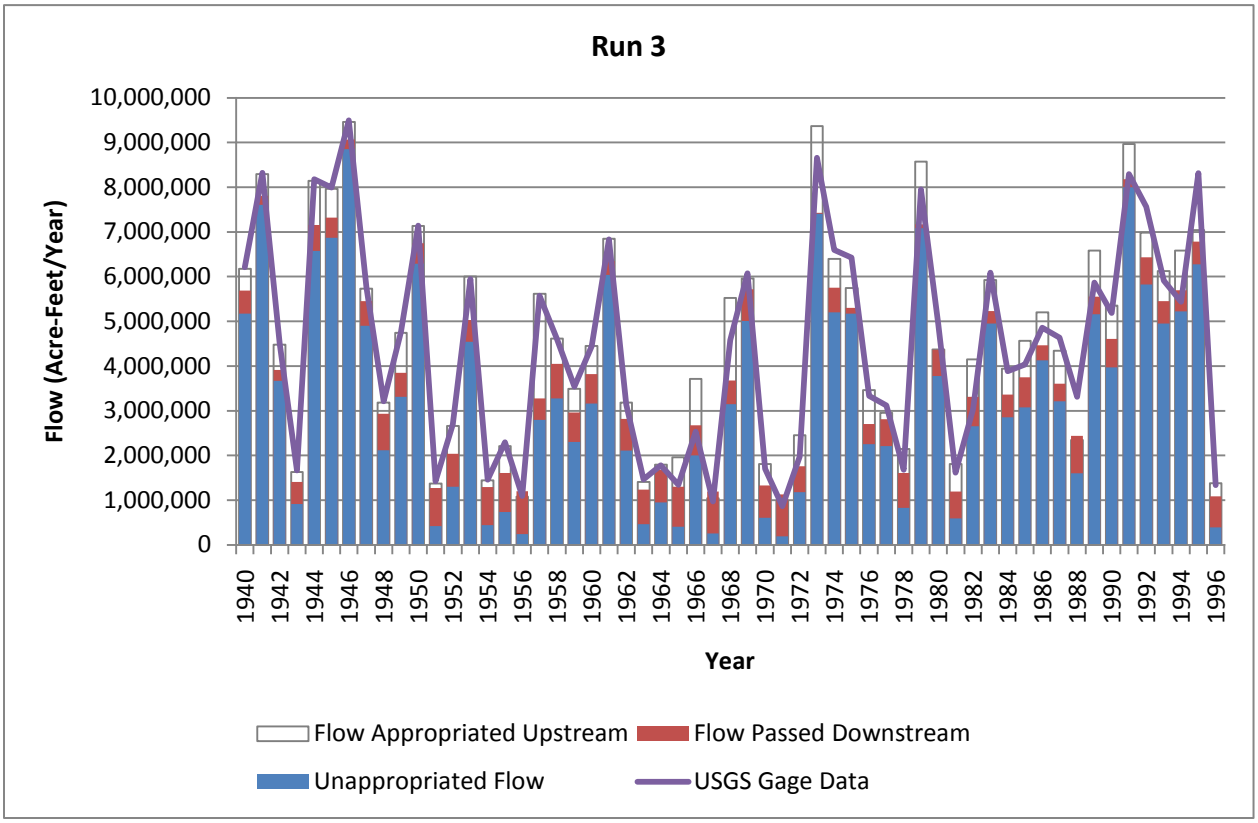


Figure 4: Comparison of Annual Flows from the Neches River at Evadale





Comparison of WAM Flows to HEFR

Table 3 compares the annual naturalized flow, Run 8 regulated flow, and Run 3 regulated flow to the annual volume from the HEFR analysis using the original percentile-based approach. (A method has not been developed at this time to translate the frequency-based approach into an annual volume.) Volumes for the HEFR were developed for a subsistence flow occurring for the entire year, for the base flows only, for base flows plus pulse flows, and for base plus pulse flows with an entire overbank event occurring some time during the year. On an annual basis, these volumes compare well. Although it is very unlikely that a subsistence flow would occur for an entire year at any of these gages, the minimum annual flows are always much greater than the annual subsistence flow. The different percentiles of the WAM flows are either very close to or greater than the equivalent HEFR volumes. Also note that most of the HEFR volume is contained in the base and overbank flows. WAM flows should be expected to have the same trend.

Although the WAM flows compare well to the HEFR results on an annual volume basis, it is unclear how well they apply on a day-to-day basis for the various components of the flow regime. In order to evaluate this situation, FNI developed daily naturalized and regulated flows at each gage and compared these flows to the HEFR results.

The monthly WAM flows were distributed to daily flows based on the historical percentage of the historical monthly totals that occurred on any given day. The chief limitation of this analysis is that the historical data have not been adjusted for modifications throughout the historical record. For example, it can be assumed that gages directly downstream of reservoirs would have fewer pulse events than before construction of the reservoir. These kinds of adjustments to the historical record are time consuming and there was not sufficient time or budget to perform this analysis for this project.

The daily naturalized and regulated flows were classified as subsistence, base, pulse and overbank using the same parameters applied to historical flows. Additional information on flow classification can be found in the Memorandum *Hydrology-Based Environmental Flow Regime (HEFR) Analyses for Sabine-Neches Bay and Basin Expert Science Team (BBEST)*.

Table 3: Comparison of Annual WAM Flows to HEFR Volumes

(Values in Acre-Feet per Year)

WAM Flows									
	Angelina River nr Alto			Attoyac Bayou nr Chireno			Neches River at Neches		
	Naturalized Flows	Run 8 Regulated Flows	Run 3 Regulated Flows	Naturalized Flows	Run 8 Regulated Flows	Run 3 Regulated Flows	Naturalized Flows	Run 8 Regulated Flows	Run 3 Regulated Flows
Min	126,621	106,431	64,280	67,212	64,502	64,502	118,476	53,744	46,746
25%	370,566	335,363	214,963	167,871	162,747	162,747	322,583	269,789	116,030
Median	666,113	622,809	528,888	355,927	351,045	351,045	591,632	530,742	259,730
75%	940,277	908,633	740,923	447,533	437,697	437,697	710,776	664,899	467,005
Max	1,492,728	1,469,446	1,296,088	703,382	691,508	691,508	1,346,137	1,310,436	1,081,900
Average	684,709	657,365	516,509	332,719	326,818	326,818	558,775	507,542	309,495
HEFR Volumes									
	Full Period	**Pre-Dam**	**Post-Dam**	**Full Period**	**40-53**	**56-84**	**Full Period**	**Pre-Dam**	**Post-Dam**
Subsistence	10,682	-	10,682	-	8,154	4,265	10,682	99,834	14,853
25th Percentile (Dry)									
Base	75,077	-	77,646	-	63,568	37,862	68,570	143,387	70,089
Base + Pulse	120,879	-	128,268	-	82,332	54,618	78,685	149,707	80,432
Base + Pulse + OB	358,969	-	356,978	-	168,282	137,561	248,096	306,960	249,466
Median (Average)									
Base	166,686	-	178,309	-	118,885	67,879	140,388	291,748	121,904
Base + Pulse	242,329	-	269,003	-	155,863	96,542	167,079	291,587	145,583
Base + Pulse + OB	473,530	-	489,603	-	238,104	177,340	328,954	427,422	310,653
75th Percentile (Wet)									
Base	311,968	-	321,147	-	179,552	123,777	291,464	568,909	259,492
Base + Pulse	406,906	-	419,219	-	220,235	149,424	308,143	533,798	281,162
Base + Pulse + OB	620,775	-	623,763	-	299,024	226,480	446,776	624,472	422,117

OB – Overbank flows

Pre-Dam conditions not available for Angelina River near Alto.

Full Period analysis not available for Attoyac near Chireno.

Table 3 (continued): Comparison of Annual WAM Flows to HEFR Volumes

(Values in Acre-Feet per Year)

WAM Flows									
	Neches River nr Rockland			Neches River at Evadale			Village Creek nr Kountze		
	Naturalized Flows	Run 8 Regulated Flows	Run 3 Regulated Flows	Naturalized Flows	Run 8 Regulated Flows	Run 3 Regulated Flows	Naturalized Flows	Run 8 Regulated Flows	Run 3 Regulated Flows
Min	311,455	257,104	195,580	996,302	785,692	1,084,438	151,549	152,115	151,446
25%	851,024	800,048	628,682	2,276,899	2,058,268	1,719,232	349,749	350,105	349,405
Median	1,681,037	1,631,033	1,398,276	4,477,779	4,366,359	3,745,308	548,719	549,144	548,167
75%	2,460,687	2,429,595	2,194,981	6,285,660	6,202,975	5,692,114	924,731	924,935	924,141
Max	4,164,838	4,138,387	3,870,954	9,462,832	9,586,470	9,069,560	1,564,617	1,565,326	1,564,482
Average	1,774,488	1,725,985	1,488,554	4,576,251	4,450,035	3,982,884	639,756	640,220	639,436
HEFR Volumes									
	Full Period	**Pre-Dam**	**Post-Dam**	**Full Period**	**Pre-Dam**	**Post-Dam**	**Full Period**	**Pre-Dam**	**Post-Dam**
Subsistence	17,912	10,317	18,841	151,049	155,281	178,485	32,588	32,056	32,770
25th Percentile (Dry)									
Base	193,147	247,857	175,762	761,351	655,885	1,698,835	91,133	83,416	110,738
Base + Pulse	259,196	301,550	243,969	854,597	827,376	1,768,576	134,148	134,581	148,181
Base + Pulse + OB	1,168,573	1,366,945	996,452	1,772,205	1,597,844	2,731,146	304,690	315,520	300,488
Median (Average)									
Base	479,679	478,579	455,488	1,642,271	1,315,486	2,115,552	151,841	133,160	184,737
Base + Pulse	642,515	673,096	626,593	1,718,694	1,456,632	2,178,038	226,355	203,045	268,446
Base + Pulse + OB	1,483,539	1,691,865	1,328,298	2,488,777	2,138,058	3,088,390	393,273	380,667	416,039
75th Percentile (Wet)									
Base	934,583	1,079,739	938,632	2,655,916	2,225,344	2,457,462	248,481	232,948	277,344
Base + Pulse	1,121,405	1,285,548	1,164,848	2,660,154	2,200,473	2,485,513	323,733	303,891	376,451
Base + Pulse + OB	1,840,294	2,196,065	1,721,926	3,352,707	2,752,701	3,333,925	484,279	476,798	517,366

OB – Overbank flows

Table 3 (continued): Comparison of Annual WAM Flows to HEFR Volumes

(Values in Acre-Feet per Year)

WAM Flows									
	Big Sandy Creek nr Big Sandy			Sabine River nr Gladewater			Sabine River nr Beckville		
	Naturalized Flows	Run 8 Regulated Flows	Run 3 Regulated Flows	Naturalized Flows	Run 8 Regulated Flows	Run 3 Regulated Flows	Naturalized Flows	Run 8 Regulated Flows	Run 3 Regulated Flows
Min	27,990	25,643	24,451	220,658	119,617	115,407	380,029	257,623	207,490
25%	88,684	86,561	85,931	1,043,163	727,251	551,497	1,421,811	906,798	710,939
Median	136,768	133,869	133,741	1,435,302	1,222,333	920,736	1,794,569	1,595,424	1,208,779
75%	187,582	185,889	185,236	2,008,557	1,776,733	1,433,251	2,885,648	2,530,632	2,096,614
Max	317,852	317,285	316,655	3,878,064	3,647,580	3,314,325	4,928,299	4,679,228	4,233,841
Average	137,594	134,750	134,135	1,570,927	1,279,503	1,025,113	2,077,932	1,767,612	1,424,551
HEFR Volumes									
	Full Period	**Pre-Dam**	**Post-Dam**	**Full Period**	**Pre-Dam**	**Post-Dam**	**Full Period**	**Pre-Dam**	**Post-Dam**
Subsistence	5,913	6,626	5,667	13,570	13,387	15,212	17,187	15,389	18,648
25th Percentile (Dry)									
Base	23,350	26,916	23,248	86,188	99,959	85,716	143,222	163,716	152,984
Base + Pulse	29,028	35,623	28,969	124,070	168,593	132,234	182,532	273,768	180,822
Base + Pulse + OB	60,384	67,463	60,448	667,950	611,905	708,095	936,576	1,081,789	874,409
Median (Average)									
Base	38,044	44,636	39,470	163,170	172,738	181,613	278,618	298,785	310,944
Base + Pulse	51,625	57,698	52,279	310,988	337,797	330,216	453,736	524,558	458,594
Base + Pulse + OB	82,043	87,960	82,716	842,159	771,937	886,435	1,183,322	1,311,533	1,119,537
75th Percentile (Wet)									
Base	65,382	70,499	65,562	326,156	312,973	390,654	597,642	609,769	674,133
Base + Pulse	77,386	84,522	77,125	473,198	516,900	580,100	790,848	804,740	940,313
Base + Pulse + OB	105,126	112,566	105,271	974,889	931,601	1,085,207	1,459,230	1,543,588	1,522,636

OB – Overbank flows

Table 3 (continued): Comparison of Annual WAM Flows to HEFR Volumes

(Values in Acre-Feet per Year)

WAM Flows						
	Sabine River nr Bon Weir			Sabine River nr Ruliff		
	Naturalized Flows	Run 8 Regulated Flows	Run 3 Regulated Flows	Naturalized Flows	Run 8 Regulated Flows	Run 3 Regulated Flows
Min	1,489,739	1,356,509	304,875	2,191,564	1,852,629	851,978
25%	3,324,211	2,894,278	976,761	4,293,504	3,769,220	1,957,509
Median	5,289,135	4,913,793	2,576,453	6,309,082	6,500,623	3,740,235
75%	7,372,119	6,921,711	4,754,677	8,540,700	8,268,729	6,287,261
Max	10,367,157	10,323,305	8,230,689	13,051,062	13,008,548	10,914,689
Average	5,354,106	4,961,195	3,107,424	6,485,355	6,091,900	4,233,295
HEFR Volumes						
	Full Period	**Pre-Dam**	**Post-Dam**	**Full Period**	**Pre-Dam**	**Post-Dam**
Subsistence	187,029	168,375	n/a	294,962	255,455	307,979
25th Percentile (Dry)						
Base	590,509	764,682	578,253	746,578	1,063,841	795,492
Base + Pulse	841,950	1,148,470	950,669	851,197	1,110,982	958,603
Base + Pulse + OB	1,740,069	2,046,998	1,851,412	1,947,270	1,945,893	2,202,764
Median (Average)						
Base	1,570,117	1,455,906	2,341,011	1,119,207	1,395,233	1,067,216
Base + Pulse	1,775,762	1,895,408	2,255,081	1,346,591	1,570,001	1,290,892
Base + Pulse + OB	2,636,031	2,681,562	3,135,757	2,387,298	2,328,858	2,499,638
75th Percentile (Wet)						
Base	4,370,534	3,326,154	5,139,736	1,970,976	2,242,123	1,956,560
Base + Pulse	4,468,246	3,418,442	4,849,241	2,159,570	2,410,043	2,200,961
Base + Pulse + OB	5,065,953	3,965,246	5,382,544	3,083,420	3,021,982	3,331,796

OB – Overbank flows

Subsistence flows do not occur in the Post-Dam period at the Sabine River near Bon Wier gage

In order to apply the HEFR results, there needs to be some sort of mechanism for identifying when the 25th Percentile (Dry), Median (Average), and 75th Percentile (Wet) apply. (Subsistence criteria can be assumed to apply at all times, and overbank criteria are not subject to seasonal conditions.) Three different methods were developed to classify historical seasons as being wet, average, or dry. The first method is based on historical Palmer Drought Severity Indices from the National Oceanic and Atmospheric Administration[1], which are available for a geographic area that covers most of the Sabine and Neches basins. The indices were classified so that for each season, 25% of the conditions were considered to be dry and 25 percent of the conditions were considered to be wet, with the rest classified as average. The second method classifies each season as wet, average, or dry based on seasonal flow totals at each BBEST gage. The classifications were adjusted so that, for each season, 25 percent of the historical conditions are dry and 25 percent of the historical conditions are wet, with the rest classified as average. The third method uses total reservoir storage from WAM Run 3 to classify the seasons. The seasons with the lowest storage are considered to be dry and the seasons with the highest storage are considered to be wet. Like the other methods, the distribution of conditions within each season was adjusted so that 25% of the conditions were wet, 25% were dry, and the rest were average. Table 4 compares the three methods. A more detailed description of the methods may be found in Attachment B.

Looking at Table 4 shows that, although the three methods agree for most seasons, there are occasional discrepancies in some. For example, the spring of 1966 is classified as being wet, average, and dry by the different methods. This particular discrepancy is likely a result of the degree climatic persistence inherent in each method used for classification. More specifically, flow responds rapidly to rainfall, the Palmer Index includes measures of cumulative rainfall sometimes preceding the period of interest, and reservoir storage may need extended periods of average flow and rainfall to return to levels typical of wet conditions.

For the WAM analyses presented herein, the WAM storage method was used. Because the values are computed for both basins, the period is limited to the years 1940 to 1996, the period covered by the Neches WAM. Other methods would probably give different results.

[1] U.S. Climate Division Temperature, Precipitation and Palmer Drought Severity Index, National Oceanic and Atmospheric Administration Earth System Research Laboratory, available on-line at http://www.cdc.noaa.gov/data/timeseries/

Tables 5 through 9 compare the percentage of time that the HEFR results are met by WAM naturalized flows, Run 8 regulated flows, and Run 3 regulated flows. The comparison of the WAM flows to the HEFR matrix for the full historical record of the gage is labeled "Full Period HEFR Matrix". The comparison to the HEFR matrix for the period from 1940 to 1960 is labeled "Pre-Dam HEFR Matrix", and the comparison to the HEFR matrix for the period from 1971 to 2008 is labeled "Post-Dam HEFR Matrix".

The percentages in Tables 5 through 7, which apply to the original percentile based approach, were calculated using the following assumptions:

- Only the criteria for the season's climatic classification apply. For example, if a season is classified as "wet", only the wet base flow and pulse flow criteria apply.
- A pulse event is counted only if it meets or exceeds the peak flow, volume and duration criteria recommendation for that particular season and climate classification. A pulse that meets or exceeds these criteria is called a "qualifying pulse".
- An overbank event is counted only if it exceeds peak, volume and duration criteria.
- A season is counted only if it has the required number of qualifying pulses during the season.
- Base flow criteria only apply during days that are classified as base flows. Flow during pulse or overbank days is not counted as meeting base flow criteria even if it is a non-qualifying event.

The percentage for the base flows in Table 5 was calculated by dividing the number of days that equaled or exceeded the criteria by the total number of base flow days for each season and climatic classification (for example Spring Wet, Spring Average, Spring Dry, Summer Wet, etc.). The percentage for pulse flows in Table 6 was calculated by dividing the number of seasons that met the frequency criteria for qualifying pulses by the total number of seasons in each season and climatic classification. The percentage of overbank events in Table 9 was calculated by dividing the number of qualifying overbank events by the total number of overbank events. The frequency in Table 9 is simply the number of qualifying overbank events divided by the 57 years in the simulation. The return period is the inverse of the frequency.

For the frequency-based criteria percentages are calculated somewhat differently. In Tables 8 and 9 the percentage of pulses meeting criteria is the number of pulses that meet peak criteria

Table 4: Comparison of Wet, Average and Dry Seasons

Year	Winter			Spring			Summer			Fall		
	Flow	Palmer Index	WAM Storage	Flow	Palmer Index	WAM Storage	Flow	Palmer Index	WAM Storage	Flow	Palmer Index	WAM Storage
1940	dry	dry	wet	average	average	average	average	average	wet	wet	wet	wet
1941	wet	wet	wet	wet	wet	wet	wet	wet	wet	wet	wet	wet
1942	average	average	average	wet	wet	wet	wet	wet	wet	average	average	wet
1943	average	dry	average	average	dry	average	average	dry	average	average	dry	average
1944	average	average	average	wet	average	wet	average	average	average	average	average	average
1945	wet	wet	wet	wet	wet	wet	wet	wet	wet	average	wet	wet
1946	wet	wet	wet	wet	wet	wet	wet	wet	wet	wet	wet	wet
1947	wet	wet	wet	average	average	wet	average	average	average	average	dry	average
1948	average	average	average	average	average	wet	dry	dry	average	dry	dry	average
1949	average	average	average	average	average	average	average	average	average	wet	average	wet
1950	wet	average	wet	wet	average	wet	average	average	wet	dry	dry	average
1951	average	dry	average	dry	dry	average	dry	dry	average	dry	dry	average
1952	dry	dry	dry	average	dry	average	dry	dry	average	dry	average	dry
1953	average	average	average	wet	average	average	average	average	average	average	average	average
1954	dry	dry	average	average	dry	dry	dry	dry	dry	average	average	dry
1955	average	average	dry	average	average	dry	dry	average	dry	dry	dry	dry
1956	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
1957	dry	dry	dry	wet	wet	dry	average	wet	average	wet	wet	average
1958	average	wet	average	average	wet	average	wet	wet	wet	average	average	wet
1959	average	average	average	average	average	average	average	average	average	average	average	average
1960	average	average	average	dry	average	average	average	average	average	wet	average	average
1961	wet	wet	wet	average	average	average	wet	wet	wet	average	wet	wet
1962	average	average	wet	average	average	average	average	average	average	average	average	average
1963	dry	dry	average	dry	dry	dry	dry	dry	dry	dry	dry	dry
1964	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
1965	dry	dry	dry	average	dry	dry	dry	dry	dry	dry	dry	dry
1966	dry	average	dry	wet	average	dry	average	average	dry	dry	average	dry
1967	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry	average	dry
1968	average	average	dry	wet	average	average	average	wet	wet	average	wet	wet
1969	average	wet	average	wet	wet	average	dry	average	average	dry	dry	average
1970	average	average	average	average	average	average	dry	average	average	average	average	average
1971	dry	dry	dry	dry	dry	dry	dry	dry	dry	average	dry	dry
1972	average	average	dry	dry	average	dry	dry	average	dry	average	average	dry
1973	wet	average	average	wet	wet	average	wet	wet	wet	wet	wet	wet
1974	wet	wet	wet	average	wet	wet	wet	wet	average	wet	wet	wet
1975	wet	wet	wet	average	wet	wet	wet	average	wet	average	average	average
1976	dry	average	average	average	average	average	wet	wet	average	average	wet	average
1977	average	average	average	average	average	average	average	average	average	average	dry	average
1978	average	dry	average	dry	dry	average	dry	dry	dry	dry	average	dry
1979	average	average	average	wet	wet	average	wet	wet	average	average	average	average
1980	average	average	average	average	average	average	dry	average	average	dry	dry	average
1981	dry	dry	dry	average	average	dry	average	average	dry	average	average	dry
1982	dry	average	dry	average	average	dry	average	average	dry	average	average	average
1983	wet	average	average	average	average	average	average	average	average	average	average	average
1984	average	average	average	dry	average	average	average	average	average	average	average	average
1985	average	average	average	average	average	average	dry	average	average	wet	average	average
1986	average	average	average	average	average	average	average	average	average	wet	average	wet
1987	average	average	average	average	average	average	average	average	average	average	average	average
1988	average	average	average	dry	dry	average	average	dry	average	average	average	average
1989	average	average	average	wet	average	average	wet	average	wet	dry	dry	average
1990	average	average	average	wet	average	wet	average	average	average	average	average	average
1991	wet	wet	wet	wet	wet	average	wet	wet	wet	wet	wet	wet
1992	wet	wet	wet	average	wet	wet	wet	wet	average	average	wet	average
1993	average	wet	wet	average	wet	wet	average	average	average	average	average	average
1994	average	average	average	average	average	average	average	average	wet	wet	wet	wet
1995	wet	wet	wet	wet	wet	wet	average	average	average	average	average	average
1996	dry	dry	dry	dry	dry	dry	average	average	dry	average	average	dry
1997	wet	wet	No Data	average	wet	No Data	average	wet	No Data	average	wet	No Data
1998	wet	wet		dry	dry		average	dry		wet	wet	
1999	wet	average		average	average		average	average		dry	dry	
2000	dry	dry		dry	dry		average	dry		average	average	
2001	wet	wet		average	wet		wet	wet		wet	wet	
2002	average	wet		average	average		average	average		wet	wet	
2003	average	average		dry	dry		average	average		average	average	
2004	average	average		average	average		wet	average		wet	average	
2005	average	average		dry	average		average	dry		dry	dry	
2006	dry	dry		dry	dry		average	dry		wet	average	
2007	average	average		average	average		wet	wet		average	average	
2008	average	average		average	average		average	average		average	average	

Table 5a: Percent of Time Meeting HEFR Base Flow Criteria - WAM Naturalized Flows from 1940 to 1996

Basin	USGS Gage Name	USGS Gage Number	Flow Condition	Full Period HEFR Matrix					Pre-Dam HEFR Matrix					Post-Dam HEFR Matrix				
				Winter	Spring	Summer	Fall	*Total*	Winter	Spring	Summer	Fall	*Total*	Winter	Spring	Summer	Fall	*Total*
Sabine	Big Sandy Creek nr Big Sandy	8019500	Dry (25th Percentile)	34%	49%	26%	45%	*36%*	28%	39%	13%	38%	*27%*	28%	53%	34%	49%	*40%*
			Average (Median)	58%	59%	45%	58%	*53%*	55%	43%	33%	52%	*45%*	53%	59%	54%	58%	*55%*
			Wet (75th Percentile)	68%	55%	60%	50%	*58%*	66%	47%	46%	49%	*51%*	65%	58%	60%	50%	*58%*
			Total	*54%*	*55%*	*42%*	*52%*	*49%*	*50%*	*43%*	*29%*	*47%*	*41%*	*49%*	*57%*	*48%*	*53%*	*51%*
Sabine	Sabine River nr Gladewater	8020000	Dry (25th Percentile)	67%	80%	36%	39%	*48%*	68%	57%	34%	41%	*45%*	70%	84%	34%	29%	*45%*
			Average (Median)	68%	74%	41%	55%	*55%*	78%	70%	38%	45%	*53%*	59%	71%	38%	54%	*51%*
			Wet (75th Percentile)	70%	59%	68%	71%	*67%*	78%	64%	66%	63%	*67%*	60%	41%	58%	73%	*59%*
			Total	*68%*	*72%*	*43%*	*53%*	*55%*	*75%*	*65%*	*41%*	*47%*	*53%*	*62%*	*67%*	*40%*	*49%*	*51%*
Sabine	Sabine River nr Beckville	8022040	Dry (25th Percentile)	74%	71%	38%	50%	*53%*	71%	55%	28%	51%	*47%*	45%	76%	36%	37%	*43%*
			Average (Median)	68%	70%	52%	53%	*58%*	71%	63%	37%	47%	*51%*	57%	64%	49%	53%	*54%*
			Wet (75th Percentile)	72%	58%	72%	68%	*68%*	72%	61%	60%	65%	*65%*	62%	50%	72%	67%	*64%*
			Total	*70%*	*67%*	*49%*	*55%*	*58%*	*71%*	*60%*	*37%*	*52%*	*52%*	*55%*	*64%*	*47%*	*51%*	*52%*
Sabine	Sabine River nr Bon Weir	8028500	Dry (25th Percentile)	49%	65%	31%	44%	*42%*	36%	33%	36%	46%	*39%*	59%	71%	**5%**	38%	*32%*
			Average (Median)	57%	71%	13%	39%	*36%*	65%	40%	18%	36%	*35%*	39%	81%	**7%**	35%	*30%*
			Wet (75th Percentile)	21%	43%	59%	71%	*50%*	73%	41%	63%	68%	*63%*	15%	34%	21%	68%	*34%*
			Total	*46%*	*63%*	*26%*	*46%*	*40%*	*59%*	*38%*	*30%*	*44%*	*41%*	*38%*	*67%*	**8%**	*41%*	*31%*
Sabine	Sabine River nr Ruliff	8030500	Dry (25th Percentile)	80%	73%	43%	37%	*49%*	50%	35%	41%	31%	*39%*	82%	75%	**7%**	28%	*31%*
			Average (Median)	75%	73%	29%	42%	*43%*	64%	40%	19%	38%	*33%*	96%	81%	**6%**	32%	*33%*
			Wet (75th Percentile)	59%	85%	69%	86%	*76%*	63%	59%	59%	66%	*62%*	63%	95%	**5%**	83%	*54%*
			Total	*75%*	*76%*	*39%*	*47%*	*50%*	*58%*	*43%*	*32%*	*40%*	*39%*	*86%*	*82%*	**6%**	*38%*	*35%*
Neches	Village Creek nr Kountze	8041500	Dry (25th Percentile)	46%	44%	31%	32%	*36%*	59%	46%	31%	33%	*39%*	22%	41%	19%	27%	*26%*
			Average (Median)	56%	60%	48%	44%	*50%*	70%	62%	45%	51%	*54%*	41%	49%	38%	31%	*38%*
			Wet (75th Percentile)	66%	49%	68%	48%	*57%*	67%	62%	63%	54%	*61%*	56%	39%	62%	37%	*48%*
			Total	*54%*	*52%*	*46%*	*41%*	*47%*	*66%*	*57%*	*43%*	*46%*	*51%*	*38%*	*44%*	*36%*	*31%*	*36%*
Neches	Neches River at Evadale	8041000	Dry (25th Percentile)	41%	32%	**8%**	21%	*20%*	40%	33%	15%	32%	*26%*	42%	12%	**0%**	**2%**	**8%**
			Average (Median)	75%	40%	**2%**	28%	*25%*	79%	48%	31%	50%	*46%*	76%	34%	**0%**	14%	*19%*
			Wet (75th Percentile)	70%	72%	**7%**	30%	*33%*	66%	59%	47%	71%	*59%*	78%	71%	**6%**	24%	*31%*
			Total	*61%*	*44%*	**5%**	*26%*	*25%*	*62%*	*46%*	*27%*	*47%*	*41%*	*62%*	*36%*	**1%**	*11%*	*17%*
Neches	Attoyac Bayou nr Chireno	8038000	Dry (25th Percentile)						13%	24%	11%	32%	*20%*	48%	50%	25%	33%	*35%*
			Average (Median)						30%	25%	29%	38%	*31%*	67%	60%	60%	48%	*58%*
			Wet (75th Percentile)						42%	30%	57%	55%	*48%*	76%	75%	85%	63%	*74%*
			Total						*27%*	*26%*	*26%*	*40%*	*31%*	*63%*	*60%*	*50%*	*46%*	*53%*
Neches	Angelina River nr Alto	8036500	Dry (25th Percentile)	35%	56%	22%	35%	*32%*						33%	56%	20%	34%	*31%*
			Average (Median)	58%	54%	21%	57%	*43%*						55%	51%	20%	53%	*41%*
			Wet (75th Percentile)	81%	43%	73%	61%	*66%*						83%	43%	71%	57%	*66%*
			Total	*55%*	*53%*	*26%*	*49%*	*42%*						*53%*	*51%*	*24%*	*46%*	*40%*
Neches	Neches River near Rockland	8033500	Dry (25th Percentile)	37%	50%	33%	35%	*36%*	41%	25%	29%	38%	*34%*	54%	52%	17%	29%	*31%*
			Average (Median)	54%	56%	38%	46%	*47%*	64%	48%	32%	39%	*43%*	55%	66%	32%	39%	*44%*
			Wet (75th Percentile)	70%	55%	77%	63%	*66%*	52%	45%	60%	51%	*52%*	78%	52%	49%	54%	*57%*
			Total	*52%*	*55%*	*41%*	*46%*	*46%*	*55%*	*42%*	*34%*	*41%*	*42%*	*59%*	*60%*	*28%*	*38%*	*42%*
Neches	Neches River at Neches	8032000	Dry (25th Percentile)	78%	56%	**9%**	36%	*37%*	58%	43%	21%	47%	*38%*	79%	60%	**2%**	34%	*35%*
			Average (Median)	66%	63%	19%	54%	*44%*	62%	54%	39%	45%	*47%*	73%	76%	18%	54%	*47%*
			Wet (75th Percentile)	72%	56%	25%	68%	*52%*	75%	56%	60%	51%	*60%*	83%	61%	23%	75%	*57%*
			Total	*71%*	*59%*	*17%*	*51%*	*43%*	*63%*	*51%*	*36%*	*47%*	*47%*	*77%*	*68%*	*14%*	*52%*	*45%*

Table 5b: Percent of Time Meeting HEFR Base Flow Criteria - WAM Run 8 Regulated Flows from 1940 to 1996

Basin	USGS Gage Name	USGS Gage Number	Flow Condition	Full Period HEFR Matrix					Pre-Dam HEFR Matrix					Post-Dam HEFR Matrix				
				Winter	Spring	Summer	Fall	*Total*	Winter	Spring	Summer	Fall	*Total*	Winter	Spring	Summer	Fall	*Total*
Sabine	Big Sandy Creek nr Big Sandy	8019500	Dry (25th Percentile)	30%	41%	23%	36%	*31%*	25%	26%	**10%**	28%	*20%*	26%	46%	29%	39%	*34%*
			Average (Median)	58%	57%	30%	50%	*45%*	54%	42%	18%	46%	*37%*	52%	57%	42%	50%	*49%*
			Wet (75ty Percentile)	66%	55%	39%	52%	*51%*	64%	48%	30%	50%	*46%*	63%	59%	39%	52%	*51%*
			Total	*51%*	*52%*	*29%*	*46%*	*42%*	*48%*	*38%*	*18%*	*41%*	*34%*	*47%*	*54%*	*37%*	*47%*	*44%*
Sabine	Sabine River nr Gladewater	8020000	Dry (25th Percentile)	21%	44%	25%	21%	*26%*	22%	17%	22%	22%	*21%*	24%	47%	22%	14%	*23%*
			Average (Median)	48%	52%	18%	33%	*31%*	52%	47%	15%	26%	*28%*	45%	47%	15%	33%	*29%*
			Wet (75ty Percentile)	57%	51%	25%	51%	*42%*	61%	54%	21%	48%	*41%*	52%	41%	13%	51%	*35%*
			Total	*41%*	*49%*	*21%*	*31%*	*31%*	*44%*	*38%*	*18%*	*27%*	*28%*	*40%*	*46%*	*17%*	*29%*	*28%*
Sabine	Sabine River nr Beckville	8022040	Dry (25th Percentile)	21%	42%	36%	35%	*34%*	18%	22%	26%	36%	*27%*	12%	50%	35%	20%	*28%*
			Average (Median)	51%	46%	35%	44%	*42%*	54%	41%	18%	34%	*32%*	46%	42%	33%	44%	*40%*
			Wet (75ty Percentile)	61%	53%	40%	56%	*52%*	61%	54%	31%	51%	*48%*	56%	48%	38%	54%	*49%*
			Total	*44%*	*46%*	*36%*	*43%*	*41%*	*44%*	*38%*	*22%*	*38%*	*33%*	*37%*	*46%*	*34%*	*37%*	*37%*
Sabine	Sabine River nr Bon Weir	8028500	Dry (25th Percentile)	**5%**	18%	98%	25%	*29%*	**4%**	**9%**	99%	25%	*27%*	**6%**	20%	93%	22%	*28%*
			Average (Median)	43%	42%	84%	24%	*41%*	50%	29%	86%	22%	*40%*	28%	51%	75%	21%	*36%*
			Wet (75ty Percentile)	18%	43%	84%	54%	*50%*	70%	43%	86%	54%	*64%*	11%	40%	48%	54%	*39%*
			Total	*25%*	*31%*	*88%*	*28%*	*39%*	*37%*	*22%*	*90%*	*27%*	*40%*	*17%*	*34%*	*74%*	*25%*	*34%*
Sabine	Sabine River nr Ruliff	8030500	Dry (25th Percentile)	20%	21%	100%	31%	*39%*	**8%**	**7%**	100%	25%	*31%*	26%	22%	92%	21%	*35%*
			Average (Median)	48%	53%	93%	24%	*47%*	46%	34%	92%	23%	*44%*	61%	59%	80%	21%	*45%*
			Wet (75ty Percentile)	62%	83%	97%	56%	*75%*	65%	49%	95%	55%	*68%*	65%	86%	35%	56%	*56%*
			Total	*37%*	*42%*	*96%*	*31%*	*49%*	*31%*	*23%*	*95%*	*28%*	*43%*	*45%*	*45%*	*73%*	*26%*	*43%*
Neches	Village Creek nr Kountze	8041500	Dry (25th Percentile)	47%	44%	32%	32%	*37%*	59%	46%	32%	34%	*40%*	22%	41%	20%	27%	*26%*
			Average (Median)	56%	60%	49%	45%	*50%*	70%	63%	46%	51%	*55%*	41%	49%	38%	31%	*38%*
			Wet (75ty Percentile)	66%	49%	68%	48%	*57%*	68%	62%	65%	55%	*62%*	56%	39%	63%	37%	*48%*
			Total	*55%*	*52%*	*47%*	*42%*	*47%*	*66%*	*57%*	*45%*	*47%*	*51%*	*38%*	*44%*	*36%*	*31%*	*36%*
Neches	Neches River at Evadale	8041000	Dry (25th Percentile)	29%	27%	15%	15%	*18%*	27%	29%	43%	19%	*28%*	29%	11%	**0%**	**1%**	**6%**
			Average (Median)	73%	31%	**1%**	16%	*19%*	75%	41%	28%	28%	*35%*	74%	28%	**0%**	**7%**	*15%*
			Wet (75ty Percentile)	68%	75%	**6%**	31%	*35%*	68%	62%	31%	50%	*48%*	79%	74%	**6%**	28%	*34%*
			Total	*54%*	*39%*	**6%**	*17%*	*21%*	*55%*	*42%*	*33%*	*27%*	*35%*	*56%*	*34%*	**1%**	**7%**	*15%*
Neches	Attoyac Bayou nr Chireno	8038000	Dry (25th Percentile)						13%	23%	10%	32%	*19%*	41%	47%	24%	33%	*33%*
			Average (Median)						30%	25%	27%	36%	*30%*	66%	59%	59%	46%	*56%*
			Wet (75ty Percentile)						41%	30%	56%	54%	*48%*	76%	75%	84%	63%	*73%*
			Total						*27%*	*25%*	*25%*	*39%*	*30%*	*60%*	*59%*	*49%*	*45%*	*51%*
Neches	Angelina River nr Alto	8036500	Dry (25th Percentile)	24%	50%	32%	34%	*34%*						22%	49%	28%	32%	*31%*
			Average (Median)	56%	52%	25%	54%	*44%*						49%	49%	21%	47%	*39%*
			Wet (75ty Percentile)	76%	44%	69%	59%	*64%*						81%	44%	66%	57%	*64%*
			Total	*50%*	*50%*	*32%*	*47%*	*43%*						*47%*	*48%*	*29%*	*43%*	*39%*
Neches	Neches River near Rockland	8033500	Dry (25th Percentile)	28%	42%	29%	27%	*29%*	32%	21%	25%	33%	*28%*	39%	43%	13%	14%	*21%*
			Average (Median)	55%	58%	30%	34%	*40%*	64%	48%	24%	28%	*36%*	56%	68%	23%	28%	*37%*
			Wet (75ty Percentile)	67%	54%	57%	61%	*60%*	49%	44%	46%	51%	*48%*	75%	52%	36%	53%	*53%*
			Total	*49%*	*53%*	*32%*	*36%*	*40%*	*51%*	*41%*	*26%*	*34%*	*35%*	*54%*	*58%*	*21%*	*28%*	*34%*
Neches	Neches River at Neches	8032000	Dry (25th Percentile)	36%	25%	**2%**	13%	*15%*	29%	18%	**6%**	21%	*16%*	20%	**9%**	15%	**9%**	*13%*
			Average (Median)	61%	47%	**10%**	23%	*27%*	77%	51%	19%	41%	*39%*	32%	20%	14%	13%	*18%*
			Wet (75ty Percentile)	69%	45%	10%	49%	*36%*	75%	62%	31%	65%	*52%*	**5%**	**5%**	**7%**	28%	*12%*
			Total	*54%*	*39%*	**7%**	*24%*	*24%*	*61%*	*42%*	*17%*	*38%*	*34%*	*23%*	*13%*	*13%*	*14%*	*15%*

Table 5c: Percent of Time Meeting HEFR Base Flow Criteria - WAM Regulated Run 3 Flows from 1940 to 1996

Basin	USGS Gage Name	USGS Gage Number	Flow Condition	Full Period HEFR Matrix					Pre-Dam HEFR Matrix					Post-Dam HEFR Matrix				
				Winter	Spring	Summer	Fall	*Total*	Winter	Spring	Summer	Fall	*Total*	Winter	Spring	Summer	Fall	*Total*
Sabine	Big Sandy Creek nr Big Sandy	8019500	Dry (25th Percentile)	27%	41%	24%	34%	*30%*	23%	25%	**9%**	28%	*19%*	24%	46%	31%	38%	*34%*
			Average (Median)	57%	56%	38%	51%	*48%*	54%	40%	21%	47%	*38%*	52%	56%	49%	51%	*51%*
			Wet (75ty Percentile)	65%	54%	48%	51%	*54%*	64%	47%	36%	48%	*48%*	63%	58%	48%	50%	*54%*
			Total	*50%*	*51%*	*35%*	*46%*	*44%*	*47%*	*37%*	*20%*	*42%*	*34%*	*46%*	*53%*	*43%*	*47%*	*46%*
Sabine	Sabine River nr Gladewater	8020000	Dry (25th Percentile)	19%	38%	22%	21%	*23%*	19%	16%	20%	23%	*20%*	21%	42%	20%	13%	*21%*
			Average (Median)	44%	36%	18%	31%	*28%*	48%	32%	14%	23%	*24%*	36%	33%	14%	31%	*25%*
			Wet (75ty Percentile)	47%	41%	22%	34%	*33%*	48%	45%	17%	31%	*31%*	45%	39%	11%	35%	*28%*
			Total	*36%*	*38%*	*20%*	*28%*	*27%*	*39%*	*29%*	*16%*	*24%*	*24%*	*33%*	*37%*	*15%*	*25%*	*24%*
Sabine	Sabine River nr Beckville	8022040	Dry (25th Percentile)	12%	21%	27%	24%	*23%*	11%	15%	18%	25%	*19%*	**8%**	26%	26%	15%	*20%*
			Average (Median)	45%	29%	22%	29%	*28%*	47%	28%	11%	22%	*22%*	39%	28%	20%	30%	*27%*
			Wet (75ty Percentile)	52%	52%	26%	36%	*38%*	52%	53%	14%	30%	*33%*	47%	47%	25%	35%	*36%*
			Total	*35%*	*31%*	*24%*	*28%*	*28%*	*36%*	*28%*	*14%*	*25%*	*23%*	*30%*	*31%*	*23%*	*25%*	*26%*
Sabine	Sabine River nr Bon Weir	8028500	Dry (25th Percentile)	**1%**	**2%**	16%	11%	**9%**	**0%**	**1%**	19%	12%	**9%**	**1%**	**4%**	**3%**	**8%**	**5%**
			Average (Median)	15%	14%	32%	20%	*21%*	19%	**10%**	35%	17%	*20%*	**6%**	17%	29%	17%	*17%*
			Wet (75ty Percentile)	11%	43%	43%	25%	*30%*	51%	43%	46%	25%	*39%*	**7%**	39%	15%	25%	*22%*
			Total	**10%**	*13%*	*26%*	*18%*	*17%*	*18%*	*10%*	*29%*	*16%*	*19%*	**4%**	*14%*	*15%*	*15%*	*13%*
Sabine	Sabine River nr Ruliff	8030500	Dry (25th Percentile)	18%	**4%**	28%	18%	*19%*	**6%**	**3%**	25%	11%	*13%*	21%	**5%**	**2%**	**8%**	**7%**
			Average (Median)	52%	23%	60%	21%	*37%*	49%	17%	52%	21%	*33%*	58%	28%	37%	18%	*32%*
			Wet (75ty Percentile)	71%	54%	73%	32%	*54%*	72%	36%	67%	29%	*48%*	73%	70%	**6%**	32%	*35%*
			Total	*43%*	*18%*	*46%*	*22%*	*31%*	*37%*	*13%*	*41%*	*18%*	*27%*	*47%*	*22%*	*16%*	*16%*	*22%*
Neches	Village Creek nr Kountze	8041500	Dry (25th Percentile)	46%	44%	31%	32%	*36%*	59%	46%	31%	33%	*39%*	22%	41%	19%	27%	*26%*
			Average (Median)	56%	60%	48%	44%	*50%*	70%	62%	45%	51%	*54%*	41%	49%	38%	31%	*38%*
			Wet (75ty Percentile)	66%	49%	67%	48%	*57%*	67%	62%	63%	54%	*61%*	56%	39%	62%	37%	*48%*
			Total	*54%*	*52%*	*46%*	*41%*	*47%*	*66%*	*57%*	*43%*	*46%*	*51%*	*38%*	*44%*	*36%*	*31%*	*36%*
Neches	Neches River at Evadale	8041000	Dry (25th Percentile)	**1%**	29%	66%	45%	*35%*	**1%**	34%	93%	75%	*51%*	**1%**	**2%**	**0%**	**0%**	**1%**
			Average (Median)	51%	28%	**10%**	17%	*21%*	53%	36%	98%	78%	*74%*	51%	23%	**0%**	**1%**	*12%*
			Wet (75ty Percentile)	65%	68%	**5%**	19%	*30%*	63%	58%	76%	39%	*58%*	79%	66%	**5%**	14%	*29%*
			Total	*31%*	*36%*	*20%*	*23%*	*26%*	*32%*	*40%*	*93%*	*72%*	*65%*	*33%*	*26%*	**1%**	**3%**	*12%*
Neches	Attoyac Bayou nr Chireno	8038000	Dry (25th Percentile)						12%	23%	11%	32%	*19%*	41%	47%	24%	33%	*33%*
			Average (Median)						29%	24%	27%	36%	*30%*	66%	59%	60%	46%	*57%*
			Wet (75ty Percentile)						41%	30%	55%	54%	*47%*	76%	74%	84%	63%	*73%*
			Total						*26%*	*25%*	*25%*	*38%*	*30%*	*60%*	*59%*	*49%*	*45%*	*52%*
Neches	Angelina River nr Alto	8036500	Dry (25th Percentile)	**5%**	33%	19%	23%	*20%*						**3%**	31%	17%	19%	*18%*
			Average (Median)	31%	41%	11%	23%	*23%*						28%	40%	**8%**	22%	*20%*
			Wet (75ty Percentile)	58%	34%	41%	53%	*48%*						58%	34%	40%	52%	*47%*
			Total	*28%*	*37%*	*17%*	*26%*	*25%*						*26%*	*36%*	*15%*	*24%*	*23%*
Neches	Neches River near Rockland	8033500	Dry (25th Percentile)	22%	39%	21%	23%	*24%*	23%	15%	18%	32%	*23%*	28%	42%	**9%**	13%	*17%*
			Average (Median)	36%	49%	20%	23%	*27%*	47%	46%	15%	16%	*25%*	36%	55%	15%	16%	*24%*
			Wet (75ty Percentile)	57%	48%	43%	44%	*47%*	48%	32%	29%	40%	*37%*	62%	45%	23%	41%	*41%*
			Total	*35%*	*46%*	*23%*	*26%*	*29%*	*39%*	*34%*	*17%*	*26%*	*26%*	*38%*	*49%*	*13%*	*19%*	*24%*
Neches	Neches River at Neches	8032000	Dry (25th Percentile)	17%	12%	45%	**7%**	*22%*	13%	**9%**	73%	20%	*33%*	19%	13%	**0%**	**6%**	**8%**
			Average (Median)	22%	28%	13%	18%	*18%*	20%	23%	63%	14%	*34%*	27%	38%	**9%**	18%	*20%*
			Wet (75ty Percentile)	35%	37%	**9%**	30%	*24%*	40%	37%	33%	25%	*33%*	44%	40%	**8%**	31%	*26%*
			Total	*23%*	*24%*	*21%*	*17%*	*21%*	*22%*	*21%*	*59%*	*18%*	*33%*	*28%*	*30%*	**6%**	*16%*	*18%*

Table 6a: Percent of Seasons Meeting Pulse Criteria from Original Percentile-Based HEFR Analysis - WAM Naturalized Flows from 1940 to 1996

Basin	USGS Gage Name	USGS Gage Number	Flow Condition	Full Period HEFR Matrix					Pre-Dam HEFR Matrix					Post-Dam HEFR Matrix				
				Winter	Spring	Summer	Fall	*Total*	Winter	Spring	Summer	Fall	*Total*	Winter	Spring	Summer	Fall	*Total*
Sabine	Big Sandy Creek nr Big Sandy	8019500	Dry (25th Percentile)	21%	50%	14%	14%	25%	14%	36%	14%	14%	20%	21%	50%	14%	14%	25%
			Average (Median)	34%	38%	38%	21%	33%	52%	34%	31%	31%	37%	28%	34%	38%	21%	30%
			Wet (75th Percentile)	71%	50%	71%	79%	68%	71%	50%	57%	79%	64%	71%	57%	57%	79%	66%
			Total	40%	44%	40%	33%	39%	47%	39%	33%	39%	39%	37%	44%	37%	33%	38%
Sabine	Sabine River nr Gladewater	8020000	Dry (25th Percentile)	14%	57%	36%	14%	30%	21%	36%	29%	14%	25%	14%	14%	43%	14%	21%
			Average (Median)	38%	41%	59%	38%	44%	48%	72%	34%	31%	47%	28%	28%	66%	38%	40%
			Wet (75th Percentile)	50%	100%	57%	64%	68%	50%	29%	36%	64%	45%	50%	14%	64%	64%	48%
			Total	35%	60%	53%	39%	46%	42%	53%	33%	35%	41%	30%	21%	60%	39%	37%
Sabine	Sabine River nr Beckville	8022040	Dry (25th Percentile)	43%	43%	43%	21%	38%	43%	36%	29%	14%	30%	43%	50%	21%	**7%**	30%
			Average (Median)	52%	69%	52%	59%	58%	28%	69%	31%	55%	46%	55%	55%	21%	59%	47%
			Wet (75th Percentile)	57%	100%	64%	57%	70%	57%	100%	64%	57%	70%	57%	21%	79%	57%	54%
			Total	51%	70%	53%	49%	56%	39%	68%	39%	46%	48%	53%	46%	35%	46%	45%
Sabine	Sabine River nr Bon Weir	8028500	Dry (25th Percentile)	50%	29%	**0%**	14%	23%	29%	57%	50%	29%	41%	71%	29%	**0%**	**0%**	25%
			Average (Median)	45%	41%	**0%**	38%	31%	38%	59%	**7%**	45%	37%	52%	41%	**0%**	14%	27%
			Wet (75th Percentile)	100%	43%	50%	57%	63%	100%	21%	36%	43%	50%	**7%**	43%	43%	29%	30%
			Total	60%	39%	12%	37%	37%	51%	49%	25%	40%	41%	46%	39%	11%	14%	27%
Sabine	Sabine River nr Ruliff	8030500	Dry (25th Percentile)	86%	36%	**7%**	29%	39%	71%	57%	50%	71%	63%	43%	**7%**	**0%**	14%	16%
			Average (Median)	38%	21%	**0%**	31%	22%	38%	100%	48%	21%	52%	38%	24%	**0%**	14%	19%
			Wet (75th Percentile)	100%	100%	21%	29%	63%	100%	100%	29%	29%	64%	100%	21%	21%	36%	45%
			Total	65%	44%	**7%**	30%	36%	61%	89%	44%	35%	57%	54%	19%	**5%**	19%	25%
Neches	Village Creek nr Kountze	8041500	Dry (25th Percentile)	14%	21%	14%	21%	18%	**0%**	21%	**0%**	21%	11%	14%	50%	14%	14%	23%
			Average (Median)	28%	55%	34%	52%	42%	28%	55%	21%	55%	40%	28%	52%	34%	45%	40%
			Wet (75th Percentile)	57%	57%	79%	64%	64%	57%	64%	79%	64%	66%	50%	57%	79%	57%	61%
			Total	32%	47%	40%	47%	42%	28%	49%	30%	49%	39%	30%	53%	40%	40%	41%
Neches	Neches River at Evadale	8041000	Dry (25th Percentile)	36%	36%	21%	29%	30%	36%	36%	14%	36%	30%	29%	36%	**0%**	21%	21%
			Average (Median)	52%	34%	34%	69%	47%	55%	24%	**3%**	62%	36%	55%	45%	21%	14%	34%
			Wet (75th Percentile)	100%	100%	100%	43%	86%	**7%**	100%	57%	29%	48%	100%	100%	50%	43%	73%
			Total	60%	51%	47%	53%	53%	39%	46%	19%	47%	38%	60%	56%	23%	23%	40%
Neches	Attoyac Bayou nr Chireno	8038000	Dry (25th Percentile)						**8%**	17%	**0%**	**8%**	**8%**	33%	17%	**0%**	**0%**	13%
			Average (Median)						41%	23%	**5%**	30%	25%	55%	45%	33%	30%	41%
			Wet (75th Percentile)						20%	50%	55%	36%	40%	60%	40%	36%	45%	45%
			Total						27%	27%	16%	26%	24%	50%	36%	25%	26%	34%
Neches	Angelina River nr Alto	8036500	Dry (25th Percentile)	10%	**0%**	**9%**	10%	**7%**						10%	**0%**	**9%**	10%	**7%**
			Average (Median)	63%	67%	21%	25%	44%						63%	67%	21%	25%	44%
			Wet (75th Percentile)	100%	33%	100%	86%	82%						100%	33%	100%	86%	82%
			Total	57%	43%	32%	32%	41%						57%	43%	32%	32%	41%
Neches	Neches River near Rockland	8033500	Dry (25th Percentile)	21%	71%	14%	29%	34%	36%	29%	14%	21%	25%	21%	29%	14%	21%	21%
			Average (Median)	38%	69%	41%	34%	46%	41%	24%	41%	34%	35%	34%	69%	38%	34%	44%
			Wet (75th Percentile)	71%	21%	64%	71%	57%	64%	50%	64%	57%	59%	71%	36%	64%	64%	59%
			Total	42%	58%	40%	42%	46%	46%	32%	40%	37%	39%	40%	51%	39%	39%	42%
Neches	Neches River at Neches	8032000	Dry (25th Percentile)	57%	36%	29%	29%	38%	43%	36%	43%	36%	39%	43%	14%	**0%**	29%	21%
			Average (Median)	55%	24%	28%	31%	34%	28%	69%	28%	17%	35%	66%	31%	24%	41%	41%
			Wet (75th Percentile)	43%	36%	71%	64%	54%	29%	29%	50%	64%	43%	50%	43%	64%	79%	59%
			Total	53%	30%	39%	39%	40%	32%	51%	37%	33%	38%	56%	30%	28%	47%	40%

Table 6b: Percent of Seasons Meeting Pulse Criteria from Original Percentile-Based HEFR Analysis - WAM Run 8 Regulated Flows from 1940 to 1996

Basin	USGS Gage Name	USGS Gage Number	Flow Condition	Full Period HEFR Matrix					Pre-Dam HEFR Matrix					Post-Dam HEFR Matrix				
				Winter	Spring	Summer	Fall	*Total*	Winter	Spring	Summer	Fall	*Total*	Winter	Spring	Summer	Fall	*Total*
Sabine	Big Sandy Creek nr Big Sandy	8019500	Dry (25th Percentile)	21%	36%	14%	14%	21%	**7%**	29%	**7%**	14%	14%	21%	36%	14%	14%	21%
			Average (Median)	31%	38%	38%	24%	33%	48%	31%	28%	31%	34%	28%	34%	38%	21%	30%
			Wet (75th Percentile)	71%	50%	57%	79%	64%	71%	50%	57%	79%	64%	71%	57%	57%	79%	66%
			Total	39%	40%	37%	35%	38%	44%	35%	30%	39%	37%	37%	40%	37%	33%	37%
Sabine	Sabine River nr Gladewater	8020000	Dry (25th Percentile)	14%	50%	21%	14%	25%	**7%**	36%	**0%**	14%	14%	**7%**	**0%**	21%	14%	11%
			Average (Median)	28%	34%	34%	34%	33%	38%	66%	**7%**	31%	35%	21%	24%	41%	34%	30%
			Wet (75th Percentile)	50%	100%	57%	50%	64%	57%	14%	29%	43%	36%	57%	14%	57%	50%	45%
			Total	30%	54%	37%	33%	39%	35%	46%	11%	30%	30%	26%	16%	40%	33%	29%
Sabine	Sabine River nr Beckville	8022040	Dry (25th Percentile)	21%	43%	36%	14%	29%	14%	36%	29%	14%	23%	21%	43%	29%	**0%**	23%
			Average (Median)	31%	72%	38%	45%	47%	14%	72%	14%	45%	36%	41%	62%	21%	45%	42%
			Wet (75th Percentile)	57%	100%	57%	64%	70%	57%	100%	36%	64%	64%	57%	21%	79%	64%	55%
			Total	35%	72%	42%	42%	48%	25%	70%	23%	42%	40%	40%	47%	37%	39%	41%
Sabine	Sabine River nr Bon Weir	8028500	Dry (25th Percentile)	14%	14%	14%	21%	16%	**7%**	50%	100%	21%	45%	14%	14%	**0%**	**0%**	**7%**
			Average (Median)	24%	55%	41%	31%	38%	21%	66%	69%	45%	50%	28%	55%	17%	**3%**	26%
			Wet (75th Percentile)	100%	43%	79%	57%	70%	100%	29%	36%	43%	52%	**7%**	57%	79%	29%	43%
			Total	40%	42%	44%	35%	40%	37%	53%	68%	39%	49%	19%	46%	28%	**9%**	25%
Sabine	Sabine River nr Ruliff	8030500	Dry (25th Percentile)	21%	36%	14%	14%	21%	**7%**	29%	**7%**	14%	14%	21%	36%	14%	14%	21%
			Average (Median)	31%	38%	38%	24%	33%	48%	31%	28%	31%	34%	28%	34%	38%	21%	30%
			Wet (75th Percentile)	71%	50%	57%	79%	64%	71%	50%	57%	79%	64%	71%	57%	57%	79%	66%
			Total	39%	40%	37%	35%	38%	44%	35%	30%	39%	37%	37%	40%	37%	33%	37%
Neches	Village Creek nr Kountze	8041500	Dry (25th Percentile)	14%	21%	14%	21%	18%	**0%**	21%	**0%**	21%	11%	14%	50%	14%	14%	23%
			Average (Median)	28%	55%	34%	52%	42%	28%	55%	21%	55%	40%	28%	52%	34%	45%	40%
			Wet (75th Percentile)	57%	57%	79%	64%	64%	57%	64%	79%	64%	66%	50%	57%	79%	57%	61%
			Total	32%	47%	40%	47%	42%	28%	49%	30%	49%	39%	30%	53%	40%	40%	41%
Neches	Neches River at Evadale	8041000	Dry (25th Percentile)	29%	29%	29%	29%	29%	29%	29%	**7%**	29%	23%	14%	29%	**0%**	**7%**	13%
			Average (Median)	52%	45%	28%	52%	44%	59%	34%	**7%**	55%	39%	52%	55%	17%	**7%**	33%
			Wet (75th Percentile)	100%	100%	100%	36%	84%	**7%**	100%	50%	21%	45%	100%	100%	43%	36%	70%
			Total	58%	54%	46%	42%	50%	39%	49%	18%	40%	36%	54%	60%	19%	14%	37%
Neches	Attoyac Bayou nr Chireno	8038000	Dry (25th Percentile)						**8%**	17%	**0%**	**8%**	**8%**	33%	17%	**0%**	**0%**	13%
			Average (Median)						36%	23%	**5%**	25%	22%	55%	41%	24%	30%	38%
			Wet (75th Percentile)						20%	50%	45%	36%	38%	60%	40%	27%	45%	43%
			Total						25%	27%	14%	23%	22%	50%	34%	18%	26%	32%
Neches	Angelina River nr Alto	8036500	Dry (25th Percentile)	10%	**0%**	**9%**	**0%**	**5%**						10%	**0%**	**9%**	**0%**	**5%**
			Average (Median)	58%	62%	21%	25%	42%						58%	62%	21%	25%	42%
			Wet (75th Percentile)	100%	33%	86%	86%	79%						100%	33%	86%	86%	79%
			Total	54%	41%	30%	30%	39%						54%	41%	30%	30%	39%
Neches	Neches River near Rockland	8033500	Dry (25th Percentile)	14%	71%	**7%**	14%	27%	36%	21%	**7%**	14%	20%	21%	21%	**7%**	14%	16%
			Average (Median)	34%	66%	31%	34%	41%	31%	24%	31%	28%	28%	28%	66%	31%	34%	40%
			Wet (75th Percentile)	71%	21%	71%	71%	59%	64%	50%	64%	64%	61%	71%	36%	71%	64%	61%
			Total	39%	56%	35%	39%	42%	40%	30%	33%	33%	34%	37%	47%	35%	37%	39%
Neches	Neches River at Neches	8032000	Dry (25th Percentile)	29%	21%	**7%**	**0%**	14%	21%	29%	**7%**	14%	18%	21%	29%	**7%**	14%	18%
			Average (Median)	48%	24%	14%	17%	26%	24%	66%	14%	17%	30%	24%	66%	14%	17%	30%
			Wet (75th Percentile)	50%	21%	57%	64%	48%	36%	21%	43%	64%	41%	36%	21%	43%	64%	41%
			Total	44%	23%	23%	25%	29%	26%	46%	19%	28%	30%	26%	46%	19%	28%	30%

Table 6c: Percent of Seasons Meeting Pulse Criteria from Original Percentile-Based HEFR Analysis - WAM Run 3 Regulated Flows from 1940 to 1996

Basin	USGS Gage Name	USGS Gage Number	Flow Condition	Full Period HEFR Matrix					Pre-Dam HEFR Matrix					Post-Dam HEFR Matrix				
				Winter	Spring	Summer	Fall	*Total*	Winter	Spring	Summer	Fall	*Total*	Winter	Spring	Summer	Fall	*Total*
Sabine	Big Sandy Creek nr Big Sandy	8019500	Dry (25th Percentile)	21%	36%	14%	14%	21%	**7%**	29%	**7%**	14%	14%	21%	36%	14%	14%	21%
			Average (Median)	31%	38%	34%	24%	32%	48%	28%	28%	31%	34%	28%	34%	34%	24%	30%
			Wet (75th Percentile)	71%	50%	57%	79%	64%	71%	50%	57%	79%	64%	71%	57%	57%	79%	66%
			Total	39%	40%	35%	35%	37%	44%	33%	30%	39%	36%	37%	40%	35%	35%	37%
Sabine	Sabine River nr Gladewater	8020000	Dry (25th Percentile)	21%	50%	14%	**7%**	23%	14%	36%	**0%**	**7%**	14%	14%	**0%**	21%	**7%**	11%
			Average (Median)	38%	41%	34%	34%	37%	28%	62%	**7%**	31%	32%	31%	24%	38%	34%	32%
			Wet (75th Percentile)	50%	100%	64%	57%	68%	57%	21%	29%	57%	41%	57%	21%	64%	43%	46%
			Total	37%	58%	37%	33%	41%	32%	46%	11%	32%	30%	33%	18%	40%	30%	30%
Sabine	Sabine River nr Beckville	8022040	Dry (25th Percentile)	29%	50%	21%	14%	29%	29%	36%	14%	14%	23%	29%	50%	14%	**7%**	25%
			Average (Median)	34%	69%	34%	45%	46%	10%	66%	**7%**	38%	30%	38%	52%	21%	48%	40%
			Wet (75th Percentile)	57%	100%	57%	64%	70%	57%	100%	21%	71%	63%	50%	14%	64%	57%	46%
			Total	39%	72%	37%	42%	47%	26%	67%	12%	40%	36%	39%	42%	30%	40%	38%
Sabine	Sabine River nr Bon Weir	8028500	Dry (25th Percentile)	**7%**	**7%**	**0%**	**0%**	**4%**	**0%**	**0%**	29%	**0%**	**7%**	**7%**	**7%**	**0%**	**0%**	**4%**
			Average (Median)	21%	21%	**7%**	31%	20%	14%	31%	66%	34%	36%	28%	24%	**3%**	**3%**	15%
			Wet (75th Percentile)	100%	71%	43%	79%	73%	100%	29%	43%	43%	54%	43%	71%	43%	36%	48%
			Total	37%	30%	14%	35%	29%	32%	23%	51%	28%	33%	26%	32%	12%	11%	20%
Sabine	Sabine River nr Ruliff	8030500	Dry (25th Percentile)	93%	29%	**0%**	43%	41%	79%	57%	29%	50%	54%	86%	**7%**	**0%**	**7%**	25%
			Average (Median)	76%	55%	48%	62%	60%	31%	100%	97%	52%	70%	93%	55%	17%	21%	47%
			Wet (75th Percentile)	100%	100%	36%	64%	75%	100%	100%	50%	43%	73%	100%	**7%**	36%	36%	45%
			Total	86%	60%	33%	58%	59%	60%	89%	68%	49%	67%	93%	32%	18%	21%	41%
Neches	Village Creek nr Kountze	8041500	Dry (25th Percentile)	14%	21%	14%	21%	18%	**0%**	21%	**0%**	21%	11%	14%	50%	14%	14%	23%
			Average (Median)	28%	55%	34%	52%	42%	28%	55%	21%	55%	40%	28%	52%	34%	45%	40%
			Wet (75th Percentile)	57%	57%	79%	64%	64%	57%	64%	79%	64%	66%	50%	57%	79%	57%	61%
			Total	32%	47%	40%	47%	42%	28%	49%	30%	49%	39%	30%	53%	40%	40%	41%
Neches	Neches River at Evadale	8041000	Dry (25th Percentile)	21%	64%	100%	86%	68%	14%	57%	100%	86%	64%	21%	43%	14%	**0%**	20%
			Average (Median)	62%	38%	86%	38%	56%	62%	34%	52%	41%	47%	62%	48%	45%	10%	41%
			Wet (75th Percentile)	100%	100%	100%	21%	80%	**7%**	100%	50%	21%	45%	100%	100%	36%	21%	64%
			Total	61%	60%	93%	46%	65%	37%	56%	63%	47%	51%	61%	60%	35%	11%	42%
Neches	Attoyac Bayou nr Chireno	8038000	Dry (25th Percentile)						**8%**	17%	**0%**	**8%**	**8%**	33%	17%	**0%**	**0%**	13%
			Average (Median)						36%	23%	**5%**	25%	22%	55%	41%	24%	30%	38%
			Wet (75th Percentile)						20%	50%	45%	36%	38%	60%	40%	27%	45%	43%
			Total						25%	27%	14%	23%	22%	50%	34%	18%	26%	32%
Neches	Angelina River nr Alto	8036500	Dry (25th Percentile)	**0%**	**0%**	**9%**	**0%**	**2%**						**0%**	**0%**	**9%**	**0%**	**2%**
			Average (Median)	53%	57%	11%	15%	34%						37%	57%	**5%**	15%	29%
			Wet (75th Percentile)	100%	33%	86%	100%	82%						100%	50%	86%	100%	86%
			Total	49%	38%	24%	27%	34%						41%	41%	22%	27%	32%
Neches	Neches River near Rockland	8033500	Dry (25th Percentile)	**7%**	64%	14%	**7%**	23%	21%	21%	14%	**7%**	16%	14%	21%	21%	**7%**	16%
			Average (Median)	24%	66%	24%	28%	35%	24%	31%	24%	21%	25%	21%	69%	24%	24%	34%
			Wet (75th Percentile)	71%	21%	71%	64%	57%	57%	43%	64%	50%	54%	71%	36%	71%	64%	61%
			Total	32%	54%	33%	32%	38%	32%	32%	32%	25%	30%	32%	49%	35%	30%	36%
Neches	Neches River at Neches	8032000	Dry (25th Percentile)	**7%**	**7%**	14%	**0%**	**7%**	**0%**	**7%**	57%	14%	20%	**0%**	**7%**	14%	**0%**	**5%**
			Average (Median)	28%	21%	21%	10%	20%	14%	41%	17%	10%	21%	45%	24%	14%	14%	24%
			Wet (75th Percentile)	71%	36%	43%	50%	50%	50%	36%	21%	36%	36%	71%	43%	36%	50%	50%
			Total	33%	21%	25%	18%	24%	19%	32%	28%	18%	24%	40%	25%	19%	19%	26%

Table 7a: Percent of Overbank Flows Meeting Original Percentile-Based HEFR Criteria - WAM Naturalized Flows from 1940 to 1996

Basin	USGS Gage Name	USGS Gage Number	Full Period HEFR Matrix			Pre-Dam HEFR Matrix			Post-Dam HEFR Matrix		
			% of Overbank Meeting Criteria	Frequency	Return Period (Years)	% of Overbank Meeting Criteria	Frequency	Return Period (Years)	% of Overbank Meeting Criteria	Frequency	Return Period (Years)
Sabine	Big Sandy Creek nr Big Sandy	8019500	25%	0.26	3.8	25%	0.26	3.8	32%	0.33	3.0
Sabine	Sabine River nr Gladewater	8020000	21%	0.25	4.1	24%	0.28	3.6	19%	0.23	4.4
Sabine	Sabine River nr Beckville	8022040	17%	0.19	5.2	13%	0.14	7.1	19%	0.21	4.8
Sabine	Sabine River nr Bon Weir	8028500	34%	0.77	1.3	26%	0.58	1.7	36%	0.81	1.2
Sabine	Sabine River nr Ruliff	8030500	33%	0.96	1.0	33%	0.96	1.0	28%	0.82	1.2
Neches	Village Creek nr Kountze	8041500	27%	0.25	4.1	22%	0.19	5.2	27%	0.25	4.1
Neches	Neches River at Evadale	8041000	30%	0.63	1.6	29%	0.61	1.6	24%	0.51	2.0
Neches	Attoyac Bayou nr Chireno	8038000				30%	0.31	3.2	30%	0.31	3.2
Neches	Angelina River nr Alto	8036500	20%	0.03	37.0				20%	0.03	37.0
Neches	Neches River near Rockland	8033500	8%	0.04	28.5	12%	0.05	19.0	24%	0.11	9.5
Neches	Neches River at Neches	8032000	19%	0.21	4.8	22%	0.25	4.1	22%	0.25	4.1

Table 7b: Percent of Overbank Flows Meeting Original Percentile-Based HEFR Criteria - WAM Run 8 Regulated Flows from 1940 to 1996

Basin	USGS Gage Name	USGS Gage Number	Full Period HEFR Matrix			Pre-Dam HEFR Matrix			Post-Dam HEFR Matrix		
			% of Overbank Meeting Criteria	Frequency	Return Period (Years)	% of Overbank Meeting Criteria	Frequency	Return Period (Years)	% of Overbank Meeting Criteria	Frequency	Return Period (Years)
Sabine	Big Sandy Creek nr Big Sandy	8019500	28%	0.30	3.4	25%	0.26	3.8	32%	0.33	3.0
Sabine	Sabine River nr Gladewater	8020000	25%	0.25	4.1	27%	0.26	3.8	20%	0.19	5.2
Sabine	Sabine River nr Beckville	8022040	26%	0.21	4.8	11%	0.09	11.4	28%	0.23	4.4
Sabine	Sabine River nr Bon Weir	8028500	28%	0.60	1.7	23%	0.49	2.0	30%	0.63	1.6
Sabine	Sabine River nr Ruliff	8030500	31%	0.79	1.3	31%	0.79	1.3	28%	0.72	1.4
Neches	Village Creek nr Kountze	8041500	27%	0.25	4.1	22%	0.19	5.2	27%	0.25	4.1
Neches	Neches River at Evadale	8041000	30%	0.63	1.6	29%	0.60	1.7	25%	0.53	1.9
Neches	Attoyac Bayou nr Chireno	8038000				30%	0.31	3.2	30%	0.31	3.2
Neches	Angelina River nr Alto	8036500	20%	0.03	37.0				20%	0.03	37.0
Neches	Neches River near Rockland	8033500	8%	0.04	28.5	12%	0.05	19.0	24%	0.11	9.5
Neches	Neches River at Neches	8032000	16%	0.18	5.7	17%	0.19	5.2	17%	0.19	5.2

Table 7c: Percent of Overbank Flows Meeting Original Percentile-Based HEFR Criteria - WAM Run 3 Regulated Flows from 1940 to 1996

Basin	USGS Gage Name	USGS Gage Number	Full Period HEFR Matrix			Pre-Dam HEFR Matrix			Post-Dam HEFR Matrix		
			% of Overbank Meeting Criteria	Frequency	Return Period (Years)	% of Overbank Meeting Criteria	Frequency	Return Period (Years)	% of Overbank Meeting Criteria	Frequency	Return Period (Years)
Sabine	Big Sandy Creek nr Big Sandy	8019500	27%	0.28	3.6	25%	0.26	3.8	30%	0.32	3.2
Sabine	Sabine River nr Gladewater	8020000	15%	0.11	9.5	23%	0.16	6.3	10%	0.07	14.3
Sabine	Sabine River nr Beckville	8022040	16%	0.11	9.5	11%	0.07	14.3	22%	0.14	7.1
Sabine	Sabine River nr Bon Weir	8028500	33%	0.32	3.2	29%	0.28	3.6	33%	0.32	3.2
Sabine	Sabine River nr Ruliff	8030500	26%	0.49	2.0	26%	0.49	2.0	22%	0.40	2.5
Neches	Village Creek nr Kountze	8041500	27%	0.25	4.1	22%	0.19	5.2	27%	0.25	4.1
Neches	Neches River at Evadale	8041000	31%	0.49	2.0	31%	0.49	2.0	28%	0.44	2.3
Neches	Attoyac Bayou nr Chireno	8038000				30%	0.31	3.2	30%	0.31	3.2
Neches	Angelina River nr Alto	8036500	20%	0.03	37.0				20%	0.03	37.0
Neches	Neches River near Rockland	8033500	12%	0.05	19.0	4%	0.02	57.0	20%	0.09	11.4
Neches	Neches River at Neches	8032000	18%	0.11	9.5	12%	0.07	14.3	18%	0.11	9.5

Talbe 8a: Meeting Annual Criteria from HEFR Fequency-Based Analysis - WAM Naturalized Flows from 1940 to 1996

Basin	USGS Gage Name	USGS Gage Number	Flow Condition	Full Period HEFR Matrix					Pre-Dam HEFR Matrix					Post-Dam HEFR Matrix				
				No of Pulses Meeting Peak Criteria	No of Pulses Meeting All Criteria	% Meeting Criteria	Frequency During Sim Period	Return During Sim Period (Years)	No of Pulses Meeting Peak Criteria	No of Pulses Meeting All Criteria	% Meeting Criteria	Frequency During Sim Period	Return During Sim Period (Years)	No of Pulses Meeting Peak Criteria	No of Pulses Meeting All Criteria	% Meeting Criteria	Frequency During Sim Period	Return During Sim Period (Years)
Sabine	Big Sandy Creek nr Big Sandy	8019500	1 per 2 years	29	23	79%	0.40	2.5	16	11	69%	0.19	5.2	29	22	76%	0.39	2.6
			1 per year	59	54	92%	0.95	1.1	51	47	92%	0.82	1.2	51	44	86%	0.77	1.3
			2 per 3 years	90	86	96%	1.51	0.7	74	72	97%	1.26	0.8	84	78	93%	1.37	0.7
			2 per year	115	114	99%	2.00	0.5	101	100	99%	1.75	0.6	108	102	94%	1.79	0.6
Sabine	Sabine River nr Gladewater	8020000	1 per 2 years	34	31	91%	0.54	1.8	13	10	77%	0.18	5.7	41	30	73%	0.53	1.9
			1 per year	67	65	97%	1.14	0.9	39	36	92%	0.63	1.6	91	83	91%	1.46	0.7
			2 per 3 years	112	111	99%	1.95	0.5	67	67	100%	1.18	0.9	116	111	96%	1.95	0.5
			2 per year	146	142	97%	2.49	0.4	98	98	100%	1.72	0.6	146	140	96%	2.46	0.4
Sabine	Sabine River nr Beckville	8022040	1 per 2 years	35	29	83%	0.51	2.0	15	10	67%	0.18	5.7	38	30	79%	0.53	1.9
			1 per year	71	65	92%	1.14	0.9	63	59	94%	1.04	1.0	66	57	86%	1.00	1.0
			2 per 3 years	115	105	91%	1.84	0.5	101	96	95%	1.68	0.6	90	79	88%	1.39	0.7
			2 per year	138	129	93%	2.26	0.4	134	127	95%	2.23	0.4	131	118	90%	2.07	0.5
Sabine	Sabine River nr Bon Weir	8028500	1 per 2 years	47	39	83%	0.68	1.5	43	26	60%	0.46	2.2	46	41	89%	0.72	1.4
			1 per year	71	63	89%	1.11	0.9	78	62	79%	1.09	0.9	64	59	92%	1.04	1.0
			2 per 3 years	112	95	85%	1.67	0.6	112	92	82%	1.61	0.6	99	85	86%	1.49	0.7
			2 per year	139	123	88%	2.16	0.5	135	110	81%	1.93	0.5	129	117	91%	2.05	0.5
Sabine	Sabine River nr Ruliff	8030500	1 per 2 years	41	31	76%	0.54	1.8	25	16	64%	0.28	3.6	42	31	74%	0.54	1.8
			1 per year	74	56	76%	0.98	1.0	61	45	74%	0.79	1.3	79	59	75%	1.04	1.0
			2 per 3 years	98	81	83%	1.42	0.7	80	63	79%	1.11	0.9	100	82	82%	1.44	0.7
			2 per year	131	124	95%	2.18	0.5	104	93	89%	1.63	0.6	137	123	90%	2.16	0.5
Neches	Village Creek nr Kountze	8041500	1 per 2 years	26	18	69%	0.32	3.2	23	15	65%	0.26	3.8	25	17	68%	0.30	3.4
			1 per year	51	51	100%	0.89	1.1	52	42	81%	0.74	1.4	45	42	93%	0.74	1.4
			2 per 3 years	80	78	98%	1.37	0.7	86	84	98%	1.47	0.7	70	67	96%	1.18	0.9
			2 per year	108	106	98%	1.86	0.5	130	130	100%	2.28	0.4	88	87	99%	1.53	0.7
Neches	Neches River at Evadale	8041000	1 per 2 years	36	30	83%	0.53	1.9	24	16	67%	0.28	3.6	39	25	64%	0.44	2.3
			1 per year	72	64	89%	1.12	0.9	51	44	86%	0.77	1.3	73	64	88%	1.12	0.9
			2 per 3 years	106	93	88%	1.63	0.6	74	68	92%	1.19	0.8	115	105	91%	1.84	0.5
			2 per year	133	132	99%	2.32	0.4	108	100	93%	1.75	0.6	135	135	100%	2.37	0.4
Neches	Attoyac Bayou nr Chireno	8038000	1 per 2 years						15	13	87%	0.29	3.5	24	19	79%	0.42	2.4
			1 per year						35	31	89%	0.69	1.5	46	40	87%	0.89	1.1
			2 per 3 years						52	48	92%	1.07	0.9	68	63	93%	1.40	0.7
			2 per year						70	66	94%	1.47	0.7	97	94	97%	2.09	0.5
Neches	Angelina River nr Alto	8036500	1 per 2 years	9	9	100%	0.24	4.1						9	7	78%	0.19	5.3
			1 per year	31	31	100%	0.84	1.2						30	26	87%	0.70	1.4
			2 per 3 years	46	46	100%	1.24	0.8						44	41	93%	1.11	0.9
			2 per year	67	67	100%	1.81	0.6						62	60	97%	1.62	0.6
Neches	Neches River near Rockland	8033500	1 per 2 years	26	20	77%	0.35	2.9	33	27	82%	0.47	2.1	20	17	85%	0.30	3.4
			1 per year	52	49	94%	0.86	1.2	60	56	93%	0.98	1.0	40	38	95%	0.67	1.5
			2 per 3 years	84	78	93%	1.37	0.7	86	78	91%	1.37	0.7	66	62	94%	1.09	0.9
			2 per year	114	110	96%	1.93	0.5	118	111	94%	1.95	0.5	103	99	96%	1.74	0.6
Neches	Neches River at Neches	8032000	1 per 2 years	27	26	96%	0.46	2.2	14	14	100%	0.25	4.1	34	29	85%	0.51	2.0
			1 per year	60	53	88%	0.93	1.1	43	41	95%	0.72	1.4	64	50	78%	0.88	1.1
			2 per 3 years	91	87	96%	1.53	0.7	70	70	100%	1.23	0.8	98	82	84%	1.44	0.7
			2 per year	125	123	98%	2.16	0.5	95	93	98%	1.63	0.6	128	118	92%	2.07	0.5

Talbe 8b: Meeting Annual Criteria from HEFR Fequency-Based Analysis - Run 8 Regulated Flows from 1940 to 1996

Basin	USGS Gage Name	USGS Gage Number	Flow Condition	Full Period HEFR Matrix					Pre-Dam HEFR Matrix					Post-Dam HEFR Matrix				
				No of Pulses Meeting Peak Criteria	No of Pulses Meeting All Criteria	% Meeting Criteria	Frequency During Sim Period	Return During Sim Period (Years)	No of Pulses Meeting Peak Criteria	No of Pulses Meeting All Criteria	% Meeting Criteria	Frequency During Sim Period	Return During Sim Period (Years)	No of Pulses Meeting Peak Criteria	No of Pulses Meeting All Criteria	% Meeting Criteria	Frequency During Sim Period	Return During Sim Period (Years)
Sabine	Big Sandy Creek nr Big Sandy	8019500	1 per 2 years	29	23	79%	0.40	2.5	16	12	75%	0.21	4.8	29	23	79%	0.40	2.5
			1 per year	59	53	90%	0.93	1.1	50	46	92%	0.81	1.2	50	44	88%	0.77	1.3
			2 per 3 years	89	84	94%	1.47	0.7	75	72	96%	1.26	0.8	82	76	93%	1.33	0.8
			2 per year	113	112	99%	1.96	0.5	101	100	99%	1.75	0.6	107	98	92%	1.72	0.6
Sabine	Sabine River nr Gladewater	8020000	1 per 2 years	28	26	93%	0.46	2.2	13	9	69%	0.16	6.3	34	28	82%	0.49	2.0
			1 per year	55	54	98%	0.95	1.1	31	30	97%	0.53	1.9	65	59	91%	1.04	1.0
			2 per 3 years	86	86	100%	1.51	0.7	55	54	98%	0.95	1.1	93	89	96%	1.56	0.6
			2 per year	111	110	99%	1.93	0.5	78	78	100%	1.37	0.7	111	109	98%	1.91	0.5
Sabine	Sabine River nr Beckville	8022040	1 per 2 years	30	28	93%	0.49	2.0	13	10	77%	0.18	5.7	31	28	90%	0.49	2.0
			1 per year	53	50	94%	0.88	1.1	45	43	96%	0.75	1.3	50	43	86%	0.75	1.3
			2 per 3 years	87	82	94%	1.44	0.7	73	71	97%	1.25	0.8	66	62	94%	1.09	0.9
			2 per year	109	104	95%	1.82	0.5	100	96	96%	1.68	0.6	99	92	93%	1.61	0.6
Sabine	Sabine River nr Bon Weir	8028500	1 per 2 years	35	29	83%	0.51	2.0	32	20	63%	0.35	2.9	35	32	91%	0.56	1.8
			1 per year	62	55	89%	0.96	1.0	67	49	73%	0.86	1.2	52	49	94%	0.86	1.2
			2 per 3 years	96	78	81%	1.37	0.7	96	74	77%	1.30	0.8	81	70	86%	1.23	0.8
			2 per year	126	101	80%	1.77	0.6	122	89	73%	1.56	0.6	118	94	80%	1.65	0.6
Sabine	Sabine River nr Ruliff	8030500	1 per 2 years	37	26	70%	0.46	2.2	21	14	67%	0.25	4.1	38	26	68%	0.46	2.2
			1 per year	66	48	73%	0.84	1.2	53	42	79%	0.74	1.4	67	48	72%	0.84	1.2
			2 per 3 years	88	69	78%	1.21	0.8	68	54	79%	0.95	1.1	89	69	78%	1.21	0.8
			2 per year	119	108	91%	1.89	0.5	90	75	83%	1.32	0.8	125	105	84%	1.84	0.5
Neches	Village Creek nr Kountze	8041500	1 per 2 years	27	19	70%	0.33	3.0	23	15	65%	0.26	3.8	25	17	68%	0.30	3.4
			1 per year	51	51	100%	0.89	1.1	53	43	81%	0.75	1.3	45	42	93%	0.74	1.4
			2 per 3 years	80	78	98%	1.37	0.7	86	84	98%	1.47	0.7	71	68	96%	1.19	0.8
			2 per year	109	107	98%	1.88	0.5	131	130	99%	2.28	0.4	89	88	99%	1.54	0.6
Neches	Neches River at Evadale	8041000	1 per 2 years	37	30	81%	0.53	1.9	26	19	73%	0.33	3.0	39	25	64%	0.44	2.3
			1 per year	72	65	90%	1.14	0.9	58	51	88%	0.89	1.1	74	65	88%	1.14	0.9
			2 per 3 years	101	87	86%	1.53	0.7	78	70	90%	1.23	0.8	113	105	93%	1.84	0.5
			2 per year	131	127	97%	2.23	0.4	105	96	91%	1.68	0.6	135	134	99%	2.35	0.4
Neches	Attoyac Bayou nr Chireno	8038000	1 per 2 years						15	13	87%	0.29	3.5	24	19	79%	0.42	2.4
			1 per year						35	31	89%	0.69	1.5	46	40	87%	0.89	1.1
			2 per 3 years						52	48	92%	1.07	0.9	68	62	91%	1.38	0.7
			2 per year						69	65	94%	1.44	0.7	95	92	97%	2.04	0.5
Neches	Angelina River nr Alto	8036500	1 per 2 years	10	10	100%	0.27	3.7						10	7	70%	0.19	5.3
			1 per year	26	26	100%	0.70	1.4						26	23	88%	0.62	1.6
			2 per 3 years	45	45	100%	1.22	0.8						44	41	93%	1.11	0.9
			2 per year	63	63	100%	1.70	0.6						59	58	98%	1.57	0.6
Neches	Neches River near Rockland	8033500	1 per 2 years	27	21	78%	0.37	2.7	32	26	81%	0.46	2.2	20	17	85%	0.30	3.4
			1 per year	52	49	94%	0.86	1.2	60	54	90%	0.95	1.1	40	38	95%	0.67	1.5
			2 per 3 years	83	77	93%	1.35	0.7	88	80	91%	1.40	0.7	65	61	94%	1.07	0.9
			2 per year	111	108	97%	1.89	0.5	116	111	96%	1.95	0.5	100	97	97%	1.70	0.6
Neches	Neches River at Neches	8032000	1 per 2 years	28	26	93%	0.46	2.2	15	15	100%	0.26	3.8	15	15	100%	0.26	3.8
			1 per year	61	52	85%	0.91	1.1	45	40	89%	0.70	1.4	45	40	89%	0.70	1.4
			2 per 3 years	88	88	100%	1.54	0.6	69	67	97%	1.18	0.9	69	67	97%	1.18	0.9
			2 per year	122	121	99%	2.12	0.5	90	89	99%	1.56	0.6	90	89	99%	1.56	0.6

Talbe 8c: Meeting Annual Criteria from HEFR Fequency-Based Analysis - Run 3 Regulated Flows from 1940 to 1996

Basin	USGS Gage Name	USGS Gage Number	Flow Condition	Full Period HEFR Matrix					Pre-Dam HEFR Matrix					Post-Dam HEFR Matrix				
				No of Pulses Meeting Peak Criteria	No of Pulses Meeting All Criteria	% Meeting Criteria	Frequency During Sim Period	Return During Sim Period (Years)	No of Pulses Meeting Peak Criteria	No of Pulses Meeting All Criteria	% Meeting Criteria	Frequency During Sim Period	Return During Sim Period (Years)	No of Pulses Meeting Peak Criteria	No of Pulses Meeting All Criteria	% Meeting Criteria	Frequency During Sim Period	Return During Sim Period (Years)
Sabine	Big Sandy Creek nr Big Sandy	8019500	1 per 2 years	29	23	79%	0.40	2.5	16	12	75%	0.21	4.8	29	22	76%	0.39	2.6
			1 per year	59	53	90%	0.93	1.1	50	46	92%	0.81	1.2	50	44	88%	0.77	1.3
			2 per 3 years	88	83	94%	1.46	0.7	75	72	96%	1.26	0.8	82	76	93%	1.33	0.8
			2 per year	112	111	99%	1.95	0.5	100	99	99%	1.74	0.6	106	97	92%	1.70	0.6
Sabine	Sabine River nr Gladewater	8020000	1 per 2 years	22	19	86%	0.33	3.0	9	5	56%	0.09	11.4	29	23	79%	0.40	2.5
			1 per year	40	39	98%	0.68	1.5	23	22	96%	0.39	2.6	46	41	89%	0.72	1.4
			2 per 3 years	57	57	100%	1.00	1.0	40	40	100%	0.70	1.4	58	56	97%	0.98	1.0
			2 per year	78	78	100%	1.37	0.7	51	51	100%	0.89	1.1	78	76	97%	1.33	0.8
Sabine	Sabine River nr Beckville	8022040	1 per 2 years	23	19	83%	0.33	3.0	9	5	56%	0.09	11.4	25	21	84%	0.37	2.7
			1 per year	40	38	95%	0.67	1.5	37	36	97%	0.63	1.6	38	33	87%	0.58	1.7
			2 per 3 years	50	49	98%	0.86	1.2	49	49	100%	0.86	1.2	45	43	96%	0.75	1.3
			2 per year	69	66	96%	1.16	0.9	65	63	97%	1.11	0.9	62	58	94%	1.02	1.0
Sabine	Sabine River nr Bon Weir	8028500	1 per 2 years	19	16	84%	0.28	3.6	18	12	67%	0.21	4.8	18	17	94%	0.30	3.4
			1 per year	30	26	87%	0.46	2.2	33	26	79%	0.46	2.2	28	24	86%	0.42	2.4
			2 per 3 years	44	39	89%	0.68	1.5	44	36	82%	0.63	1.6	34	32	94%	0.56	1.8
			2 per year	62	55	89%	0.96	1.0	58	48	83%	0.84	1.2	53	47	89%	0.82	1.2
Sabine	Sabine River nr Ruliff	8030500	1 per 2 years	17	15	88%	0.26	3.8	13	11	85%	0.19	5.2	18	15	83%	0.26	3.8
			1 per year	40	30	75%	0.53	1.9	29	21	72%	0.37	2.7	43	31	72%	0.54	1.8
			2 per 3 years	55	43	78%	0.75	1.3	45	31	69%	0.54	1.8	57	43	75%	0.75	1.3
			2 per year	79	71	90%	1.25	0.8	58	48	83%	0.84	1.2	84	68	81%	1.19	0.8
Neches	Village Creek nr Kountze	8041500	1 per 2 years	26	18	69%	0.32	3.2	23	15	65%	0.26	3.8	25	17	68%	0.30	3.4
			1 per year	51	51	100%	0.89	1.1	52	42	81%	0.74	1.4	45	42	93%	0.74	1.4
			2 per 3 years	80	78	98%	1.37	0.7	86	84	98%	1.47	0.7	70	67	96%	1.18	0.9
			2 per year	107	106	99%	1.86	0.5	130	130	100%	2.28	0.4	88	87	99%	1.53	0.7
Neches	Neches River at Evadale	8041000	1 per 2 years	29	23	79%	0.40	2.5	19	13	68%	0.23	4.4	31	18	58%	0.32	3.2
			1 per year	59	53	90%	0.93	1.1	38	34	89%	0.60	1.7	60	52	87%	0.91	1.1
			2 per 3 years	76	73	96%	1.28	0.8	60	56	93%	0.98	1.0	86	83	97%	1.46	0.7
			2 per year	95	95	100%	1.67	0.6	79	78	99%	1.37	0.7	96	96	100%	1.68	0.6
Neches	Attoyac Bayou nr Chireno	8038000	1 per 2 years						15	13	87%	0.29	3.5	24	19	79%	0.42	2.4
			1 per year						34	30	88%	0.67	1.5	46	40	87%	0.89	1.1
			2 per 3 years						52	48	92%	1.07	0.9	66	60	91%	1.33	0.8
			2 per year						69	65	94%	1.44	0.7	95	92	97%	2.04	0.5
Neches	Angelina River nr Alto	8036500	1 per 2 years	10	10	100%	0.27	3.7						10	5	50%	0.14	7.4
			1 per year	20	20	100%	0.54	1.9						20	20	100%	0.54	1.9
			2 per 3 years	39	39	100%	1.05	0.9						38	35	92%	0.95	1.1
			2 per year	57	57	100%	1.54	0.6						56	56	100%	1.51	0.7
Neches	Neches River near Rockland	8033500	1 per 2 years	20	16	80%	0.28	3.6	28	21	75%	0.37	2.7	18	14	78%	0.25	4.1
			1 per year	41	40	98%	0.70	1.4	49	46	94%	0.81	1.2	34	31	91%	0.54	1.8
			2 per 3 years	70	66	94%	1.16	0.9	73	68	93%	1.19	0.8	56	54	96%	0.95	1.1
			2 per year	101	97	96%	1.70	0.6	104	100	96%	1.75	0.6	92	88	96%	1.54	0.6
Neches	Neches River at Neches	8032000	1 per 2 years	12	10	83%	0.18	5.7	7	5	71%	0.09	11.4	19	9	47%	0.16	6.3
			1 per year	31	27	87%	0.47	2.1	24	21	88%	0.37	2.7	33	25	76%	0.44	2.3
			2 per 3 years	49	47	96%	0.82	1.2	40	38	95%	0.67	1.5	51	41	80%	0.72	1.4
			2 per year	74	74	100%	1.30	0.8	50	49	98%	0.86	1.2	76	69	91%	1.21	0.8

Table 9a: Meeting Monthly Criteria from HEFR Frequency-Based Analysis - WAM Naturalized Flows from 1940 to 1996

Basin	USGS Gage Name	USGS Gage Number	Flow Condition	Full Period HEFR Matrix					Pre-Dam HEFR Matrix					Post-Dam HEFR Matrix				
				No of Pulses Meeting Peak Criteria	No of Pulses Meeting All Criteria	% Meeting Criteria	Frequency During Sim Period	Return During Sim Period (Years)	No of Pulses Meeting Peak Criteria	No of Pulses Meeting All Criteria	% Meeting Criteria	Frequency During Sim Period	Return During Sim Period (Years)	No of Pulses Meeting Peak Criteria	No of Pulses Meeting All Criteria	% Meeting Criteria	Frequency During Sim Period	Return During Sim Period (Years)
Sabine	Big Sandy Creek nr Big Sandy	8019500	1 per season	226	223	99%	3.91	0.3	213	210	99%	3.68	0.3	206	204	99%	3.58	0.3
			2 per season	457	450	98%	7.89	0.1	432	424	98%	7.44	0.1	425	422	99%	7.40	0.1
Sabine	Sabine River nr Gladewater	8020000	1 per season	283	278	98%	4.88	0.2	220	217	99%	3.81	0.3	288	284	99%	4.98	0.2
			2 per season	512	493	96%	8.65	0.1	460	445	97%	7.81	0.1	503	480	95%	8.42	0.1
Sabine	Sabine River nr Beckville	8022040	1 per season	254	249	98%	4.37	0.2	259	250	97%	4.39	0.2	244	239	98%	4.19	0.2
			2 per season	504	480	95%	8.42	0.1	462	443	96%	7.77	0.1	490	490	100%	8.60	0.1
Sabine	Sabine River nr Bon Weir	8028500	1 per season	224	211	94%	3.70	0.3	258	244	95%	4.28	0.2	215	197	92%	3.46	0.3
			2 per season	425	390	92%	6.84	0.1	554	514	93%	9.02	0.1	374	347	93%	6.09	0.2
Sabine	Sabine River nr Ruliff	8030500	1 per season	226	219	97%	3.84	0.3	230	224	97%	3.93	0.3	229	225	98%	3.95	0.3
			2 per season	405	391	97%	6.86	0.1	500	477	95%	8.37	0.1	369	346	94%	6.07	0.2
Neches	Village Creek nr Kountze	8041500	1 per season	218	218	100%	3.82	0.3	243	242	100%	4.25	0.2	182	182	100%	3.19	0.3
			2 per season	444	436	98%	7.65	0.1	463	451	97%	7.91	0.1	395	394	100%	6.91	0.1
Neches	Neches River at Evadale	8041000	1 per season	226	219	97%	3.84	0.3	235	221	94%	3.88	0.3	214	211	99%	3.70	0.3
			2 per season	446	422	95%	7.40	0.1	465	429	92%	7.53	0.1	352	341	97%	5.98	0.2
Neches	Attoyac Bayou nr Chireno	8038000	1 per season						156	152	97%	3.38	0.3	180	174	97%	3.87	0.3
			2 per season						297	294	99%	6.53	0.2	374	366	98%	8.13	0.1
Neches	Angelina River nr Alto	8036500	1 per season	144	144	100%	3.89	0.3						136	135	99%	3.65	0.3
			2 per season	290	290	100%	7.84	0.1						267	266	100%	7.19	0.1
Neches	Neches River near Rockland	8033500	1 per season	224	213	95%	3.74	0.3	235	223	95%	3.91	0.3	202	196	97%	3.44	0.3
			2 per season	475	441	93%	7.74	0.1	456	420	92%	7.37	0.1	407	381	94%	6.68	0.1
Neches	Neches River at Neches	8032000	1 per season	247	243	98%	4.26	0.2	214	207	97%	3.63	0.3	250	245	98%	4.30	0.2
			2 per season	499	477	96%	8.37	0.1	489	467	96%	8.19	0.1	474	457	96%	8.02	0.1

Table 9b: Meeting Monthly Criteria from HEFR Frequency-Based Analysis - WAM Run 8 Regulated Flows from 1940 to 1996

Basin	USGS Gage Name	USGS Gage Number	Flow Condition	Full Period HEFR Matrix					Pre-Dam HEFR Matrix					Post-Dam HEFR Matrix				
				No of Pulses Meeting Peak Criteria	No of Pulses Meeting All Criteria	% Meeting Criteria	Frequency During Sim Period	Return During Sim Period (Years)	No of Pulses Meeting Peak Criteria	No of Pulses Meeting All Criteria	% Meeting Criteria	Frequency During Sim Period	Return During Sim Period (Years)	No of Pulses Meeting Peak Criteria	No of Pulses Meeting All Criteria	% Meeting Criteria	Frequency During Sim Period	Return During Sim Period (Years)
Sabine	Big Sandy Creek nr Big Sandy	8019500	1 per season	215	214	100%	3.75	0.3	204	203	100%	3.56	0.3	198	195	98%	3.42	0.3
			2 per season	437	431	99%	7.56	0.1	417	409	98%	7.18	0.1	411	405	99%	7.11	0.1
Sabine	Sabine River nr Gladewater	8020000	1 per season	200	198	99%	3.47	0.3	155	155	100%	2.72	0.4	199	196	98%	3.44	0.3
			2 per season	424	408	96%	7.16	0.1	372	363	98%	6.37	0.2	415	399	96%	7.00	0.1
Sabine	Sabine River nr Beckville	8022040	1 per season	206	201	98%	3.53	0.3	205	195	95%	3.42	0.3	176	173	98%	3.04	0.3
			2 per season	440	423	96%	7.42	0.1	383	371	97%	6.51	0.2	428	428	100%	7.51	0.1
Sabine	Sabine River nr Bon Weir	8028500	1 per season	254	236	93%	4.14	0.2	365	337	92%	5.91	0.2	232	212	91%	3.72	0.3
			2 per season	486	451	93%	7.91	0.1	653	608	93%	10.67	0.1	425	396	93%	6.95	0.1
Sabine	Sabine River nr Ruliff	8030500	1 per season	283	275	97%	4.82	0.2	354	333	94%	5.84	0.2	258	254	98%	4.46	0.2
			2 per season	527	500	95%	8.77	0.1	577	557	97%	9.77	0.1	461	376	82%	6.60	0.2
Neches	Village Creek nr Kountze	8041500	1 per season	221	220	100%	3.86	0.3	243	242	100%	4.25	0.2	184	184	100%	3.23	0.3
			2 per season	448	440	98%	7.72	0.1	466	454	97%	7.96	0.1	396	395	100%	6.93	0.1
Neches	Neches River at Evadale	8041000	1 per season	219	213	97%	3.74	0.3	210	202	96%	3.54	0.3	211	206	98%	3.61	0.3
			2 per season	398	376	94%	6.60	0.2	417	390	94%	6.84	0.1	325	314	97%	5.51	0.2
Neches	Attoyac Bayou nr Chireno	8038000	1 per season						156	152	97%	3.38	0.3	179	173	97%	3.84	0.3
			2 per season						293	291	99%	6.47	0.2	371	364	98%	8.09	0.1
Neches	Angelina River nr Alto	8036500	1 per season	133	133	100%	3.59	0.3						121	119	98%	3.22	0.3
			2 per season	265	265	100%	7.16	0.1						243	243	100%	6.57	0.2
Neches	Neches River near Rockland	8033500	1 per season	216	206	95%	3.61	0.3	222	210	95%	3.68	0.3	196	189	96%	3.32	0.3
			2 per season	444	413	93%	7.25	0.1	424	393	93%	6.89	0.1	385	362	94%	6.35	0.2
Neches	Neches River at Neches	8032000	1 per season	202	200	99%	3.51	0.3	169	168	99%	2.95	0.3	169	168	99%	2.95	0.3
			2 per season	377	366	97%	6.42	0.2	373	358	96%	6.28	0.2	373	358	96%	6.28	0.2

Table 9c: Meeting Monthly Criteria from HEFR Frequency-Based Analysis - WAM Run 3 Regulated Flows from 1940 to 1996

Basin	USGS Gage Name	USGS Gage Number	Flow Condition	Full Period HEFR Matrix					Pre-Dam HEFR Matrix					Post-Dam HEFR Matrix				
				No of Pulses Meeting Peak Criteria	No of Pulses Meeting All Criteria	% Meeting Criteria	Frequency During Sim Period	Return During Sim Period (Years)	No of Pulses Meeting Peak Criteria	No of Pulses Meeting All Criteria	% Meeting Criteria	Frequency During Sim Period	Return During Sim Period (Years)	No of Pulses Meeting Peak Criteria	No of Pulses Meeting All Criteria	% Meeting Criteria	Frequency During Sim Period	Return During Sim Period (Years)
Sabine	Big Sandy Creek nr Big Sandy	8019500	1 per season	214	213	100%	3.74	0.3	204	203	100%	3.56	0.3	199	196	98%	3.44	0.3
			2 per season	437	431	99%	7.56	0.1	414	405	98%	7.11	0.1	414	409	99%	7.18	0.1
Sabine	Sabine River nr Gladewater	8020000	1 per season	171	171	100%	3.00	0.3	127	126	99%	2.21	0.5	170	168	99%	2.95	0.3
			2 per season	408	396	97%	6.95	0.1	351	344	98%	6.04	0.2	406	391	96%	6.86	0.1
Sabine	Sabine River nr Beckville	8022040	1 per season	160	158	99%	2.77	0.4	173	167	97%	2.93	0.3	139	138	99%	2.42	0.4
			2 per season	395	384	97%	6.74	0.1	349	340	97%	5.96	0.2	390	390	100%	6.84	0.1
Sabine	Sabine River nr Bon Weir	8028500	1 per season	125	121	97%	2.12	0.5	170	164	96%	2.88	0.3	111	101	91%	1.77	0.6
			2 per season	272	266	98%	4.67	0.2	409	398	97%	6.98	0.1	234	232	99%	4.07	0.2
Sabine	Sabine River nr Ruliff	8030500	1 per season	175	173	99%	3.04	0.3	235	231	98%	4.05	0.2	177	175	99%	3.07	0.3
			2 per season	453	445	98%	7.81	0.1	513	505	98%	8.86	0.1	393	348	89%	6.11	0.2
Neches	Village Creek nr Kountze	8041500	1 per season	218	218	100%	3.82	0.3	243	242	100%	4.25	0.2	183	183	100%	3.21	0.3
			2 per season	445	437	98%	7.67	0.1	464	452	97%	7.93	0.1	395	394	100%	6.91	0.1
Neches	Neches River at Evadale	8041000	1 per season	194	190	98%	3.33	0.3	274	258	94%	4.53	0.2	169	165	98%	2.89	0.3
			2 per season	528	496	94%	8.70	0.1	559	506	91%	8.88	0.1	330	322	98%	5.65	0.2
Neches	Attoyac Bayou nr Chireno	8038000	1 per season						154	151	98%	3.36	0.3	177	172	97%	3.82	0.3
			2 per season						290	289	100%	6.42	0.2	368	362	98%	8.04	0.1
Neches	Angelina River nr Alto	8036500	1 per season	107	107	100%	2.89	0.3						105	105	100%	2.84	0.4
			2 per season	231	231	100%	6.24	0.2						208	208	100%	5.62	0.2
Neches	Neches River near Rockland	8033500	1 per season	195	190	97%	3.33	0.3	203	193	95%	3.39	0.3	175	170	97%	2.98	0.3
			2 per season	396	374	94%	6.56	0.2	381	361	95%	6.33	0.2	348	333	96%	5.84	0.2
Neches	Neches River at Neches	8032000	1 per season	142	141	99%	2.47	0.4	123	120	98%	2.11	0.5	146	144	99%	2.53	0.4
			2 per season	306	297	97%	5.21	0.2	329	320	97%	5.61	0.2	285	276	97%	4.84	0.2

and the minimum criteria for volume and duration divided by the total number of pulses meeting the peak criteria. The frequency is the number of the events meeting all three criteria divided by the number of years. The return period is simply the inverse of the frequency.

The method of calculating return periods in these tables do not match the method used to calculate return periods in HEFR.

Looking at these results shows that the daily analysis is less favorable than looking at flows on an annual basis. Quite a few of the matrix values are met less than 10 percent of the time, even for the base flows. For the base flows, it is particularly evident that the naturalized flows do not meet the summer criteria for the gages impacted by hydropower, namely Evadale, Ruliff, and Bon Wier. It is unclear if this discrepancy is the result of inconsistencies between the methods for determining wet, average, or dry, the result of having flow at times of the year that are different than the HEFR matrix values, or some other factors.

In Table 5 another discrepancy in the frequency of meeting base flows in the winter at the Ruliff and Bon Wier gages. The Bon Wier gage is located upstream of the Ruliff gage, and both are downstream of Toledo Bend Reservoir. The wet and average base flow criteria are larger at Bon Wier than at Ruliff. This is the result of using National Weather Service (NWS) stage data to define overbanking events. According to the NWS, a bankfull stage at Bon Wier is 22,500 cfs, which is about the 94th percentile of all flows. At Ruliff, the NWS bankfull stage is much lower at 9,880 cfs, or about the 71st percentile of all flows. These flows were used as thresholds in the HEFR analysis. As a result fewer base flows events are reclassified as pulse flows at Bon Wier when compared to Ruliff. As a result there are higher base flows in the Bon Wier HEFR analysis than in the Ruliff analysis. This is a good example of how parameter selection can affect results. In addition, there are relatively few base flow days during the winter months. As a result there are fewer days with which to generate statistics, and a few high or low values can have a larger influence on results than seasons with more base flows.

In general, it would be expected that naturalized flows would meet HEFR criteria at least half of the time. However the results show that the frequency of meeting criteria for base flows and pulse flows using the original percentile-based method can be less than expected. Possible explanations include:

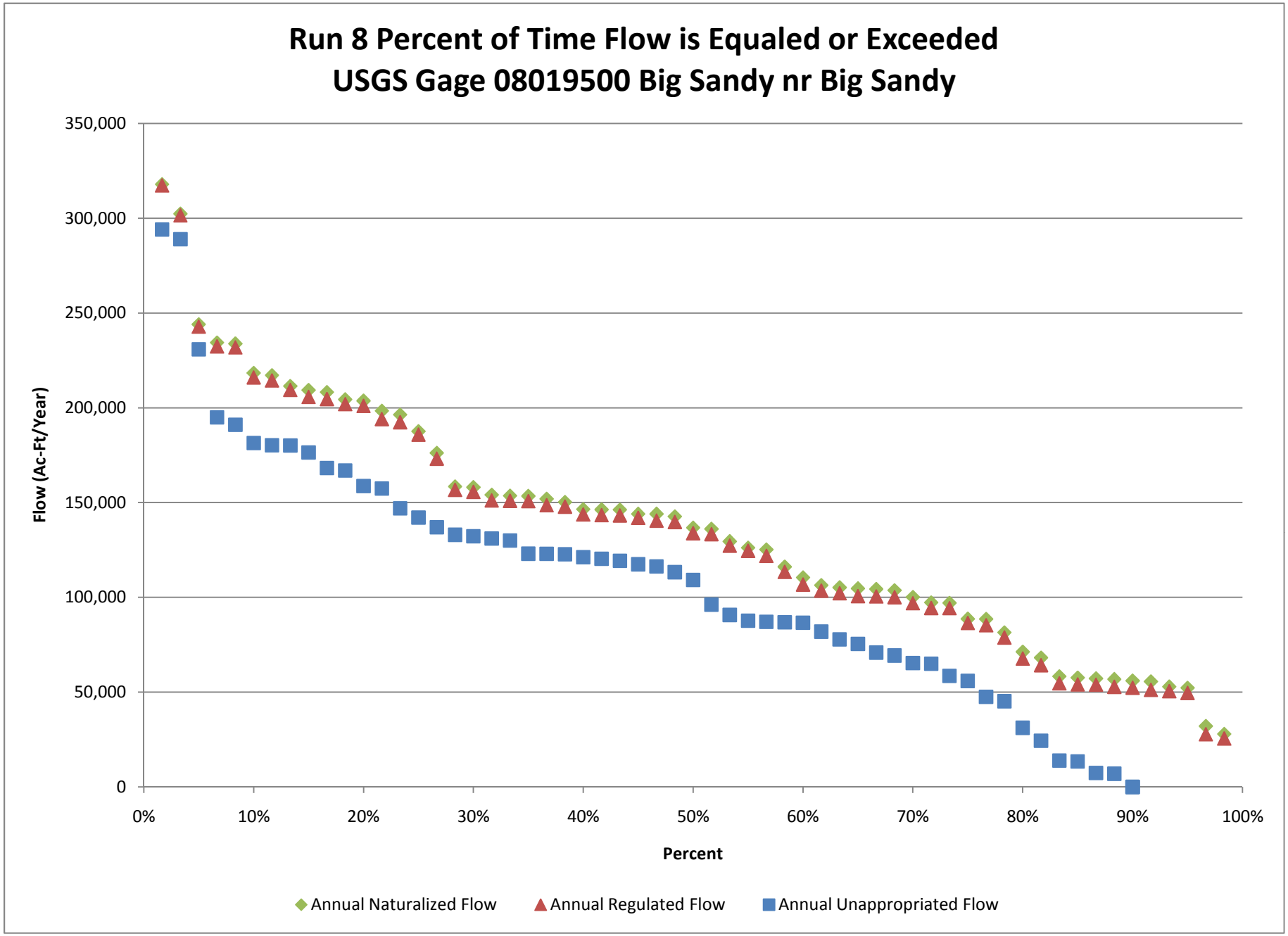
- *Definition of wet, average and dry conditions.* The HEFR analysis does not have any external reference to climatic conditions. It only assumes that different percentiles are applicable to these conditions. The WAM applications in this memorandum use an external reference to determine wet, average or dry conditions. As a result, fewer pulse events qualify than assumed in the HEFR analysis.
- *Inconsistencies between WAM flows and historical flows.* Flow naturalization is not a perfect process. Inaccurate data, timing issues and unaccounted-for losses in flow adjustments can bias results. There are also inherent inaccuracies with distributing monthly WAM flows to daily values that could also bias results.
- *Inconsistent periods of record.* The period of record can change HEFR results, sometimes significantly. The WAM has a different period of analysis than any of the HEFR periods.

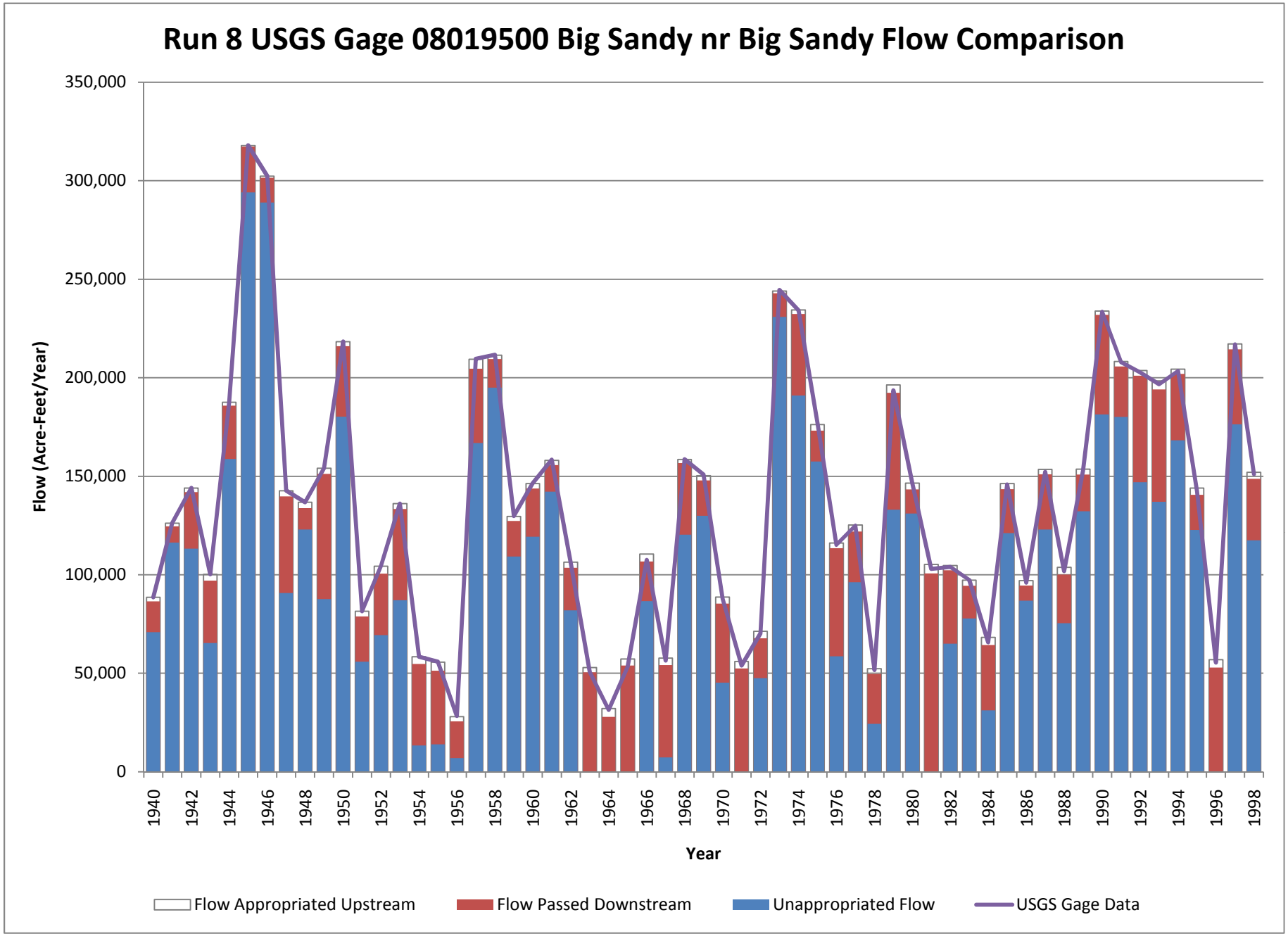
Summary and Conclusions

Flow data from the Sabine and Neches WAMs were extracted for 11 of the 12 BBEST stream gages. (Big Cow Creek near Newton is not in the Sabine WAM.) An analysis of these flows shows that, even though there are portions of these basins with little unappropriated flow, a fairly substantial amount of instream flow is attributable to the combination of unappropriated water plus water reserved for existing water rights. The WAM results imply that, even with full development of existing water rights, substantial flows occur in the Sabine and Neches Rivers that can be managed for environmental and other purposes.

The regulated flow volumes from the WAM compare favorably to the HEFR volumes on an annual basis, with most of the volumes very close to or exceeding their HEFR statistical equivalents. However, when the HEFR matrices are applied to estimated daily flows, it appears that the requirements would be met less frequently than the annual volumes imply. It is unclear how much of this discrepancy is the result of application of the HEFR matrices that is inconsistent with the HEFR calculations or an actual problem with the distribution of the flow components.

Attachment A
Annual WAM Flow Graphics for BBEST Gages


Run 8 Percent of Time Flow is Equaled or Exceeded
USGS Gage 08019500 Big Sandy nr Big Sandy
Flow (Ac-Ft/Year)
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percent
Annual Naturalized Flow
Annual Regulated Flow
Annual Unappropriated Flow


Run 8 USGS Gage 08019500 Big Sandy nr Big Sandy Flow Comparison
Flow (Acre-Feet/Year)
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
1940
1942
1944
1946
1948
1950
1952
1954
1956
1958
1960
1962
1964
1966
1968
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1980
1982
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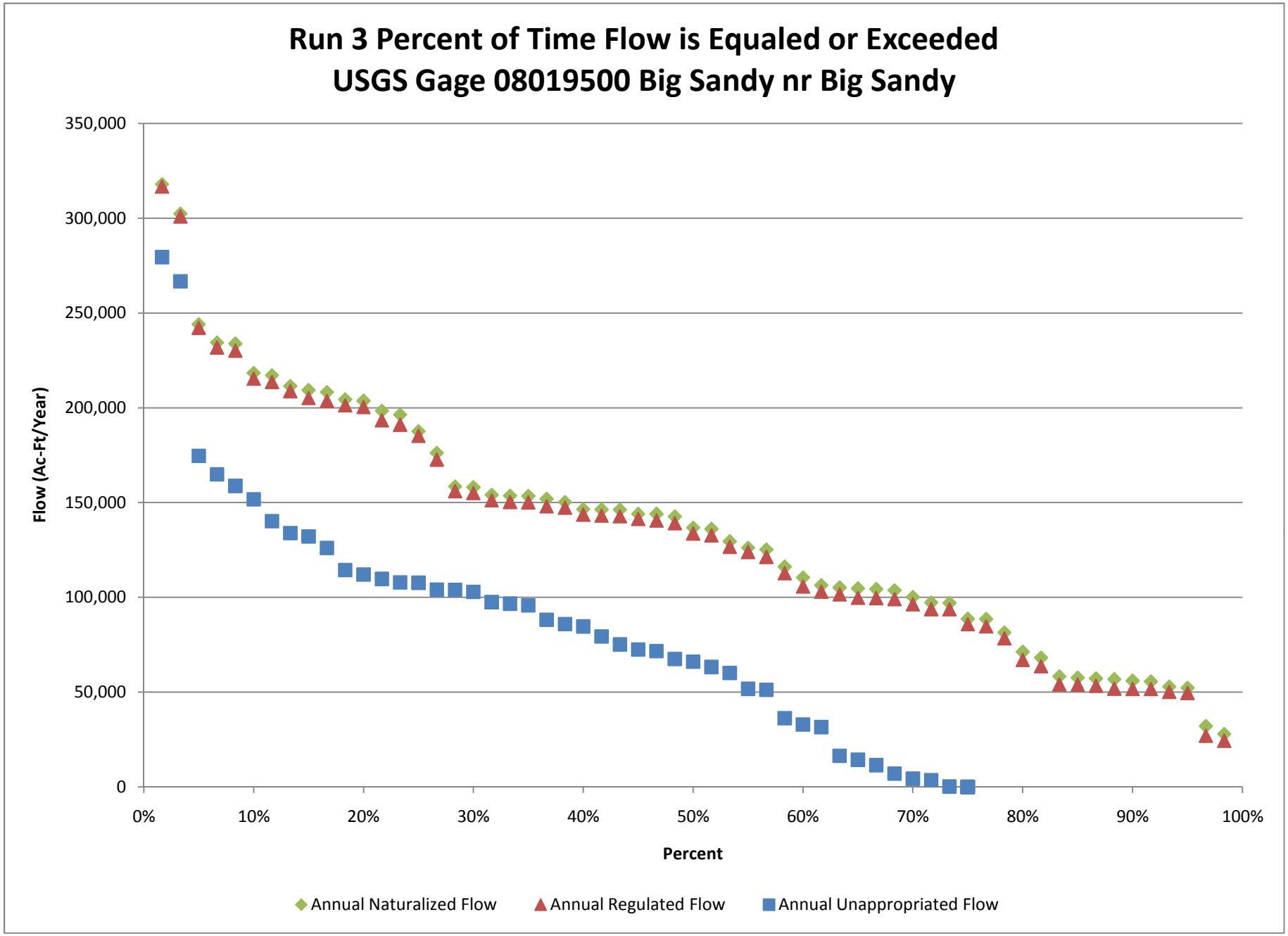
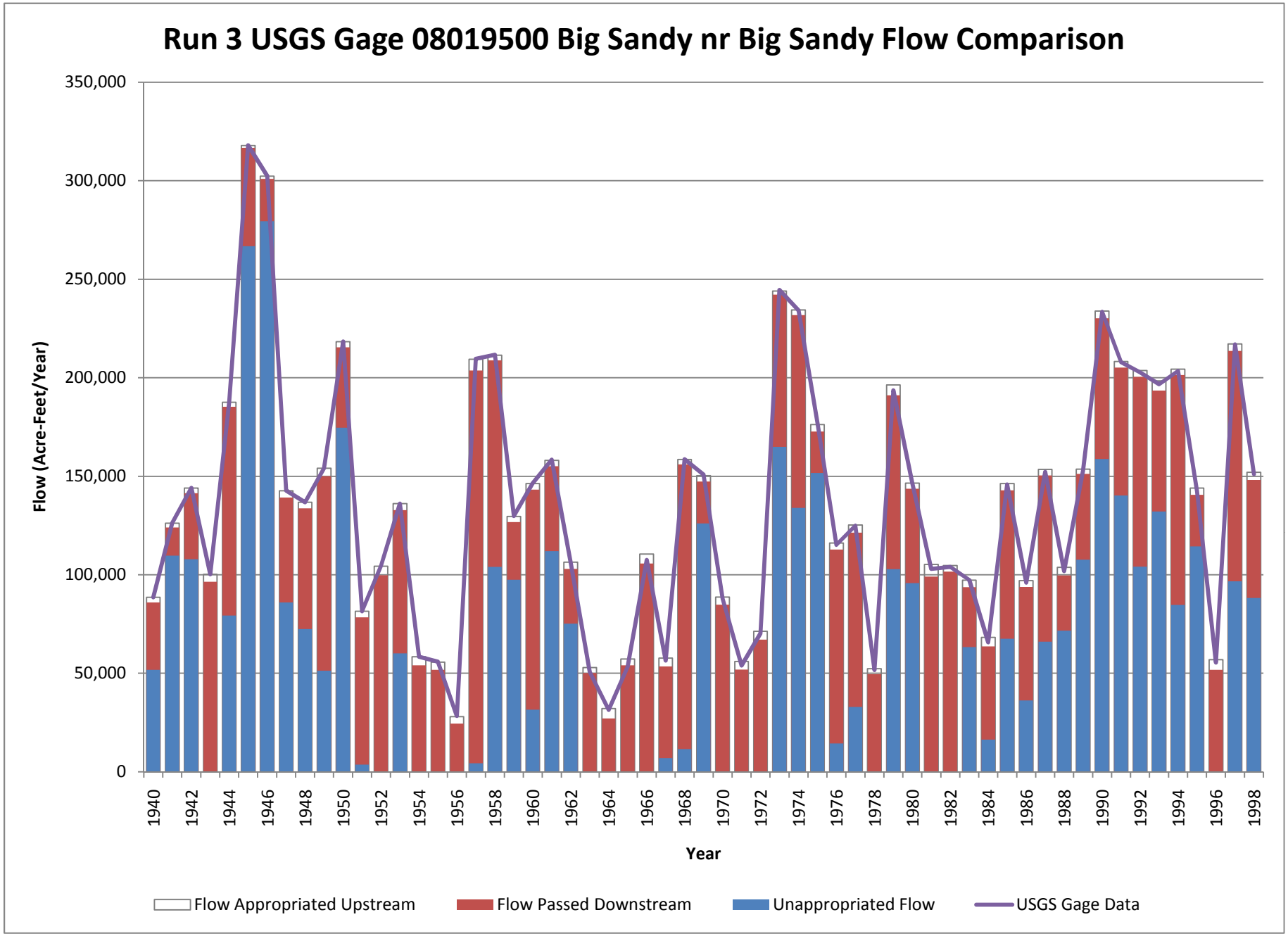
1988
1990
1992
1994
1996
1998
Year
Flow Appropriated Upstream
Flow Passed Downstream
Unappropriated Flow
USGS Gage Data


Run 3 Percent of Time Flow is Equaled or Exceeded
USGS Gage 08019500 Big Sandy nr Big Sandy
Flow (Ac-Ft/Year)
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percent
Annual Naturalized Flow
Annual Regulated Flow
Annual Unappropriated Flow


Run 3 USGS Gage 08019500 Big Sandy nr Big Sandy Flow Comparison
Flow (Acre-Feet/Year)
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
1940
1942
1944
1946
1948
1950
1952
1954
1956
1958
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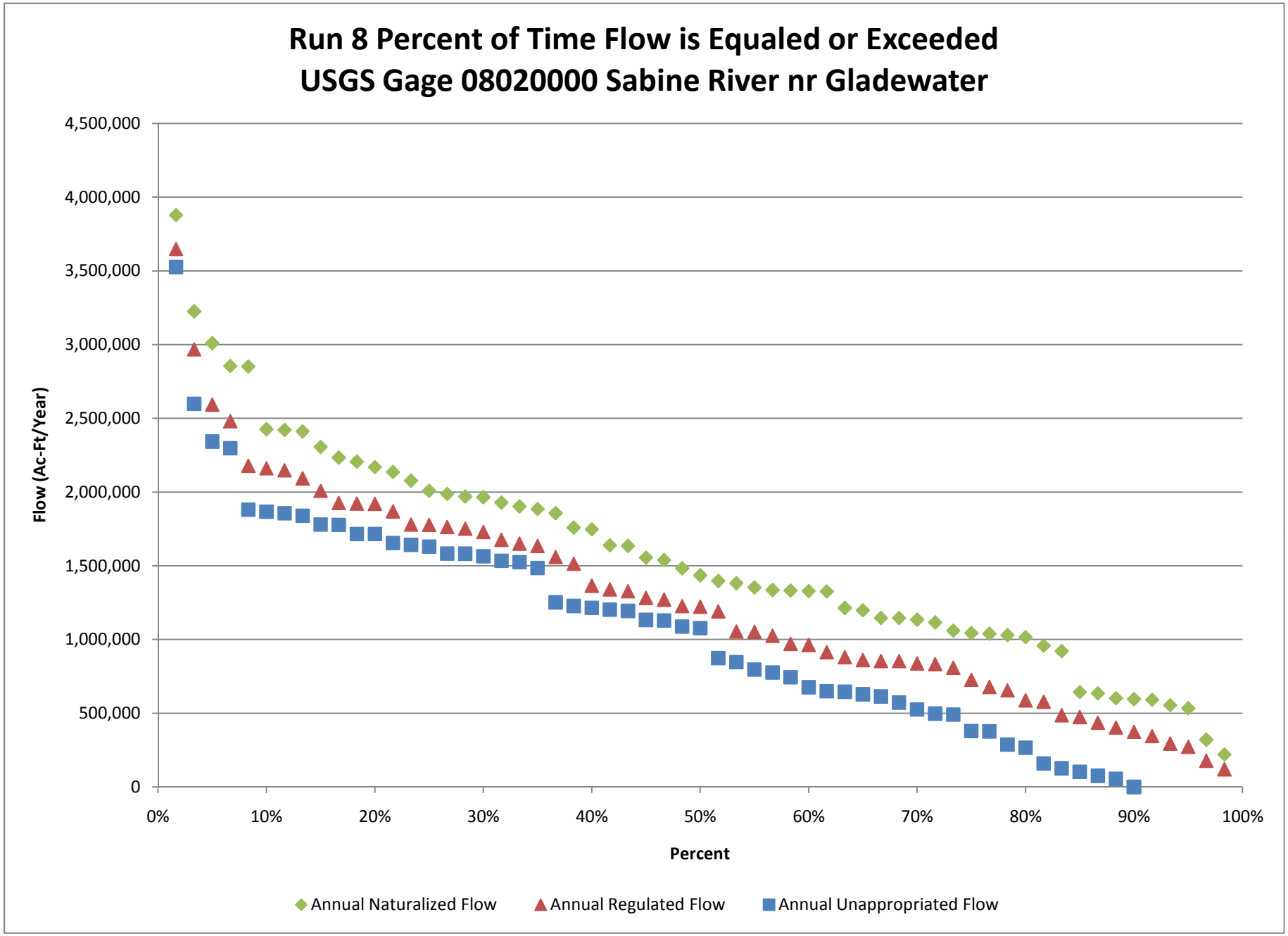
1996
1998
Year
Flow Appropriated Upstream
Flow Passed Downstream
Unappropriated Flow
USGS Gage Data


Run 8 Percent of Time Flow is Equaled or Exceeded
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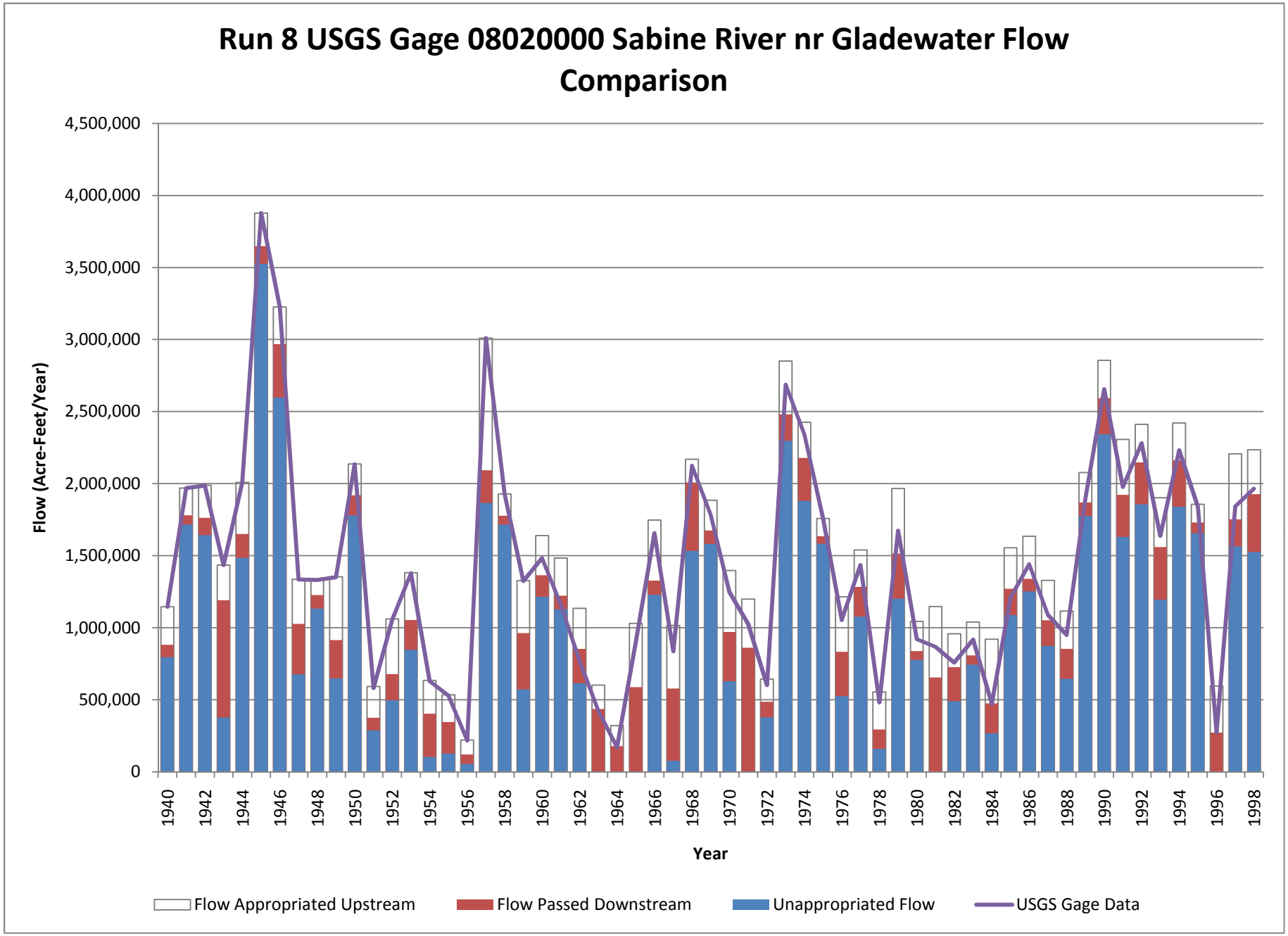
Flow (Ac-Ft/Year)
4,500,000
4,000,000
3,500,000
3,000,000
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percent
Annual Naturalized Flow
Annual Regulated Flow
Annual Unappropriated Flow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Flow (Acre-Feet/Year)
4,500,000
4,000,000
3,500,000
3,000,000
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
1940
1942
1944
1946
1948
1950
1952
1954
1956
1958
1960
1962
1964
1966
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1970
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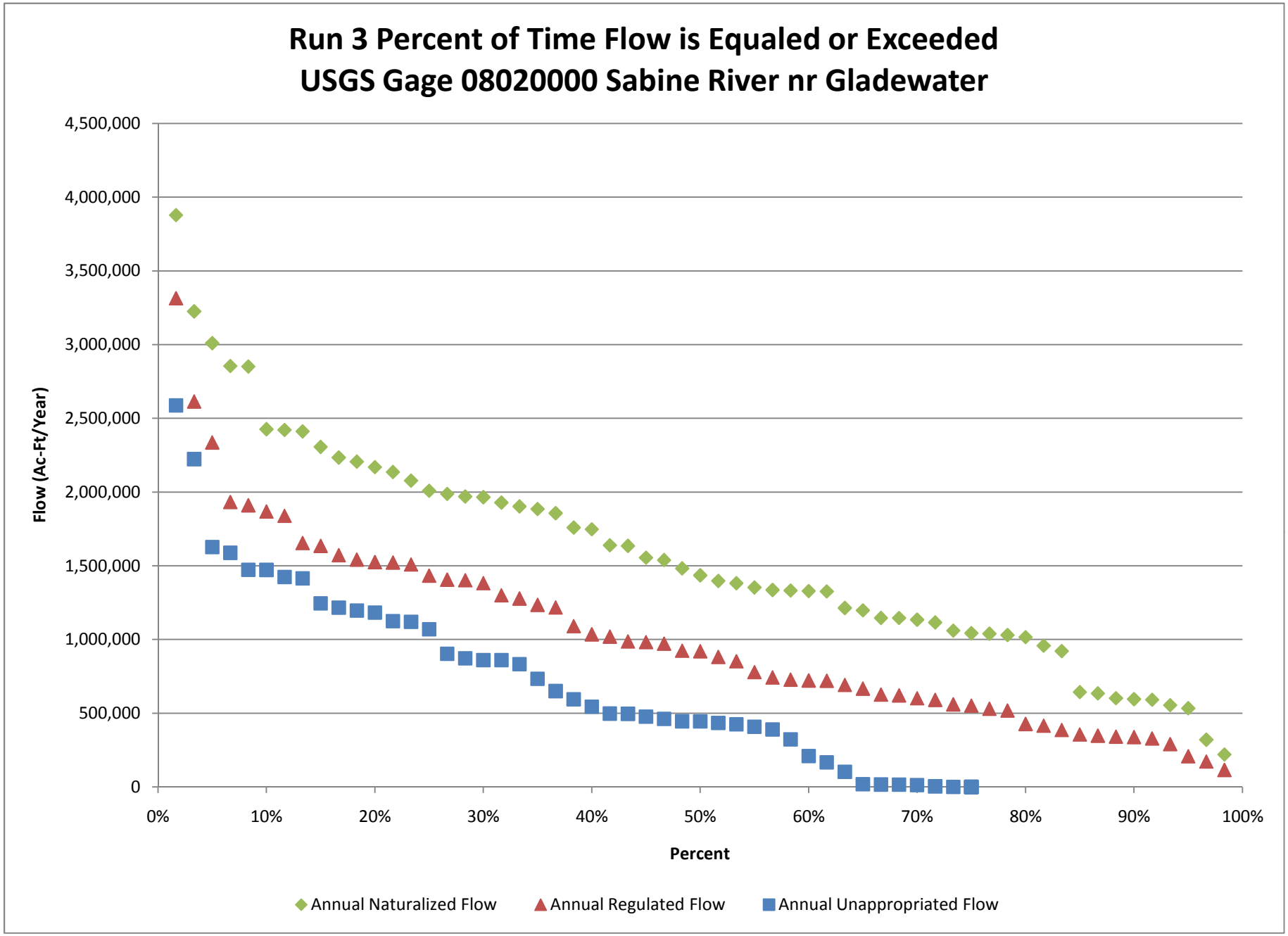
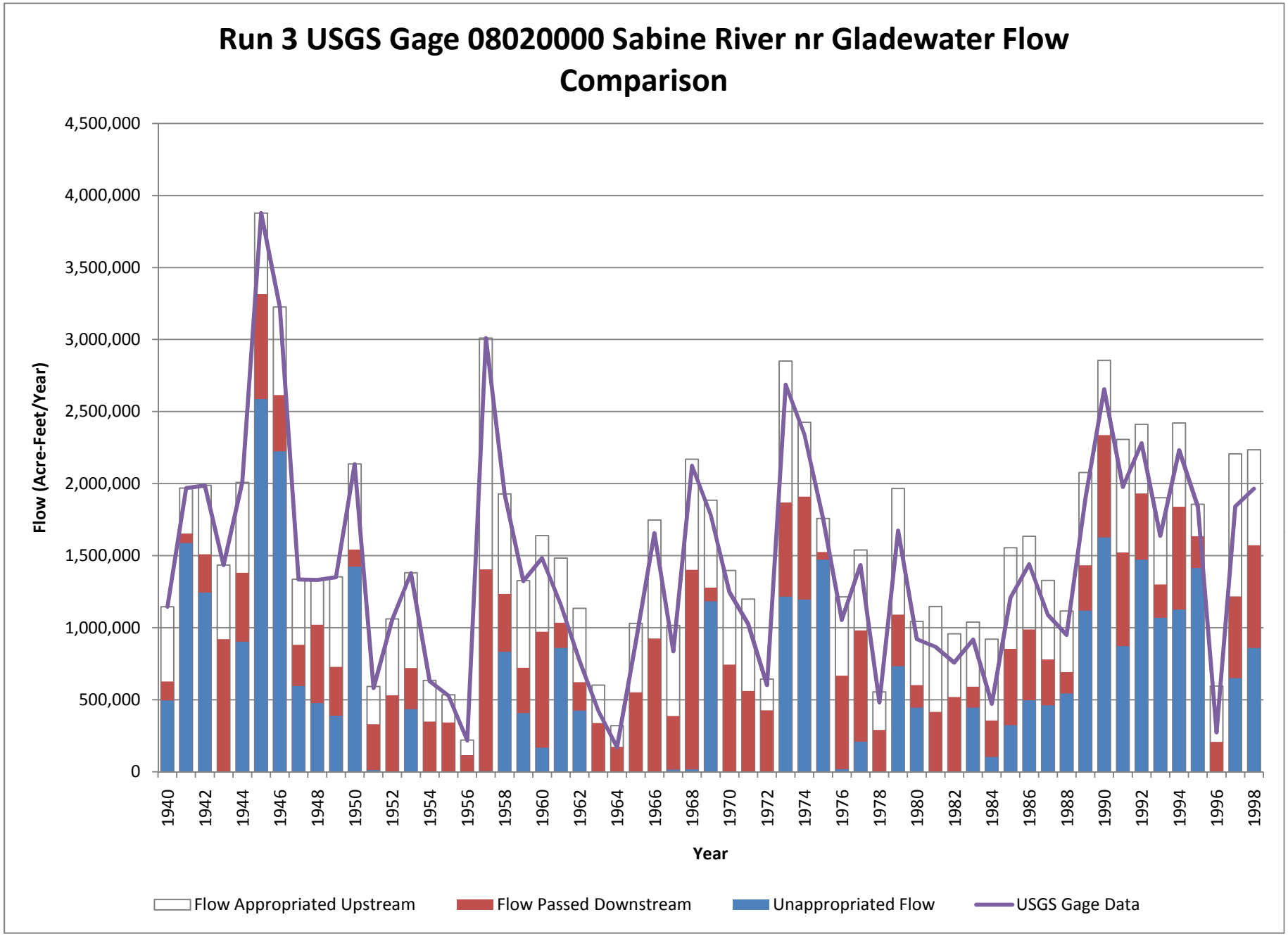
1996
1998
Year
Flow Appropriated Upstream
Flow Passed Downstream
Unappropriated Flow
USGS Gage Data


Run 3 Percent of Time Flow is Equaled or Exceeded
USGS Gage 08020000 Sabine River nr Gladewater
Flow (Ac-Ft/Year)
4,500,000
4,000,000
3,500,000
3,000,000
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percent
Annual Naturalized Flow
Annual Regulated Flow
Annual Unappropriated Flow


Run 3 USGS Gage 08020000 Sabine River nr Gladewater Flow Comparison
Flow (Acre-Feet/Year)
4,500,000
4,000,000
3,500,000
3,000,000
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
1940
1942
1944
1946
1948
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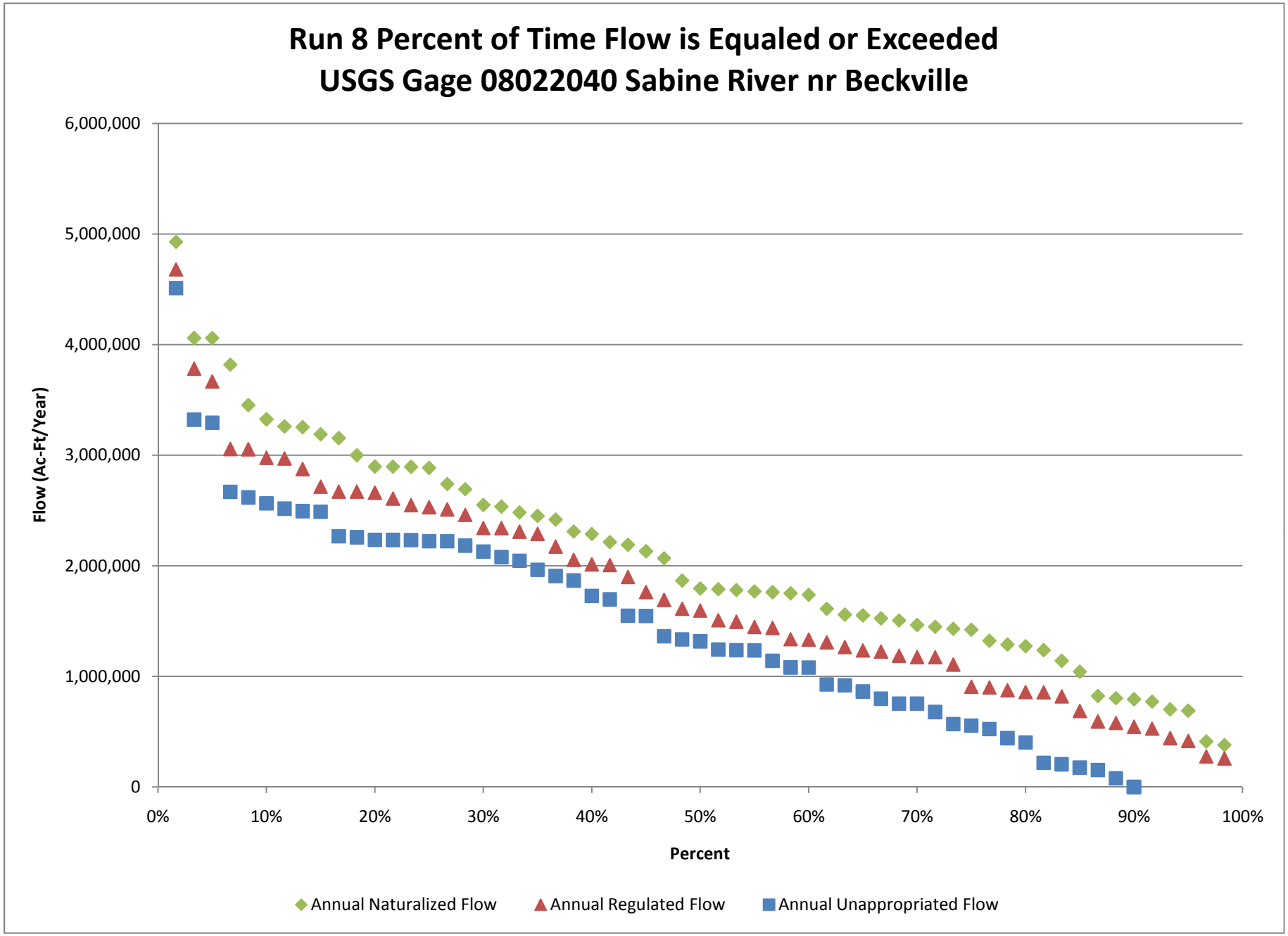
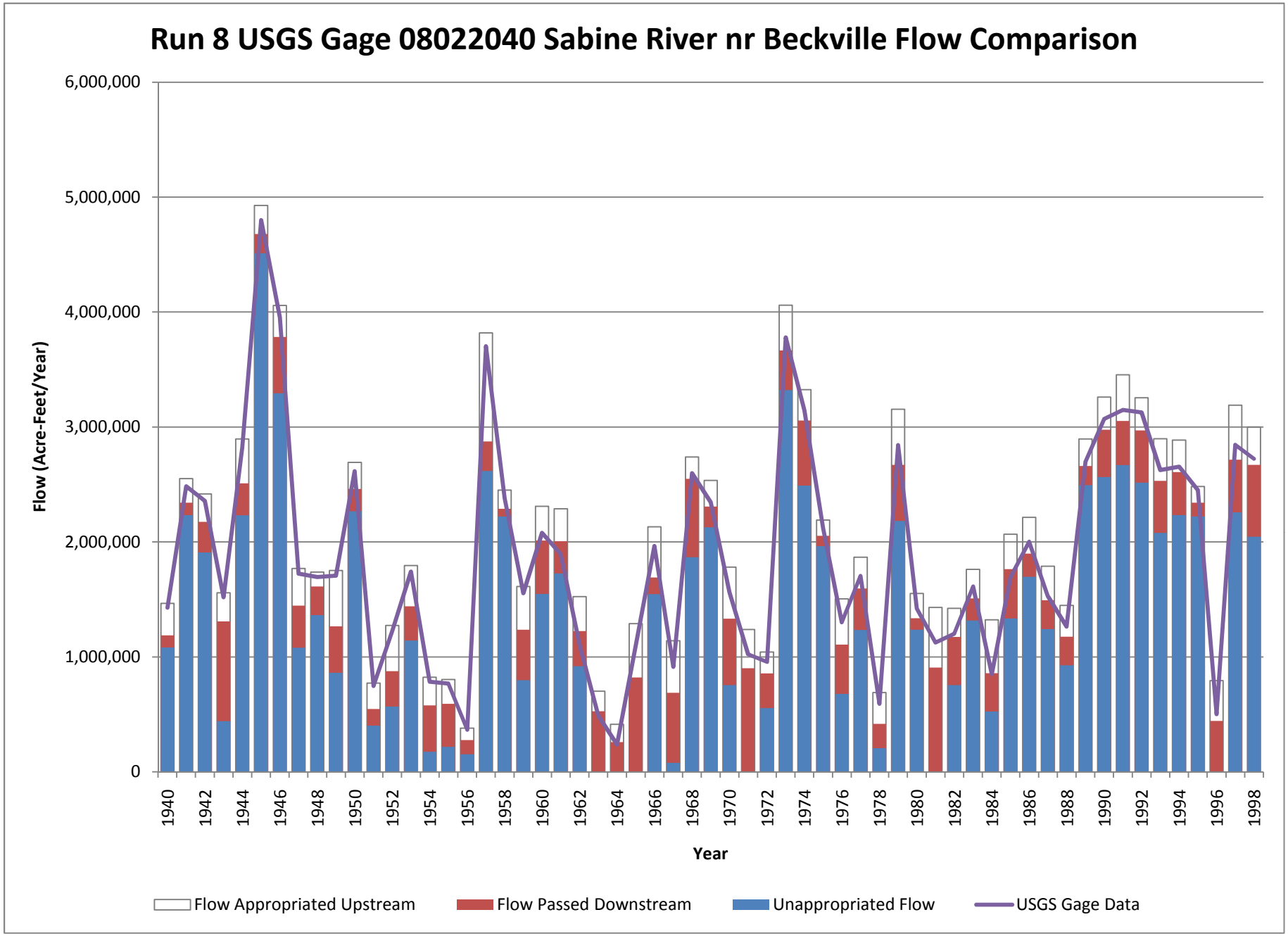
1998
Year
Flow Appropriated Upstream
Flow Passed Downstream
Unappropriated Flow
USGS Gage Data


Run 8 Percent of Time Flow is Equaled or Exceeded
USGS Gage 08022040 Sabine River nr Beckville
6,000,000
5,000,000
4,000,000
3,000,000
2,000,000
1,000,000
0
Flow (Ac-Ft/Year)
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percent
Annual Naturalized Flow
Annual Regulated Flow
Annual Unappropriated Flow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6,000,000
5,000,000
4,000,000
3,000,000
2,000,000
1,000,000
0
Flow (Acre-Feet/Year)
1940
1942
1944
1946
1948
1950
1952
1954
1956
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1970
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1974
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1986
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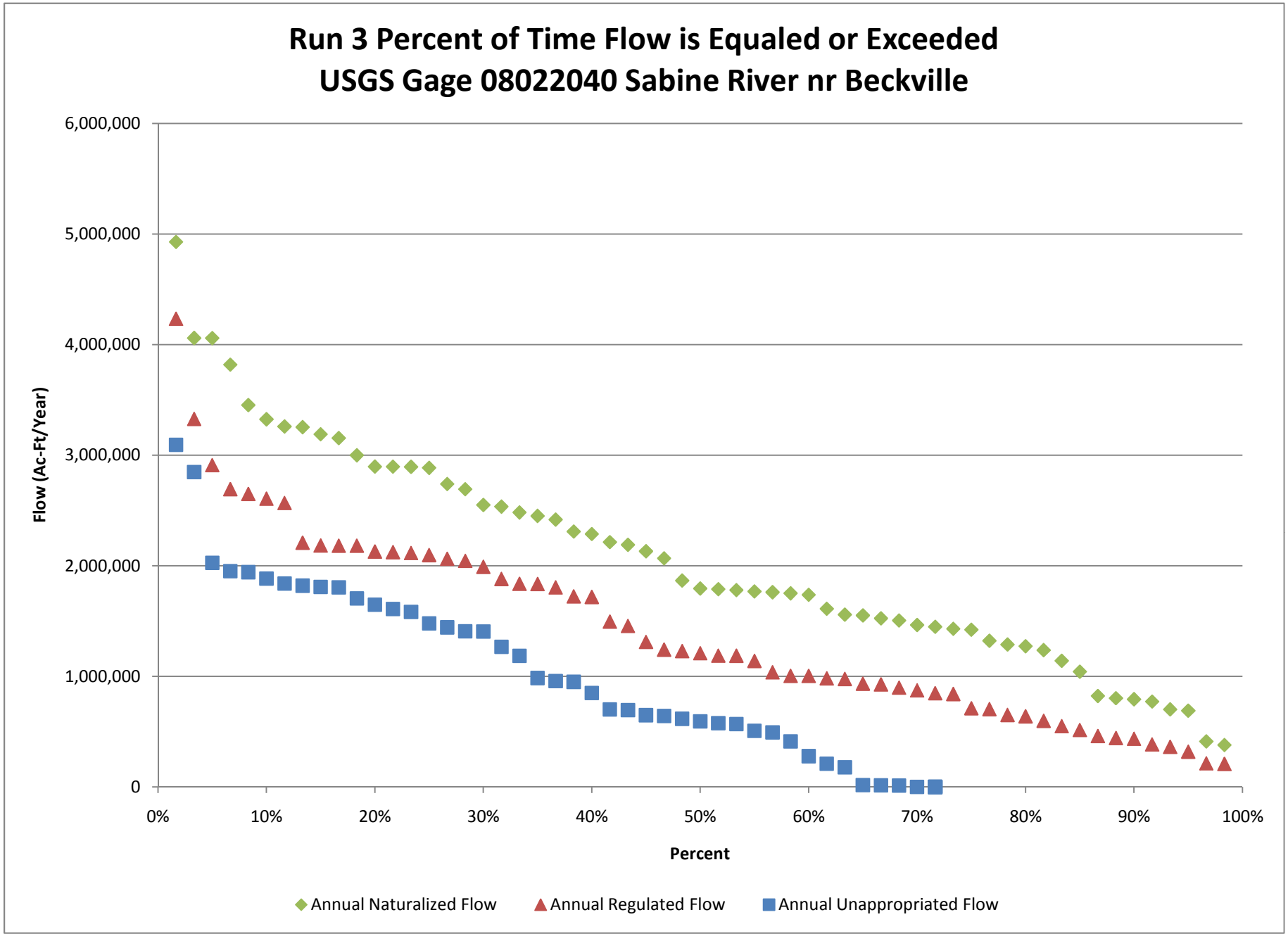
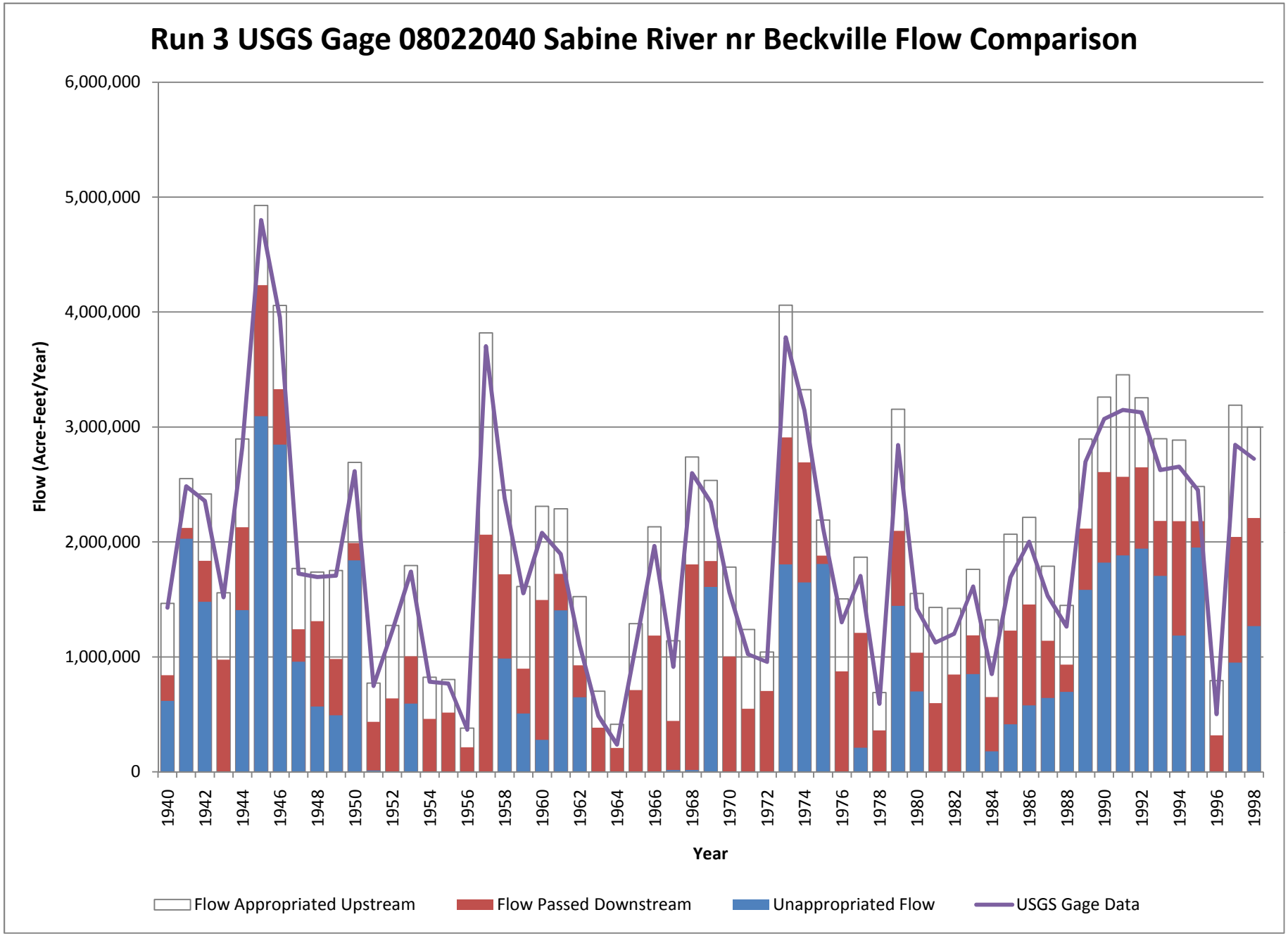
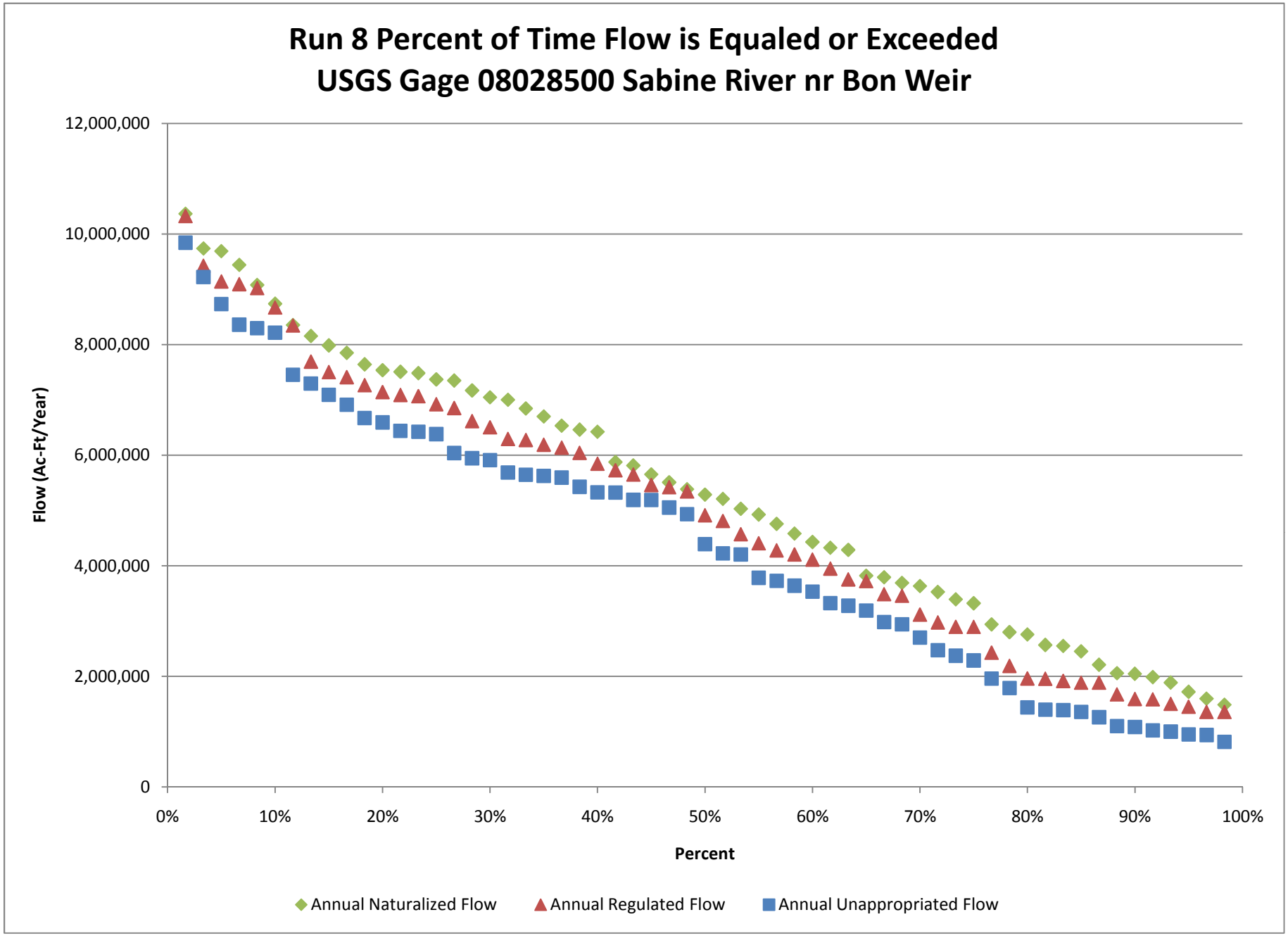
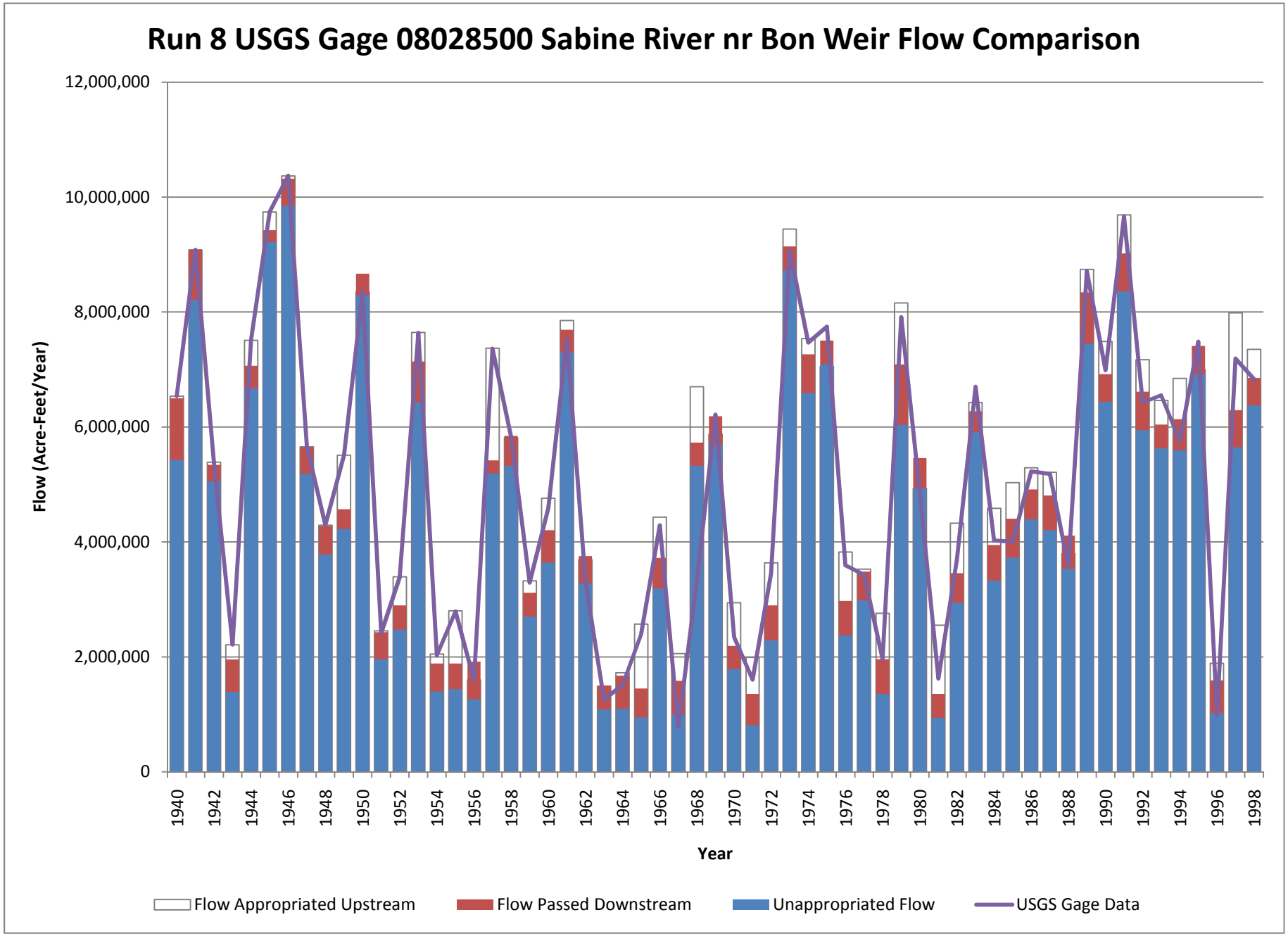
1996
1998
Year
Flow Appropriated Upstream
Flow Passed Downstream
Unappropriated Flow
USGS Gage Data


Run 3 Percent of Time Flow is Equaled or Exceeded
USGS Gage 08022040 Sabine River nr Beckville
Flow (Ac-Ft/Year)
6,000,000
5,000,000
4,000,000
3,000,000
2,000,000
1,000,000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percent
Annual Naturalized Flow
Annual Regulated Flow
Annual Unappropriated Flow


Run 3 USGS Gage 08022040 Sabine River nr Beckville Flow Comparison
6,000,000
5,000,000
4,000,000
3,000,000
2,000,000
1,000,000
0
Flow (Acre-Feet/Year)
1940
1942
1944
1946
1948
1950
1952
1954
1956
1958
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
Year
Flow Appropriated Upstream
Flow Passed Downstream
Unappropriated Flow
USGS Gage Data


Run 8 Percent of Time Flow is Equaled or Exceeded
USGS Gage 08028500 Sabine River nr Bon Weir
12,000,000
10,000,000
8,000,000
6,000,000
4,000,000
2,000,000
0
Flow (Ac-Ft/Year)
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percent
Annual Naturalized Flow
Annual Regulated Flow
Annual Unappropriated Flow


Run 8 USGS Gage 08028500 Sabine River nr Bon Weir Flow Comparison
12,000,000
10,000,000
8,000,000
6,000,000
4,000,000
2,000,000
0
Flow (Acre-Feet/Year)
1940
1942
1944
1946
1948
1950
1952
1954
1956
1958
1960
1962
1964
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1970
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1974
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1992
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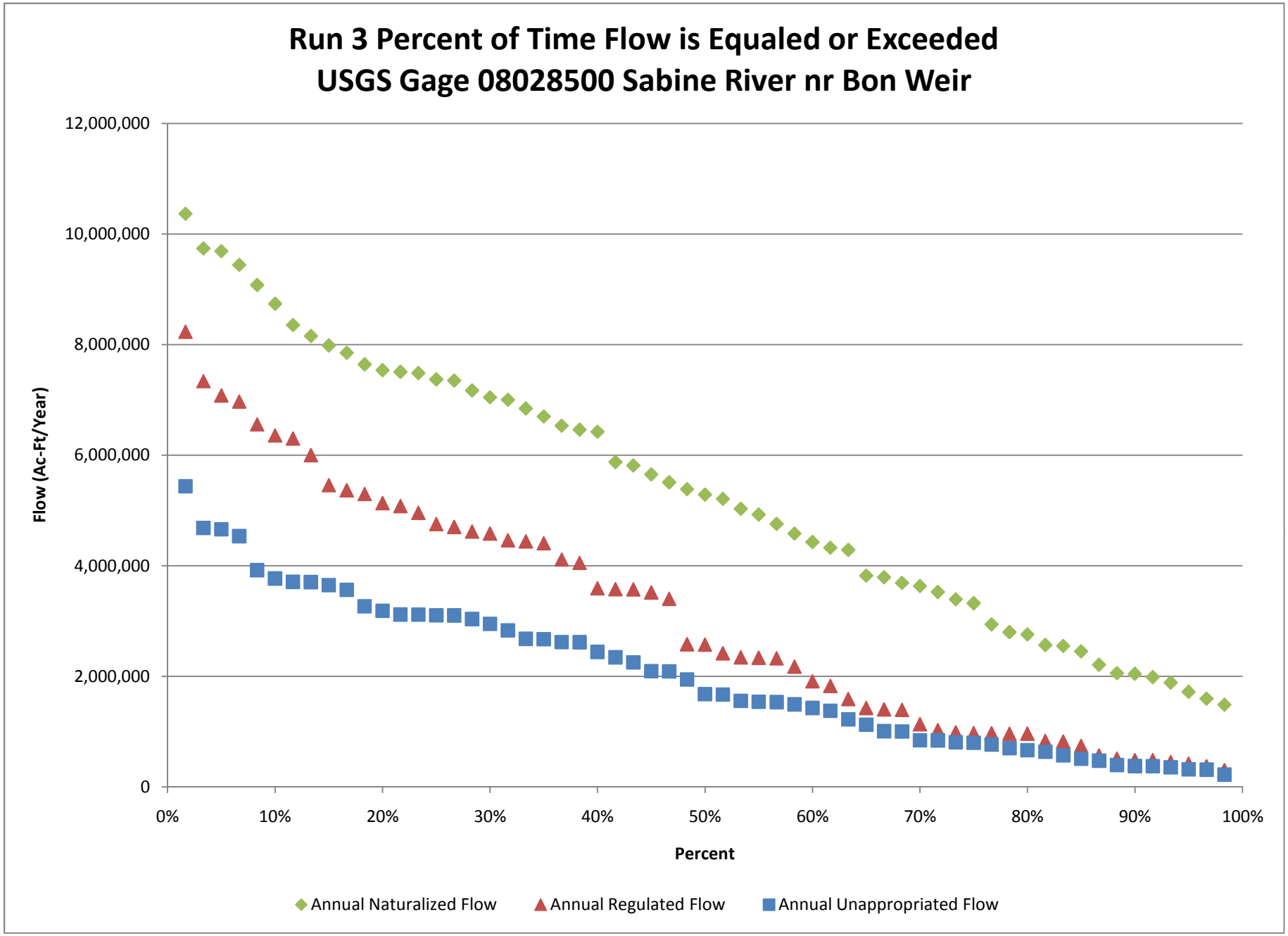
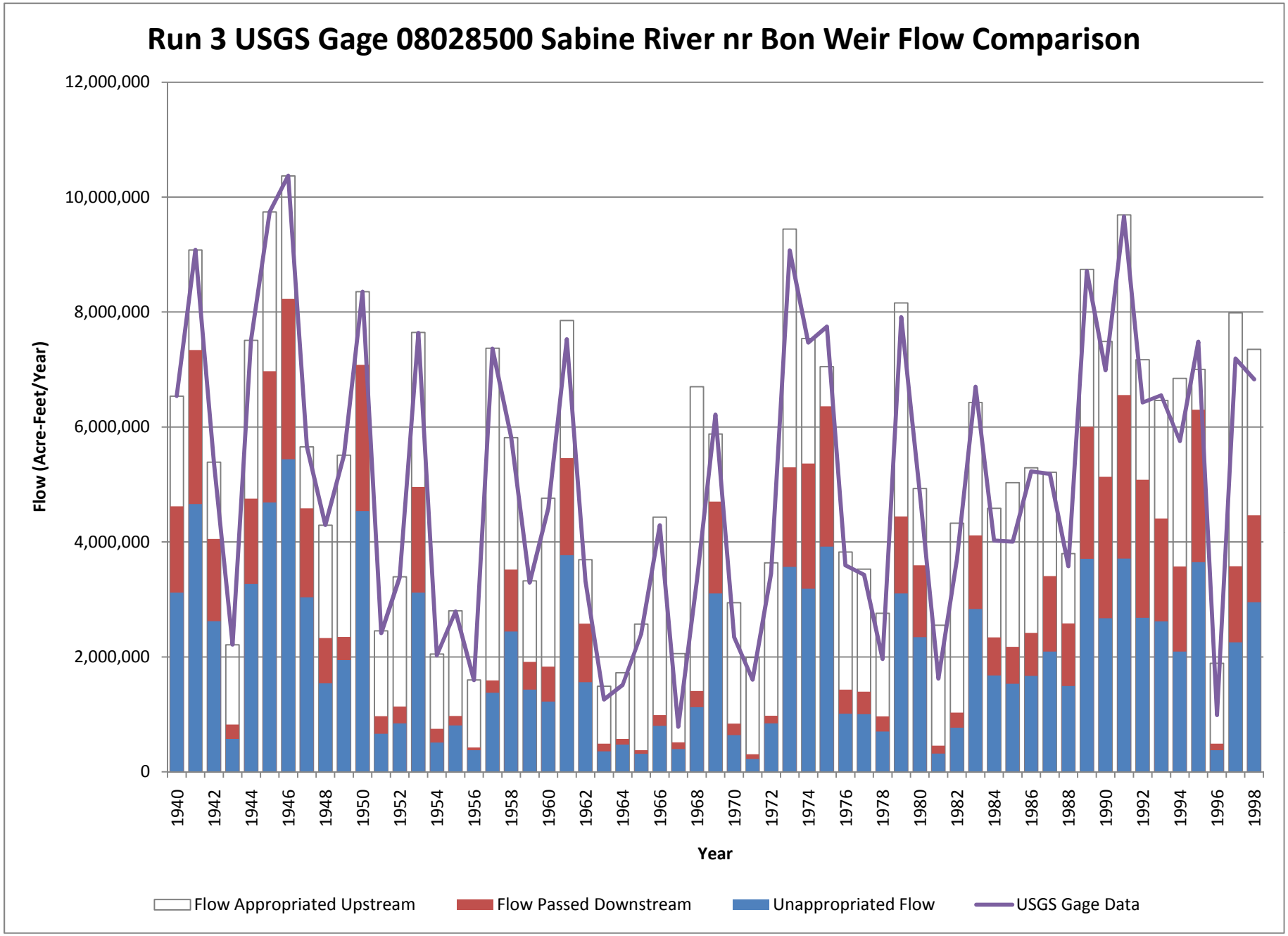
1996
1998
Year
Flow Appropriated Upstream
Flow Passed Downstream
Unappropriated Flow
USGS Gage Data


Run 3 Percent of Time Flow is Equaled or Exceeded
USGS Gage 08028500 Sabine River nr Bon Weir
12,000,000
10,000,000
8,000,000
6,000,000
4,000,000
2,000,000
0
Flow (Ac-Ft/Year)
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percent
Annual Naturalized Flow
Annual Regulated Flow
Annual Unappropriated Flow


Run 3 USGS Gage 08028500 Sabine River nr Bon Weir Flow Comparison
12,000,000
10,000,000
8,000,000
6,000,000
4,000,000
2,000,000
0
Flow (Acre-Feet/Year)
1940
1942
1944
1946
1948
1950
1952
1954
1956
1958
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
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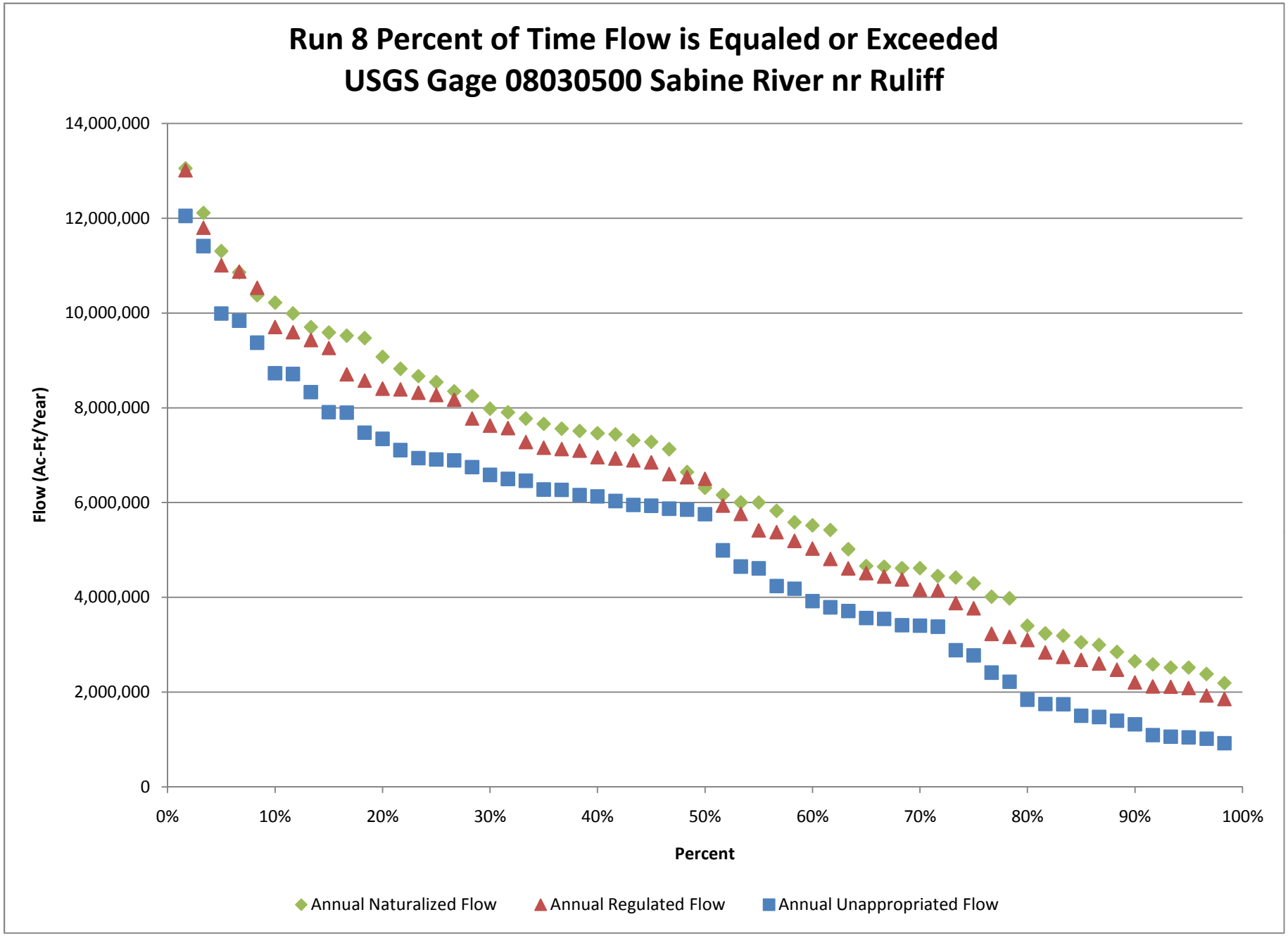
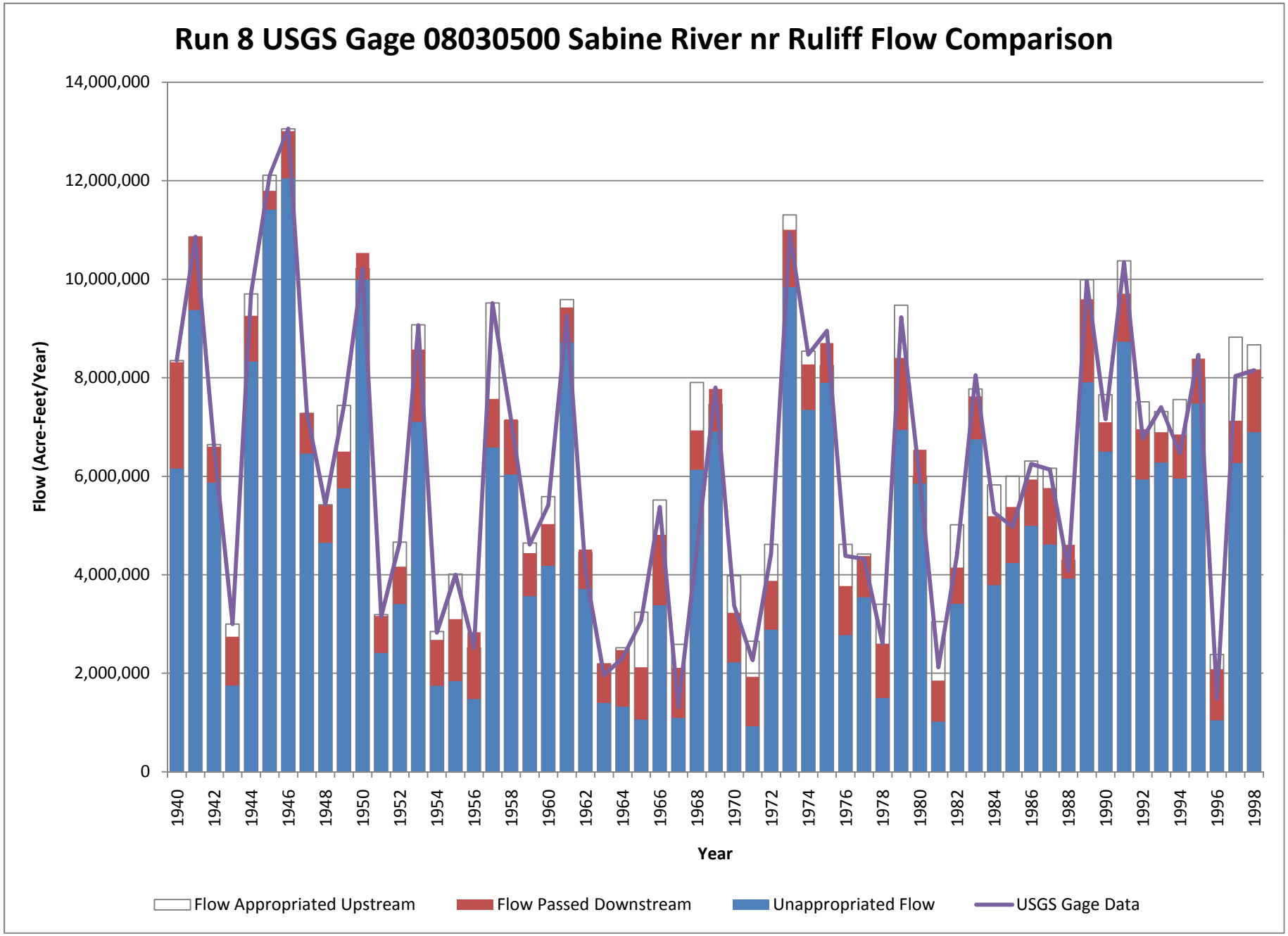
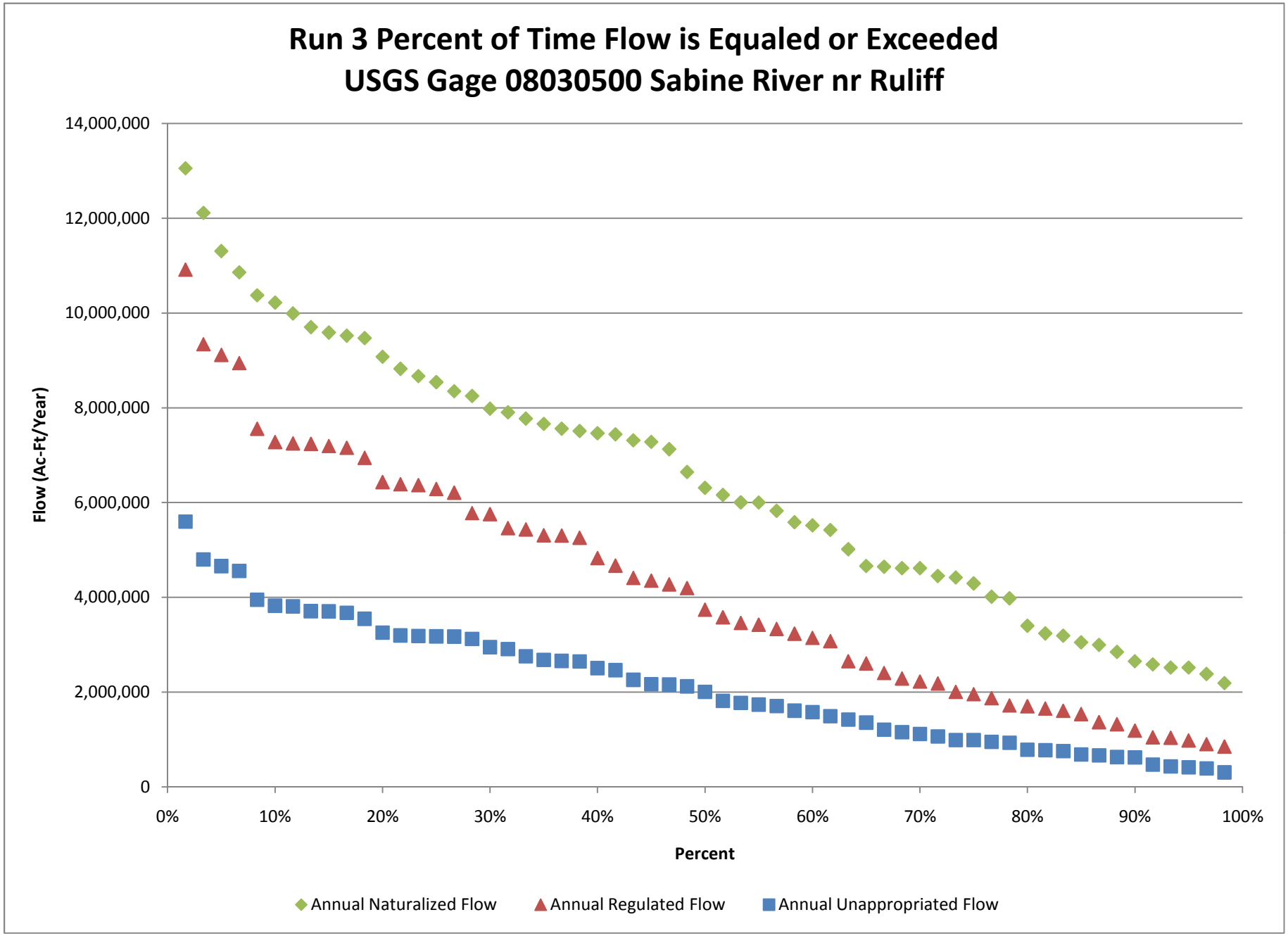
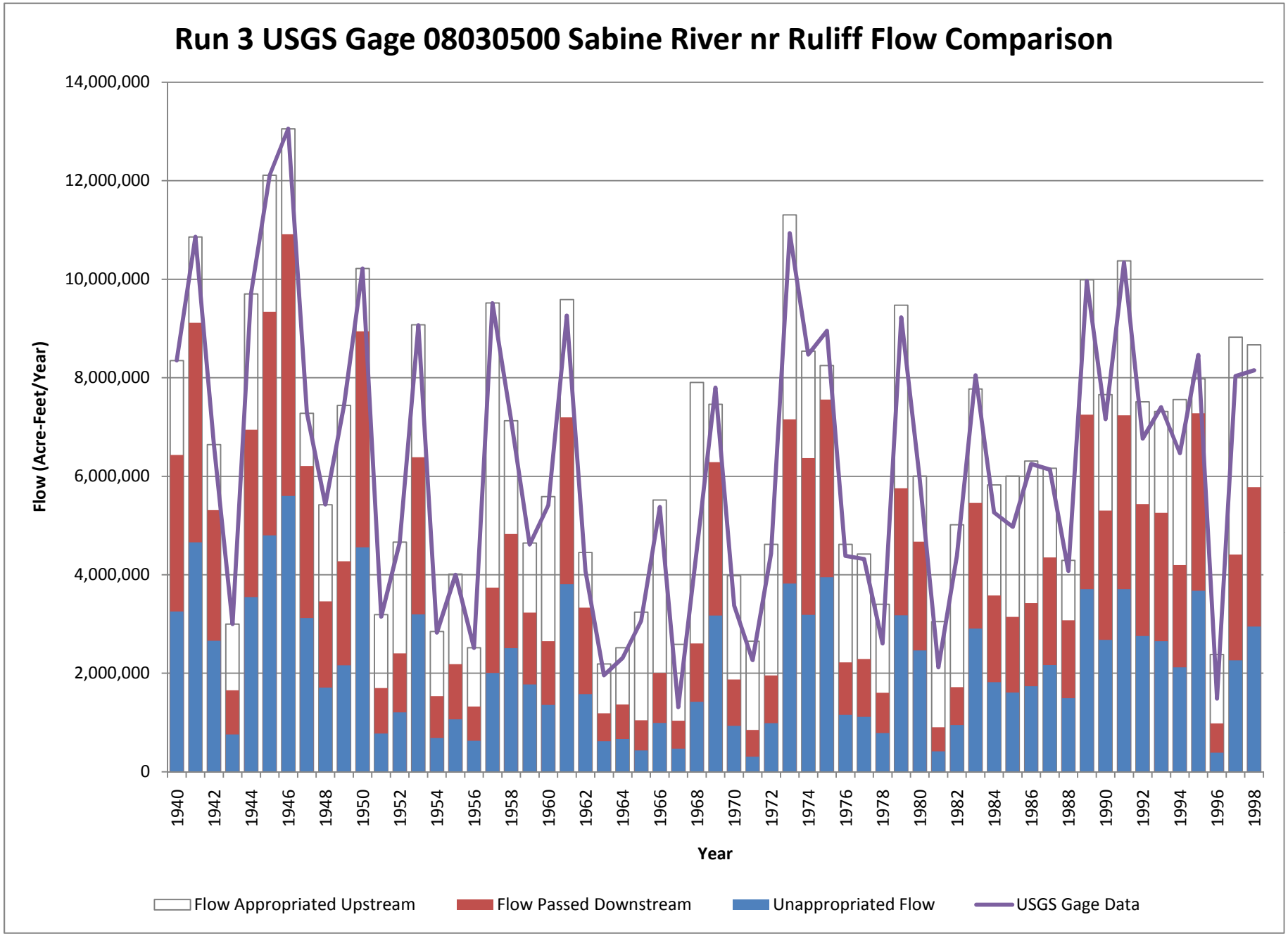
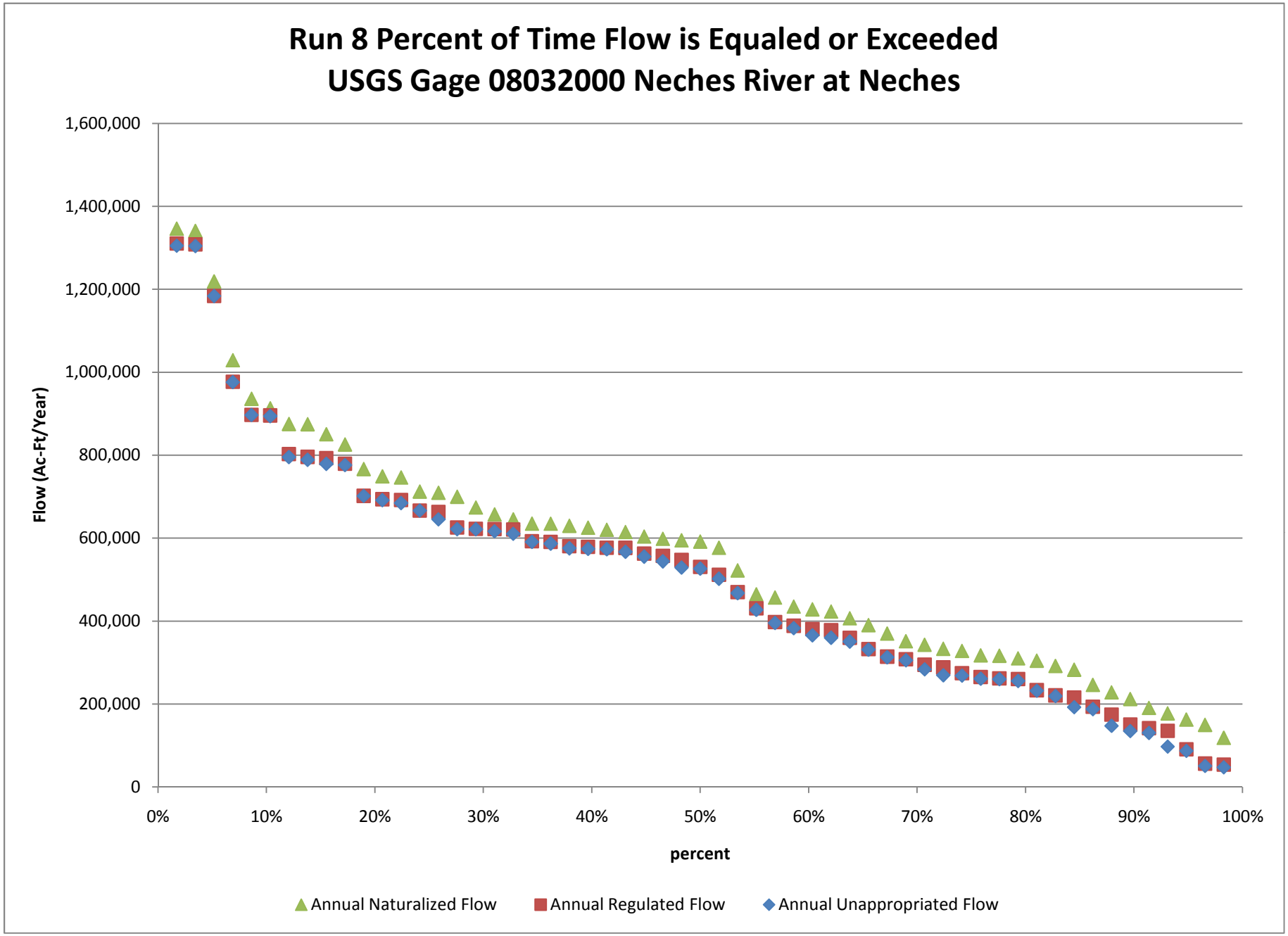
1996
1998
Year
Flow Appropriated Upstream
Flow Passed Downstream
Unappropriated Flow
USGS Gage Data

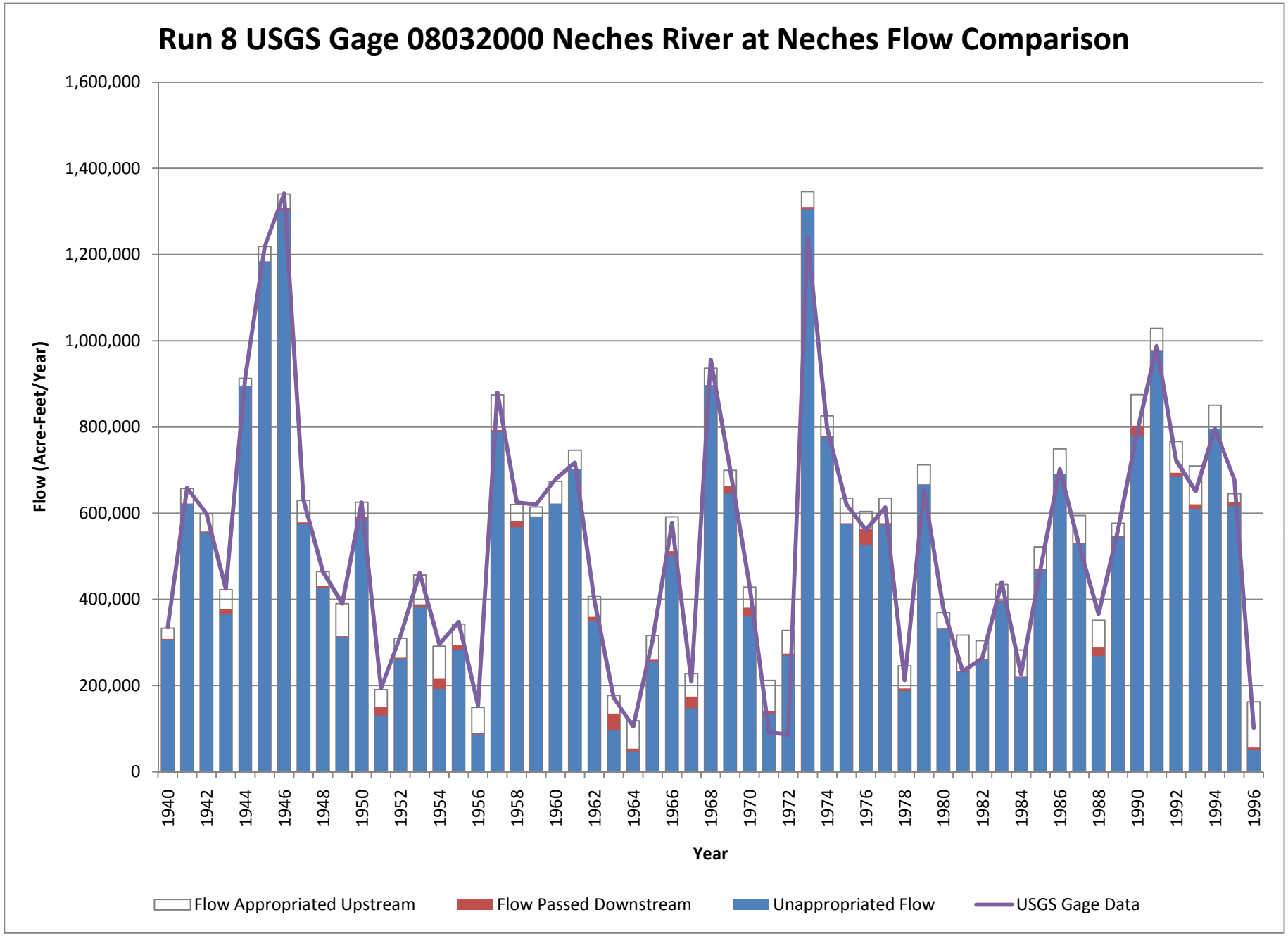

Run 8 Percent of Time Flow is Equaled or Exceeded
USGS Gage 08030500 Sabine River nr Ruliff
14,000,000
12,000,000
10,000,000
8,000,000
6,000,000
4,000,000
2,000,000
0
Flow (Ac-Ft/Year)
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percent
Annual Naturalized Flow
Annual Regulated Flow
Annual Unappropriated Flow

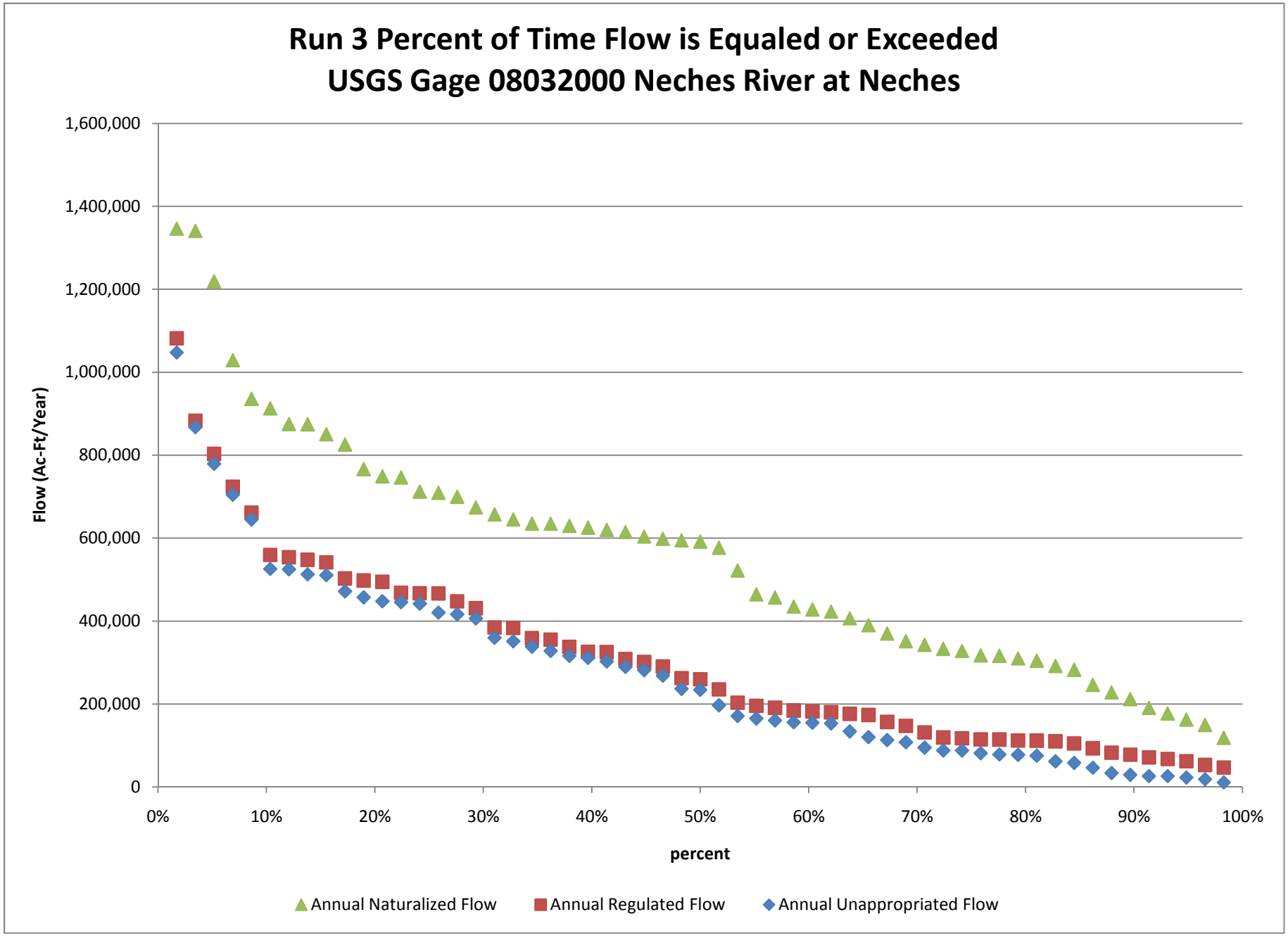

Run 8 USGS Gage 08030500 Sabine River nr Ruliff Flow Comparison
14,000,000
12,000,000
10,000,000
8,000,000
6,000,000
4,000,000
2,000,000
0
Flow (Acre-Feet/Year)
1940
1942
1944
1946
1948
1950
1952
1954
1956
1958
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
Year
Flow Appropriated Upstream
Flow Passed Downstream
Unappropriated Flow
USGS Gage Data

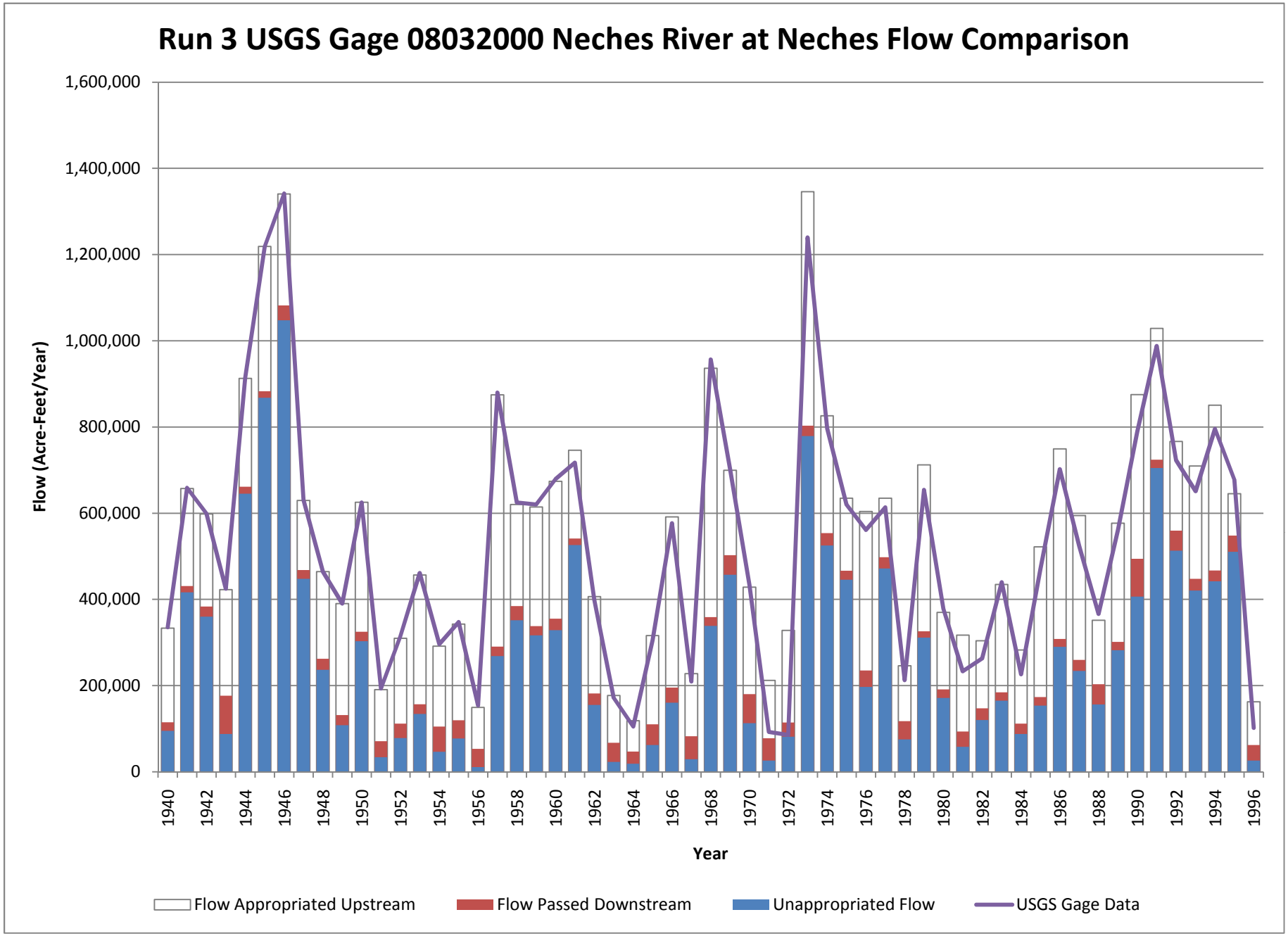

Run 3 Percent of Time Flow is Equaled or Exceeded
USGS Gage 08030500 Sabine River nr Ruliff
Flow (Ac-Ft/Year)
14,000,000
12,000,000
10,000,000
8,000,000
6,000,000
4,000,000
2,000,000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percent
Annual Naturalized Flow
Annual Regulated Flow
Annual Unappropriated Flow

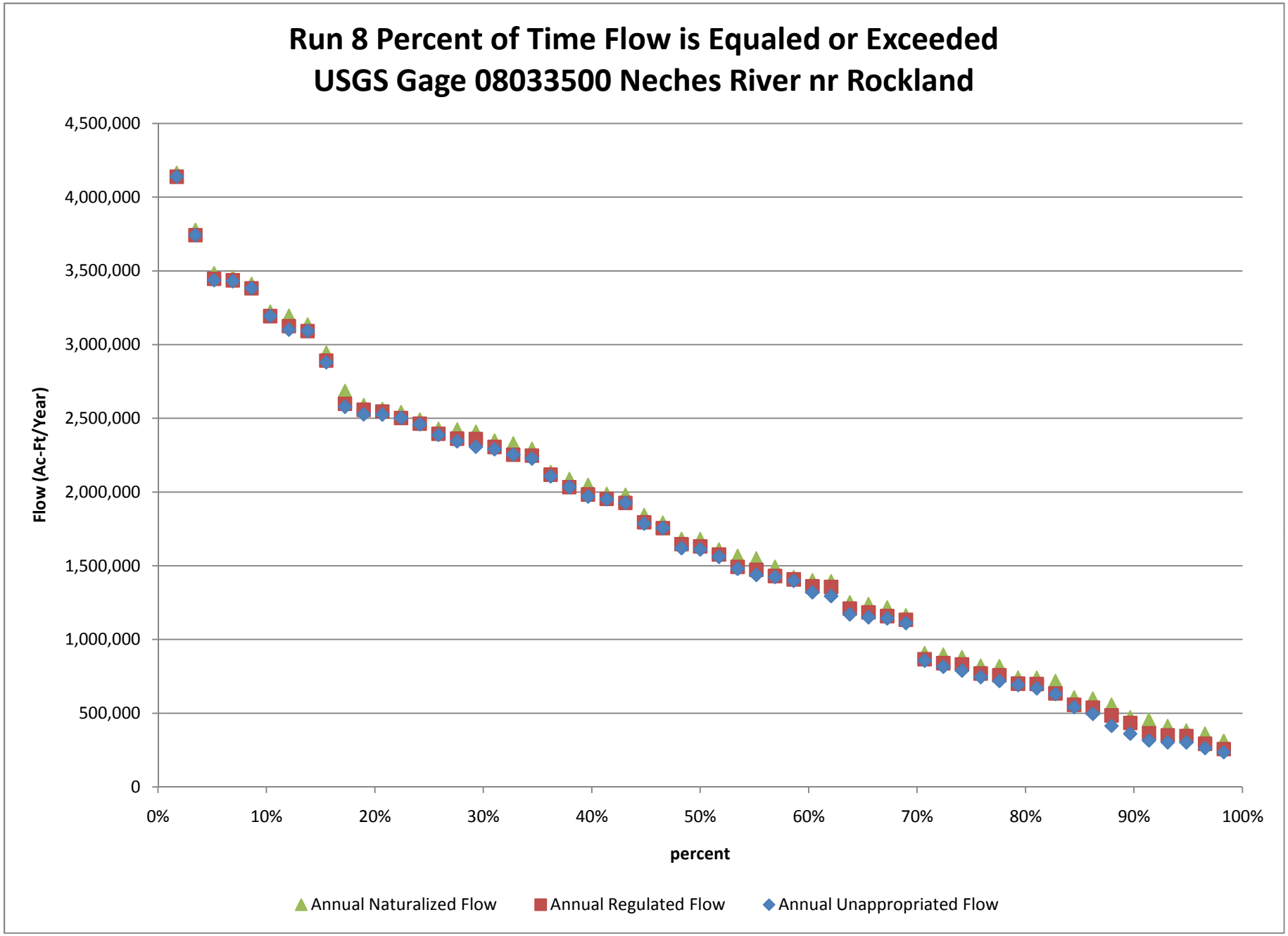

Run 3 USGS Gage 08030500 Sabine River nr Ruliff Flow Comparison
14,000,000
12,000,000
10,000,000
8,000,000
6,000,000
4,000,000
2,000,000
0
Flow (Acre-Feet/Year)
1940
1942
1944
1946
1948
1950
1952
1954
1956
1958
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
Year
Flow Appropriated Upstream
Flow Passed Downstream
Unappropriated Flow
USGS Gage Data

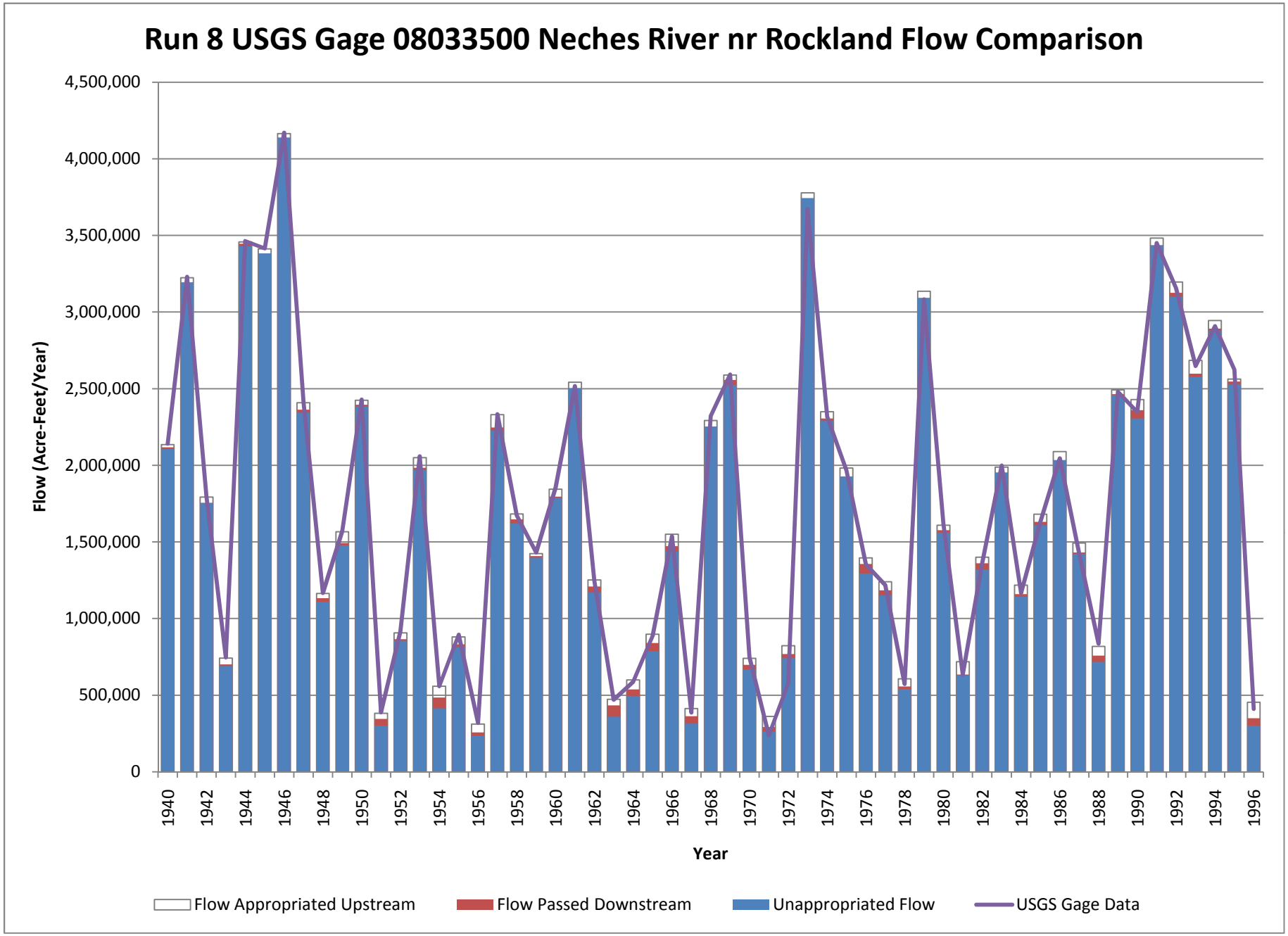

Run 8 Percent of Time Flow is Equaled or Exceeded
USGS Gage 08032000 Neches River at Neches
Flow (Ac-Ft/Year)
1,600,000
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
percent
Annual Naturalized Flow
Annual Regulated Flow
Annual Unappropriated Flow

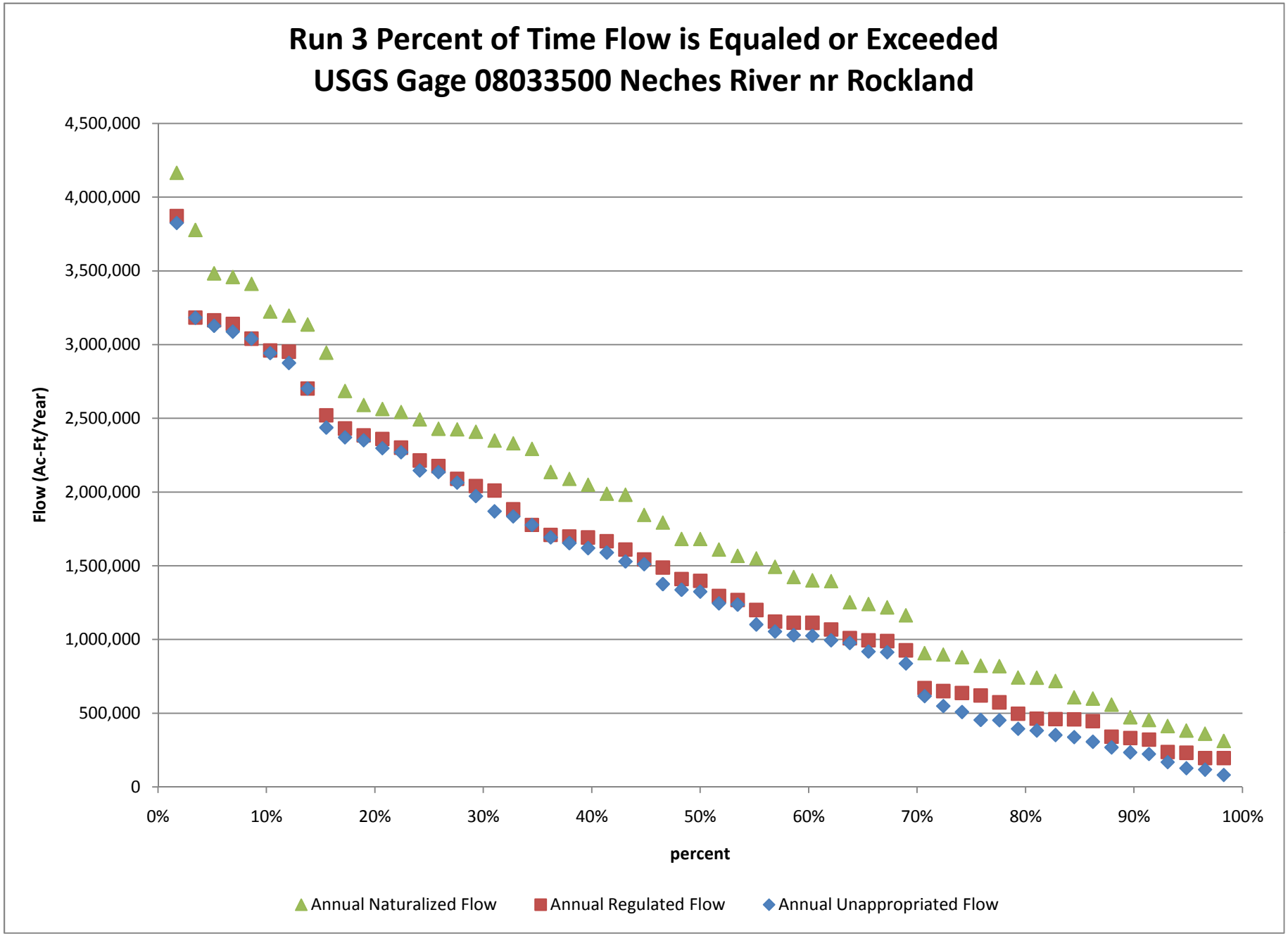

Run 8 USGS Gage 08032000 Neches River at Neches Flow Comparison
Flow (Acre-Feet/Year)
1,600,000
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
1940
1942
1944
1946
1948
1950
1952
1954
1956
1958
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
Year
Flow Appropriated Upstream
Flow Passed Downstream
Unappropriated Flow
USGS Gage Data

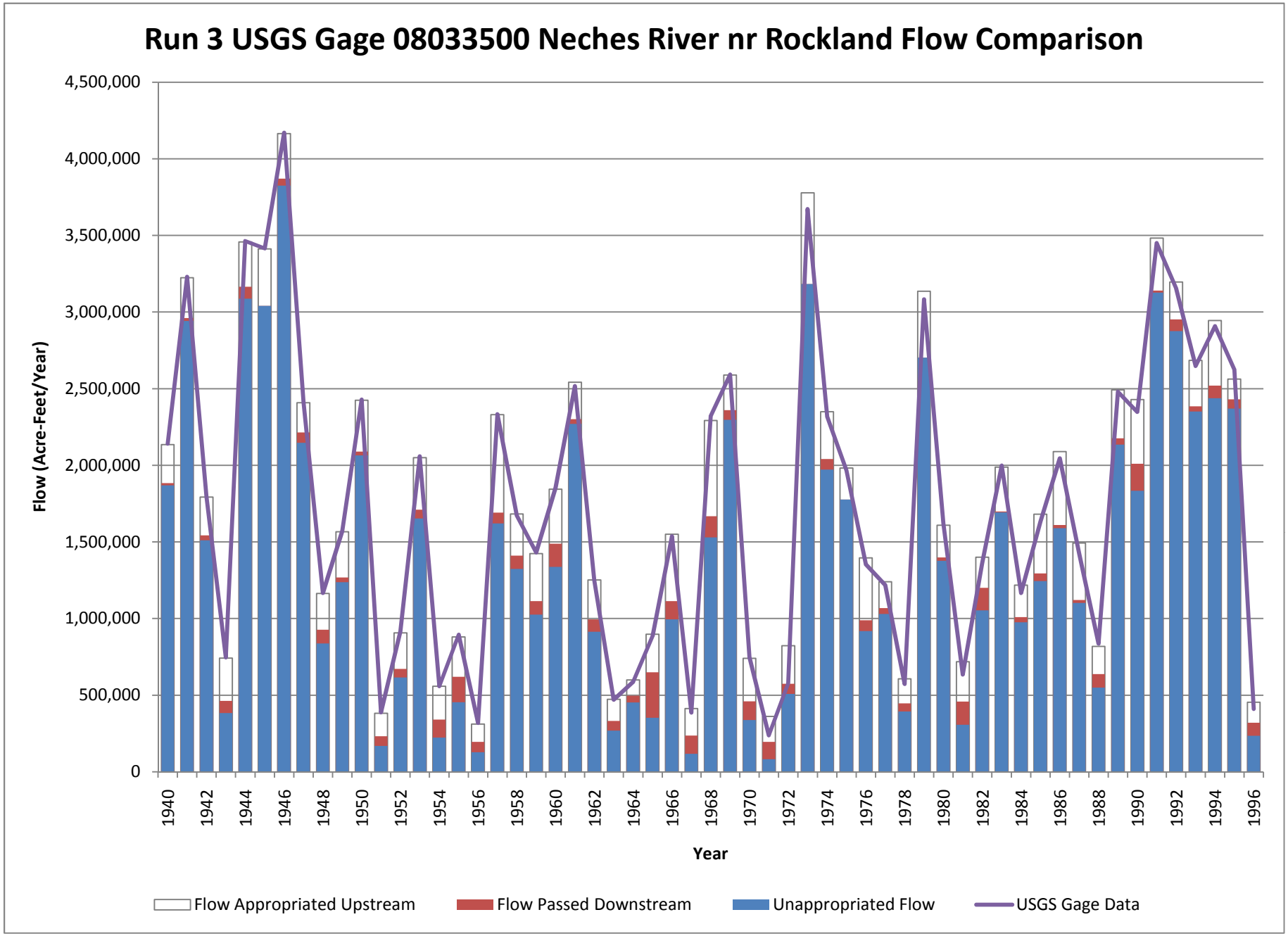

Run 3 Percent of Time Flow is Equaled or Exceeded
USGS Gage 08032000 Neches River at Neches
Flow (Ac-Ft/Year)
1,600,000
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
percent
Annual Naturalized Flow
Annual Regulated Flow
Annual Unappropriated Flow

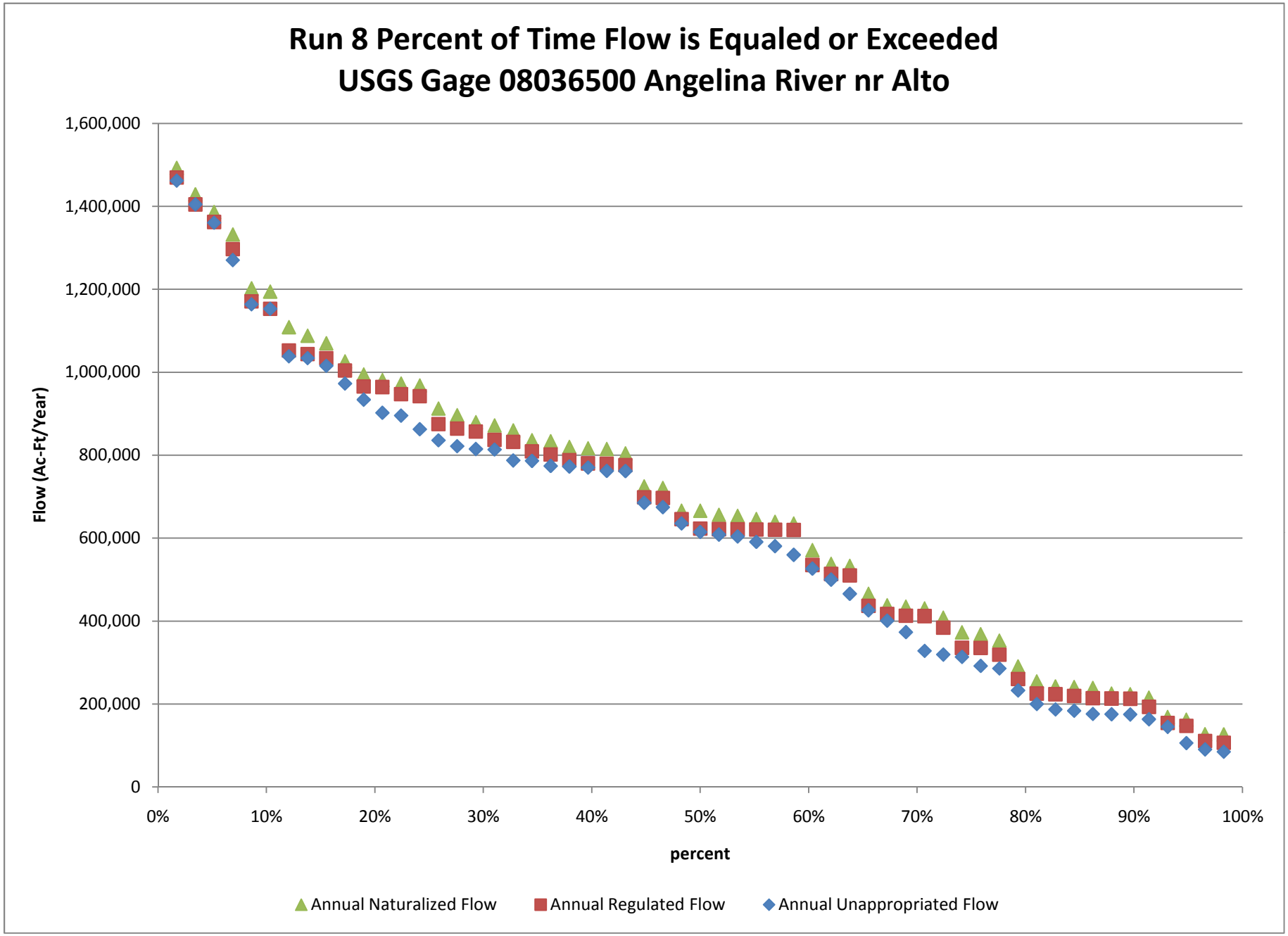

Run 3 USGS Gage 08032000 Neches River at Neches Flow Comparison
Flow (Acre-Feet/Year)
1,600,000
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
1940
1942
1944
1946
1948
1950
1952
1954
1956
1958
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
Year
Flow Appropriated Upstream
Flow Passed Downstream
Unappropriated Flow
USGS Gage Data

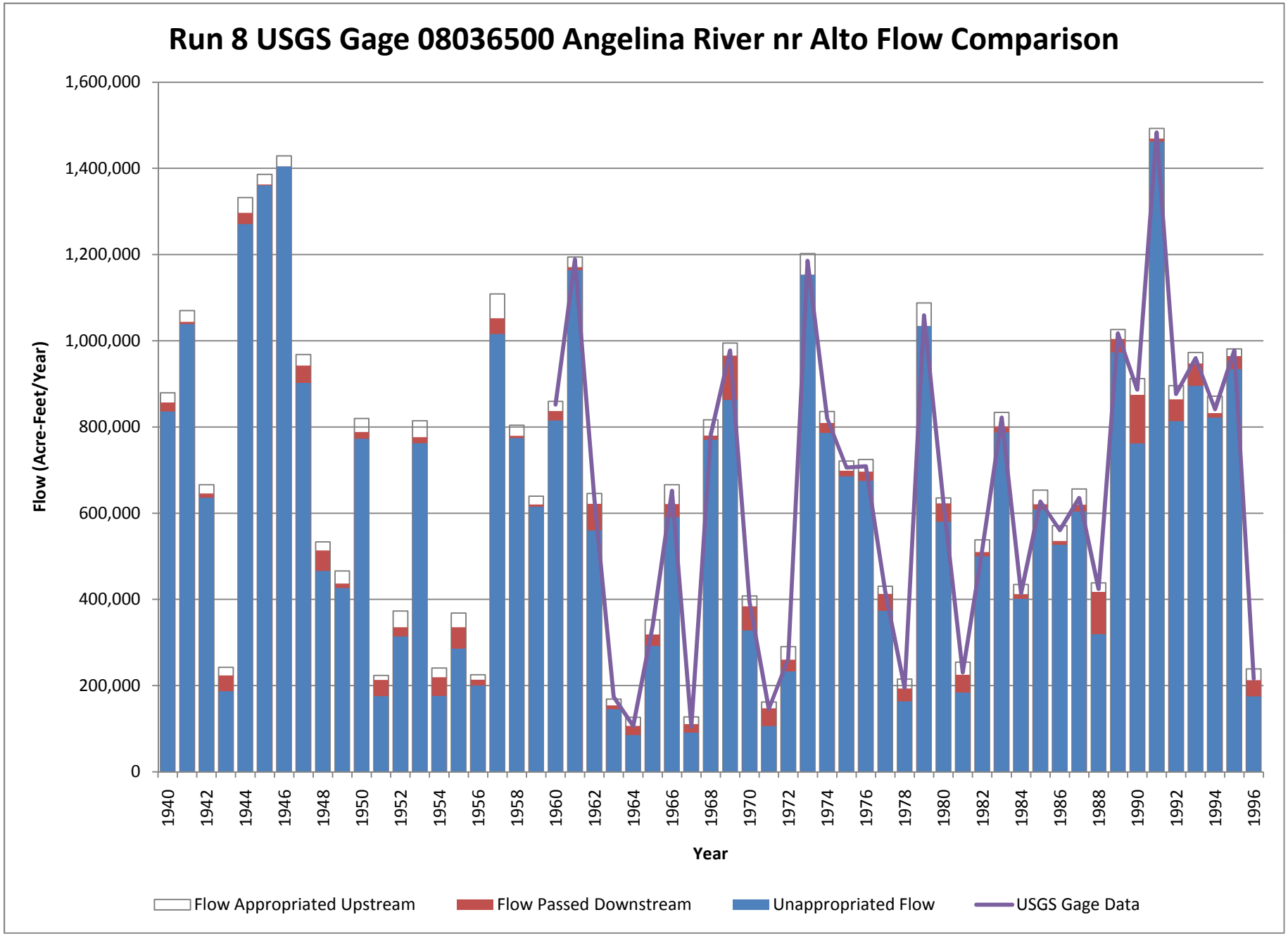

Run 8 Percent of Time Flow is Equaled or Exceeded
USGS Gage 08033500 Neches River nr Rockland
Flow (Ac-Ft/Year)
4,500,000
4,000,000
3,500,000
3,000,000
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
percent
Annual Naturalized Flow
Annual Regulated Flow
Annual Unappropriated Flow

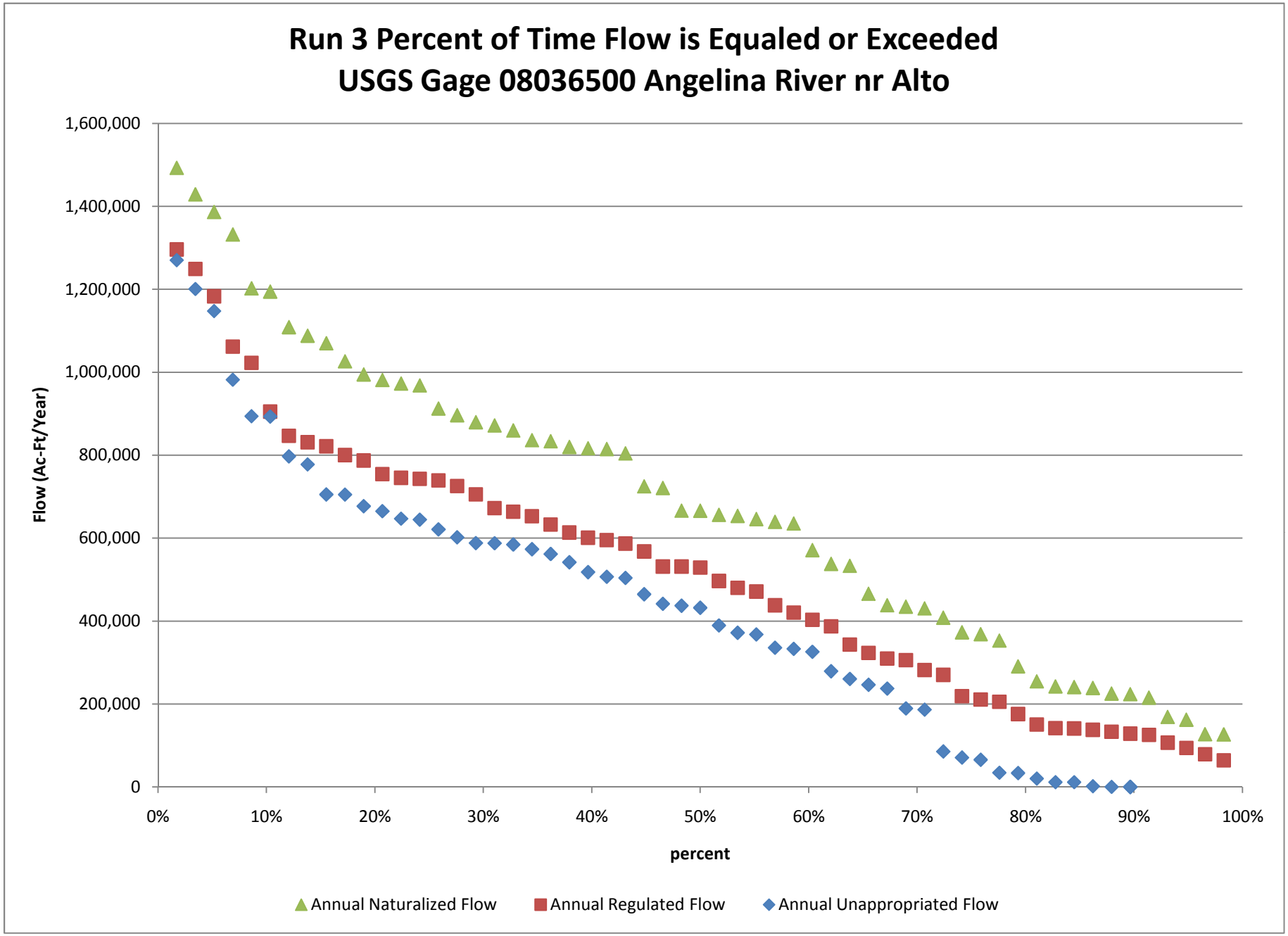

Run 8 USGS Gage 08033500 Neches River nr Rockland Flow Comparison
Flow (Acre-Feet/Year)
4,500,000
4,000,000
3,500,000
3,000,000
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
1940
1942
1944
1946
1948
1950
1952
1954
1956
1958
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
Year
Flow Appropriated Upstream
Flow Passed Downstream
Unappropriated Flow
USGS Gage Data

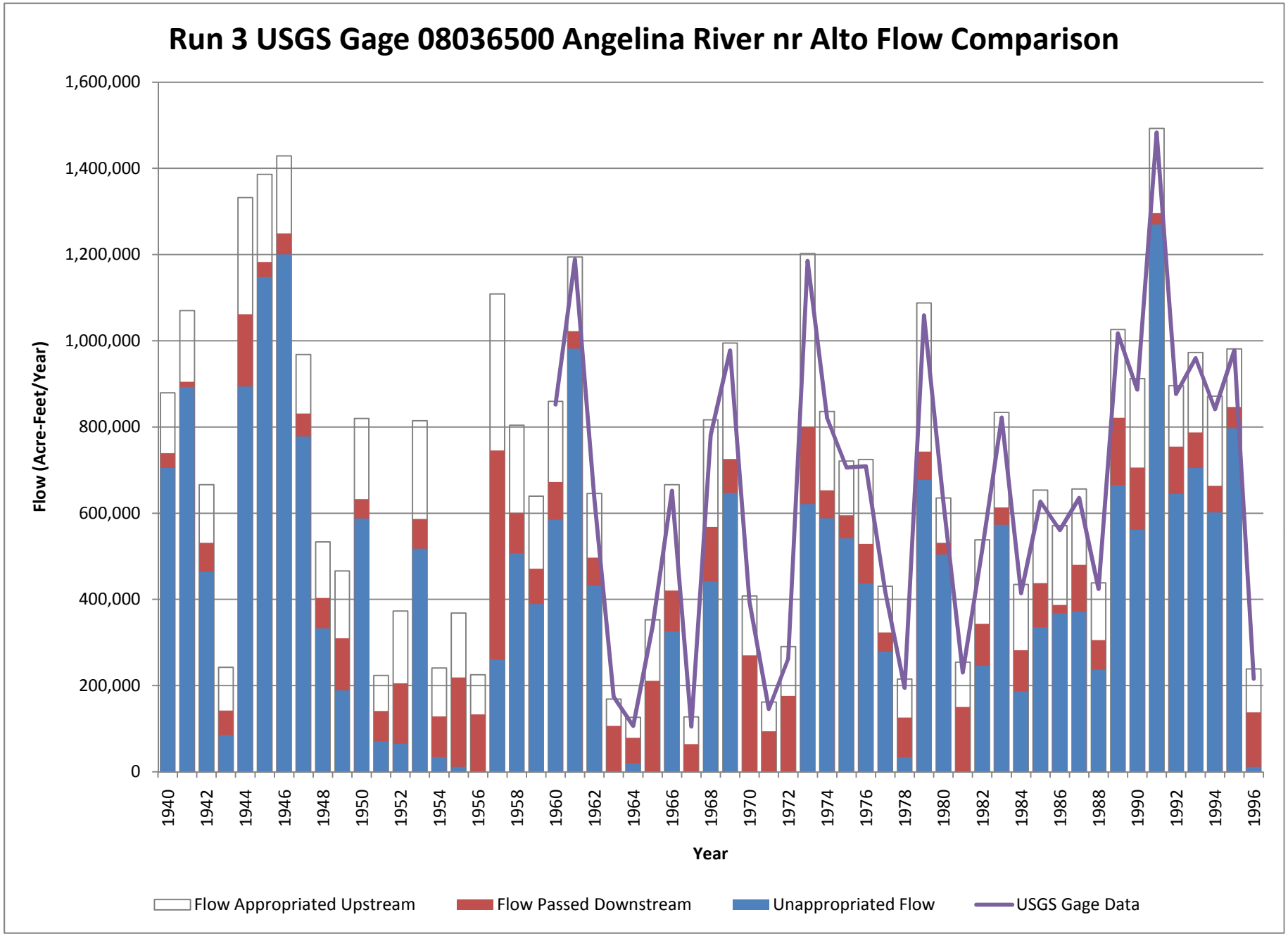

Run 3 Percent of Time Flow is Equaled or Exceeded
USGS Gage 08033500 Neches River nr Rockland
Flow (Ac-Ft/Year)
4,500,000
4,000,000
3,500,000
3,000,000
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
percent
Annual Naturalized Flow
Annual Regulated Flow
Annual Unappropriated Flow

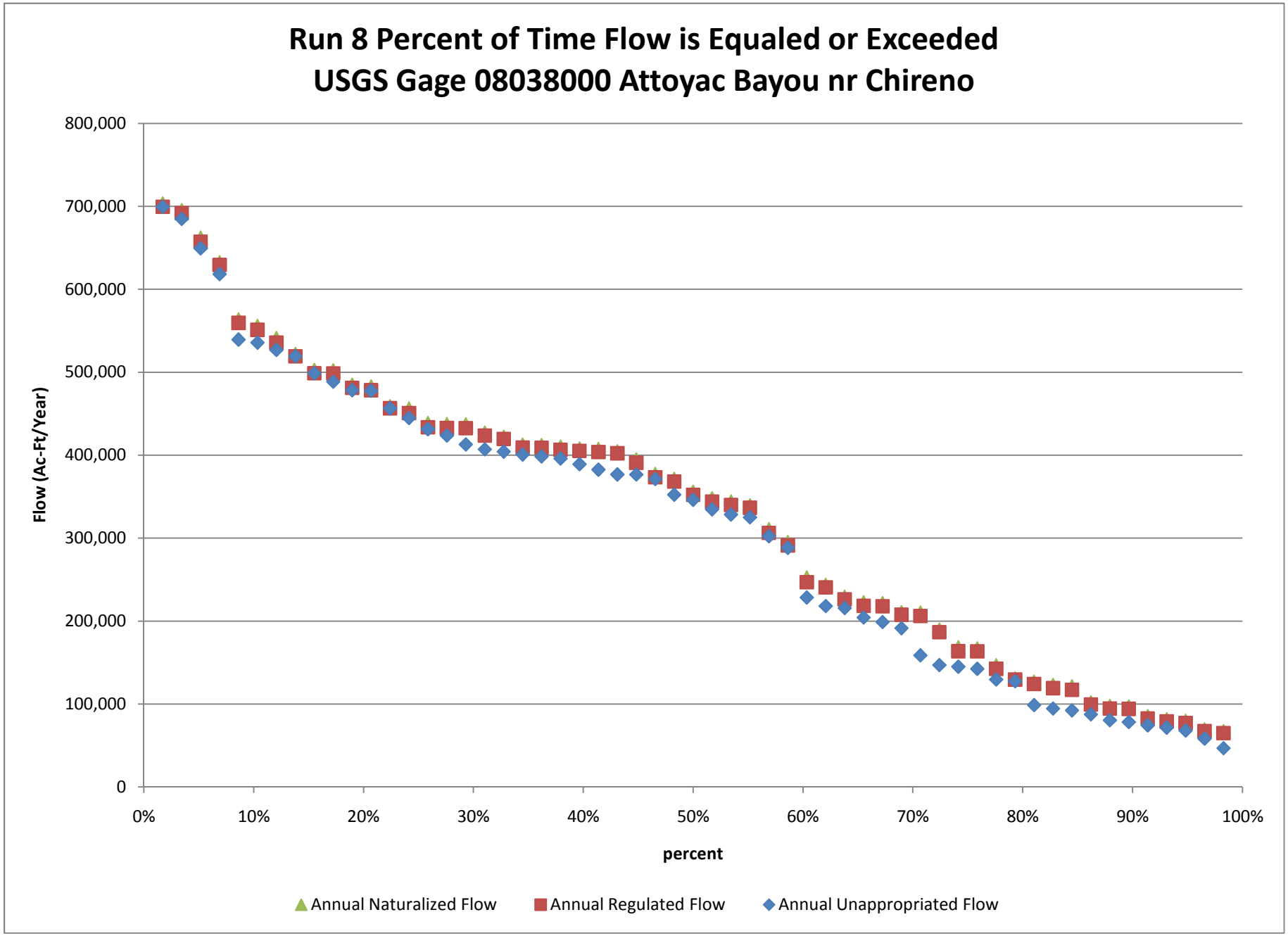

Run 3 USGS Gage 08033500 Neches River nr Rockland Flow Comparison
Flow (Acre-Feet/Year)
4,500,000
4,000,000
3,500,000
3,000,000
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
1940
1942
1944
1946
1948
1950
1952
1954
1956
1958
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
Year
Flow Appropriated Upstream
Flow Passed Downstream
Unappropriated Flow
USGS Gage Data

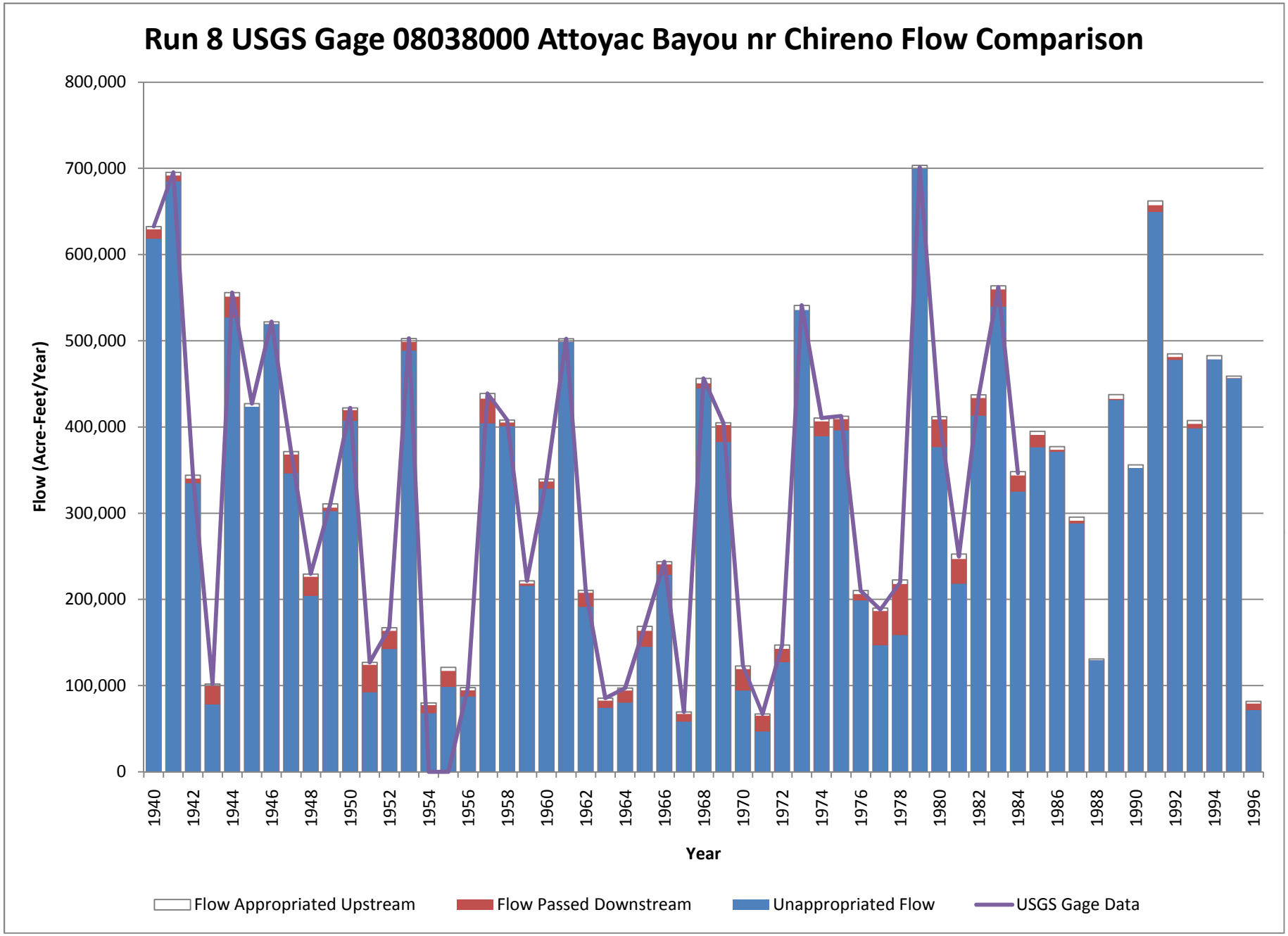

Run 8 Percent of Time Flow is Equaled or Exceeded
USGS Gage 08036500 Angelina River nr Alto
Flow (Ac-Ft/Year)
1,600,000
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
percent
Annual Naturalized Flow
Annual Regulated Flow
Annual Unappropriated Flow

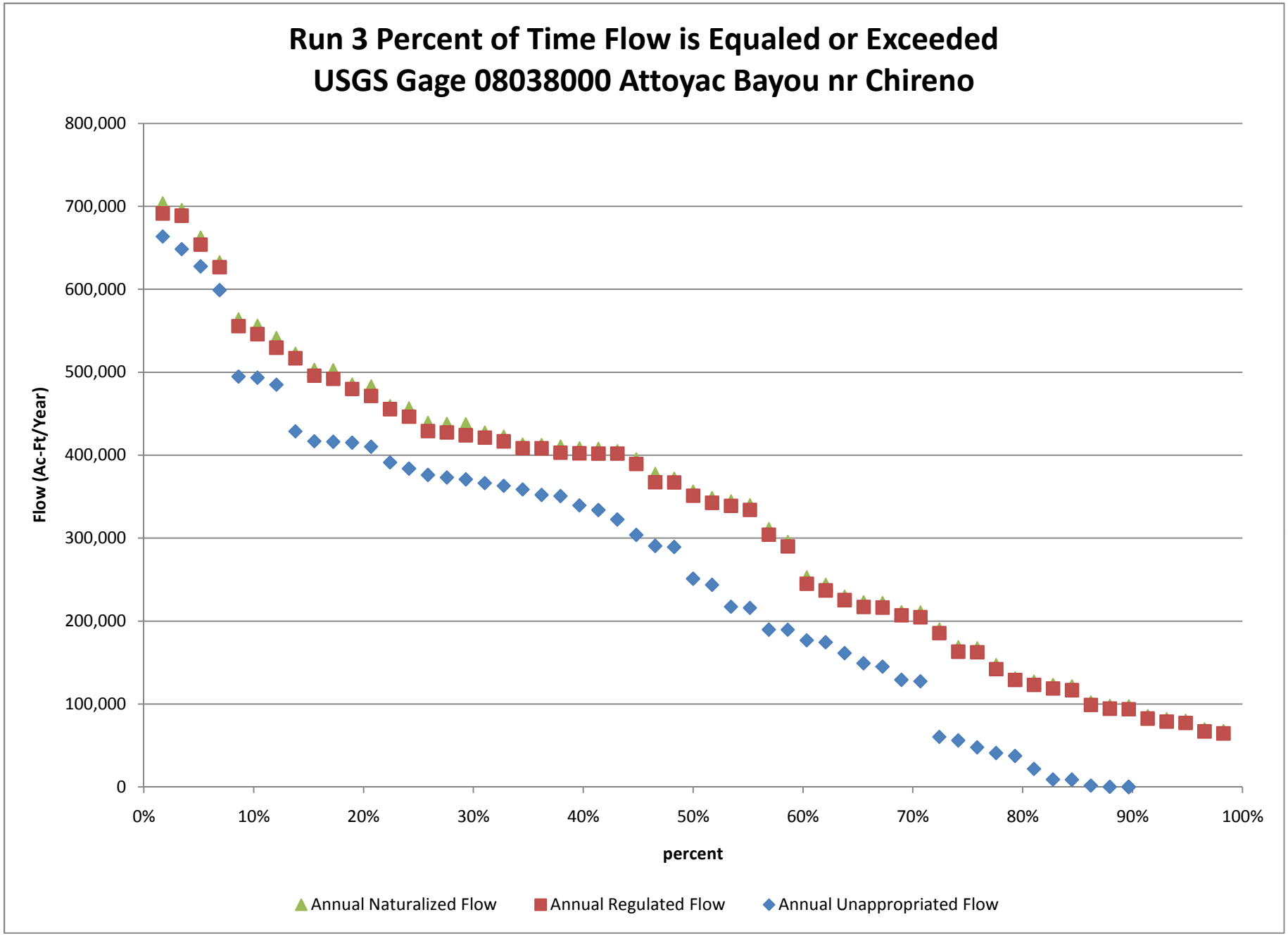

Run 8 USGS Gage 08036500 Angelina River nr Alto Flow Comparison
Flow (Acre-Feet/Year)
1,600,000
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
1940
1942
1944
1946
1948
1950
1952
1954
1956
1958
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
Year
Flow Appropriated Upstream
Flow Passed Downstream
Unappropriated Flow
USGS Gage Data

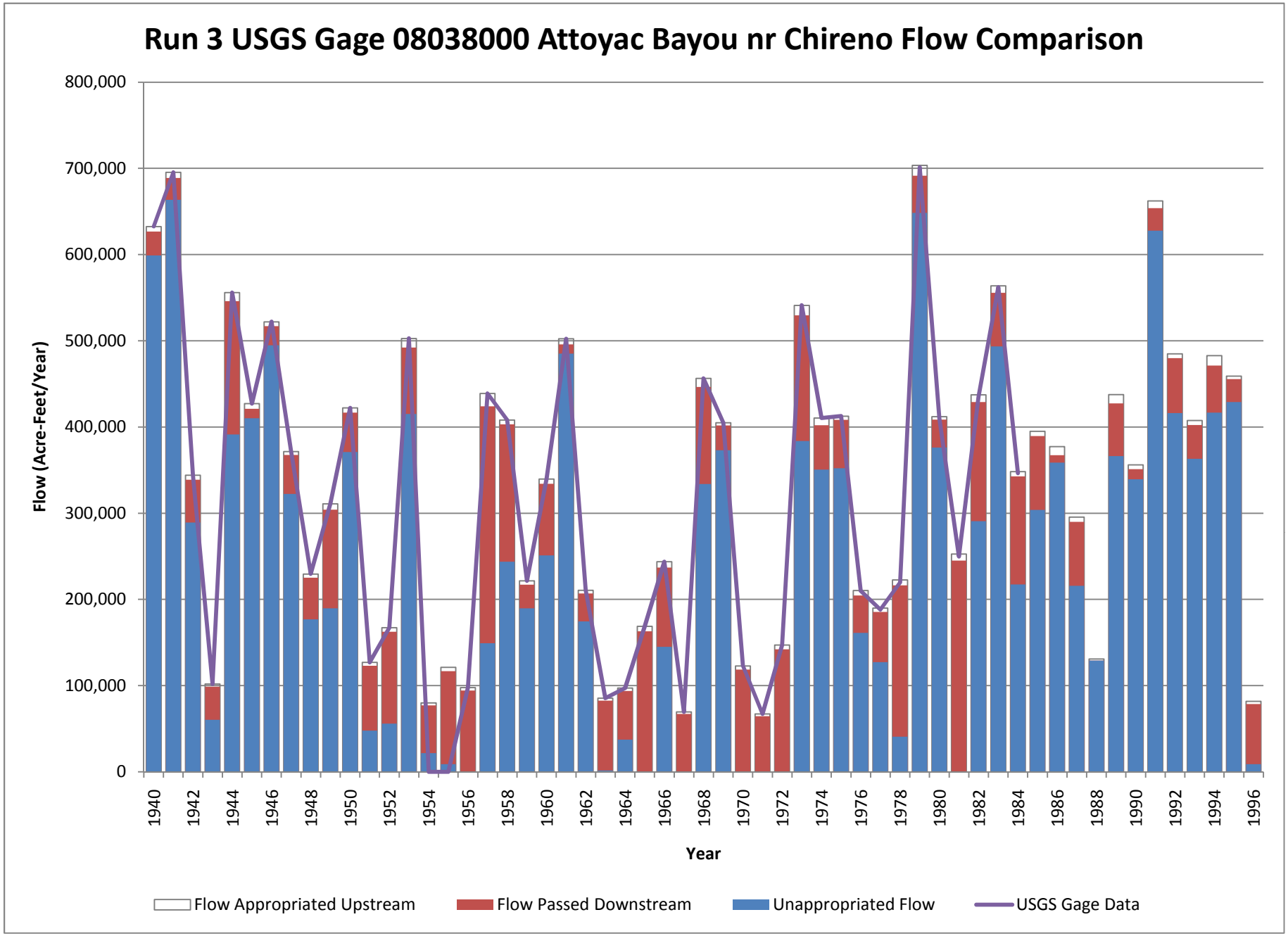

Run 3 Percent of Time Flow is Equaled or Exceeded
USGS Gage 08036500 Angelina River nr Alto
Flow (Ac-Ft/Year)
1,600,000
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
percent
Annual Naturalized Flow
Annual Regulated Flow
Annual Unappropriated Flow


Run 3 USGS Gage 08036500 Angelina River nr Alto Flow Comparison
Flow (Acre-Feet/Year)
1,600,000
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
1940
1942
1944
1946
1948
1950
1952
1954
1956
1958
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
Year
Flow Appropriated Upstream
Flow Passed Downstream
Unappropriated Flow
USGS Gage Data


Run 8 Percent of Time Flow is Equaled or Exceeded
USGS Gage 08038000 Attoyac Bayou nr Chireno
Flow (Ac-Ft/Year)
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
percent
Annual Naturalized Flow
Annual Regulated Flow
Annual Unappropriated Flow


Run 8 USGS Gage 08038000 Attoyac Bayou nr Chireno Flow Comparison
Flow (Acre-Feet/Year)
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
1940
1942
1944
1946
1948
1950
1952
1954
1956
1958
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
Year
Flow Appropriated Upstream
Flow Passed Downstream
Unappropriated Flow
USGS Gage Data


Run 3 Percent of Time Flow is Equaled or Exceeded
USGS Gage 08038000 Attoyac Bayou nr Chireno
Flow (Ac-Ft/Year)
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
percent
Annual Naturalized Flow
Annual Regulated Flow
Annual Unappropriated Flow


Run 3 USGS Gage 08038000 Attoyac Bayou nr Chireno Flow Comparison
Flow (Acre-Feet/Year)
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
1940
1942
1944
1946
1948
1950
1952
1954
1956
1958
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1962
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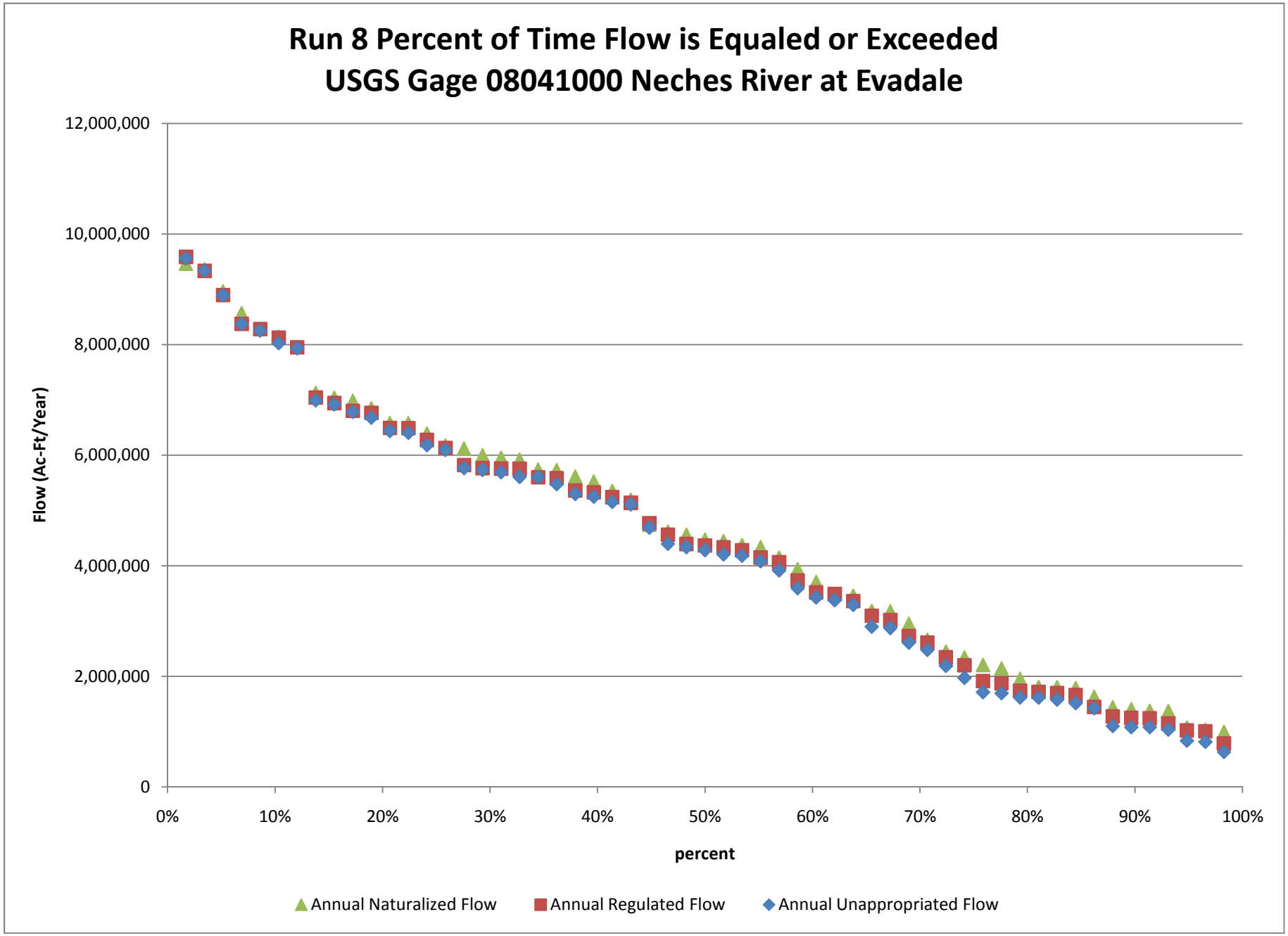
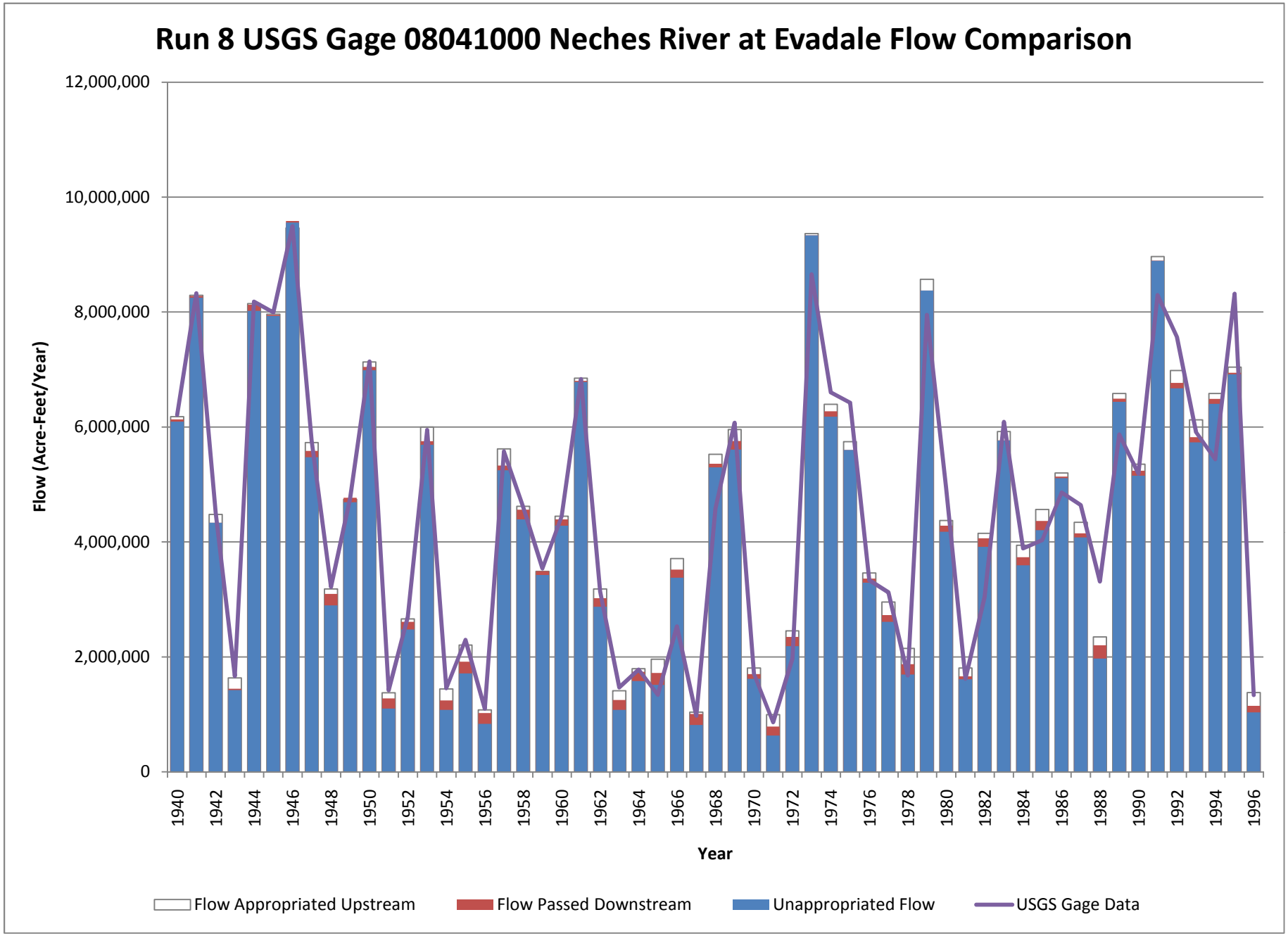
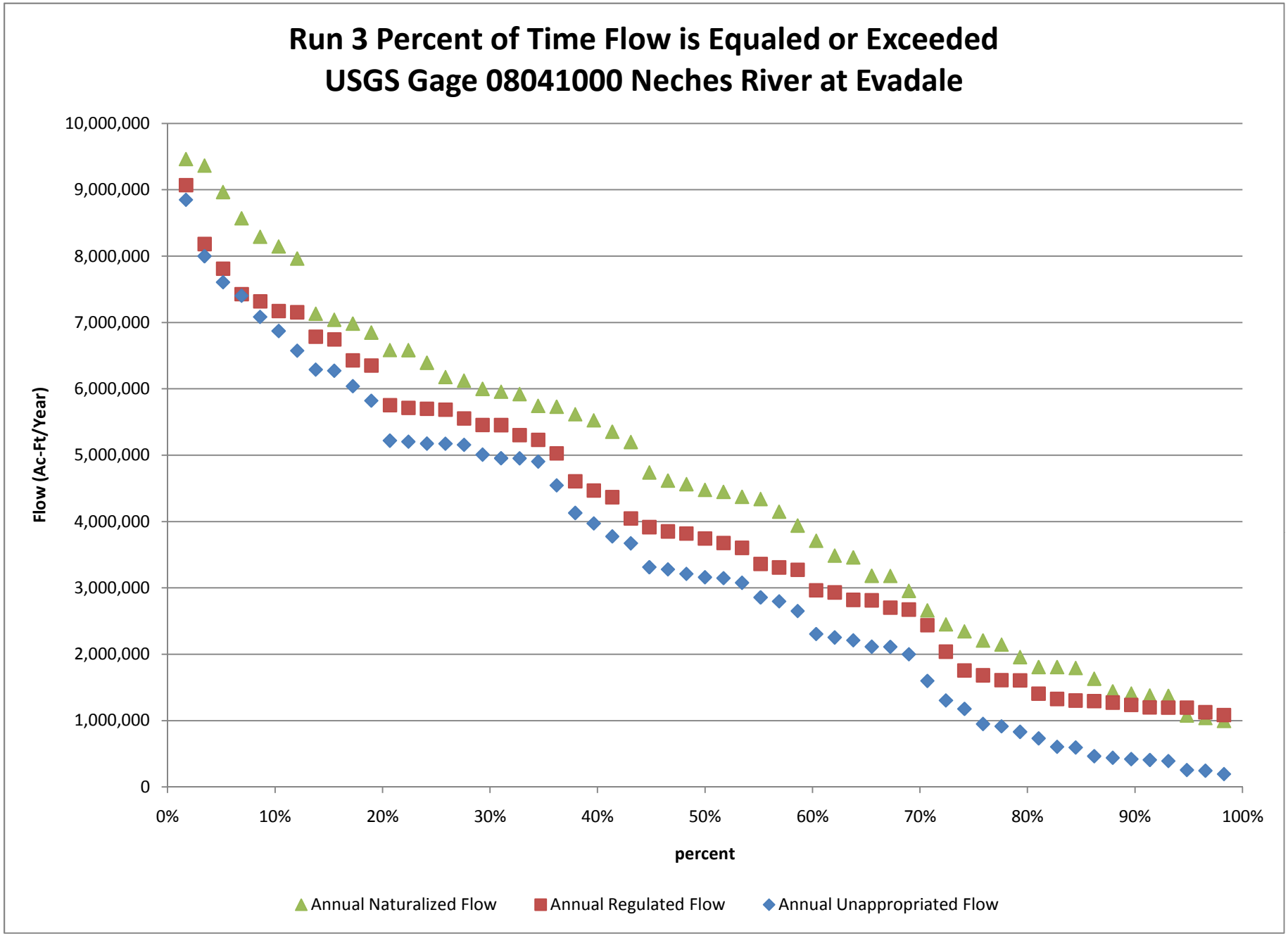
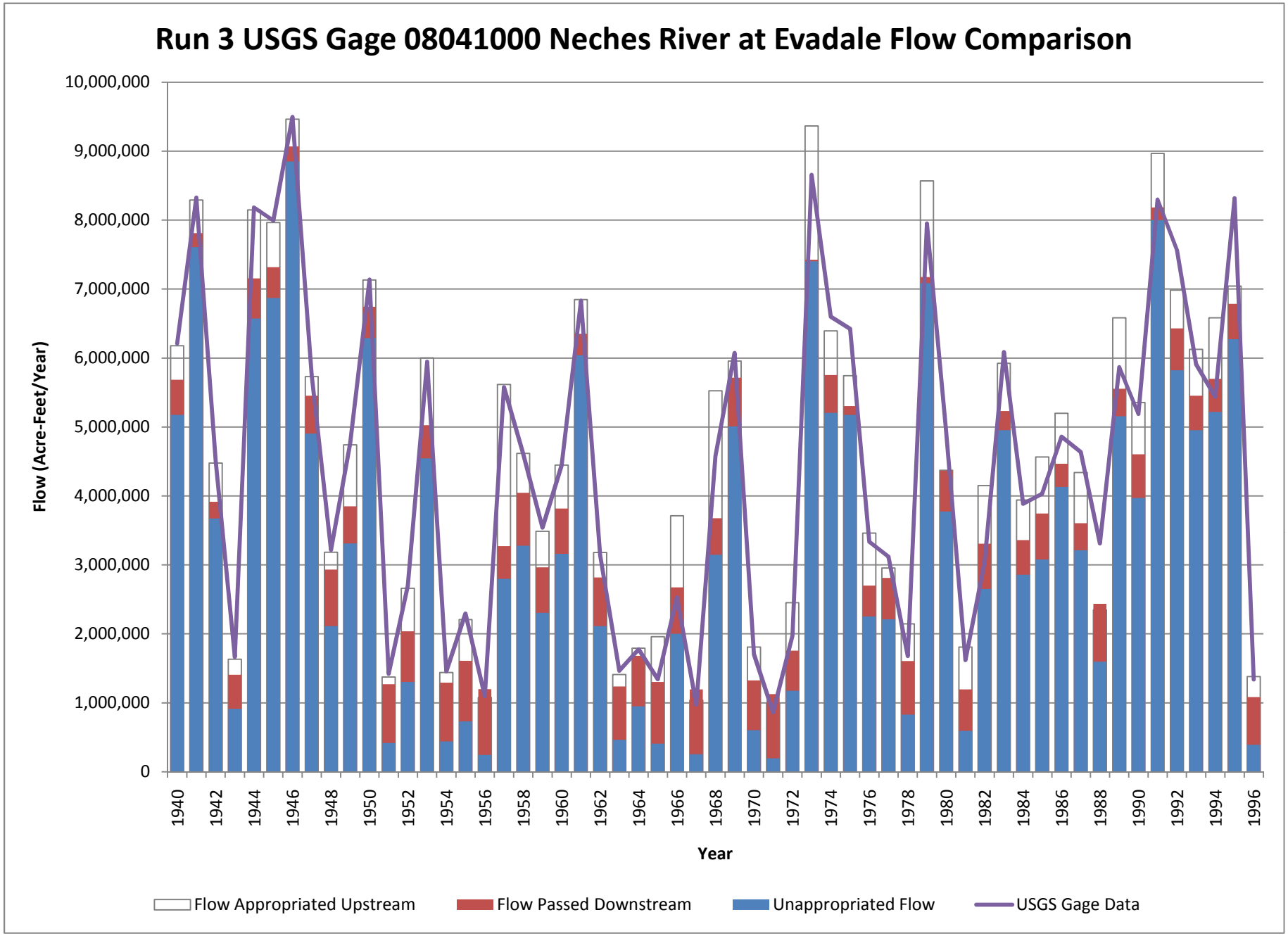
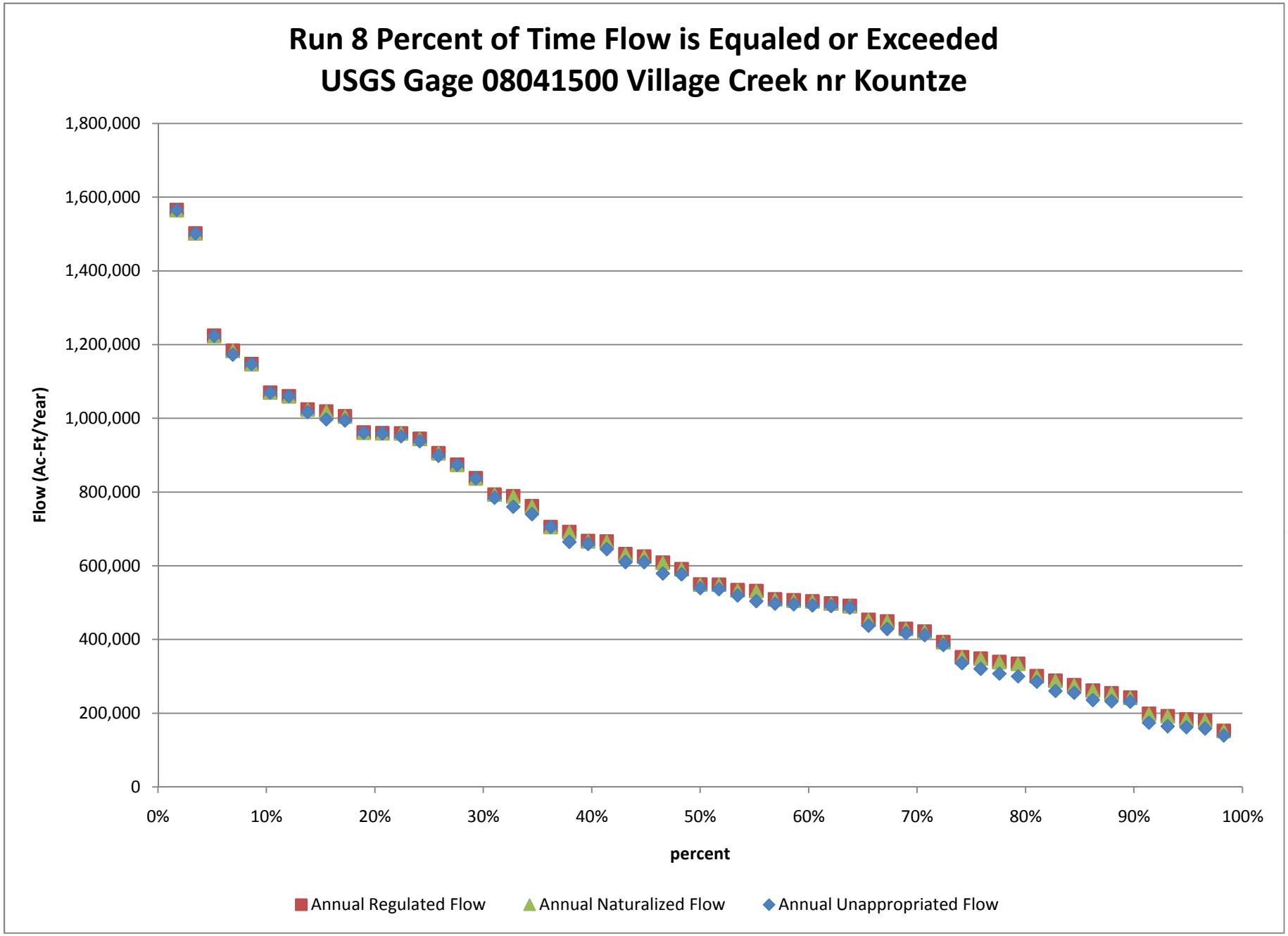
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
Year
Flow Appropriated Upstream
Flow Passed Downstream
Unappropriated Flow
USGS Gage Data

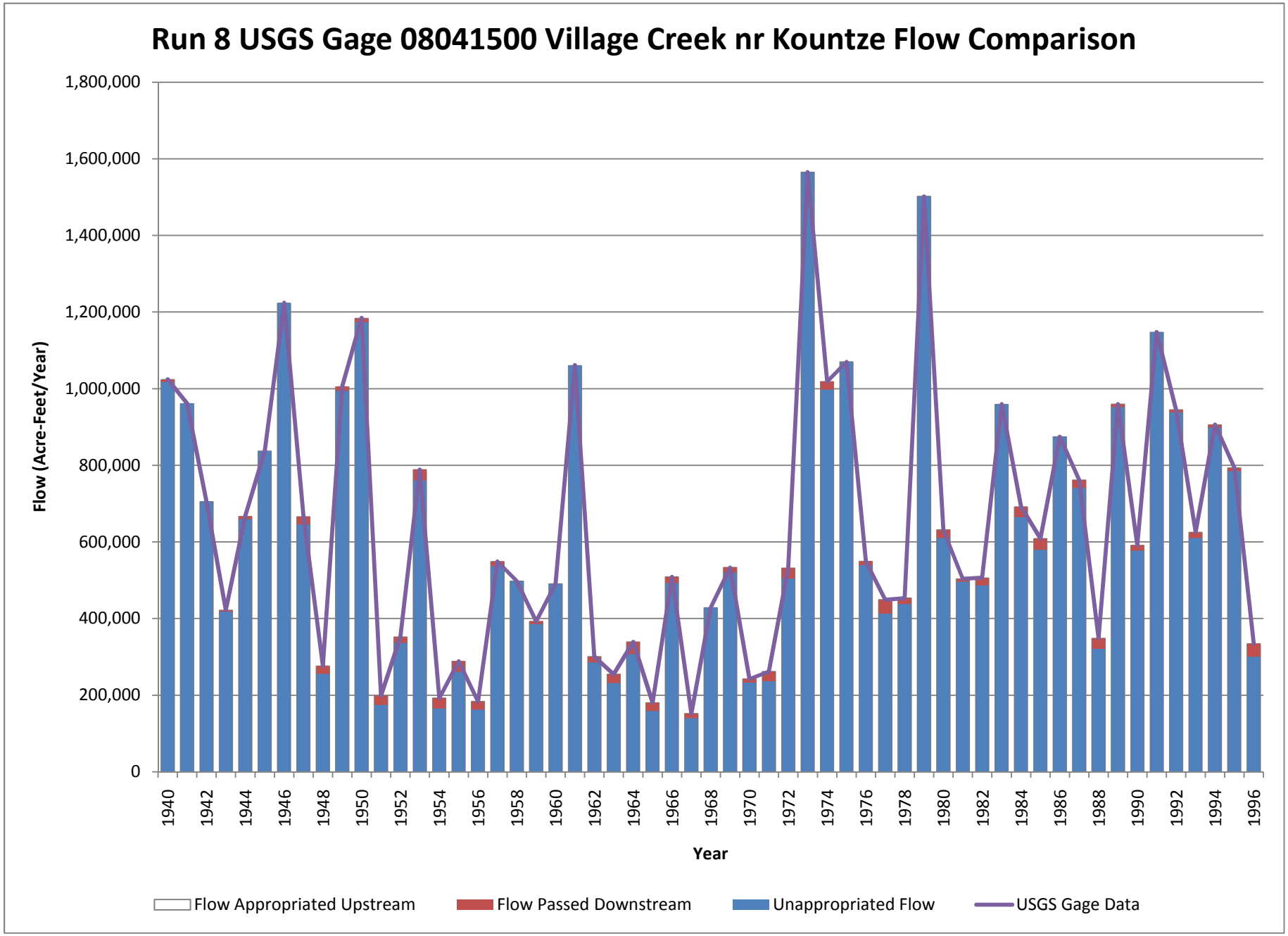

Run 8 Percent of Time Flow is Equaled or Exceeded
USGS Gage 08041000 Neches River at Evadale
12,000,000
10,000,000
8,000,000
6,000,000
4,000,000
2,000,000
0
Flow (Ac-Ft/Year)
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
percent
Annual Naturalized Flow
Annual Regulated Flow
Annual Unappropriated Flow

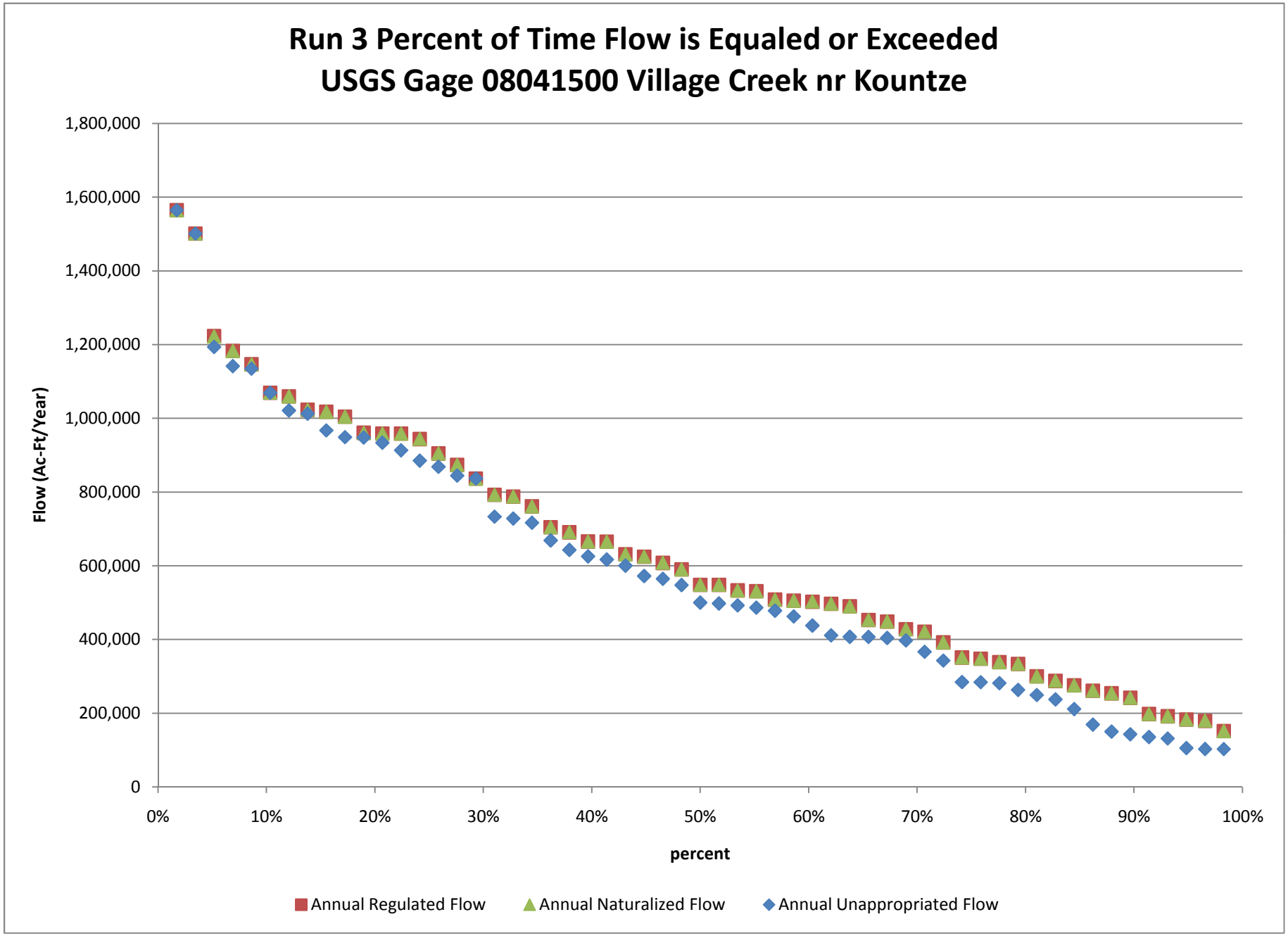

Run 8 USGS Gage 08041000 Neches River at Evadale Flow Comparison
12,000,000
10,000,000
8,000,000
6,000,000
4,000,000
2,000,000
0
Flow (Acre-Feet/Year)
1940
1942
1944
1946
1948
1950
1952
1954
1956
1958
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
Year
Flow Appropriated Upstream
Flow Passed Downstream
Unappropriated Flow
USGS Gage Data

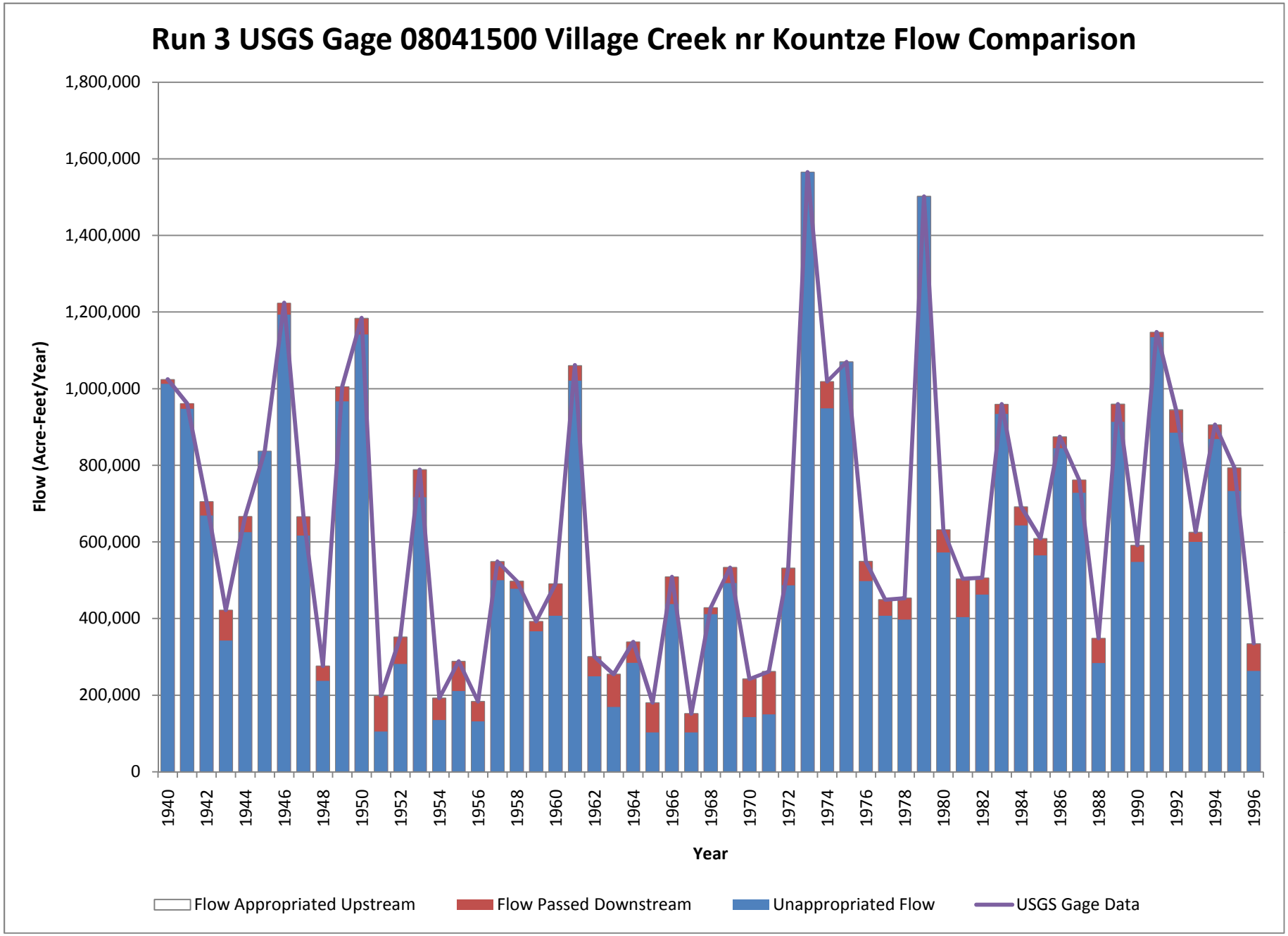

Run 3 Percent of Time Flow is Equaled or Exceeded
USGS Gage 08041000 Neches River at Evadale
Flow (Ac-Ft/Year)
10,000,000
9,000,000
8,000,000
7,000,000
6,000,000
5,000,000
4,000,000
3,000,000
2,000,000
1,000,000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
percent
Annual Naturalized Flow
Annual Regulated Flow
Annual Unappropriated Flow


Run 3 USGS Gage 08041000 Neches River at Evadale Flow Comparison
Flow (Acre-Feet/Year)
10,000,000
9,000,000
8,000,000
7,000,000
6,000,000
5,000,000
4,000,000
3,000,000
2,000,000
1,000,000
0
1940
1942
1944
1946
1948
1950
1952
1954
1956
1958
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
Year
Flow Appropriated Upstream
Flow Passed Downstream
Unappropriated Flow
USGS Gage Data


Run 8 Percent of Time Flow is Equaled or Exceeded
USGS Gage 08041500 Village Creek nr Kountze
Flow (Ac-Ft/Year)
1,800,000
1,600,000
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
percent
Annual Regulated Flow
Annual Naturalized Flow
Annual Unappropriated Flow


Run 8 USGS Gage 08041500 Village Creek nr Kountze Flow Comparison
Flow (Acre-Feet/Year)
1,800,000
1,600,000
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
1940
1942
1944
1946
1948
1950
1952
1954
1956
1958
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
Year
Flow Appropriated Upstream
Flow Passed Downstream
Unappropriated Flow
USGS Gage Data


Run 3 Percent of Time Flow is Equaled or Exceeded
USGS Gage 08041500 Village Creek nr Kountze
Flow (Ac-Ft/Year)
1,800,000
1,600,000
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
percent
Annual Regulated Flow
Annual Naturalized Flow
Annual Unappropriated Flow


Run 3 USGS Gage 08041500 Village Creek nr Kountze Flow Comparison
Flow (Acre-Feet/Year)
1,800,000
1,600,000
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
1940
1942
1944
1946
1948
1950
1952
1954
1956
1958
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
Year
Flow Appropriated Upstream
Flow Passed Downstream
Unappropriated Flow
USGS Gage Data

Attachment B
Method to Classify Historical Wet, Average and Dry Seasons

Attachment B: Method to Classify Historical Wet, Average and Dry Seasons

Determining Dry, Average, and Wet Seasons Using Flow Data

First the 12 months were divided into 4 seasons labeled A, B, C, and D. These seasons correspond to the Winter, Spring, Summer and Fall seasons in the HEFR Analysis.

For all 12 gages in the Sabine and Neches basins, the total flow was summed for each season from 1940 to 2008. For gages with missing data for that time period, the available data was summed and any flow totals for incomplete seasons were deleted.

For each gage, the seasonal total was filtered to order the data from smallest flow to largest flow. The top 25% of the smallest flows were designated as dry flows, the middle 50% as average flows and the bottom 25% as wet flow. All dry flows were marked with the number one, average flows were marked with the number 2, and wet flows were marked with the number 3. The filter was undone so the data would be in chronological order with the flow designation still attached to each season.

All flow designation for all the gages were pasted in to a new spreadsheet. Flow designations for all gages for the same year and season were lined up in this spreadsheet. For each season from 1940 to 2008 the number if dry, average, and wet gages was counted (using the 1, 2, or 3 flow designation). Each season was designated as dry, average or wet, based on the number of gages that were dry, average, or wet during that season. For example, if the majority of gages were dry, then that season was labeled as a dry season.

For seasons that had the same number of gages designated as, for example wet and average, either wet or average was chosen in order to make the total number of dry seasons and wet seasons 25% each and average seasons 50% of the total.

Determining Dry, Average, and Wet Seasons Using Palmer Index Data

Palmer Index data came from http://www.cdc.noaa.gov/data/timeseries/. The time series used was the "US Climate Division: temperature, precipitation and Palmer Drought Severity Index (PDSI)" dataset for division 4 and years 1940-2009.

In an Excel spreadsheet the seasonal average was calculated for each year. Wet/Average/Dry Seasons were determined by sorting all the season from smallest to largest Palmer index. The top 25% of the smallest indexes were designated as dry seasons, the middle 50% were marked as average seasons, and 25% of the largest indexes were designated as wet seasons.

Determining Dry, Average, and Wet Seasons Using WAM Storage

Reservoir storage data were extracted from the WAM Run 3 output for each major reservoir in the Sabine and Neches Basins. The total reservoir storage was calculated for each month in the simulation. The monthly totals were grouped by season and the average storage in each season was calculated from the monthly total. The analysis was limited to the 57-year period of the Neches WAM: 1940 to 1996. For each season, the monthly storages were ranked from smallest to largest. Within each season, the 14 seasons with the least storage were classified as dry, and the 14 seasons with the most storage were classified as wet. The remaining 29 seasons were classified as average.

APPENDIX XII-1

WATER QUALITY IMPAIRMENTS IN THE SABINE AND NECHES BASINS

As required under Sections 303(d) and 304(a) of the federal Clean Water Act, the Texas Commission on Environmental Quality (TCEQ) is charged with assessing water quality impairments for the State's water bodies. Every two years, the TCEQ prepares a draft list of water bodies in the State that are impaired for one or more parameters of concern. After a public comment period and review by the United States Environmental Protection Agency (USEPA), the list is finalized. The currently approved list of impaired water bodies is known as the "2008 Texas 303(d) List." The list identifies water bodies for which effluent limitations are not sufficiently stringent to implement water quality standards and for which the associated pollutants are suitable for measurement by a maximum daily load. For each impaired water body and each impairment, one of three subcategories is assigned in order to provide additional information about water quality status and management activities (in particular a Total Maximum Daily Load [or TMDL]) on the water body. The categories are defined as follows:

Category 5a - A TMDL is underway, scheduled, or will be scheduled.

Category *5b* - A review of the water quality standards for this water body will be conducted before a TMDL is scheduled.

Category 5c - Additional data and information will be collected before a TMDL is scheduled.

The inclusion of a water body on the 2008 Texas 303(d) List could complicate the development of environmental flow regime recommendations. However, as stated above, the impaired water bodies list and consequent water management activities to address impairments are actually aimed at pollutant loadings from point sources and non-point sources into the watershed. Therefore, environmental flow regimes should not be developed or used for the purpose of resolving water quality impairments. Rather, the 2008 Texas 303(d) List (and subsequent evolutions of this list) is useful as part of the process of checking the appropriateness of environmental flow recommendations.

The 2008 Texas 303(d) List is divided by basin. A brief description of the current impairments for each basin and for the coastal areas associated with Sabine Lake Estuary follows. The basins for the Sabine and Neches Rivers and the coastal drainage areas include a total of 73 classified segments. All of these classified segments are routinely monitored and assessed for water quality impairments. There are numerous unclassified stream segments within the basin that are also monitored and assessed. For purposes of this discussion, only classified segments will be addressed in this report.

WATER QUALITY IMPAIRMENTS FOR CLASSIFIED SEGMENTS IN THE SABINE BASIN

The Sabine River Basin includes 31 classified segments. Of these, six are represented in the hydrologic analysis associated with the environmental flow recommendations. Not all of the six classified segments are on the impaired water bodies list, however. Table XII-1.1 summarizes water quality impairments identified in the 2008 Texas 303(d) List for the Sabine River Basin's classified segments. The one impaired classified segment represented in the hydrologic analysis (i.e., Big Sandy Creek) is highlighted in the table. As may be seen, the only water quality impairment for Big Sandy Creek is for bacteria.

WATER QUALITY IMPAIRMENTS FOR CLASSIFIED SEGMENTS IN THE NECHES BASIN

The Neches River Basin includes 42 classified segments. Of these, five are represented in the hydrologic analysis associated with the environmental flow recommendations. Not all of these classified segments are on the impaired water bodies list, however. Table XII-1.2 summarizes water quality impairments identified in the 2008 Texas 303(d) List for the Neches River Basin's classified segments. Impaired classified segments represented in the hydrologic analysis on the Neches River are highlighted in the table. Impairments on these highlighted segments include pH (Segment 0608 Village Creek); bacteria (Segment 0611 Angelina River above Sam Rayburn Reservoir and Segment 612 Attoyac Bayou); and lead (Segment 0604 Neches River below Lake Palestine).

TABLE XII-1.1: SABINE BASIN WATER QUALITY IMPAIRMENTS (2008 TEXAS 303(d) LIST)

Impairment	0501 (Sabine above Toledo Bend Res.)	0504 (Toledo Bend Res.)	0505 (Sabine above Toledo Bend Res.)	0507 (Lake Tawakoni)	0514 (Big Sandy Creek)
Depressed dissolved oxygen		X[1]			
pH				X[2]	
Bacteria	X		X		X
Mercury in edible tissue		X			
Selected USGS Gage	N/A	N/A	N/A	N/A	

Notes:
1 Only in Tenaha Creek arm of the lake
2 Only in Cow Leech Fork arm of the lake

TABLE XII-1.2: NECHES BASIN WATER QUALITY IMPAIRMENTS (2008 TEXAS 303(d) LIST)

Impairment	0603 (Steinhagen Res.)	0604 (Neches below L. Palestine)	0605 (L. Palestine)	0606 (Neches above L. Palestine)	0607 (Pine Island Bayou)	0608 (Village Creek)	0610 (Sam Rayburn Res.)	0611 (Angelina above Sam Rayburn Res.)	0612 (Attoyac Bayou)	0615 (Riverine portion of Sam Rayburn Res.)
Depressed dissolved oxygen					X					X
pH			X	X		X				
Bacteria				X	X			X	X	X
Mercury/edible tissue	X						X			X
Lead in water		X								
Zinc in water				X						
Impaired fish community										X
Selected USGS Gage	N/A		N/A	N/A	N/A		N/A			N/A

APPENDIX XII-2

WATER QUALITY VS. FLOW DISCUSSION

Water quality data, collected primarily at the selected USGS gages, and mean daily discharge (i.e., flow; cubic feet per second) at each respective gage were used to develop water quality parameter - flow relationships. The period of record for flow at each gage is generally significantly longer than that for water quality. The water quality data periods of record were not equal for all gages, but ranged from as early as 1960 to 2009.

In order to develop a sufficient number of flow-quality points for total phosphorus and chlorophyll-a, however, data from both USGS gages and nearby CRP sampling stations were sometimes utilized. Stations were selected if they were a short distance upstream or downstream and were not influenced by tributaries. Data agglomeration was performed in order to capture a sufficient amount of total phosphorus and chlorophyll-a data to make a more complete evaluation. Nutrient data from 1972 to 2008 were used in this analysis.

Included below are descriptions of the relationships, or lack thereof, between water quality and flow. Graphs of each water quality parameter assessed are also included, which display the lowest subsistence flow (i.e., summer subsistence value) and highest subsistence flow (i.e., fall or winter subsistence value).

DISSOLVED OXYGEN

Dissolved oxygen (DO) is highly variable across the assessed range of flows at each gage. Very little relationship exists between concentration and flow. Concentrations generally range from 4 to 13 mg/L, with occasional outliers at lower concentrations. Results at the lower flows do not show significant downward trends. As would be expected, summer DO concentrations are generally lower than for other seasons. Diurnal data for DO are not available at this time.

WATER TEMPERATURE

Water Temperature was highest during the summer and lowest during fall and winter. The highest summer temperature measurements typically corresponded to lower flows associated with most gages. Seasonal analyses indicated that water temperature generally decreased with increased flow during spring, summer and fall yet remained consistent or increased during the winter.

pH

pH decreased with increased flow at all but one gage; however, the relationship was quite weak. Variability was high throughout a broad range of flows, though the range of pH tended to decrease at higher flows.

ALKALINITY

Alkalinity was less variable across the range of flows at some gages but exhibited a weak negative relationship at others. The latter analyses indicated higher correlation between concentration and flow; however, only approximately 20% of the variability was explained on average. Data were available for all of the Neches River basin gages but only two of the Sabine River gages.

TOTAL PHOSPHORUS AND CHLOROPHYLL-A

Nutrient data were typically sparse even when data from CRP stations were included. Total phosphorus and chlorophyll-a generally decreased or remained consistent throughout the assessed range of flows. Only weak relationships were evident because of variability and, possibly, paucity of data.

CONDUCTIVITY (FIELD AND LABORATORY)

Field and laboratory conductivity were approximately equal at each gage, and the relationship with flow was generally consistent among each gage. Conductivity followed an inverse power relationship (ax^{-b}; similar to an inverse logarithmic relationship) at most gages; variability was highest at the lowest flows and decreased exponentially with increased flow. Up to approximately 80% of variability was explained by the inverse power relationship. Only field conductivity is displayed here.

TOTAL DISSOLVED SOLIDS

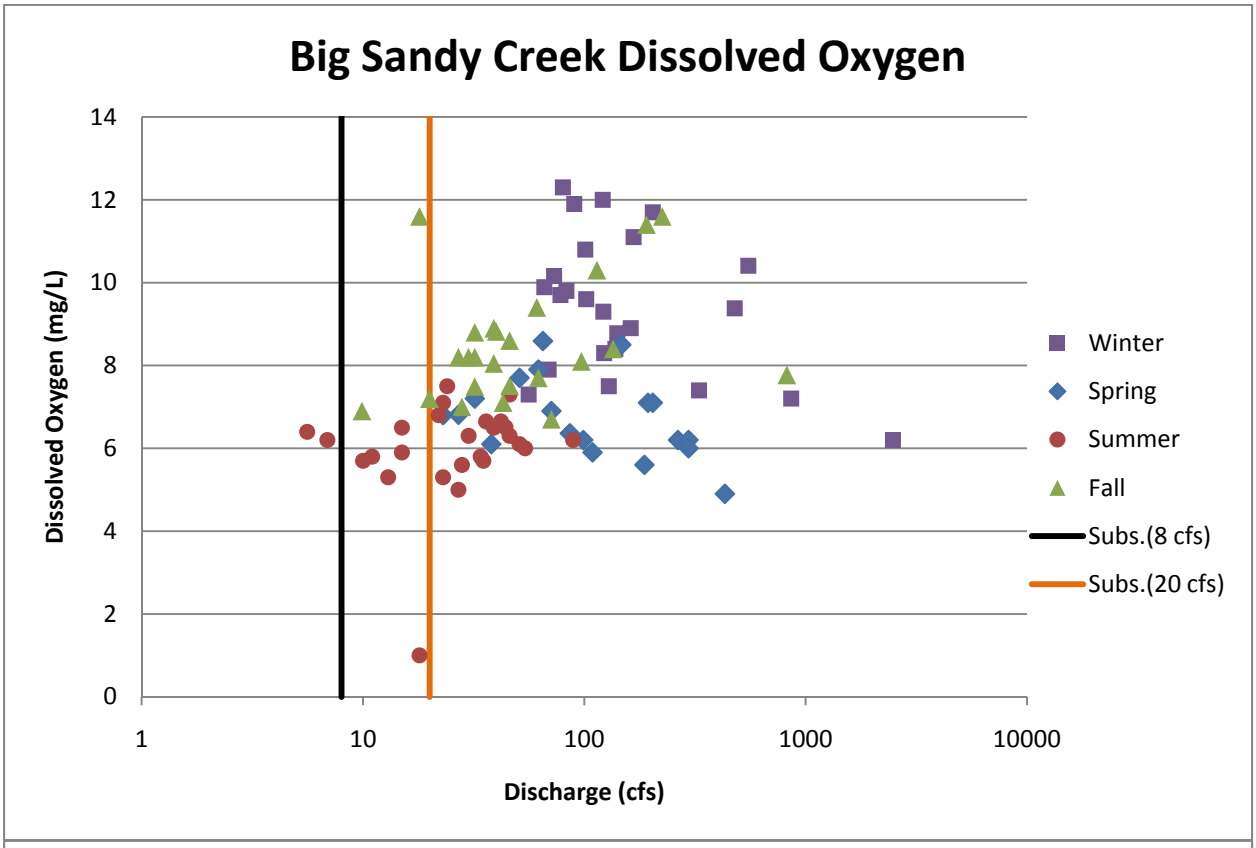
Total dissolved solids were somewhat variable across the range of flows assessed. Concentration decreased with increased flows except at one gage.

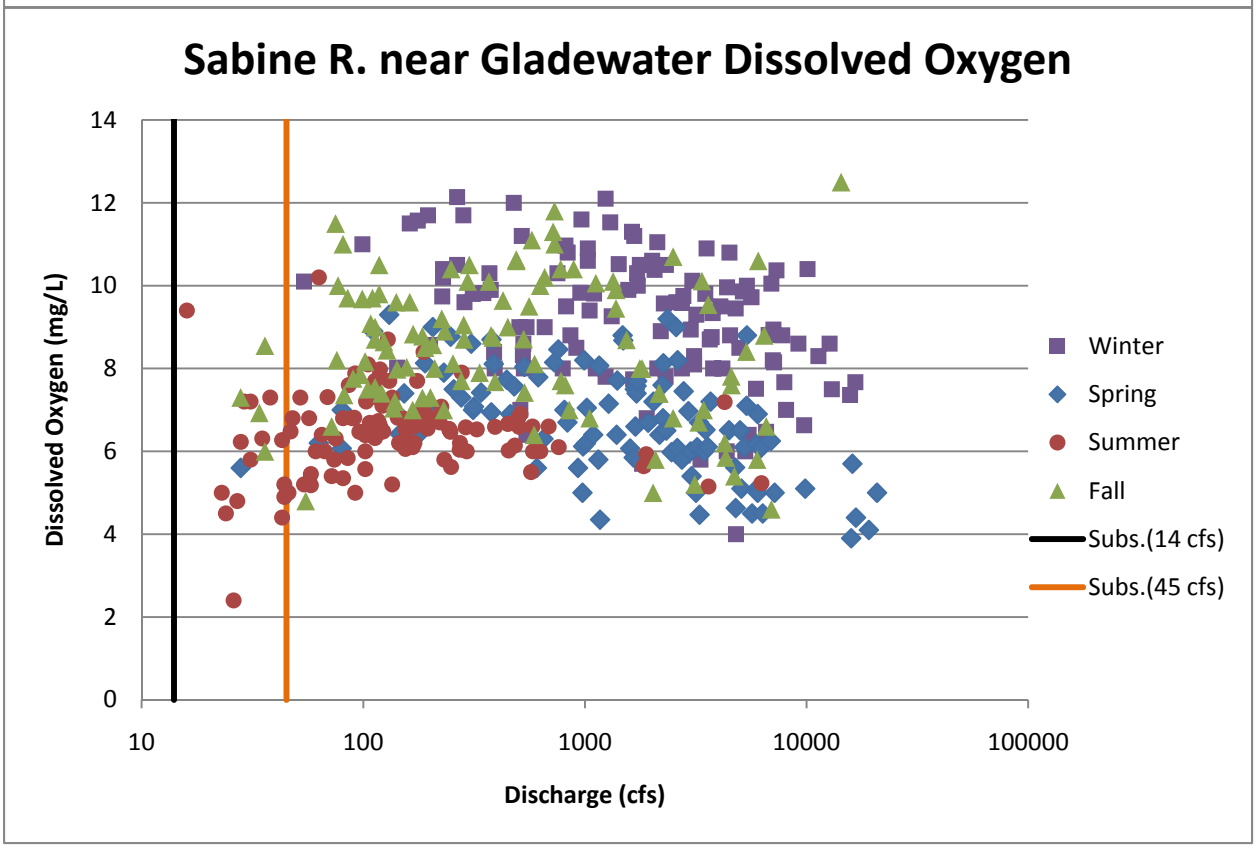
TURBIDITY

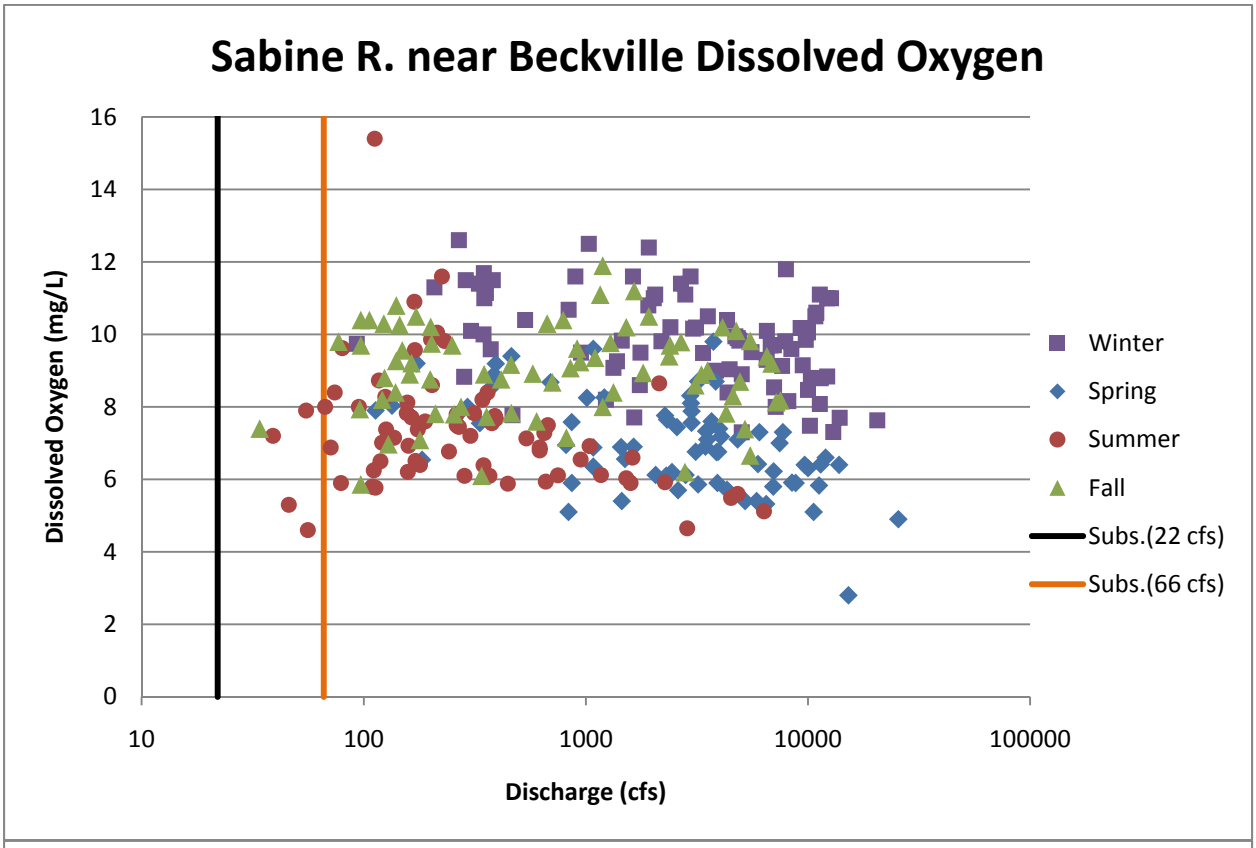
Turbidity was relatively low, though data were only available for less than half of the gages. Variability was large throughout the range of flows and increased at some gages, while it decreased or remained consistent at others. Only weak relationships were indicated.

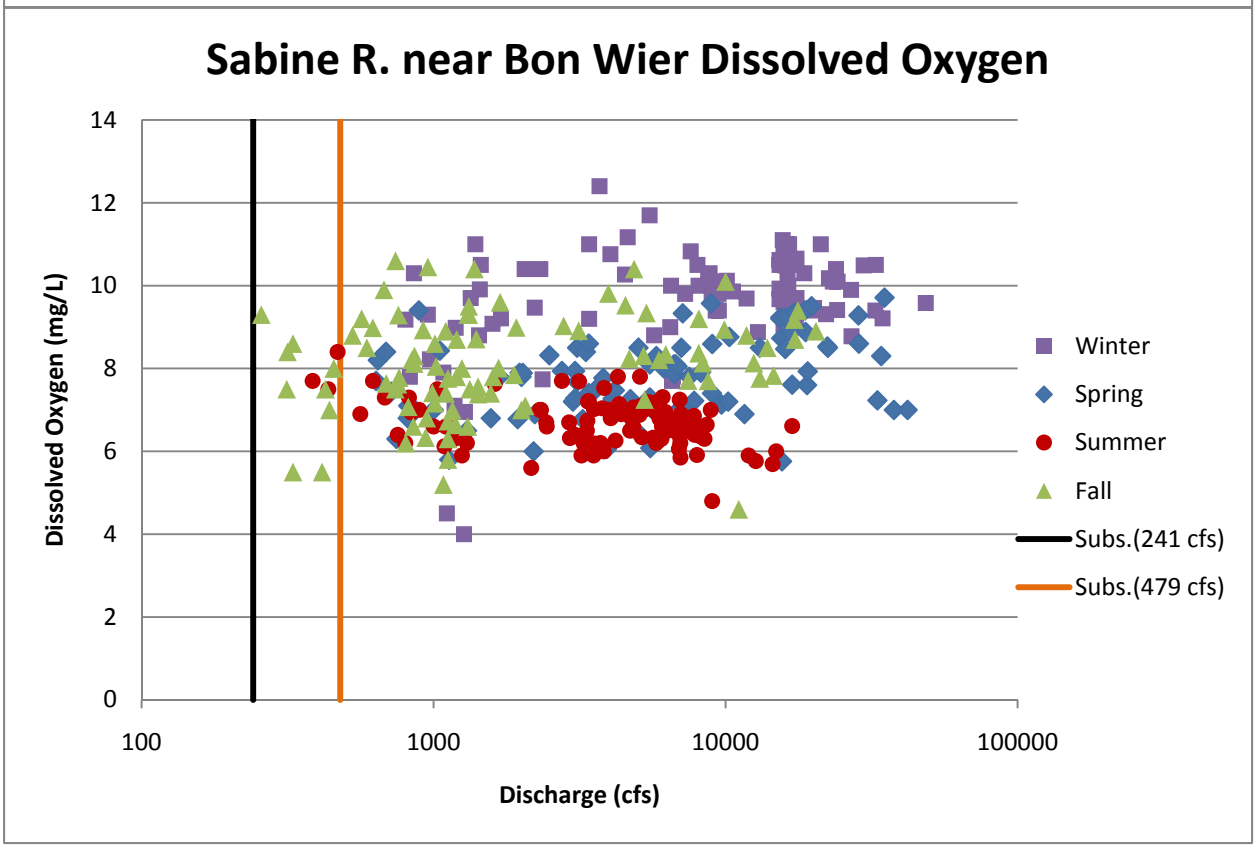
FECAL COLIFORM

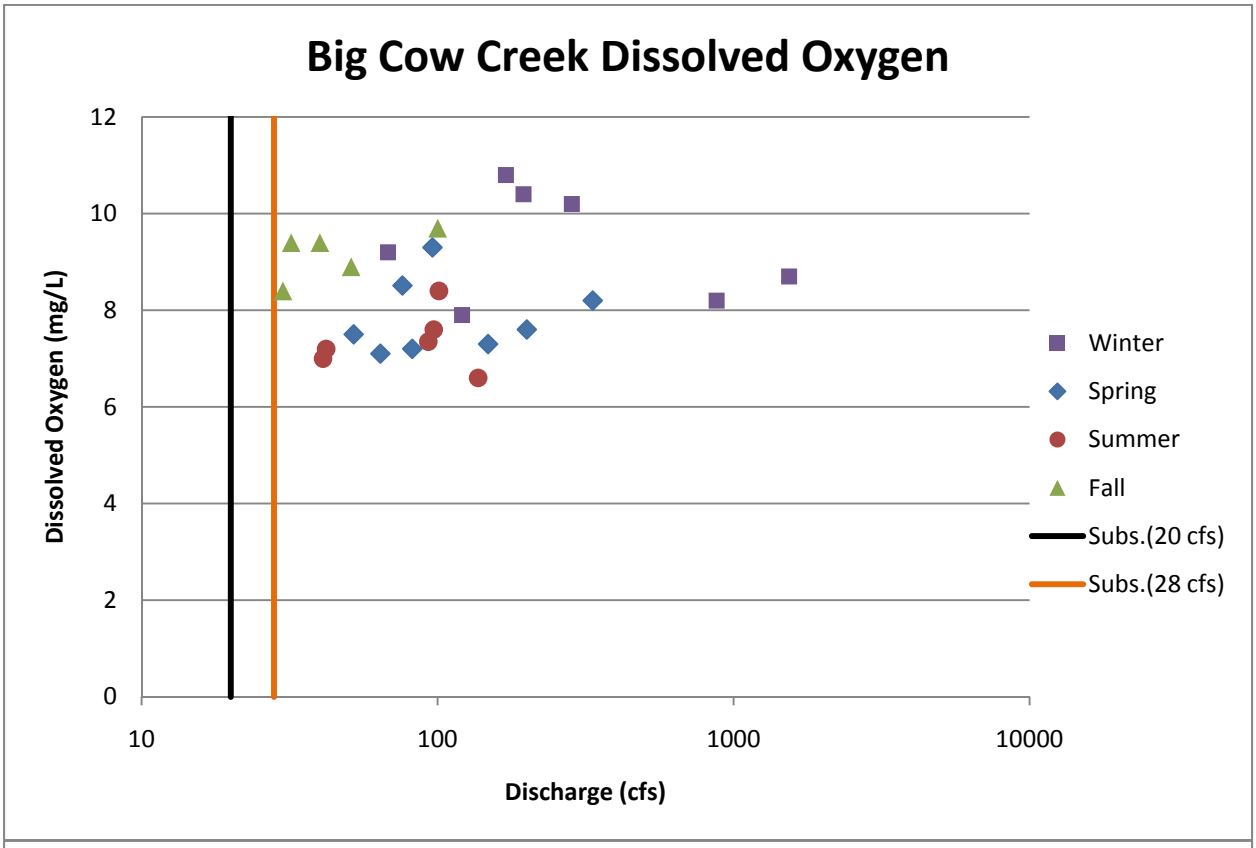
Weak positive relationships were observed for the two gages with sufficient fecal coliform data. Values were generally low with a few higher scattered points generating a positive trend.

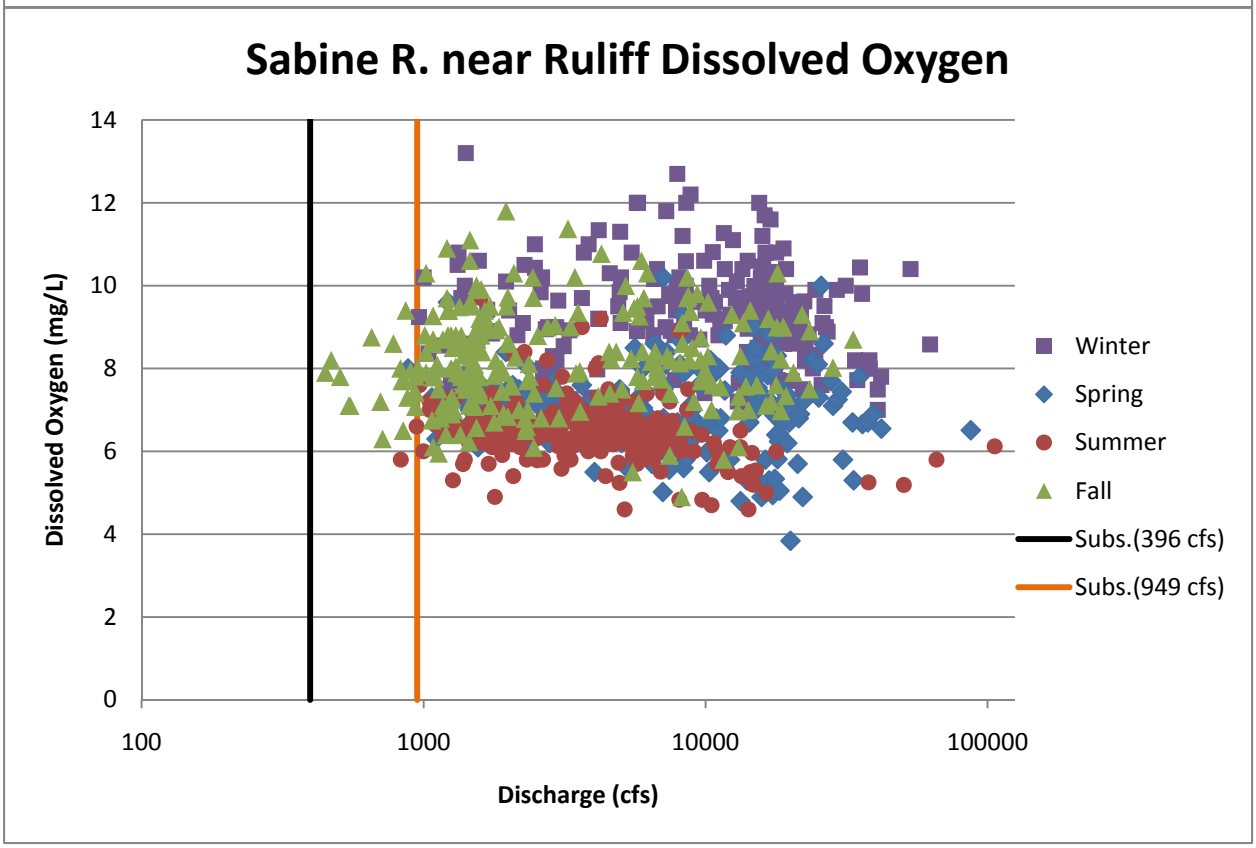

Big Sandy Creek Dissolved Oxygen
Dissolved Oxygen (mg/L)
14
12
10
8
6
4
2
0
1
10
100
1000
10000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(8 cfs)
Subs.(20 cfs)

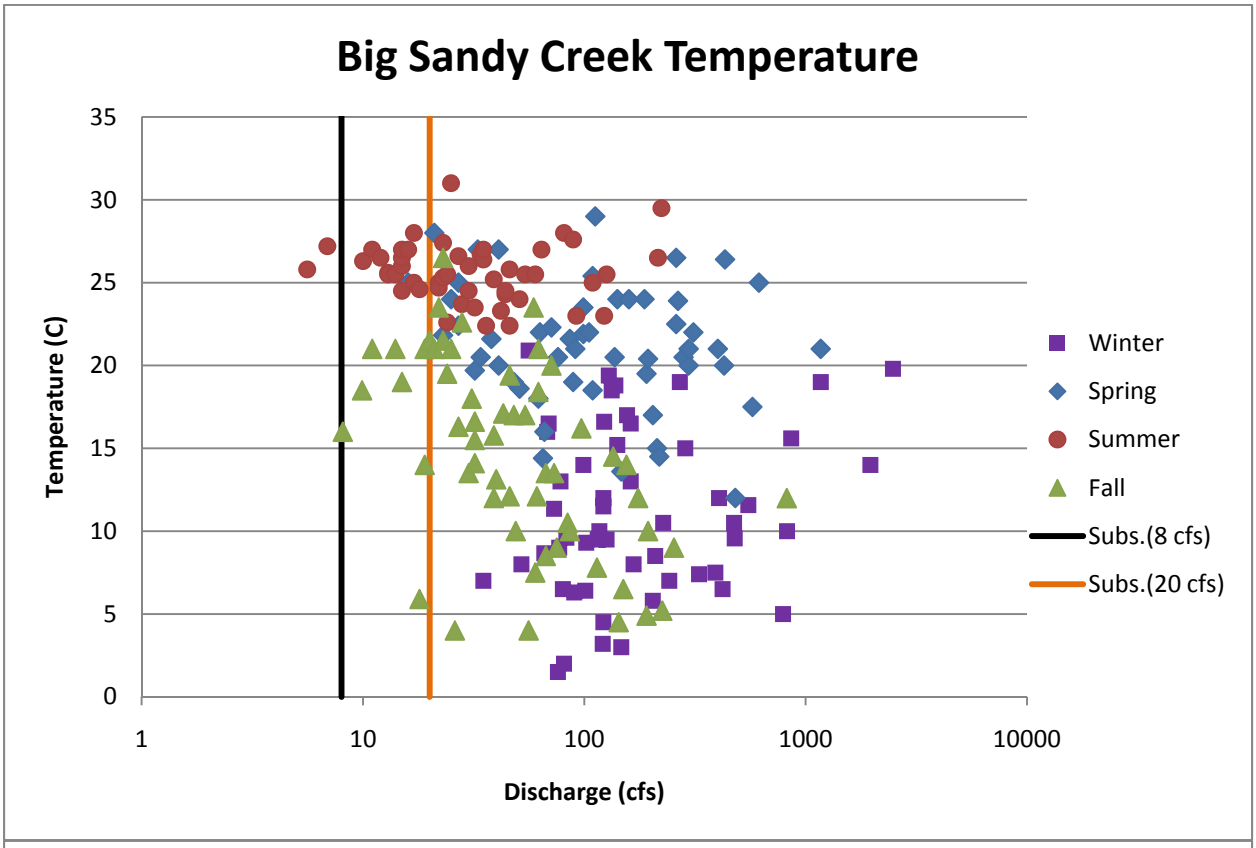

Sabine R. near Gladewater Dissolved Oxygen
Dissolved Oxygen (mg/L)
14
12
10
8
6
4
2
0
10
100
1000
10000
100000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(14 cfs)
Subs.(45 cfs)

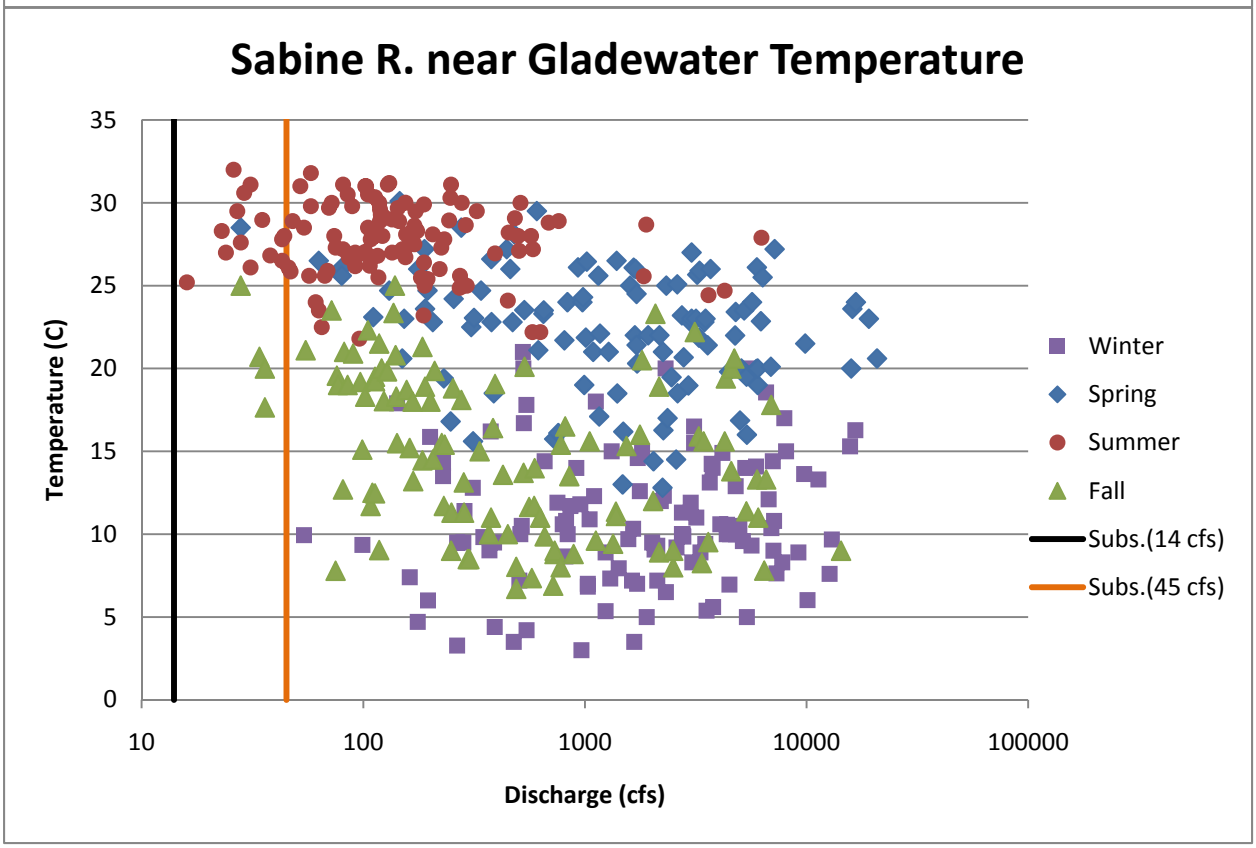

Sabine R. near Beckville Dissolved Oxygen
Dissolved Oxygen (mg/L)
16
14
12
10
8
6
4
2
0
10
100
1000
10000
100000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(22 cfs)
Subs.(66 cfs)

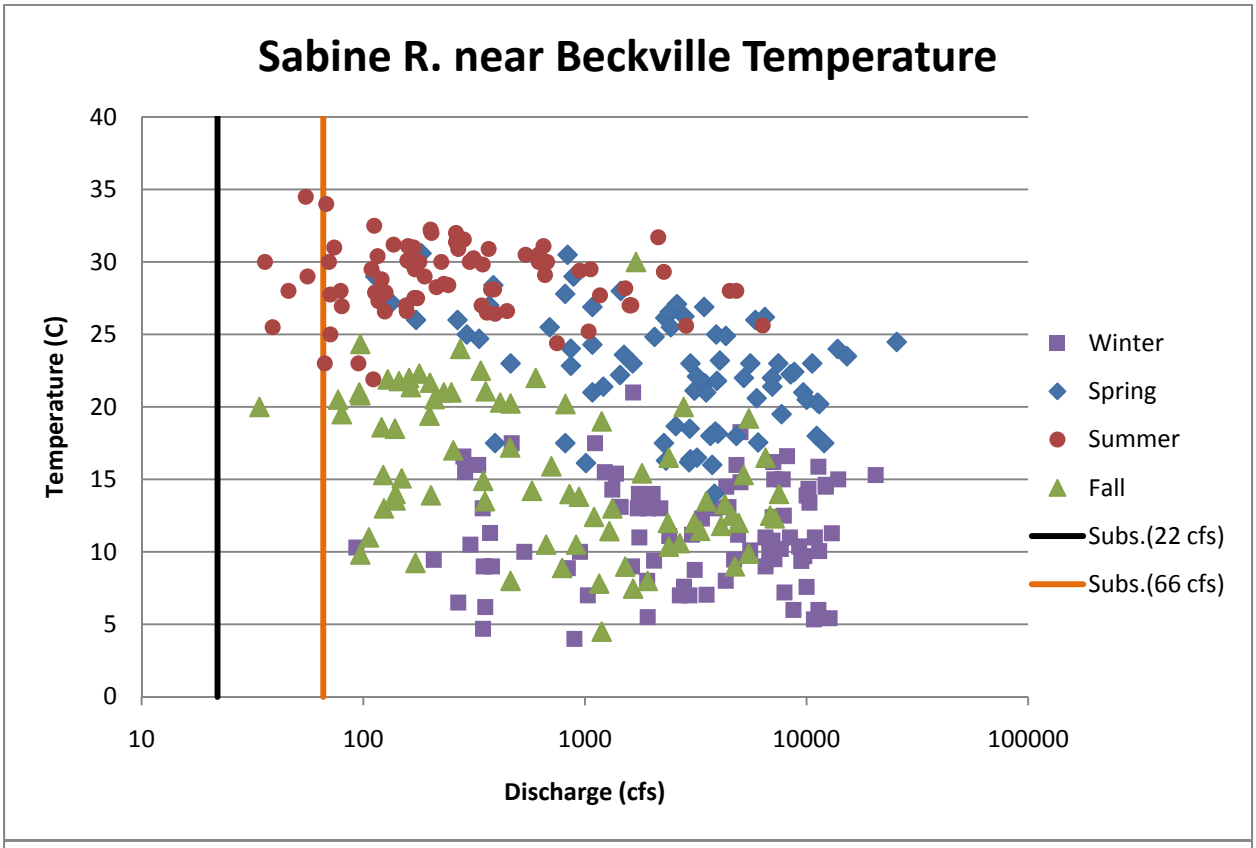

Sabine R. near Bon Wier Dissolved Oxygen
Dissolved Oxygen (mg/L)
14
12
10
8
6
4
2
0
100
1000
10000
100000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(241 cfs)
Subs.(479 cfs)

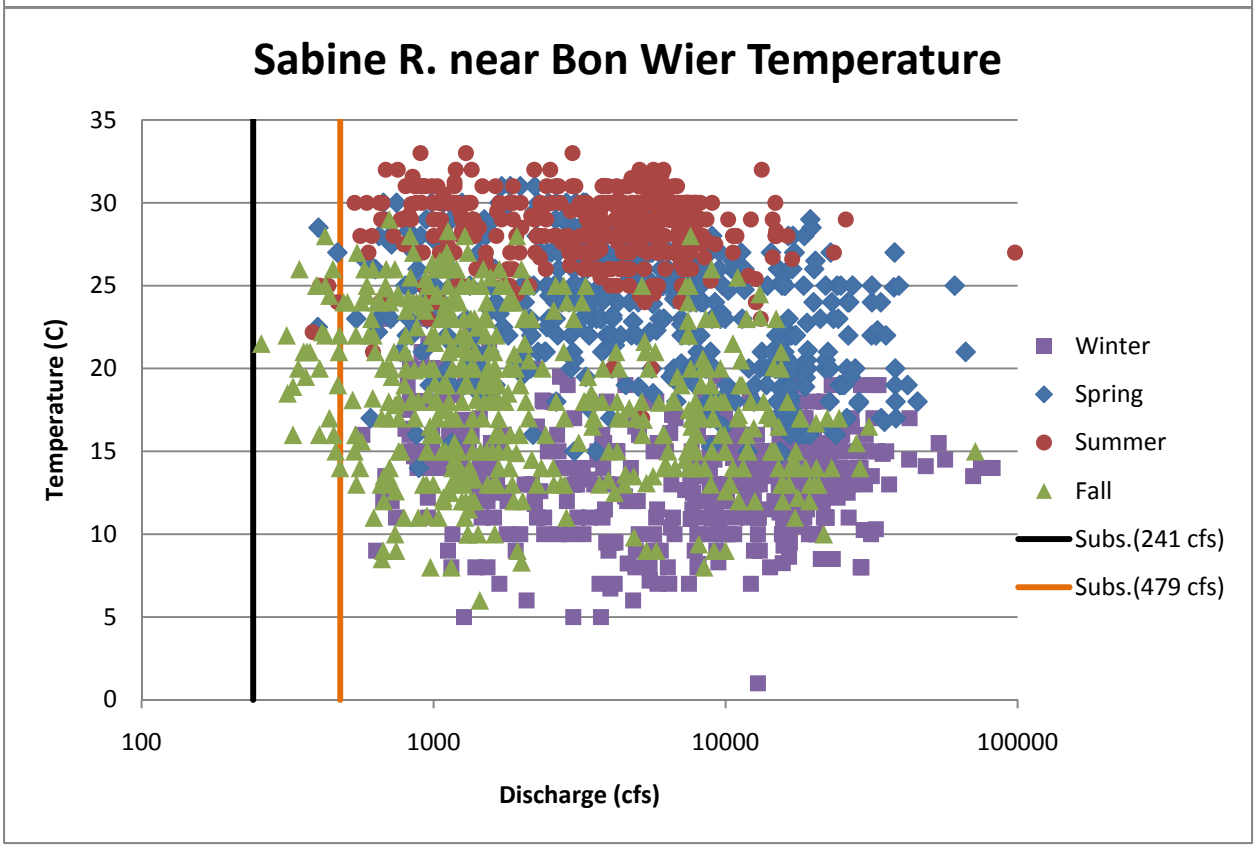

Big Cow Creek Dissolved Oxygen
Dissolved Oxygen (mg/L)
12
10
8
6
4
2
0
10
100
1000
10000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(20 cfs)
Subs.(28 cfs)

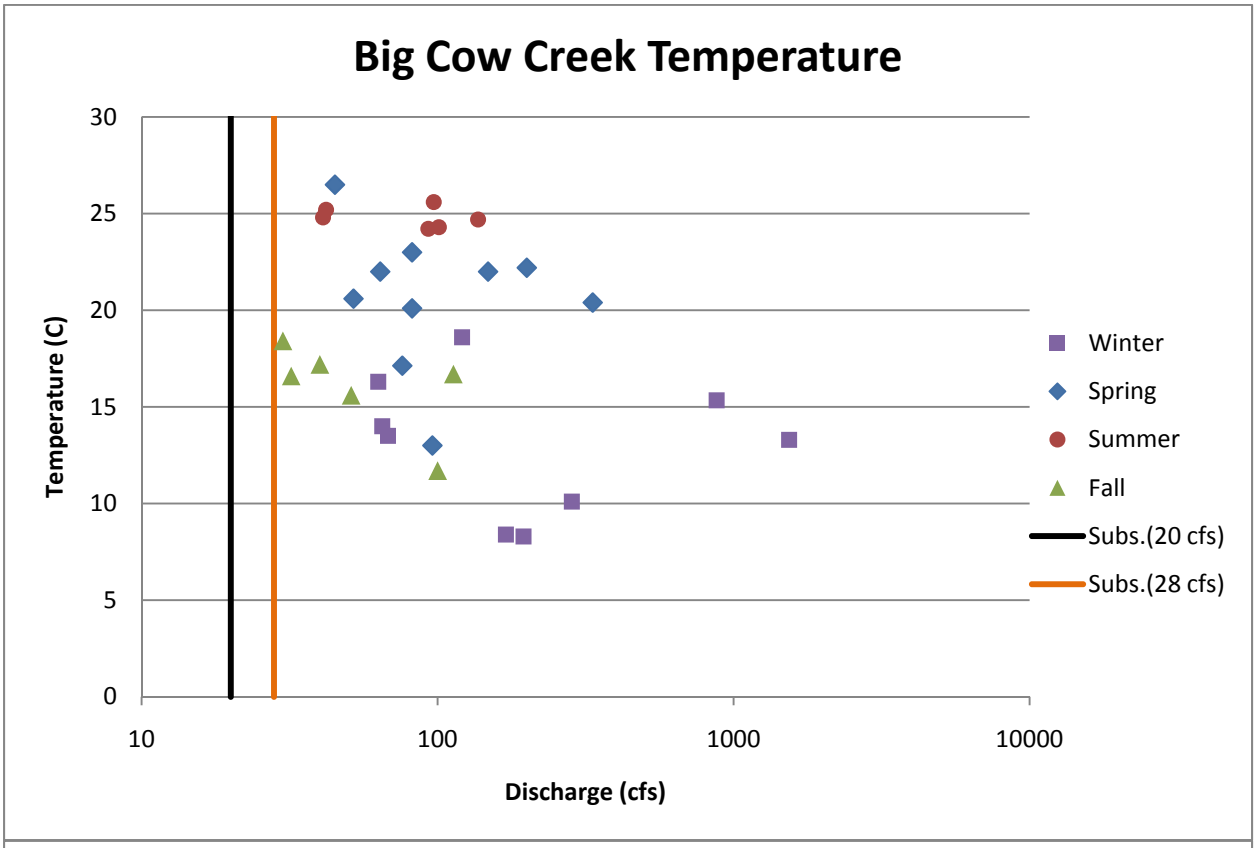

Sabine R. near Ruliff Dissolved Oxygen
Dissolved Oxygen (mg/L)
14
12
10
8
6
4
2
0
100
1000
10000
100000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(396 cfs)
Subs.(949 cfs)

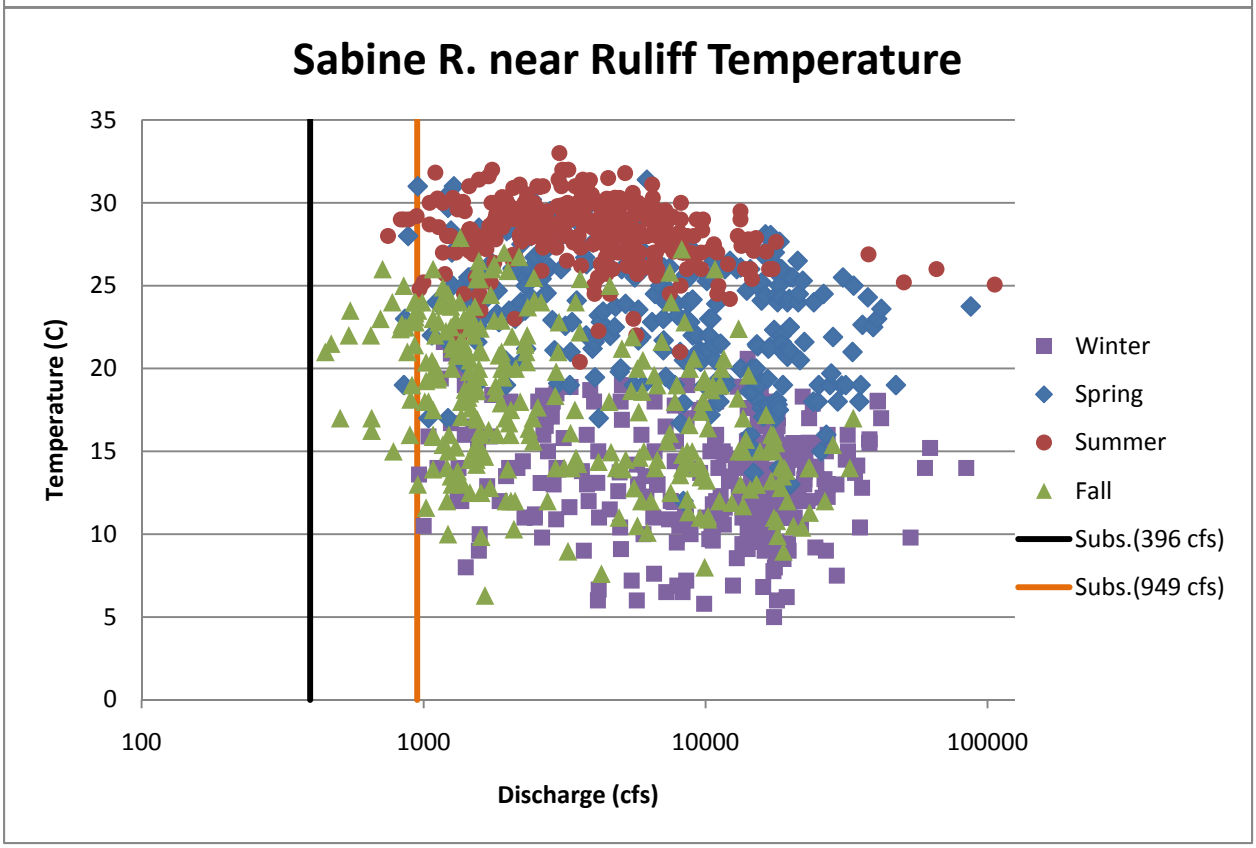

Big Sandy Creek Temperature
Temperature (C)
35
30
25
20
15
10
5
0
1
10
100
1000
10000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(8 cfs)
Subs.(20 cfs)

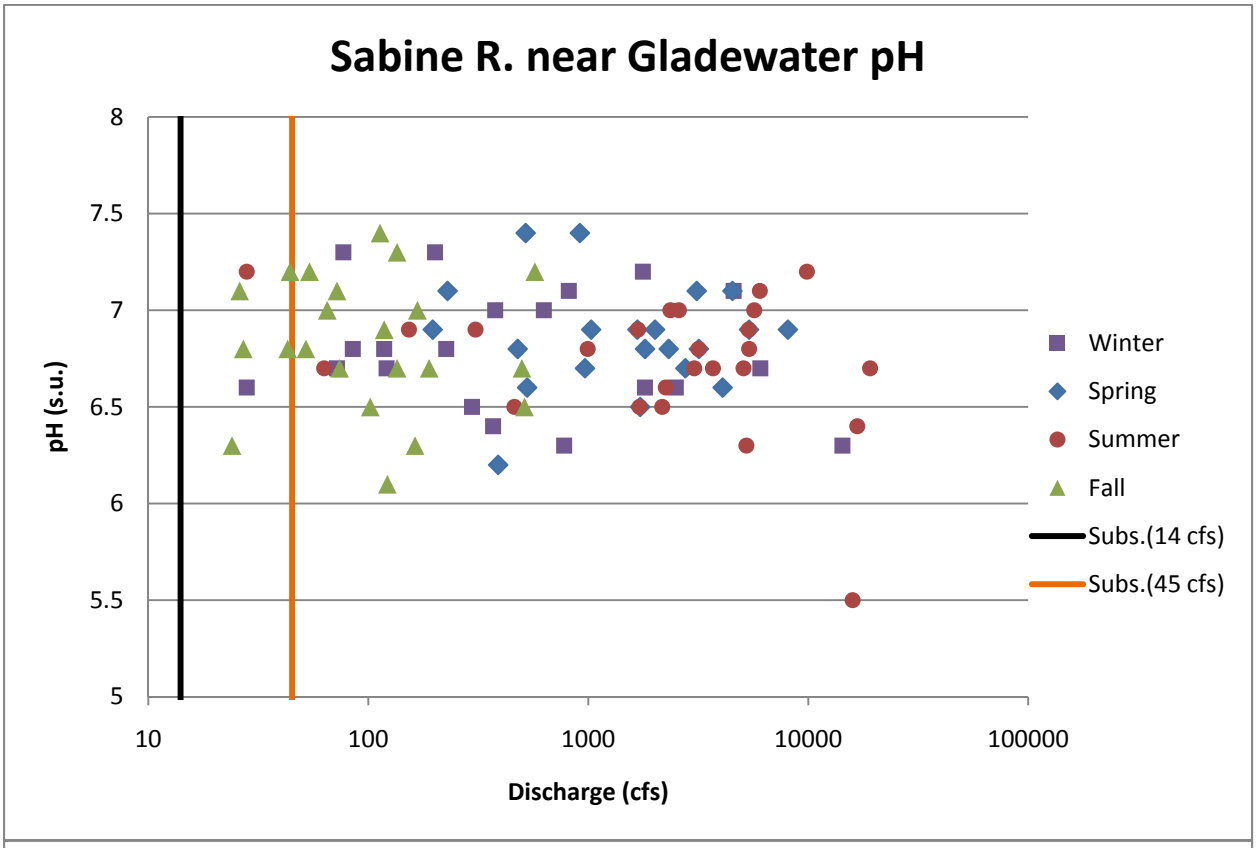

Sabine R. near Gladewater Temperature
Temperature (C)
35
30
25
20
15
10
5
0
10
100
1000
10000
100000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(14 cfs)
Subs.(45 cfs)

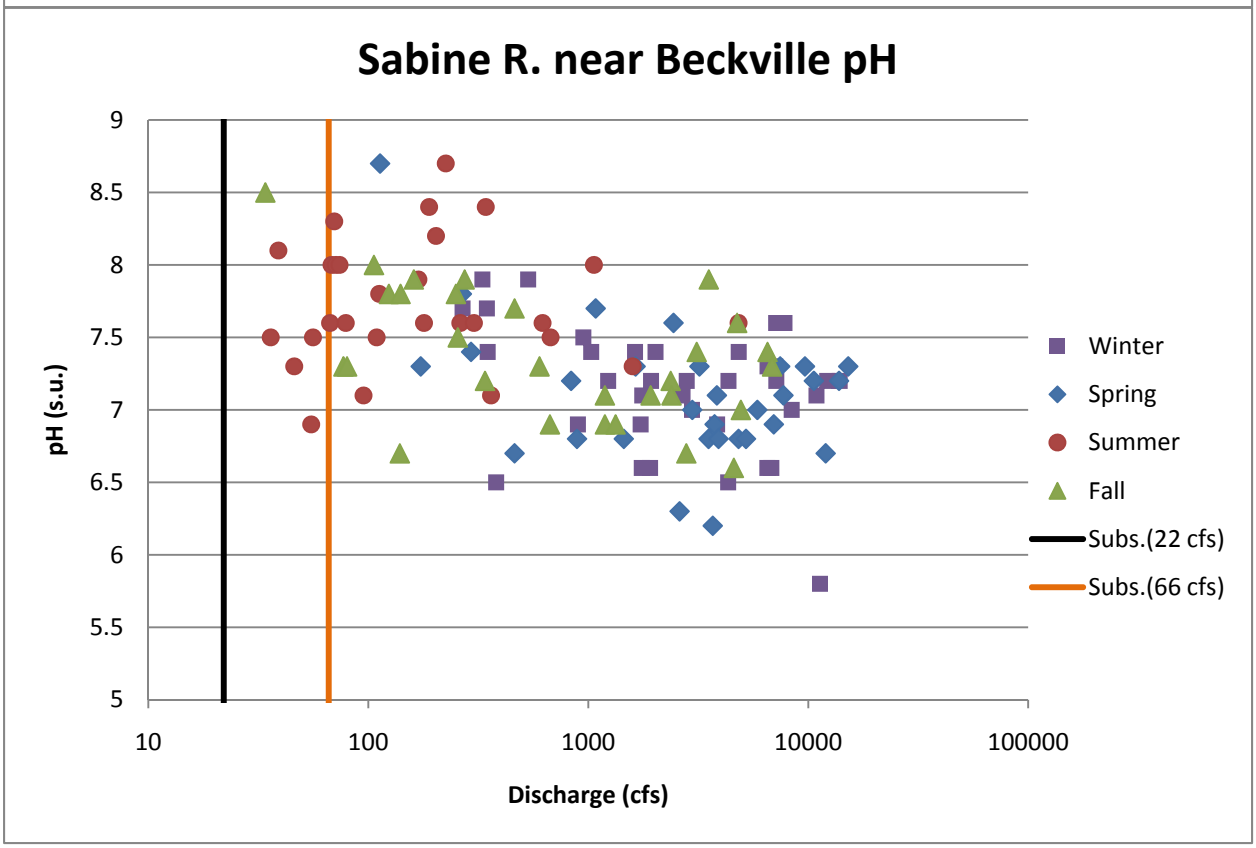

Sabine R. near Beckville Temperature
Temperature (C)
40
35
30
25
20
15
10
5
0
10
100
1000
10000
100000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(22 cfs)
Subs.(66 cfs)

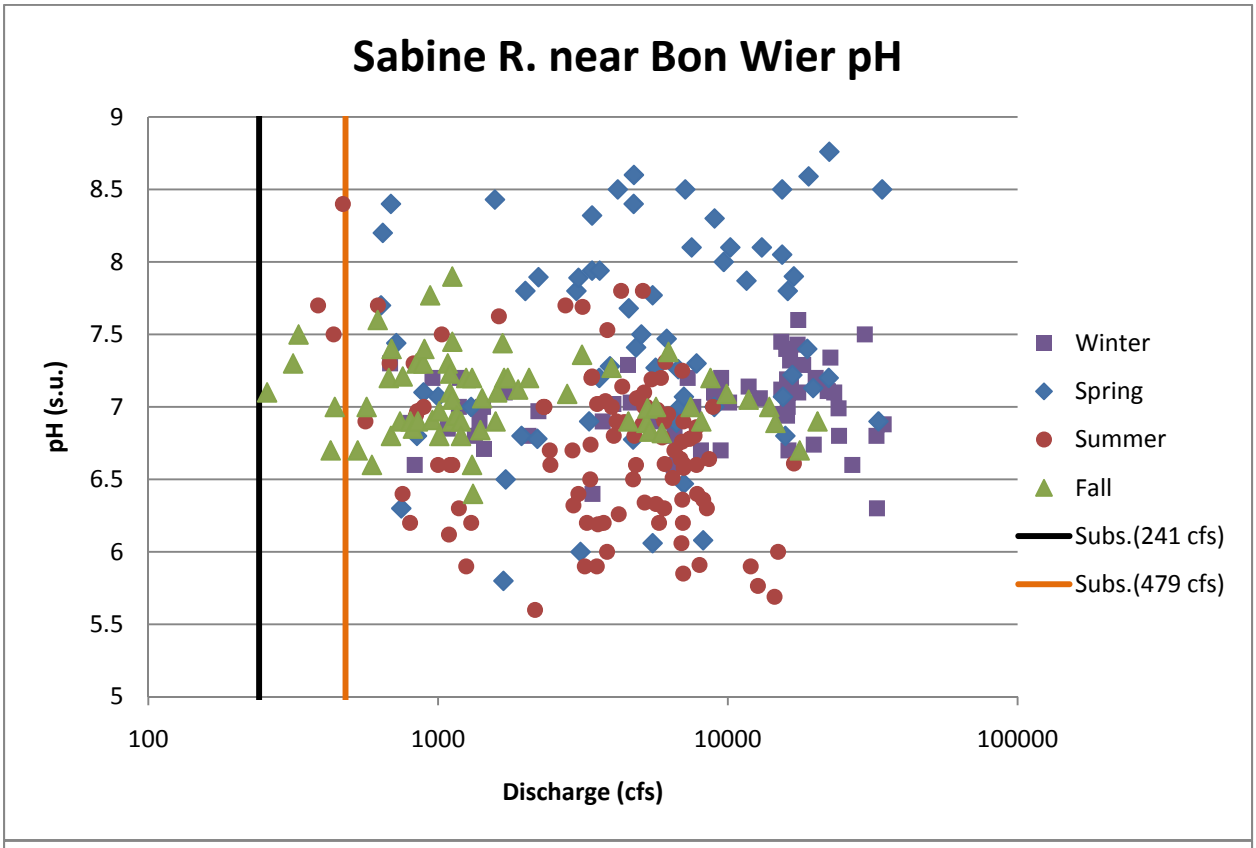

Sabine R. near Bon Wier Temperature
Temperature (C)
35
30
25
20
15
10
5
0
100
1000
10000
100000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(241 cfs)
Subs.(479 cfs)

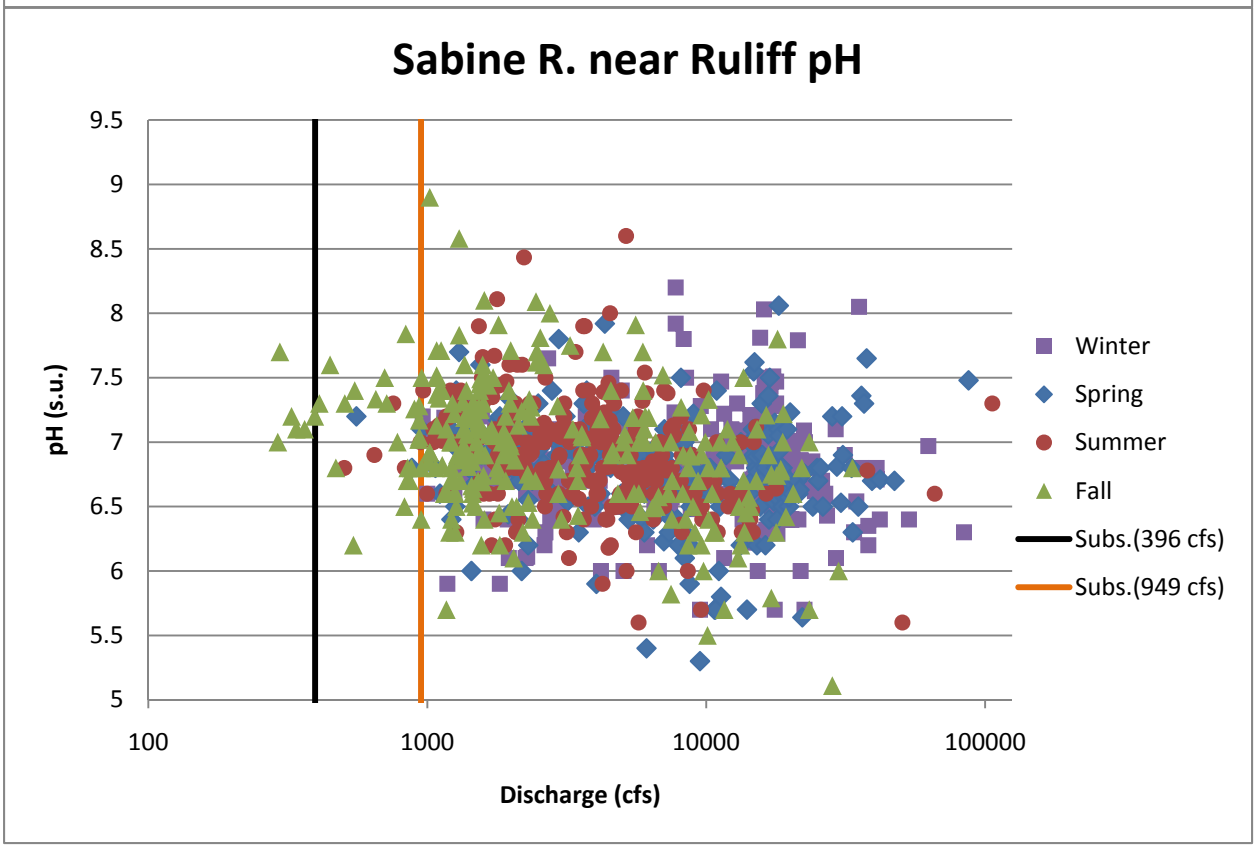

Big Cow Creek Temperature
Temperature (C)
30
25
20
15
10
5
0
10
100
1000
10000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(20 cfs)
Subs.(28 cfs)

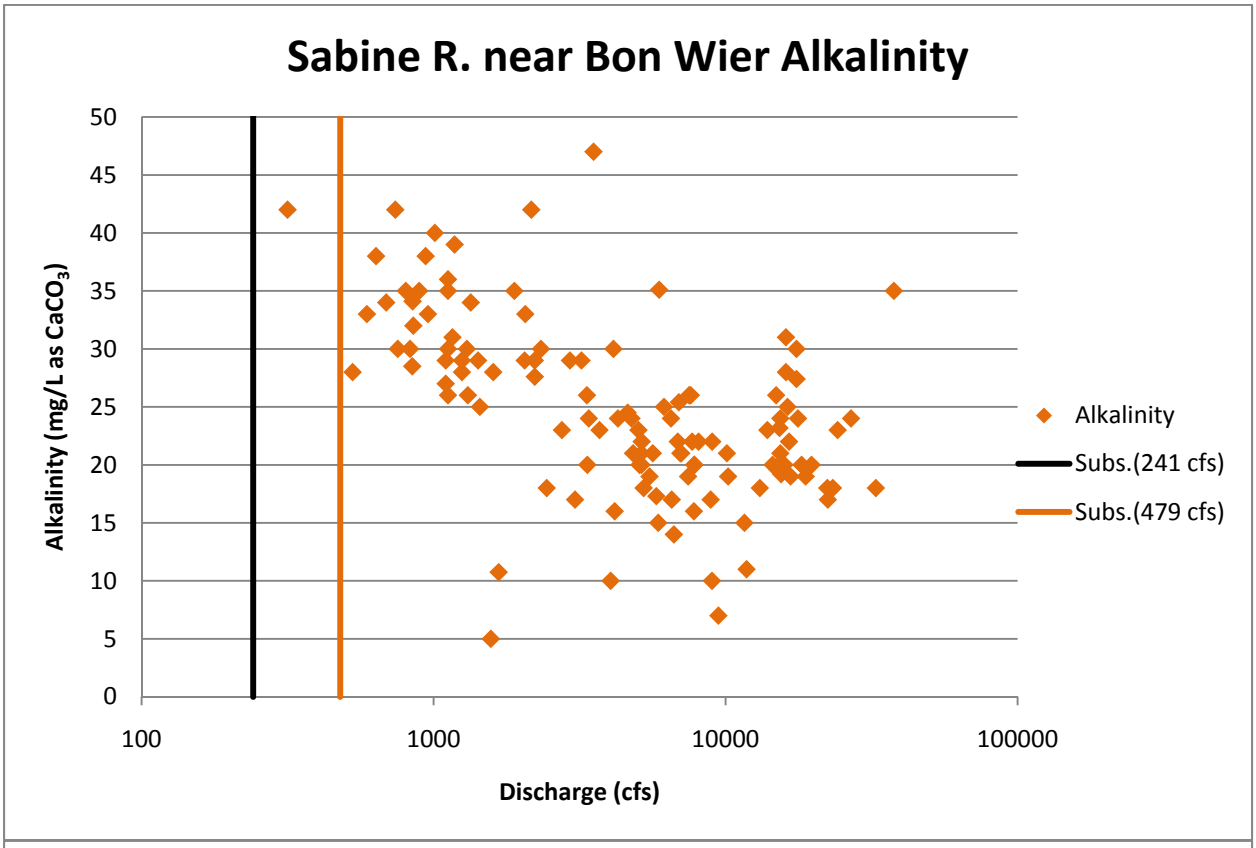

Sabine R. near Ruliff Temperature
Temperature (C)
35
30
25
20
15
10
5
0
100
1000
10000
100000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(396 cfs)
Subs.(949 cfs)

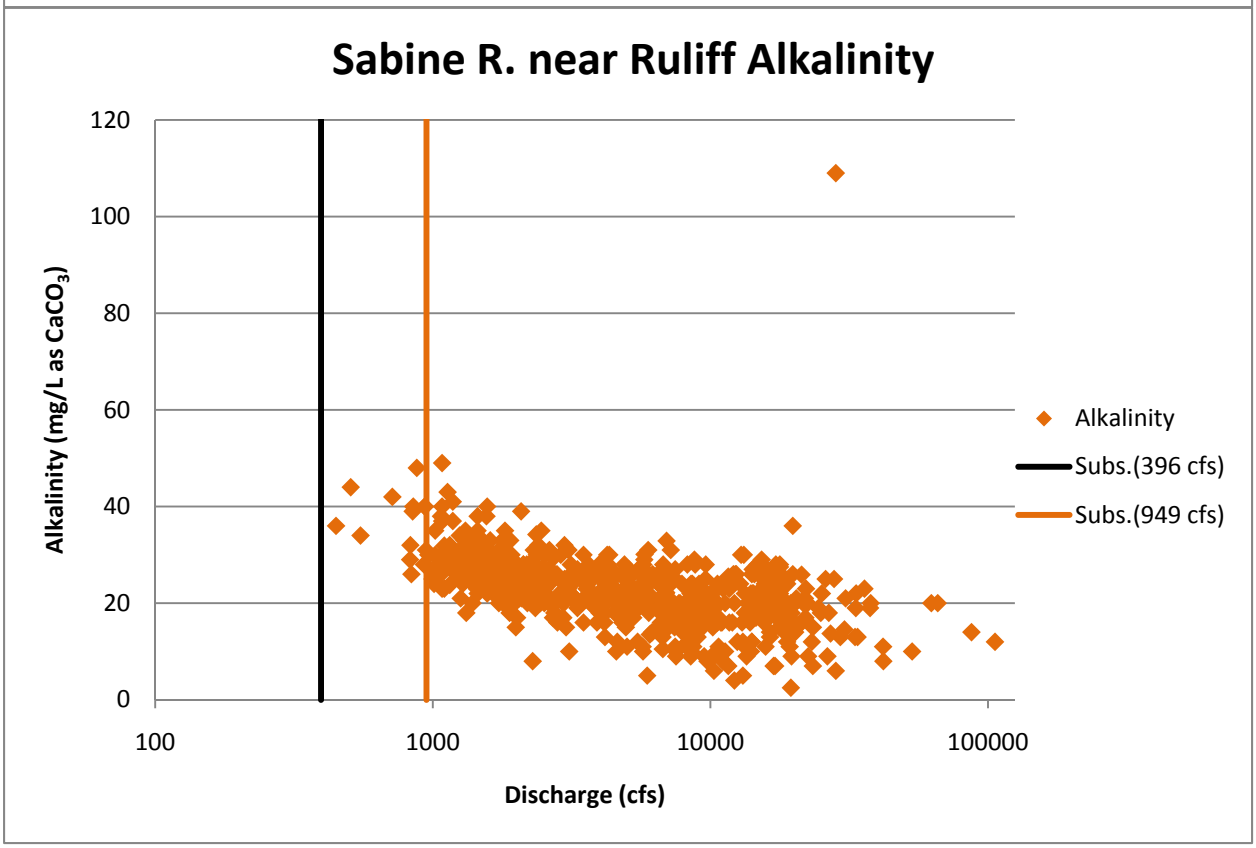

Sabine R. near Gladewater pH
pH (s.u.)
8
7.5
7
6.5
6
5.5
5
10
100
1000
10000
100000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(14 cfs)
Subs.(45 cfs)

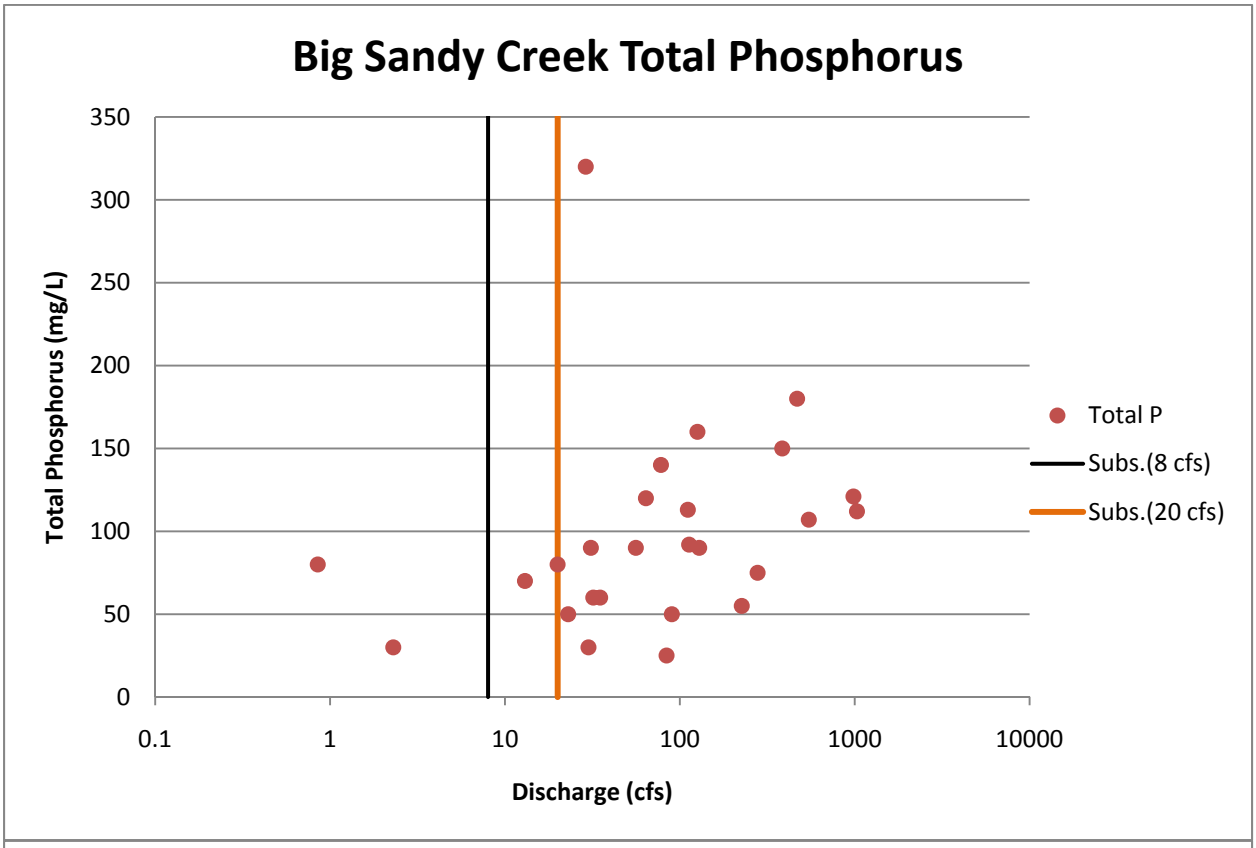

Sabine R. near Beckville pH
pH (s.u.)
9
8.5
8
7.5
7
6.5
6
5.5
5
10
100
1000
10000
100000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(22 cfs)
Subs.(66 cfs)

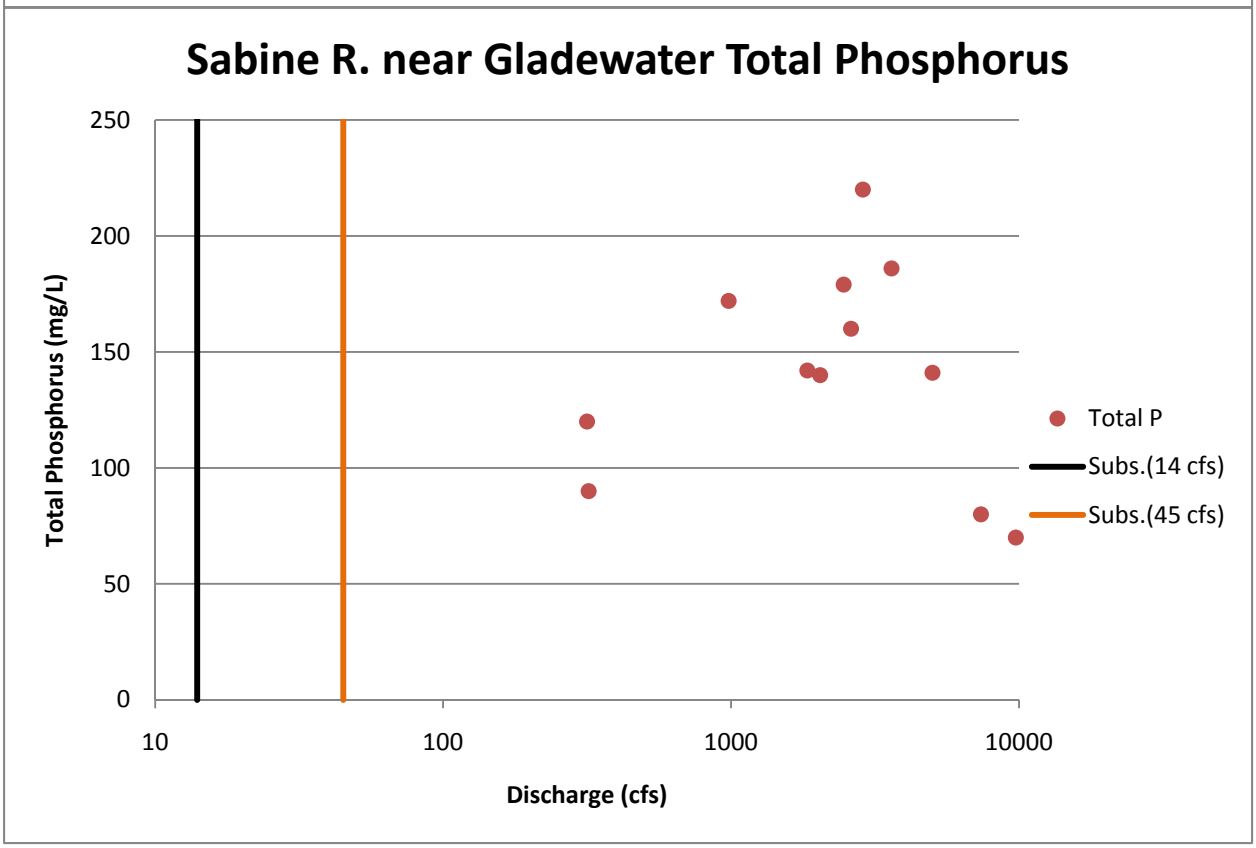

Sabine R. near Bon Wier pH
pH (s.u.)
9
8.5
8
7.5
7
6.5
6
5.5
5
100
1000
10000
100000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(241 cfs)
Subs.(479 cfs)

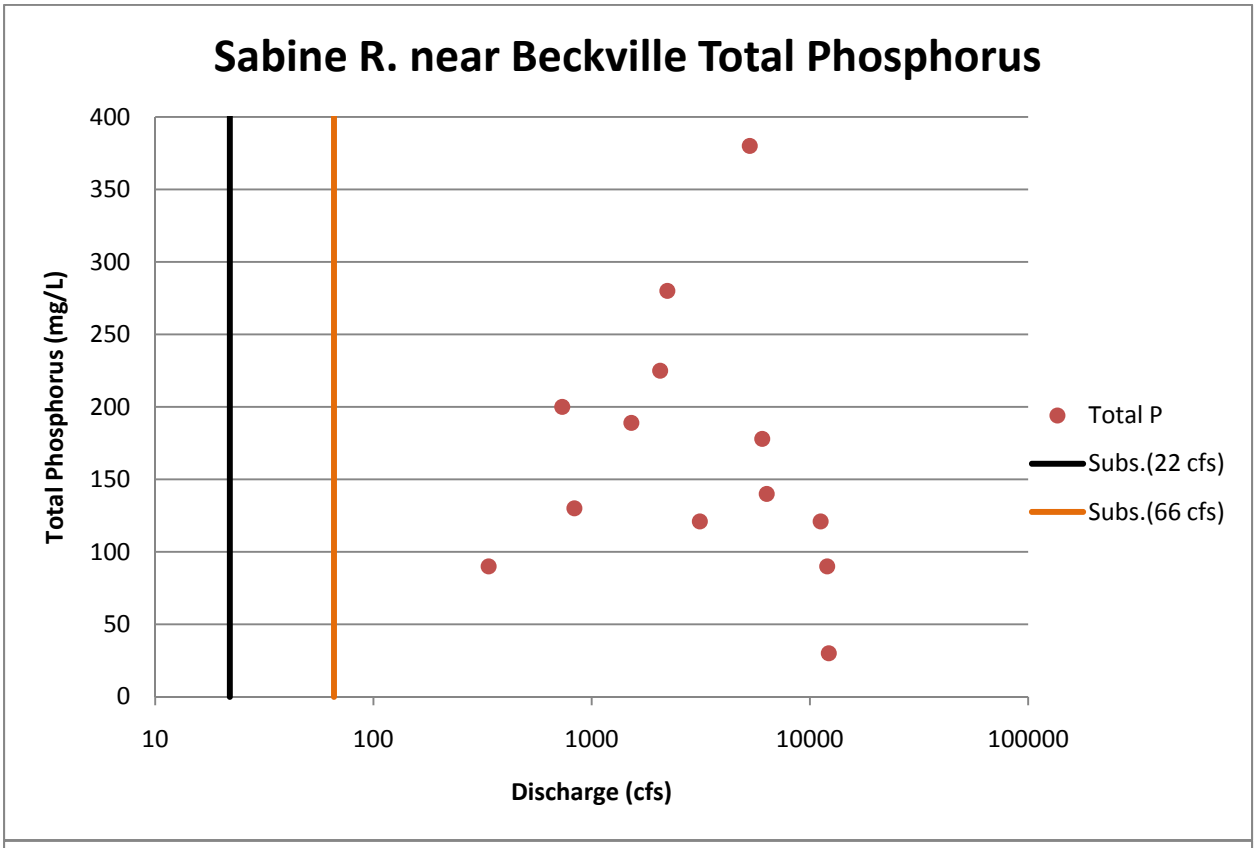

Sabine R. near Ruliff pH
pH (s.u.)
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
100
1000
10000
100000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(396 cfs)
Subs.(949 cfs)

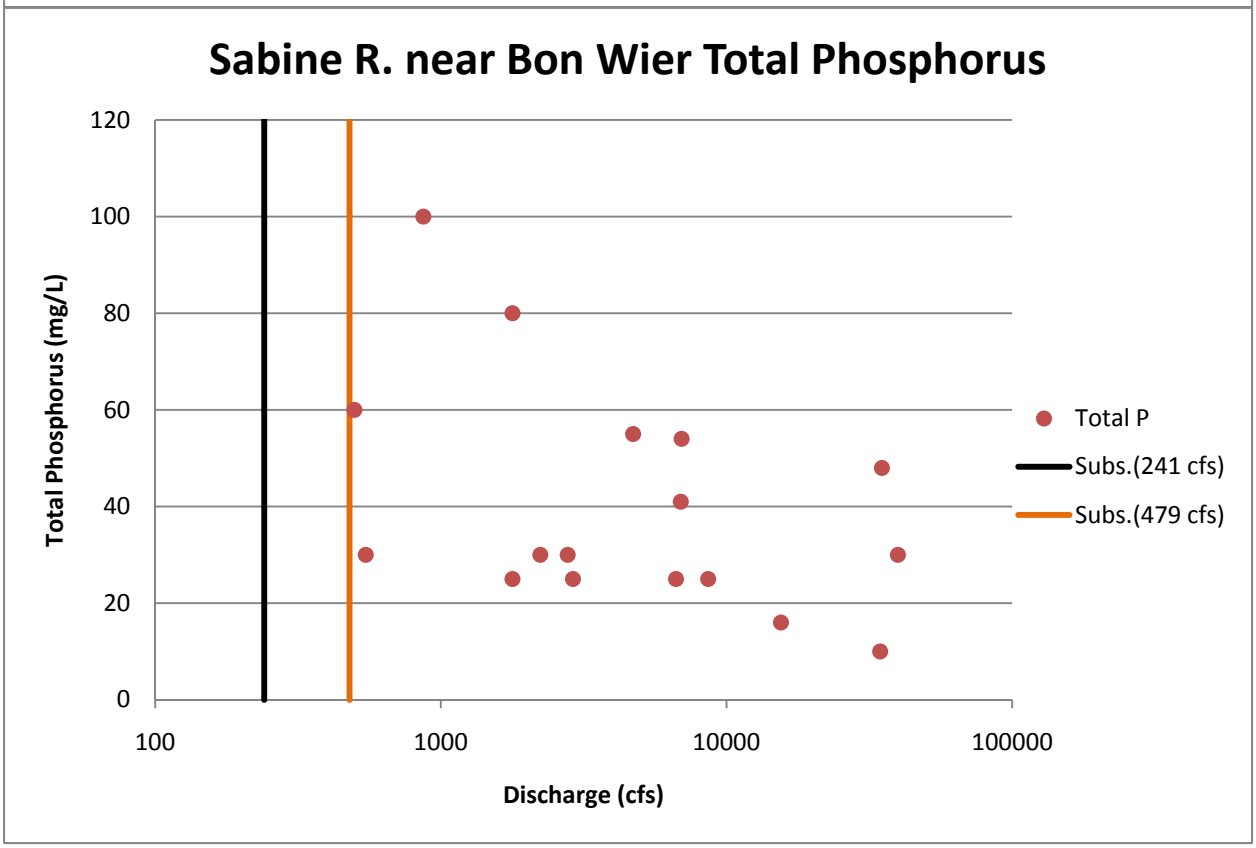

Sabine R. near Bon Wier Alkalinity
Alkalinity (mg/L as CaCO3)
50
45
40
35
30
25
20
15
10
5
0
100
1000
10000
100000
Discharge (cfs)
Alkalinity
Subs.(241 cfs)
Subs.(479 cfs)

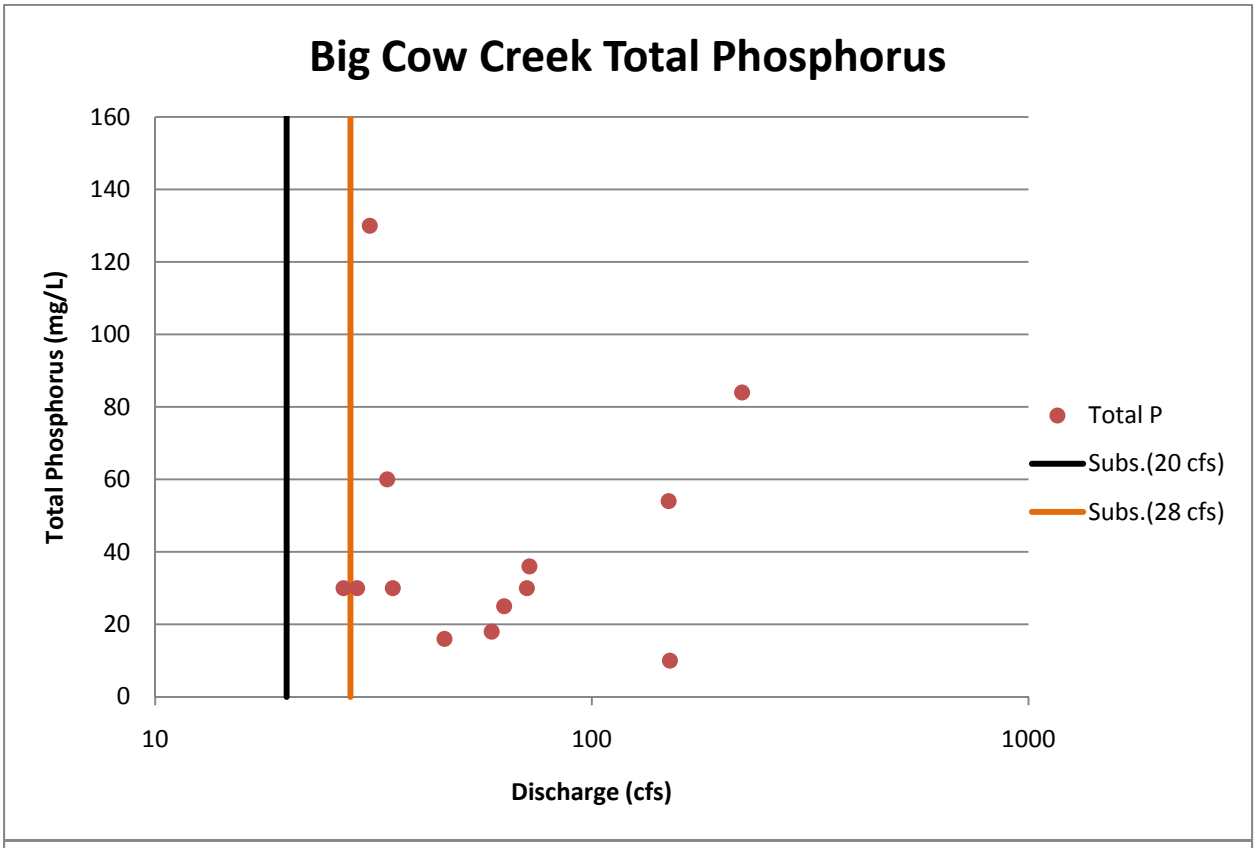

Sabine R. near Ruliff Alkalinity
Alkalinity (mg/L as CaCO3)
120
100
80
60
40
20
0
100
1000
10000
100000
Discharge (cfs)
Alkalinity
Subs.(396 cfs)
Subs.(949 cfs)

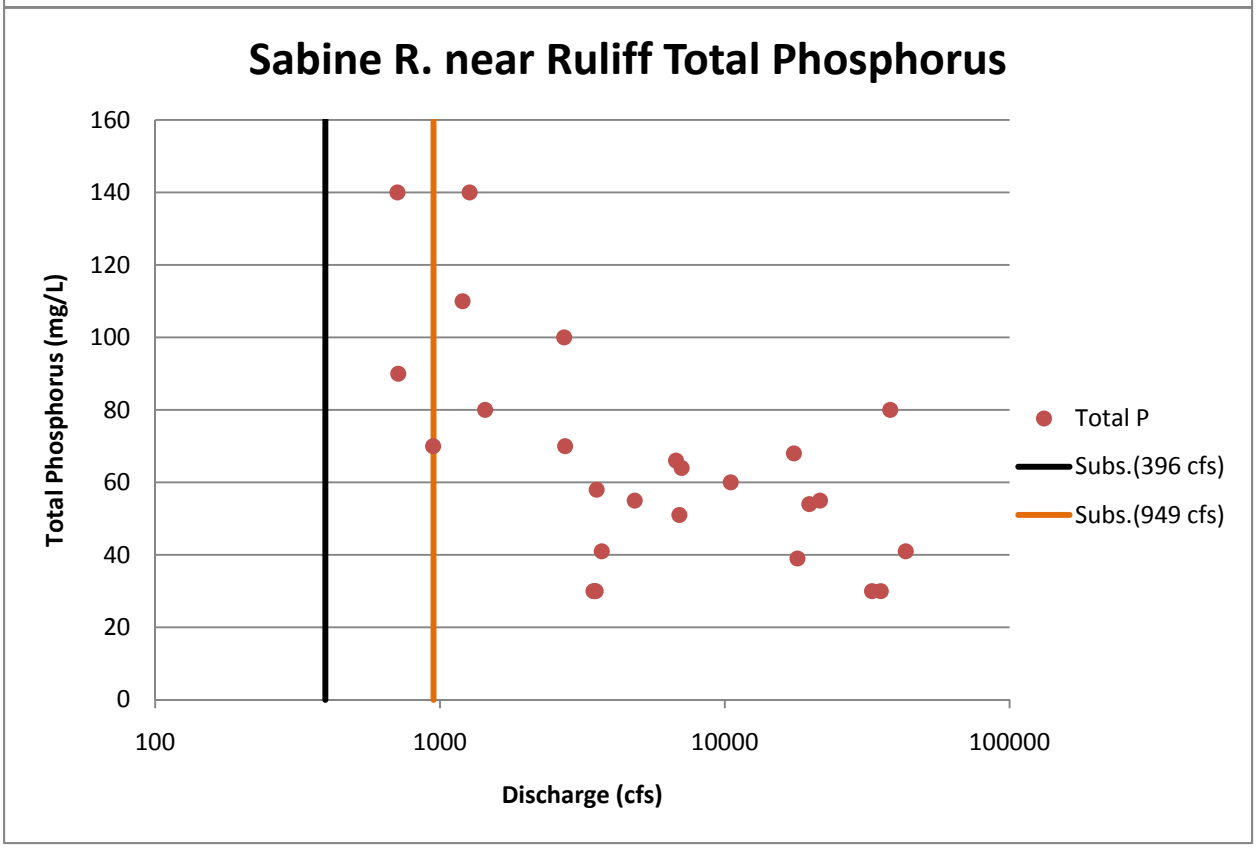

Big Sandy Creek Total Phosphorus
Total Phosphorus (mg/L)
350
300
250
200
150
100
50
0
0.1
1
10
100
1000
10000
Discharge (cfs)
Total P
Subs.(8 cfs)
Subs.(20 cfs)

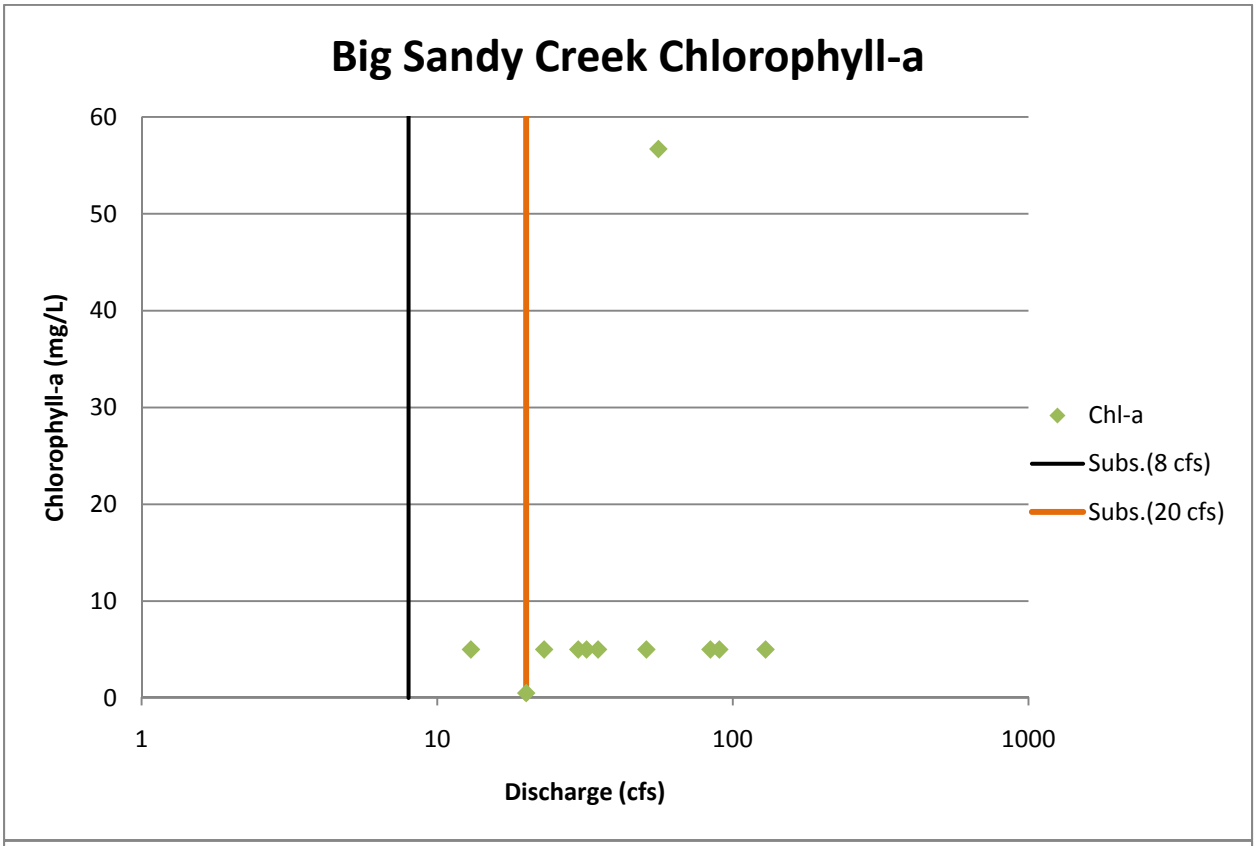

Sabine R. near Gladewater Total Phosphorus
Total Phosphorus (mg/L)
250
200
150
100
50
0
10
100
1000
10000
Discharge (cfs)
Total P
Subs.(14 cfs)
Subs.(45 cfs)

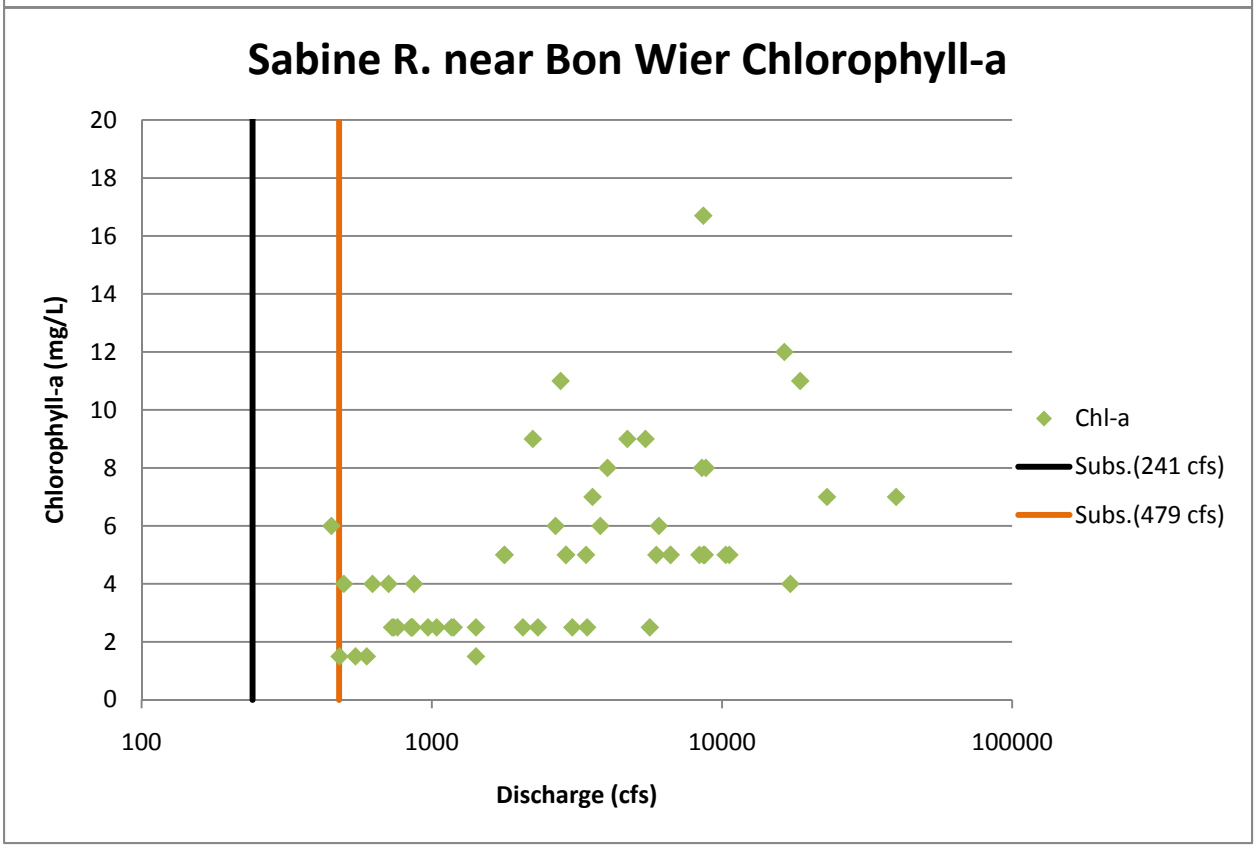

Sabine R. near Beckville Total Phosphorus
Total Phosphorus (mg/L)
400
350
300
250
200
150
100
50
0
10
100
1000
10000
100000
Discharge (cfs)
Total P
Subs.(22 cfs)
Subs.(66 cfs)

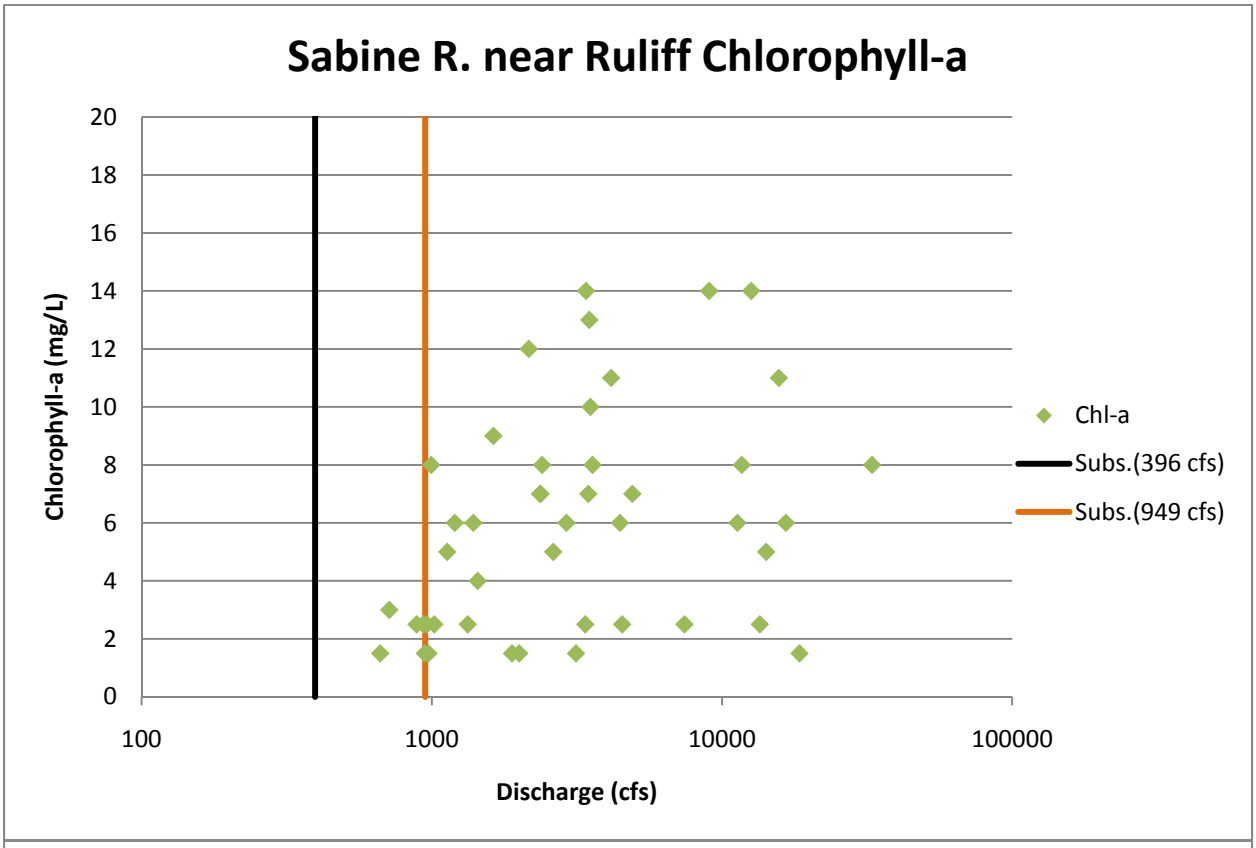

Sabine R. near Bon Wier Total Phosphorus
Total Phosphorus (mg/L)
120
100
80
60
40
20
0
100
1000
10000
100000
Discharge (cfs)
Total P
Subs.(241 cfs)
Subs.(479 cfs)

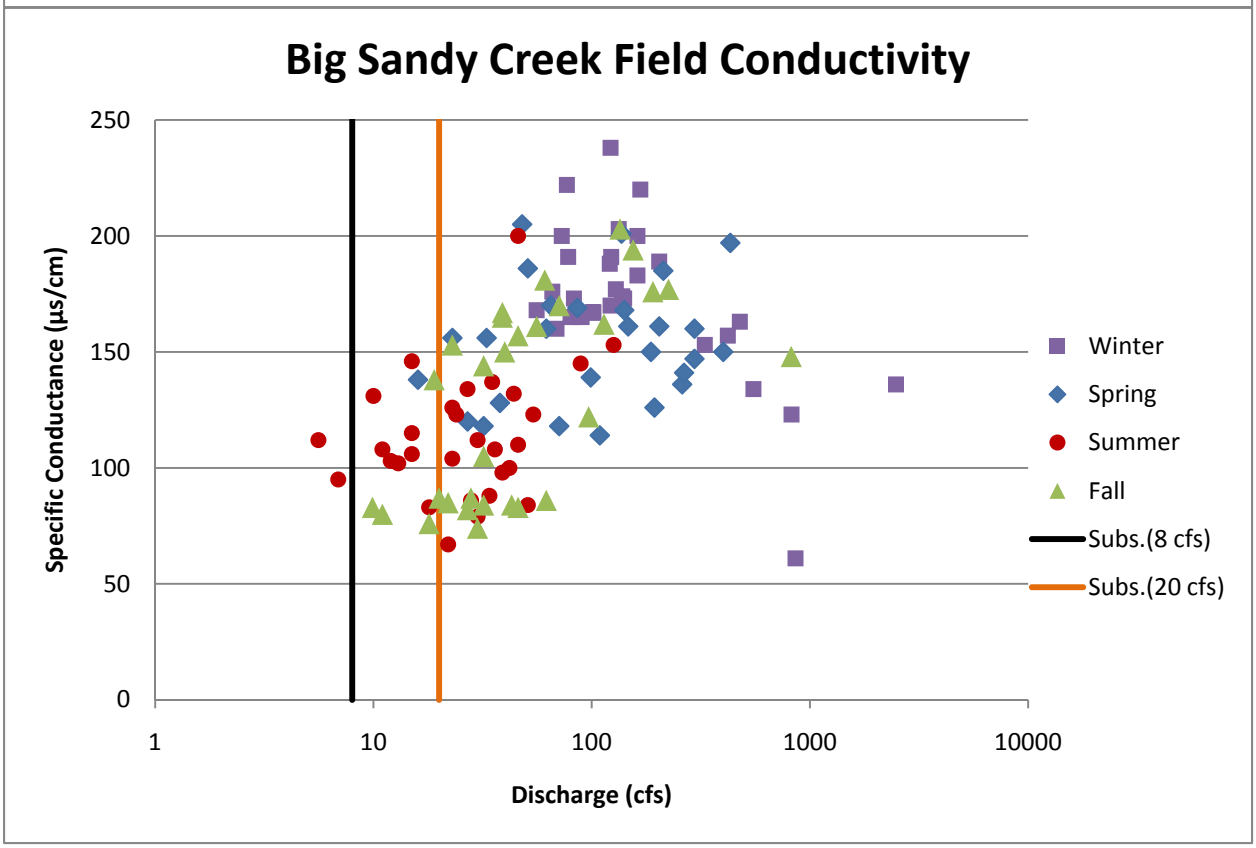

Big Cow Creek Total Phosphorus
Total Phosphorus (mg/L)
160
140
120
100
80
60
40
20
0
10
100
1000
Discharge (cfs)
Total P
Subs.(20 cfs)
Subs.(28 cfs)

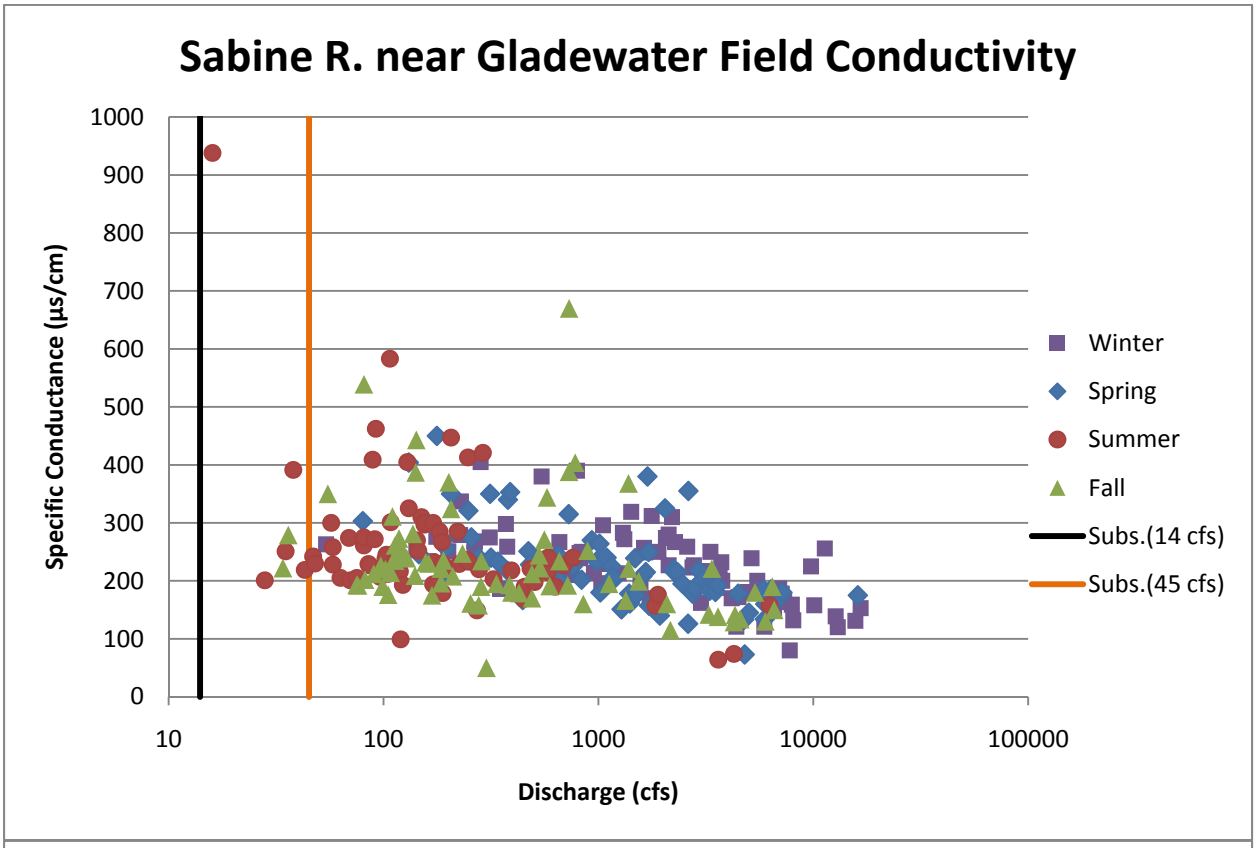

Sabine R. near Ruliff Total Phosphorus
Total Phosphorus (mg/L)
160
140
120
100
80
60
40
20
0
100
1000
10000
100000
Discharge (cfs)
Total P
Subs.(396 cfs)
Subs.(949 cfs)

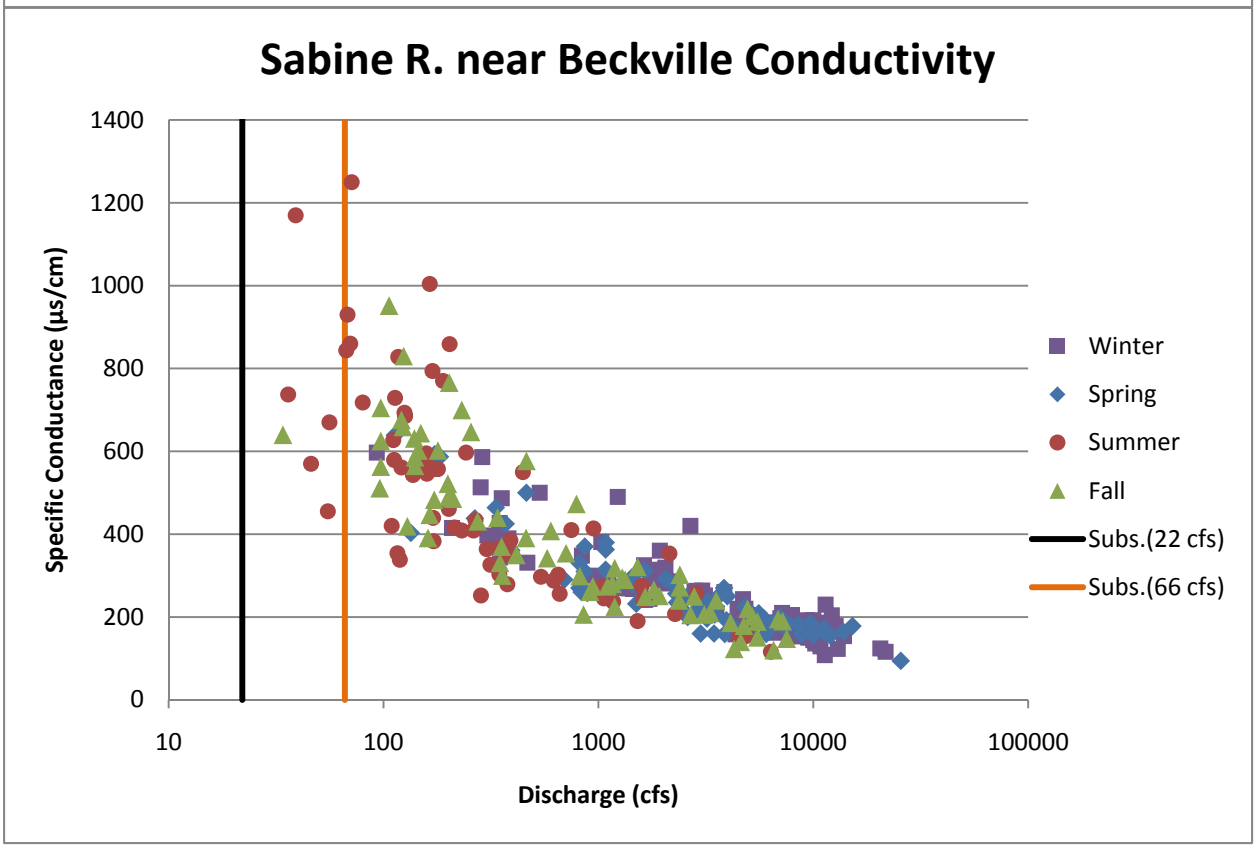

Big Sandy Creek Chlorophyll-a
Chlorophyll-a (mg/L)
60
50
40
30
20
10
0
1
10
100
1000
Discharge (cfs)
Chl-a
Subs.(8 cfs)
Subs.(20 cfs)

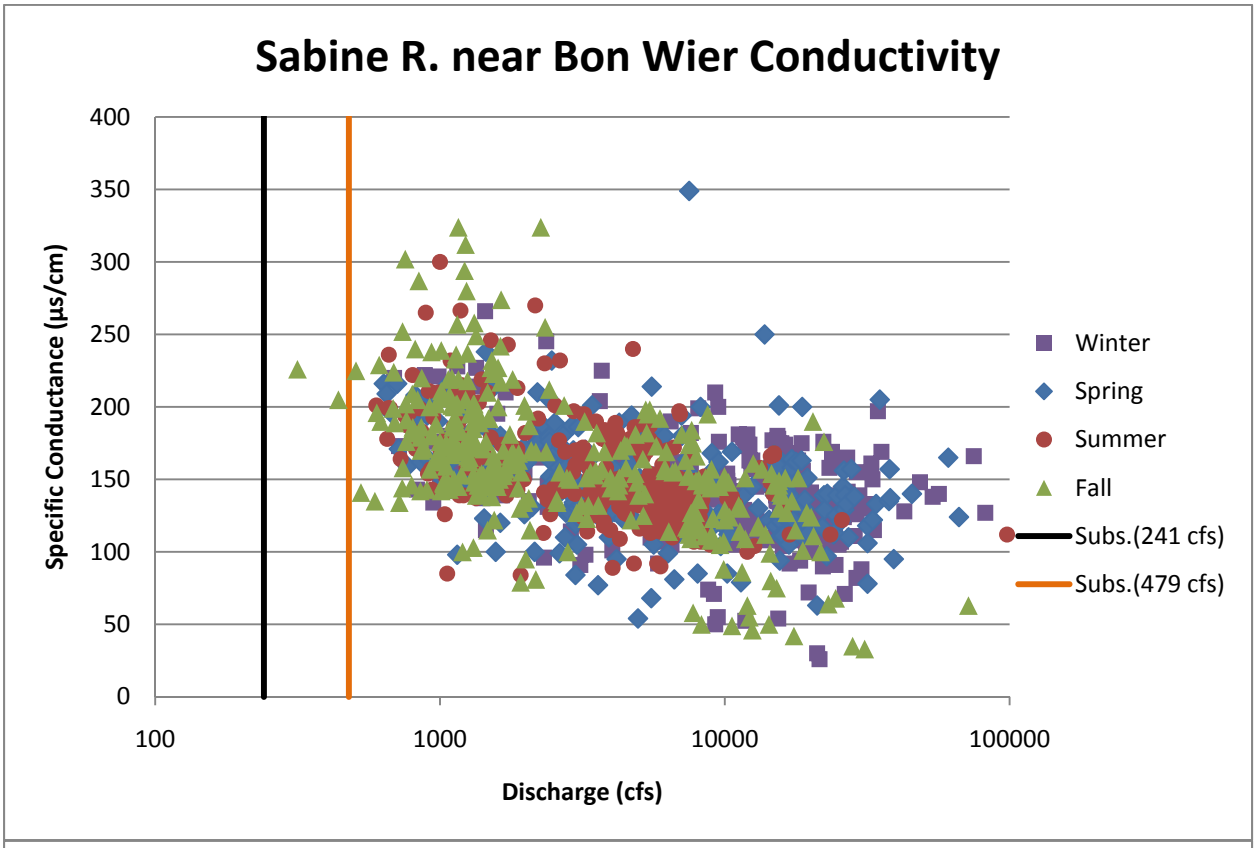

Sabine R. near Bon Wier Chlorophyll-a
Chlorophyll-a (mg/L)
20
18
16
14
12
10
8
6
4
2
0
100
1000
10000
100000
Discharge (cfs)
Chl-a
Subs.(241 cfs)
Subs.(479 cfs)

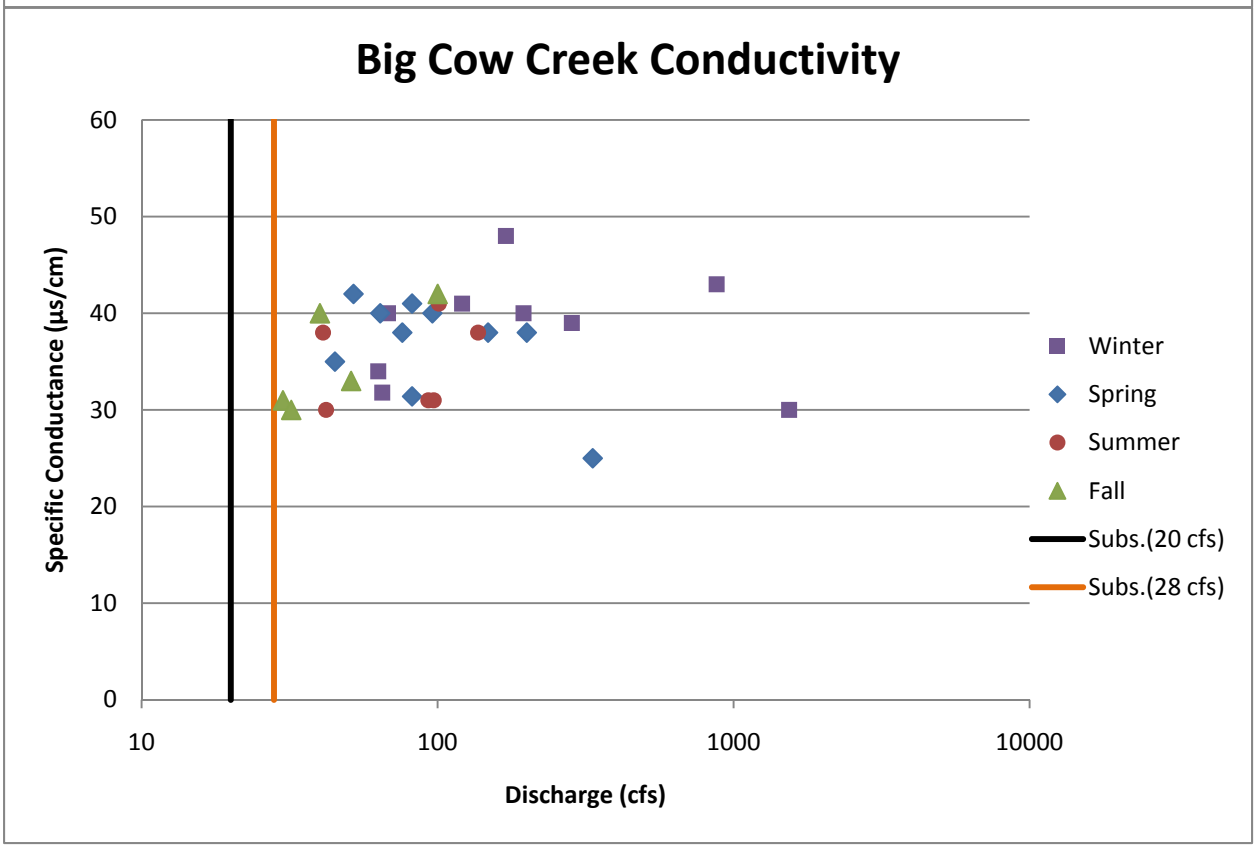

Sabine R. near Ruliff Chlorophyll-a
Chlorophyll-a (mg/L)
20
18
16
14
12
10
8
6
4
2
0
100
1000
10000
100000
Discharge (cfs)
Chl-a
Subs.(396 cfs)
Subs.(949 cfs)

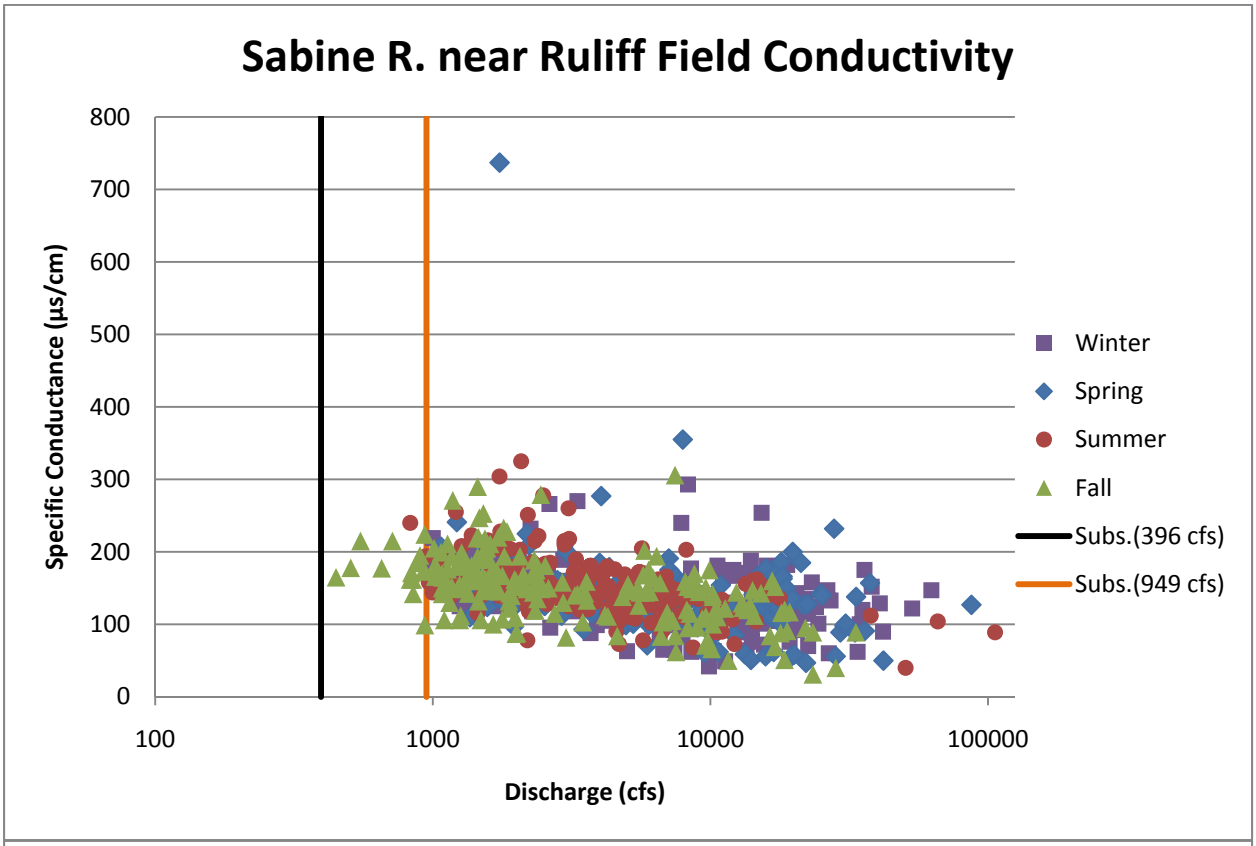

Big Sandy Creek Field Conductivity
Specific Conductance (µs/cm)
250
200
150
100
50
0
1
10
100
1000
10000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(8 cfs)
Subs.(20 cfs)

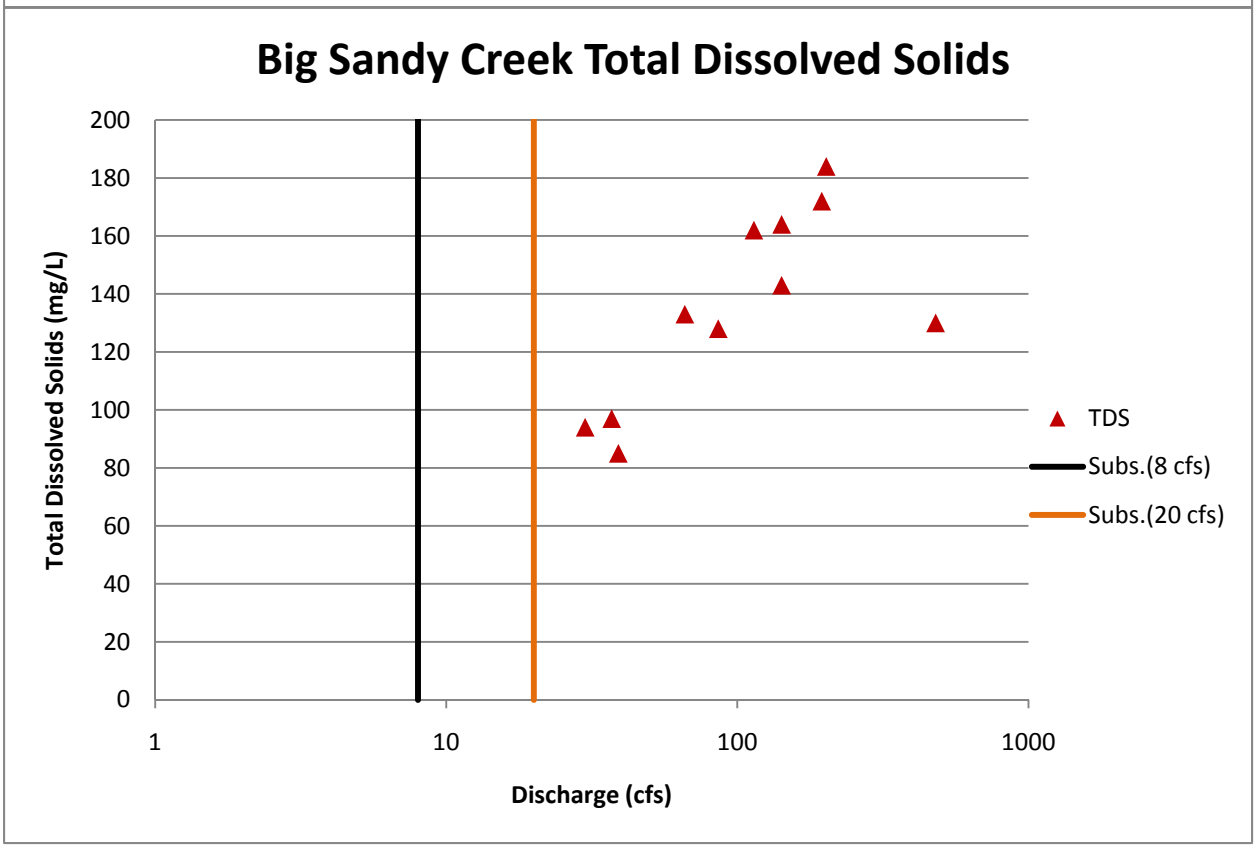

Sabine R. near Gladewater Field Conductivity
Specific Conductance (µs/cm)
1000
900
800
700
600
500
400
300
200
100
0
10
100
1000
10000
100000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(14 cfs)
Subs.(45 cfs)

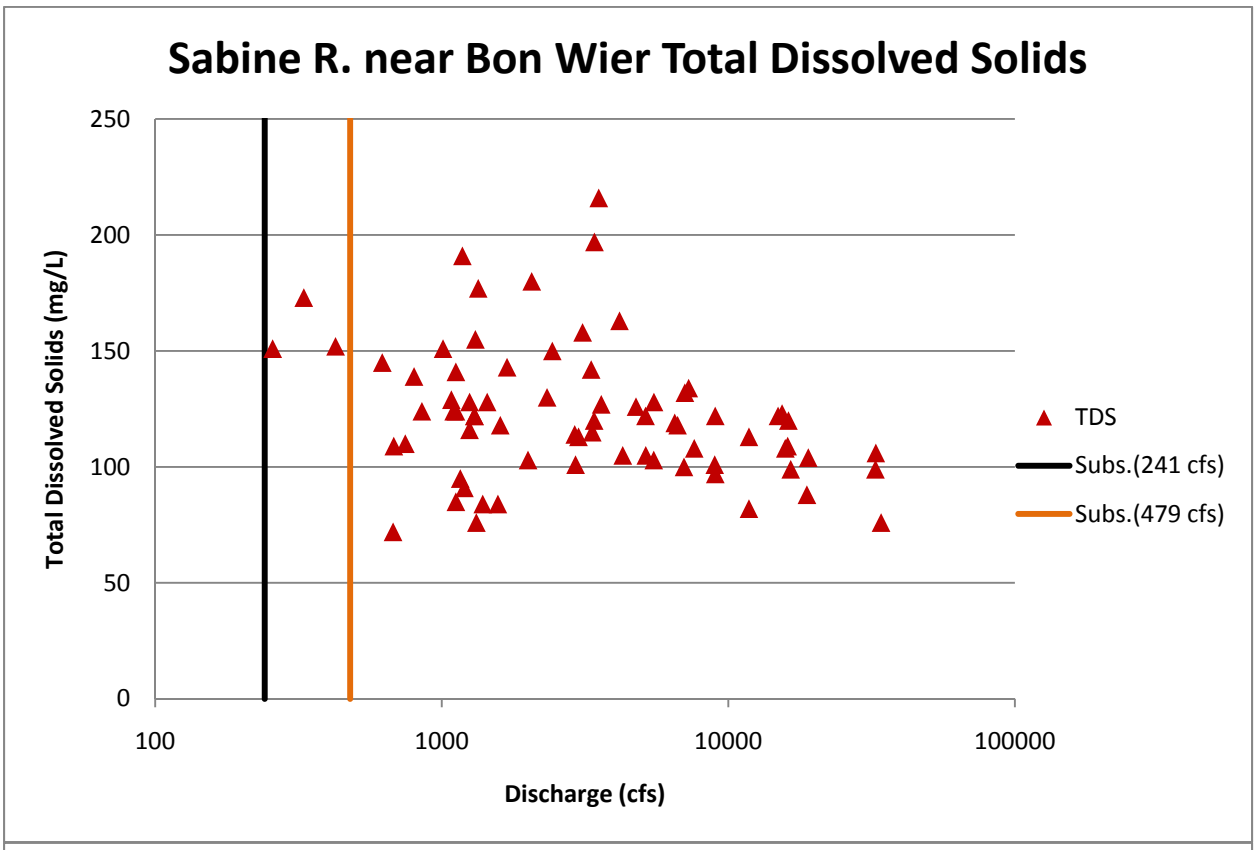

Sabine R. near Beckville Conductivity
Specific Conductance (µs/cm)
1400
1200
1000
800
600
400
200
0
10
100
1000
10000
100000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(22 cfs)
Subs.(66 cfs)

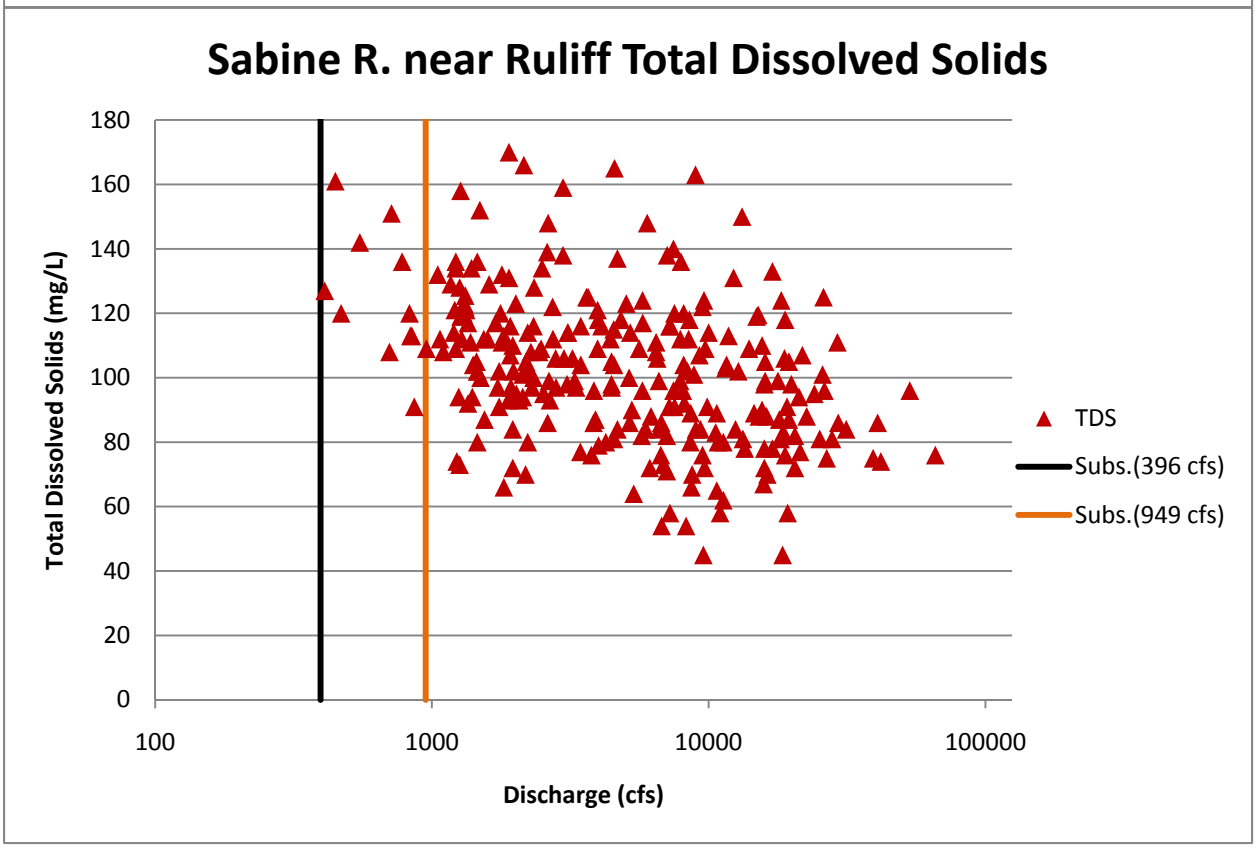

Sabine R. near Bon Wier Conductivity
Specific Conductance (µs/cm)
400
350
300
250
200
150
100
50
0
100
1000
10000
100000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(241 cfs)
Subs.(479 cfs)

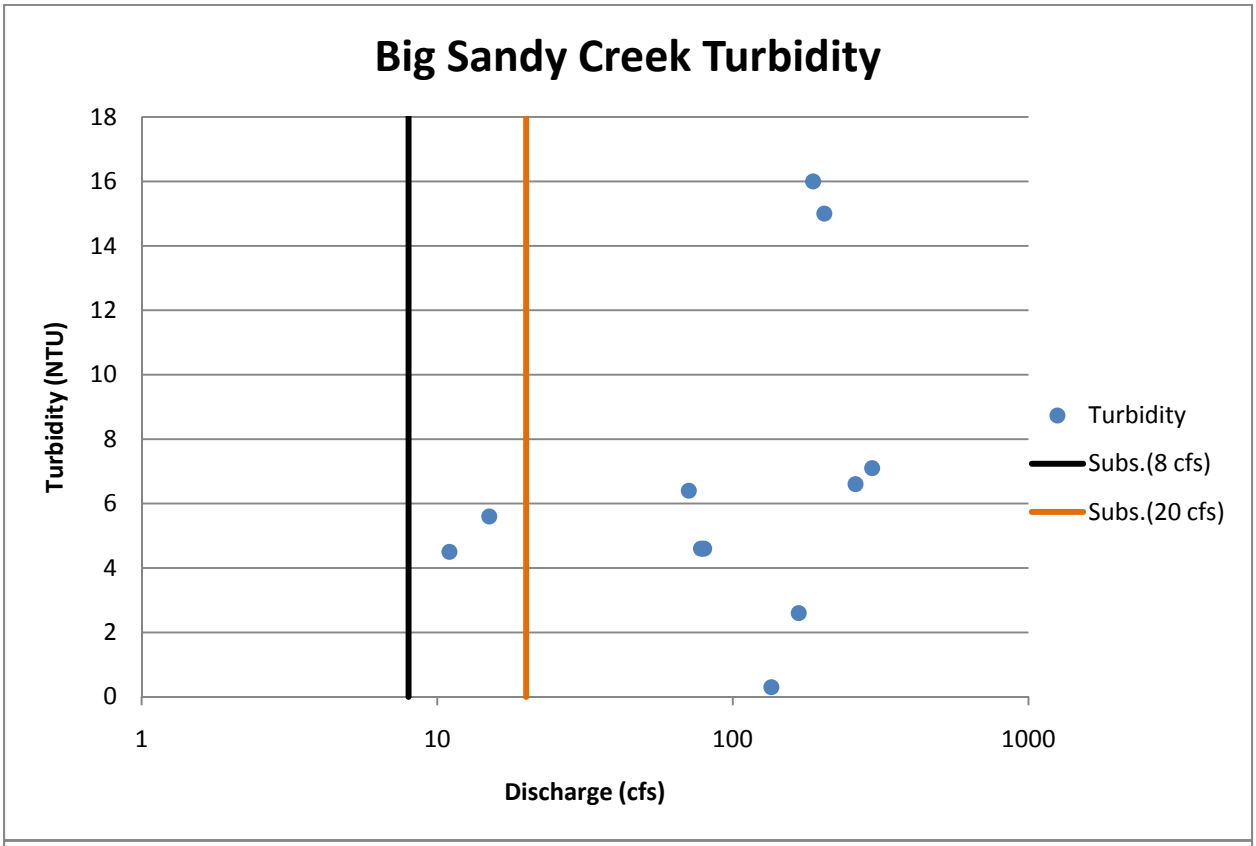

Big Cow Creek Conductivity
Specific Conductance (µs/cm)
60
50
40
30
20
10
0
10
100
1000
10000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(20 cfs)
Subs.(28 cfs)

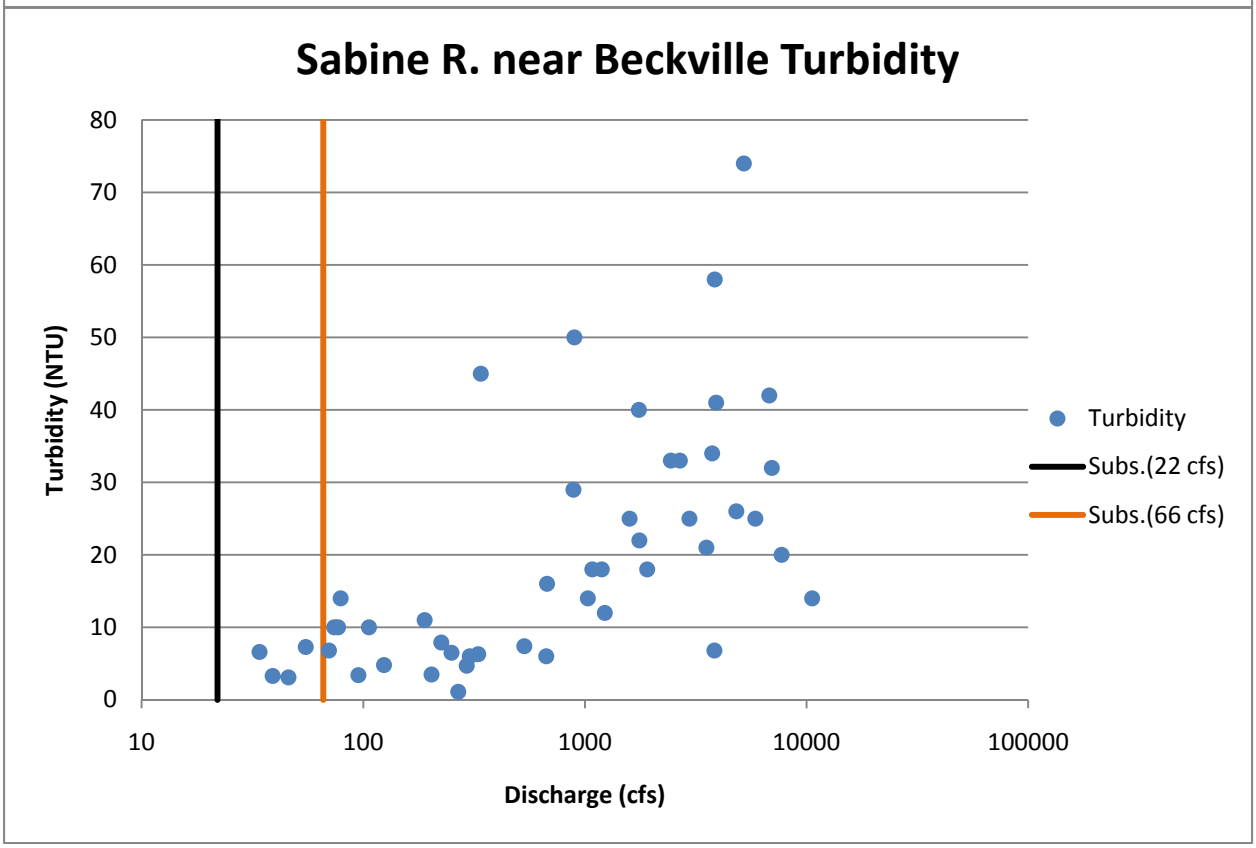

Sabine R. near Ruliff Field Conductivity
Specific Conductance (µs/cm)
800
700
600
500
400
300
200
100
0
100
1000
10000
100000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(396 cfs)
Subs.(949 cfs)

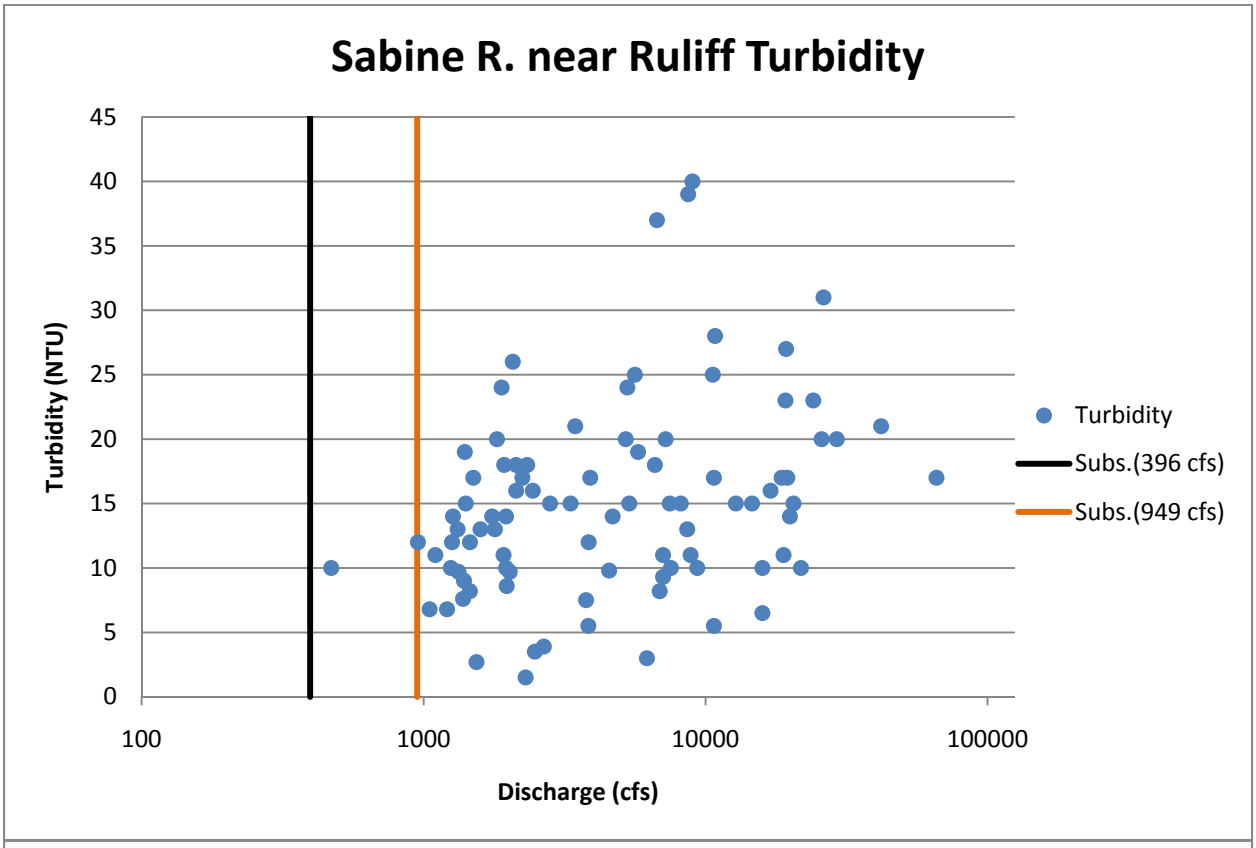

Big Sandy Creek Total Dissolved Solids
Total Dissolved Solids (mg/L)
200
180
160
140
120
100
80
60
40
20
0
1
10
100
1000
Discharge (cfs)
TDS
Subs.(8 cfs)
Subs.(20 cfs)

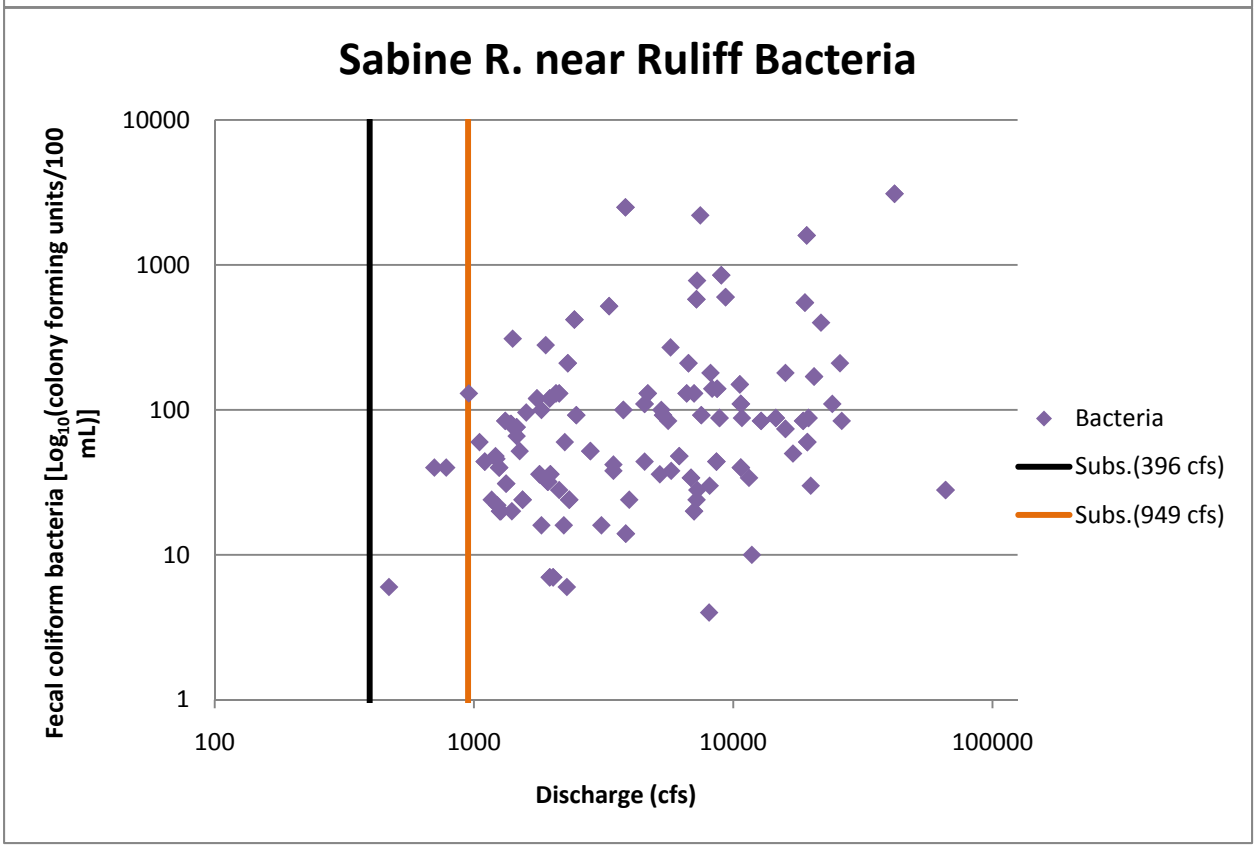

Sabine R. near Bon Wier Total Dissolved Solids
Total Dissolved Solids (mg/L)
250
200
150
100
50
0
100
1000
10000
100000
Discharge (cfs)
TDS
Subs.(241 cfs)
Subs.(479 cfs)

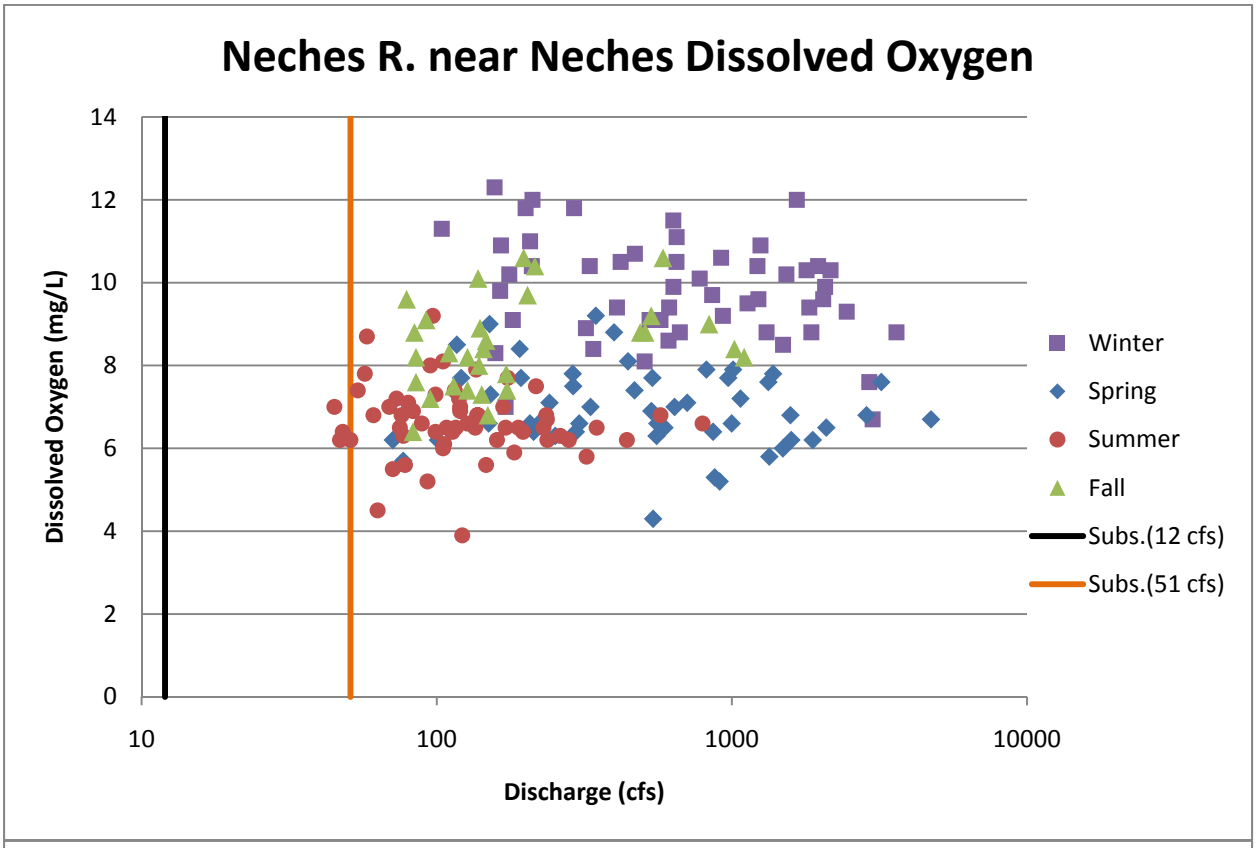

Sabine R. near Ruliff Total Dissolved Solids
Total Dissolved Solids (mg/L)
180
160
140
120
100
80
60
40
20
0
100
1000
10000
100000
Discharge (cfs)
TDS
Subs.(396 cfs)
Subs.(949 cfs)

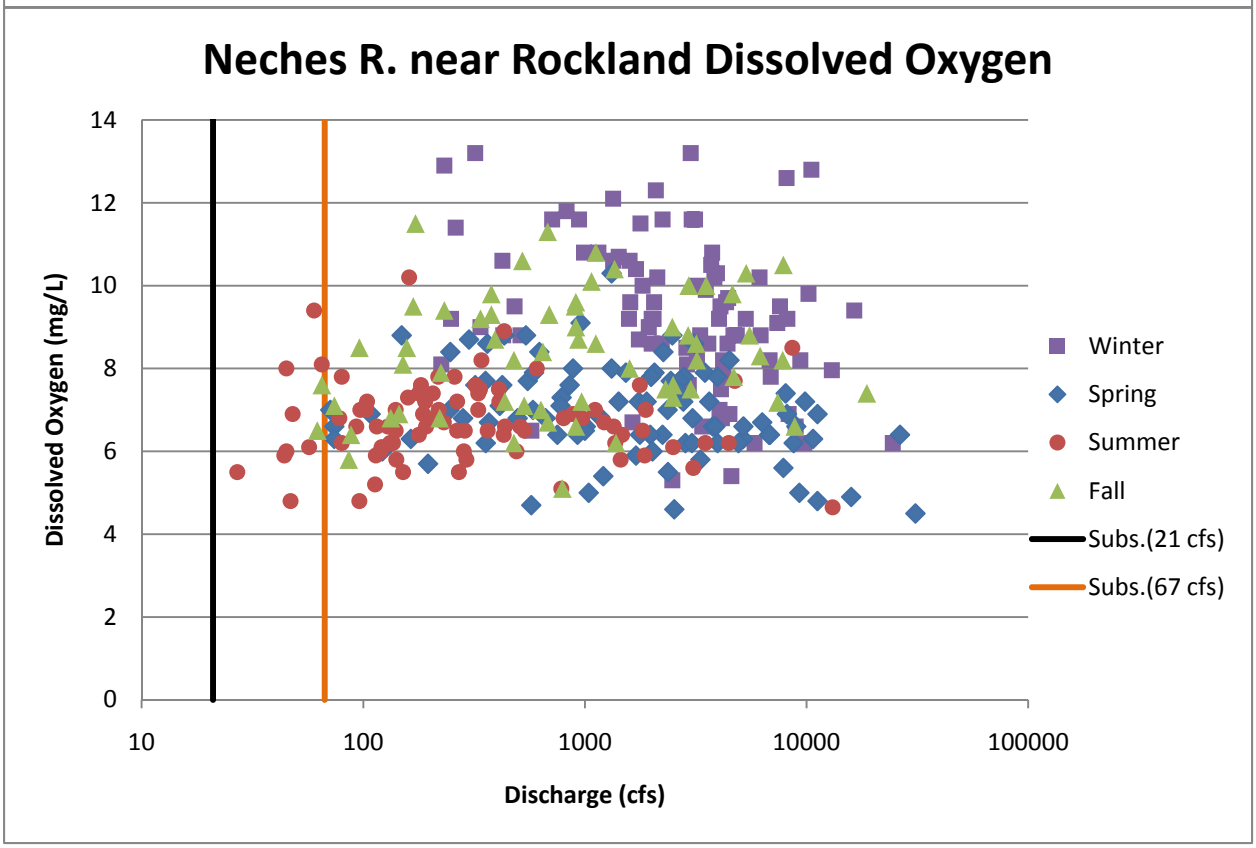

Big Sandy Creek Turbidity
Turbidity (NTU)
18
16
14
12
10
8
6
4
2
0
1
10
100
1000
Discharge (cfs)
Turbidity
Subs.(8 cfs)
Subs.(20 cfs)

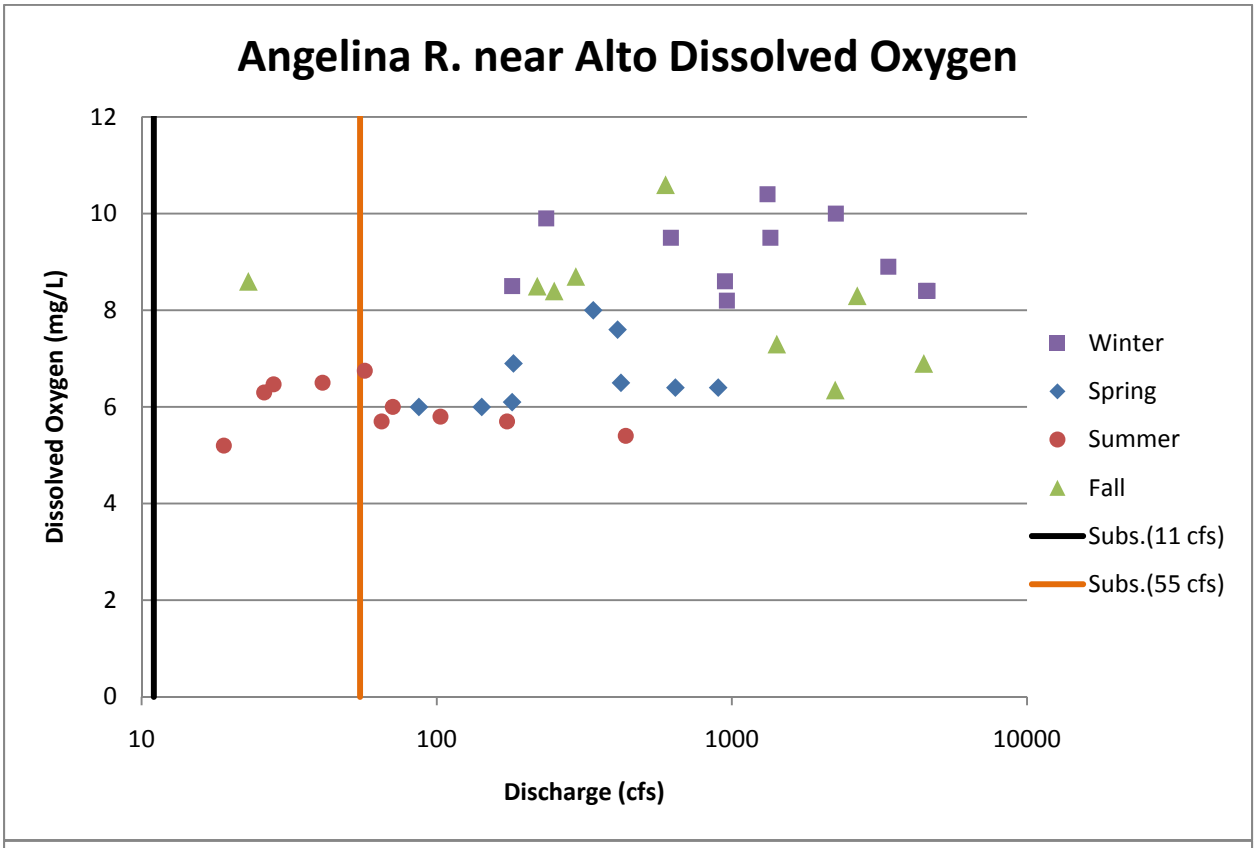

Sabine R. near Beckville Turbidity
Turbidity (NTU)
80
70
60
50
40
30
20
10
0
10
100
1000
10000
100000
Discharge (cfs)
Turbidity
Subs.(22 cfs)
Subs.(66 cfs)

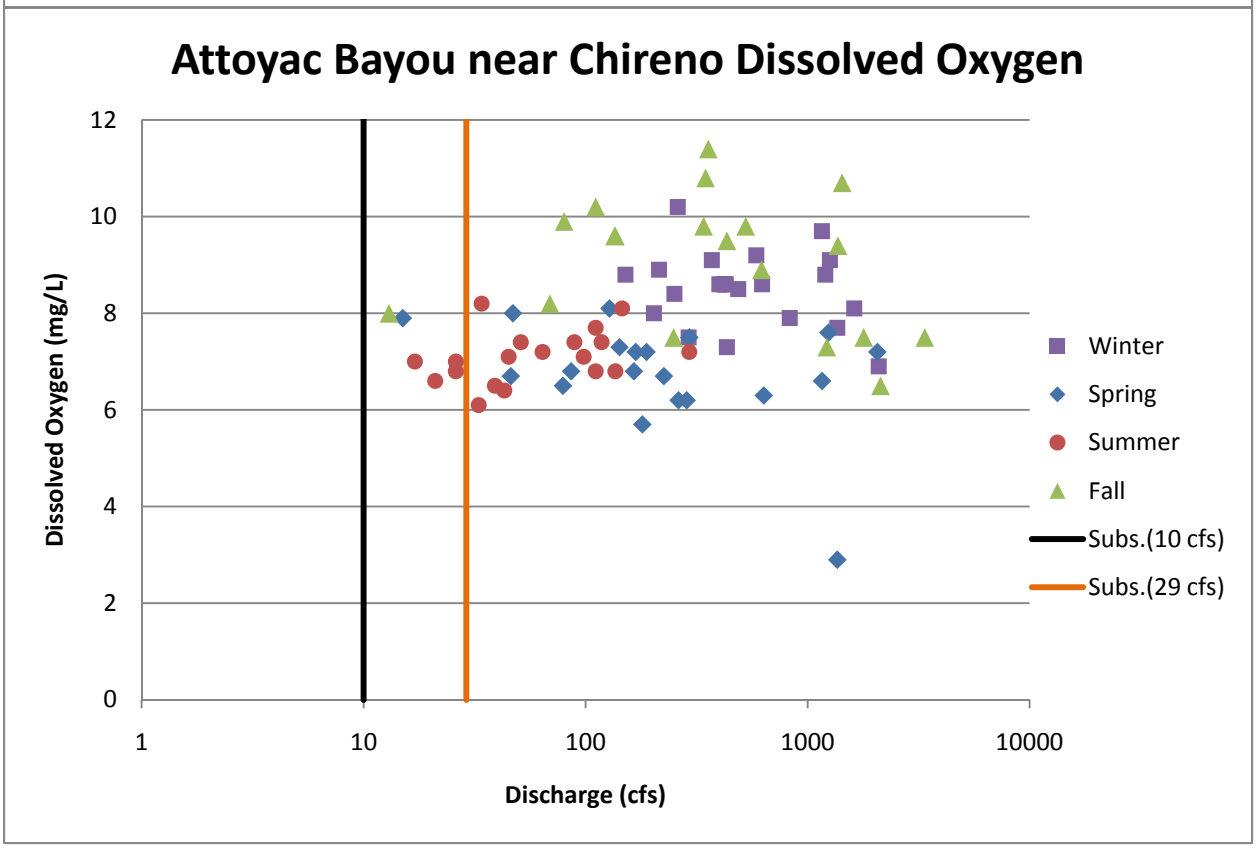

Sabine R. near Ruliff Turbidity
Turbidity (NTU)
45
40
35
30
25
20
15
10
5
0
100
1000
10000
100000
Discharge (cfs)
Turbidity
Subs.(396 cfs)
Subs.(949 cfs)

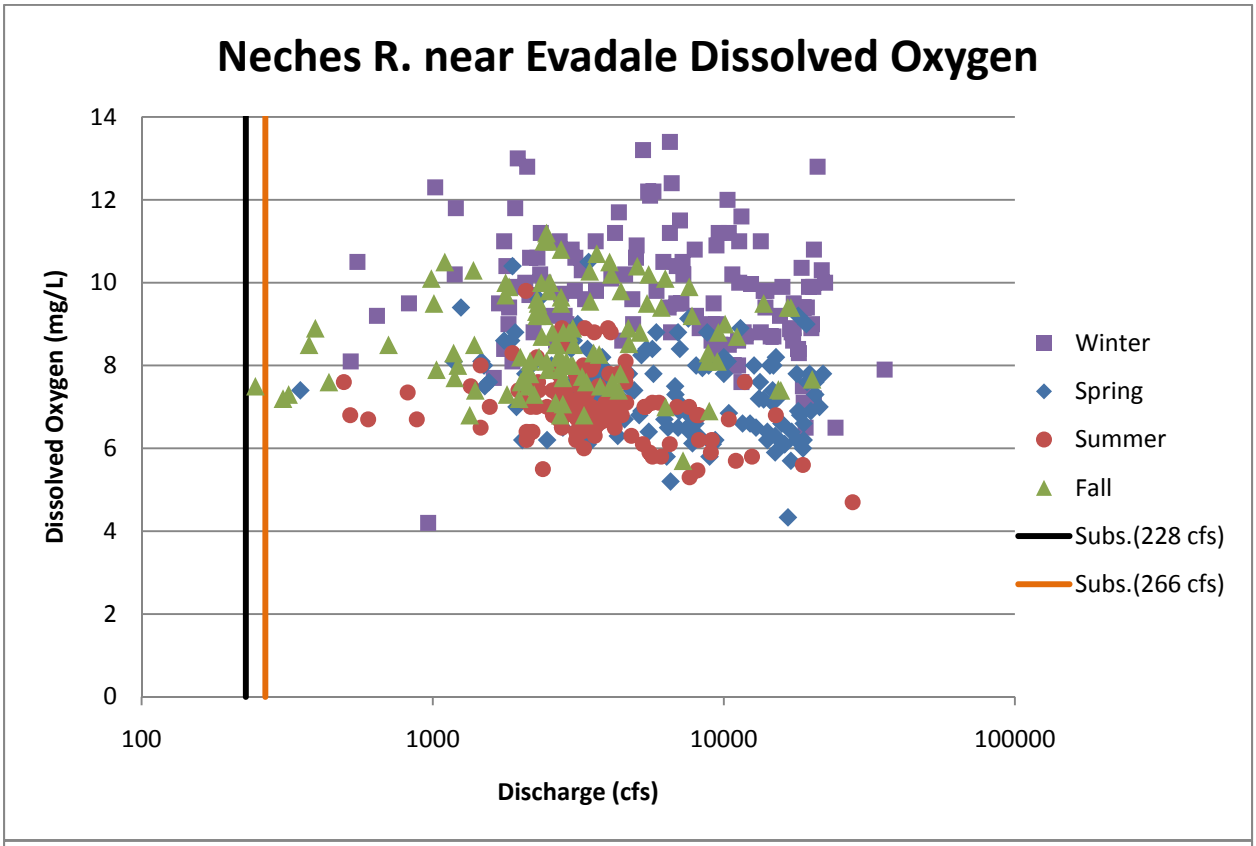

Sabine R. near Ruliff Bacteria
Fecal coliform bacteria [Log10(colony forming units/100 mL)]
10000
1000
100
10
1
100
1000
10000
100000
Discharge (cfs)
Bacteria
Subs.(396 cfs)
Subs.(949 cfs)

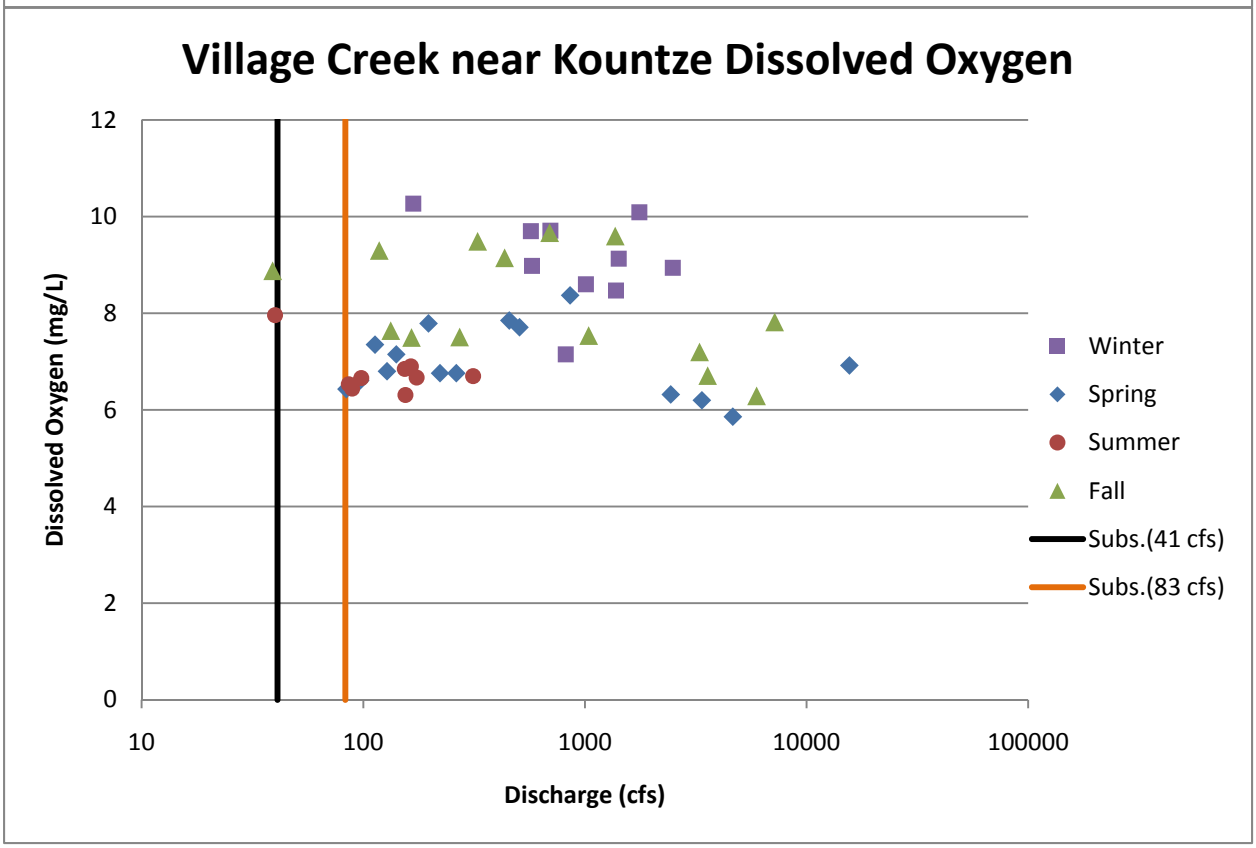

Neches R. near Neches Dissolved Oxygen
Dissolved Oxygen (mg/L)
14
12
10
8
6
4
2
0
10
100
1000
10000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(12 cfs)
Subs.(51 cfs)

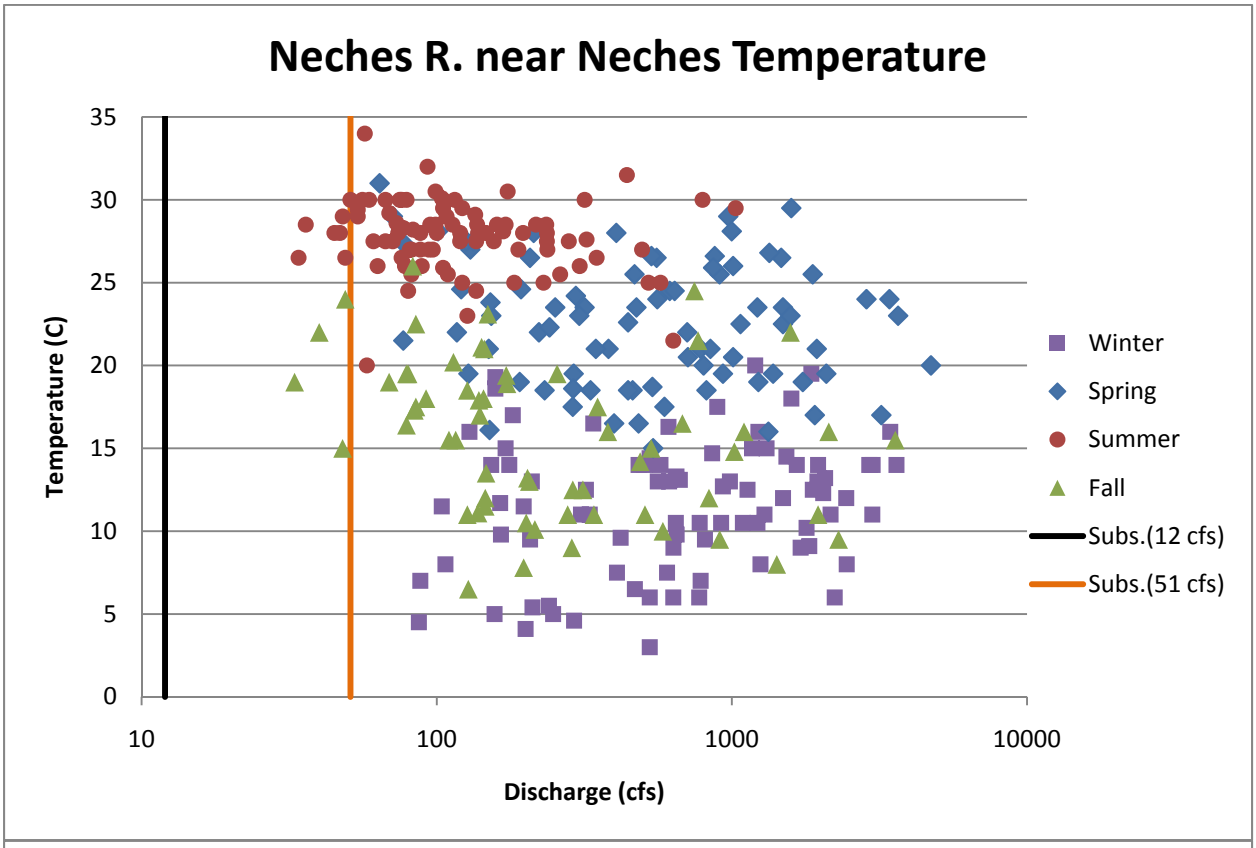

Neches R. near Rockland Dissolved Oxygen
Dissolved Oxygen (mg/L)
14
12
10
8
6
4
2
0
10
100
1000
10000
100000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(21 cfs)
Subs.(67 cfs)

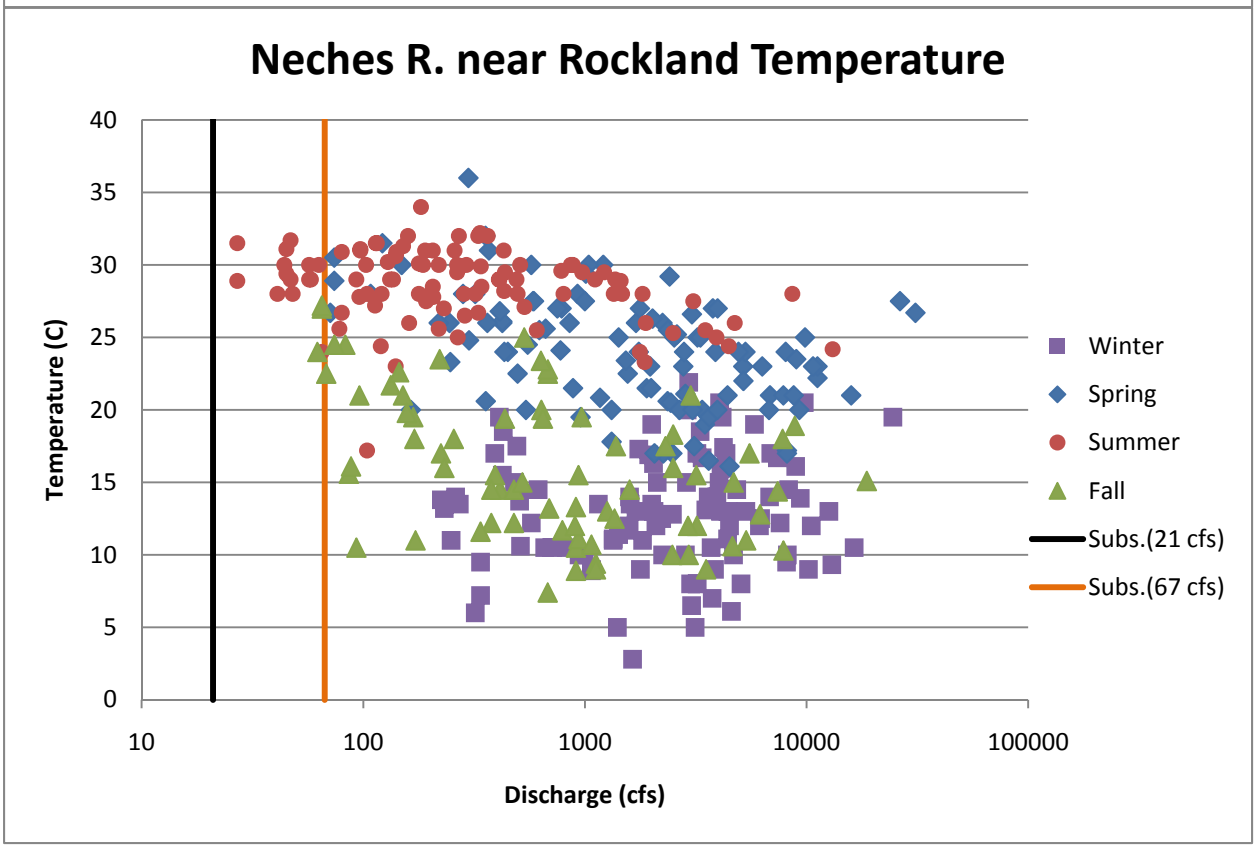

Angelina R. near Alto Dissolved Oxygen
Dissolved Oxygen (mg/L)
12
10
8
6
4
2
0
10
100
1000
10000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(11 cfs)
Subs.(55 cfs)

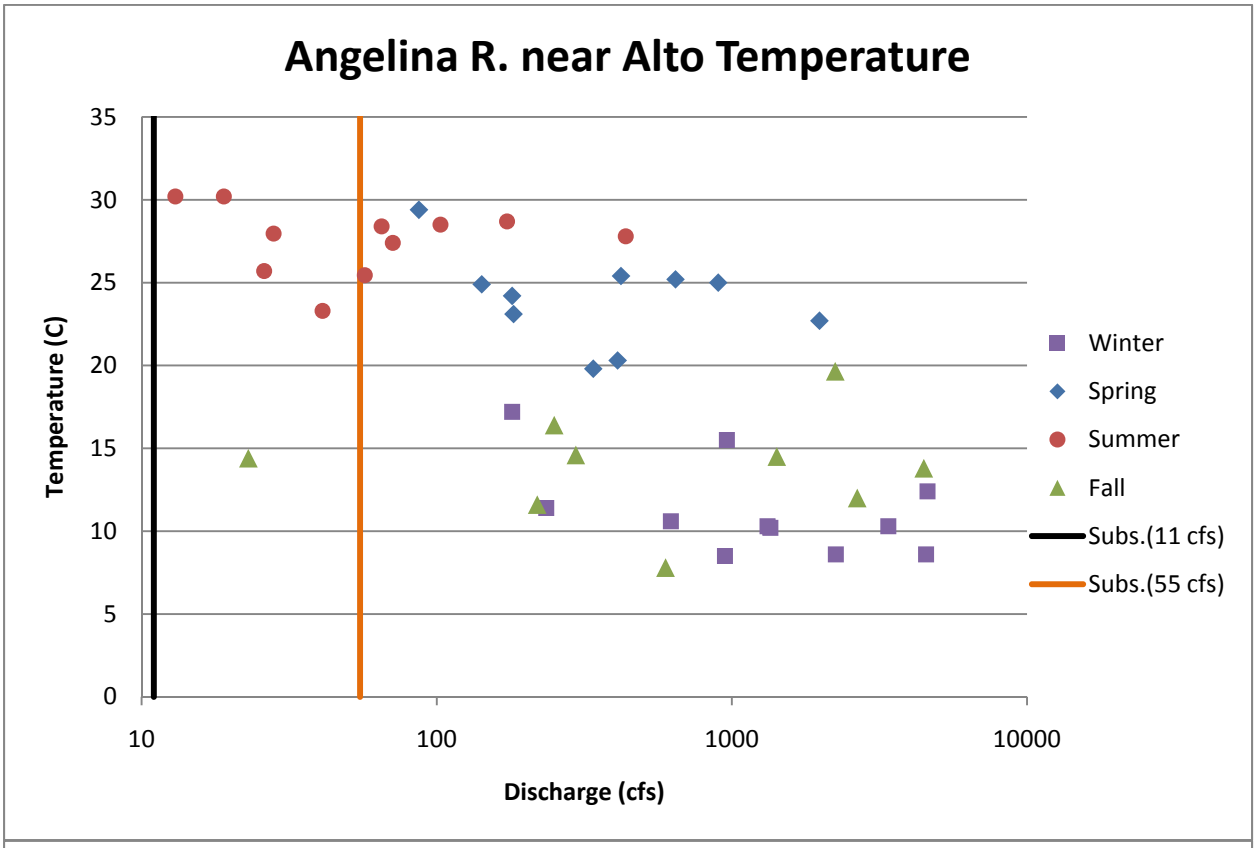

Attoyac Bayou near Chireno Dissolved Oxygen
Dissolved Oxygen (mg/L)
12
10
8
6
4
2
0
1
10
100
1000
10000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(10 cfs)
Subs.(29 cfs)

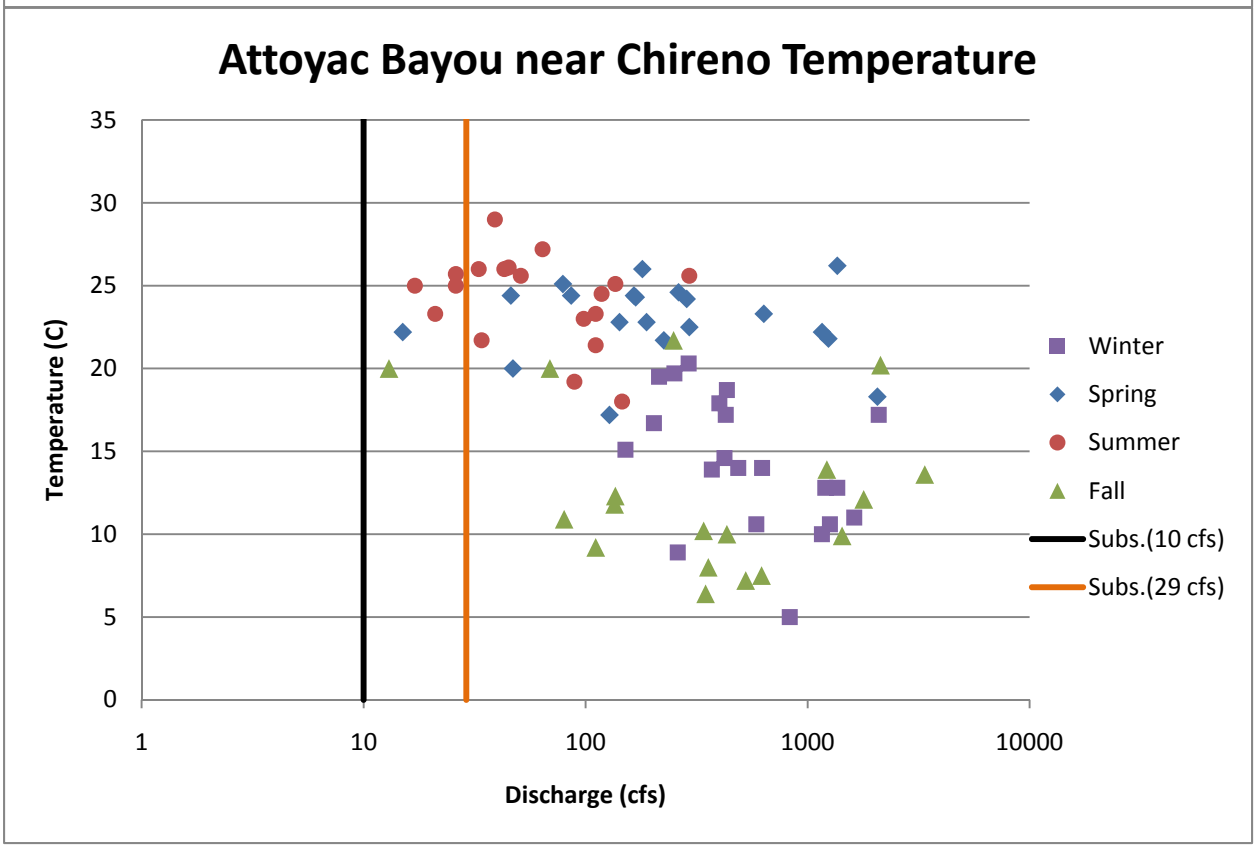

Neches R. near Evadale Dissolved Oxygen
Dissolved Oxygen (mg/L)
14
12
10
8
6
4
2
0
100
1000
10000
100000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(228 cfs)
Subs.(266 cfs)

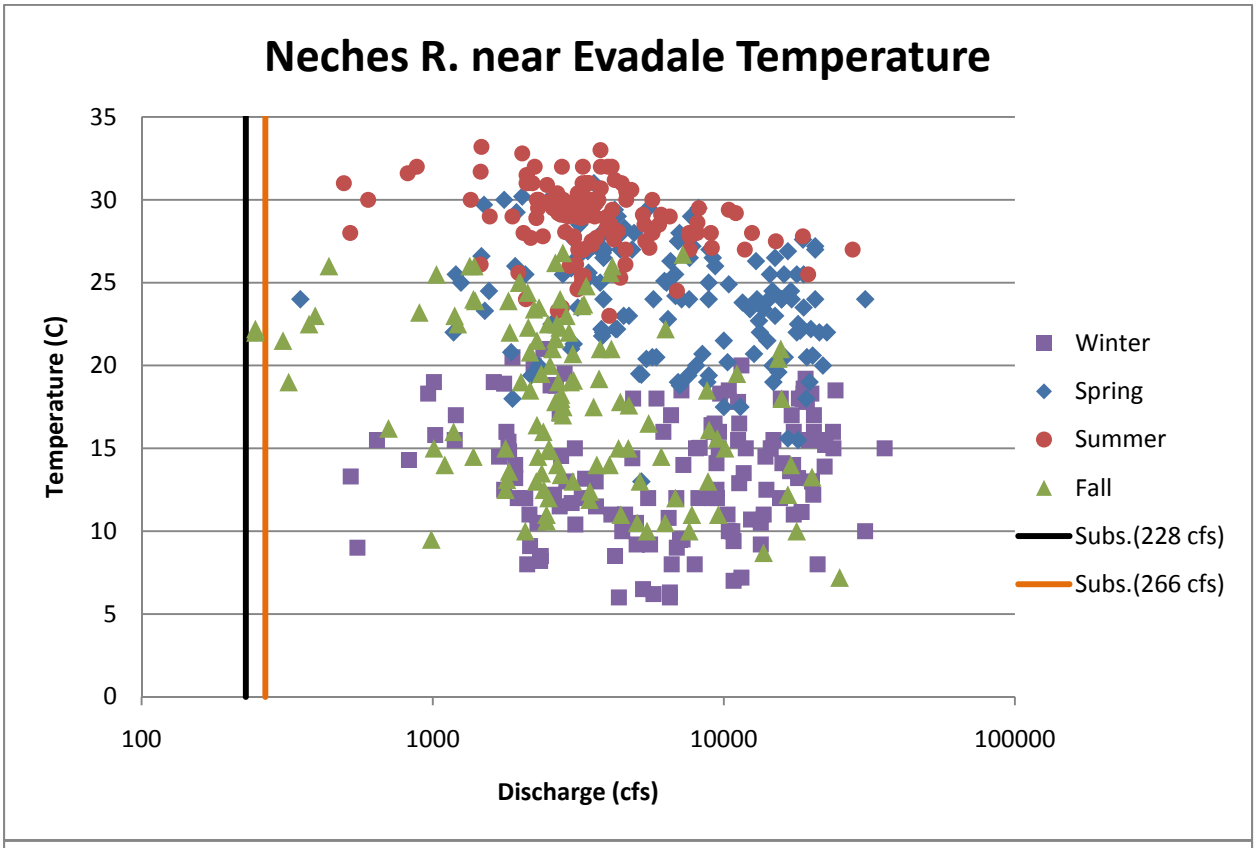

Village Creek near Kountze Dissolved Oxygen
Dissolved Oxygen (mg/L)
12
10
8
6
4
2
0
10
100
1000
10000
100000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(41 cfs)
Subs.(83 cfs)

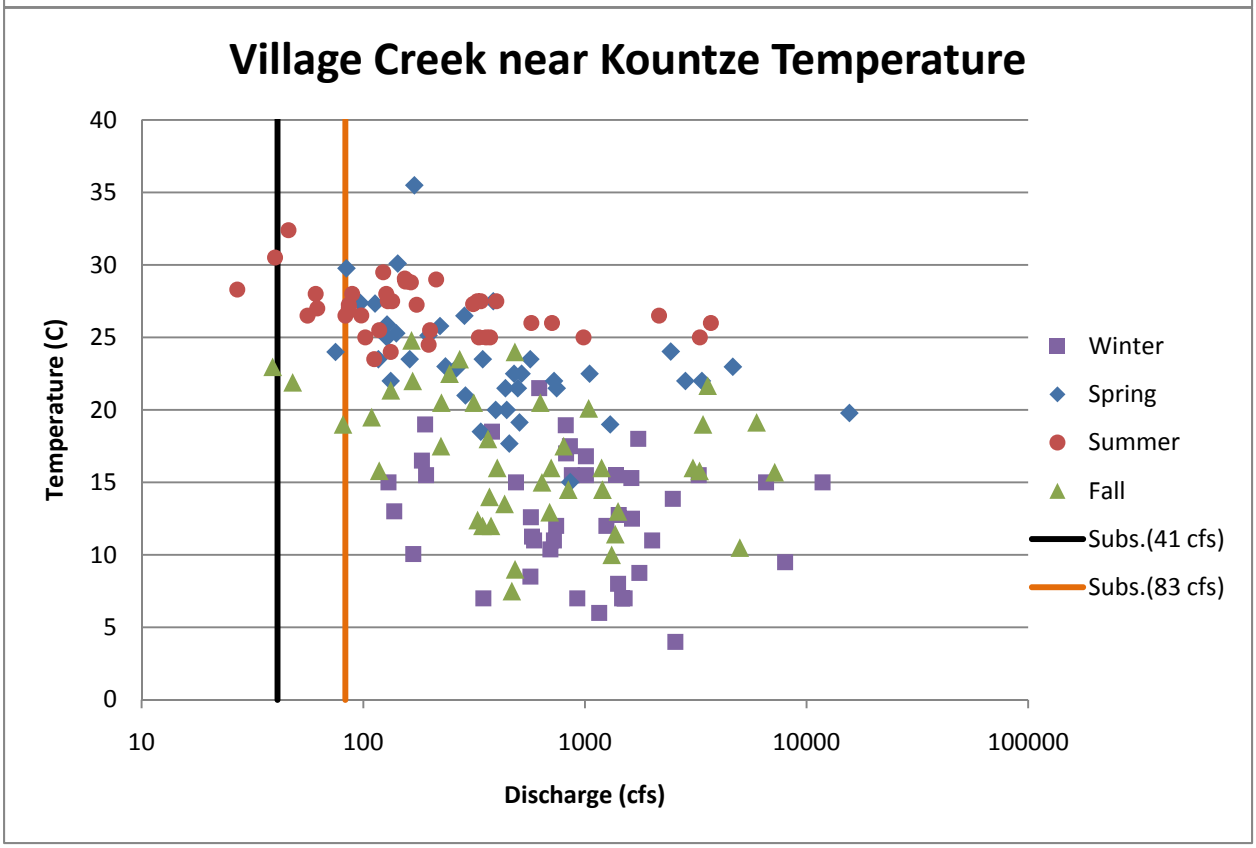

Neches R. near Neches Temperature
Temperature (C)
35
30
25
20
15
10
5
0
10
100
1000
10000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(12 cfs)
Subs.(51 cfs)

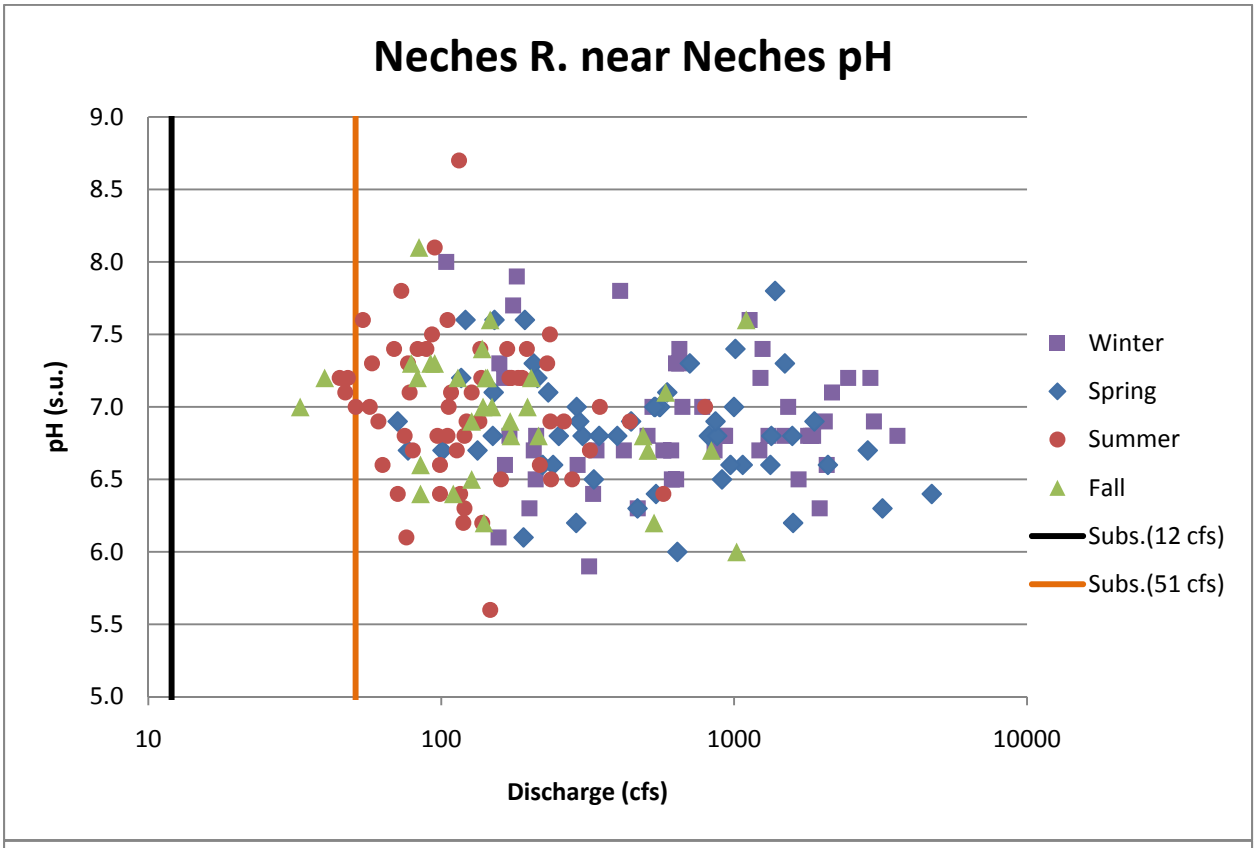

Neches R. near Rockland Temperature
Temperature (C)
40
35
30
25
20
15
10
5
0
10
100
1000
10000
100000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(21 cfs)
Subs.(67 cfs)

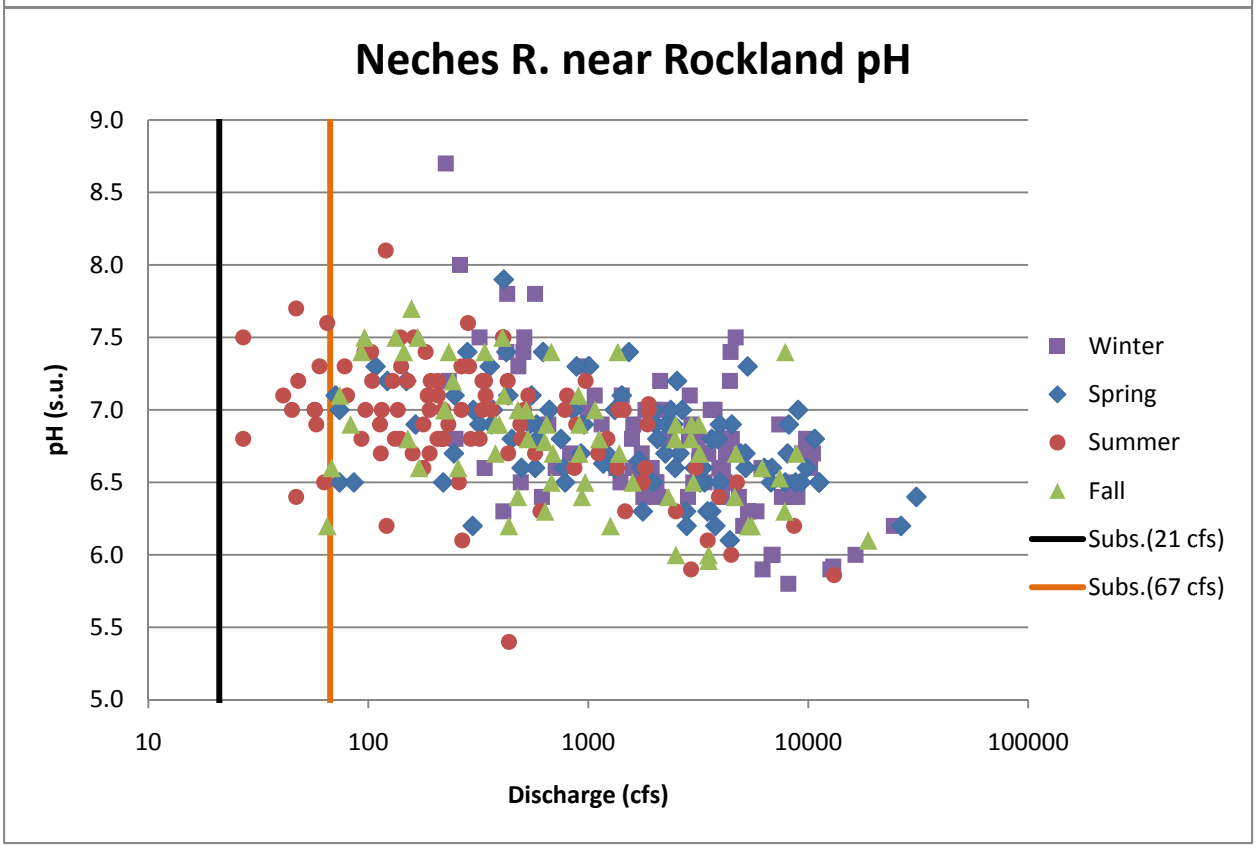

Angelina R. near Alto Temperature
Temperature (C)
35
30
25
20
15
10
5
0
10
100
1000
10000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(11 cfs)
Subs.(55 cfs)

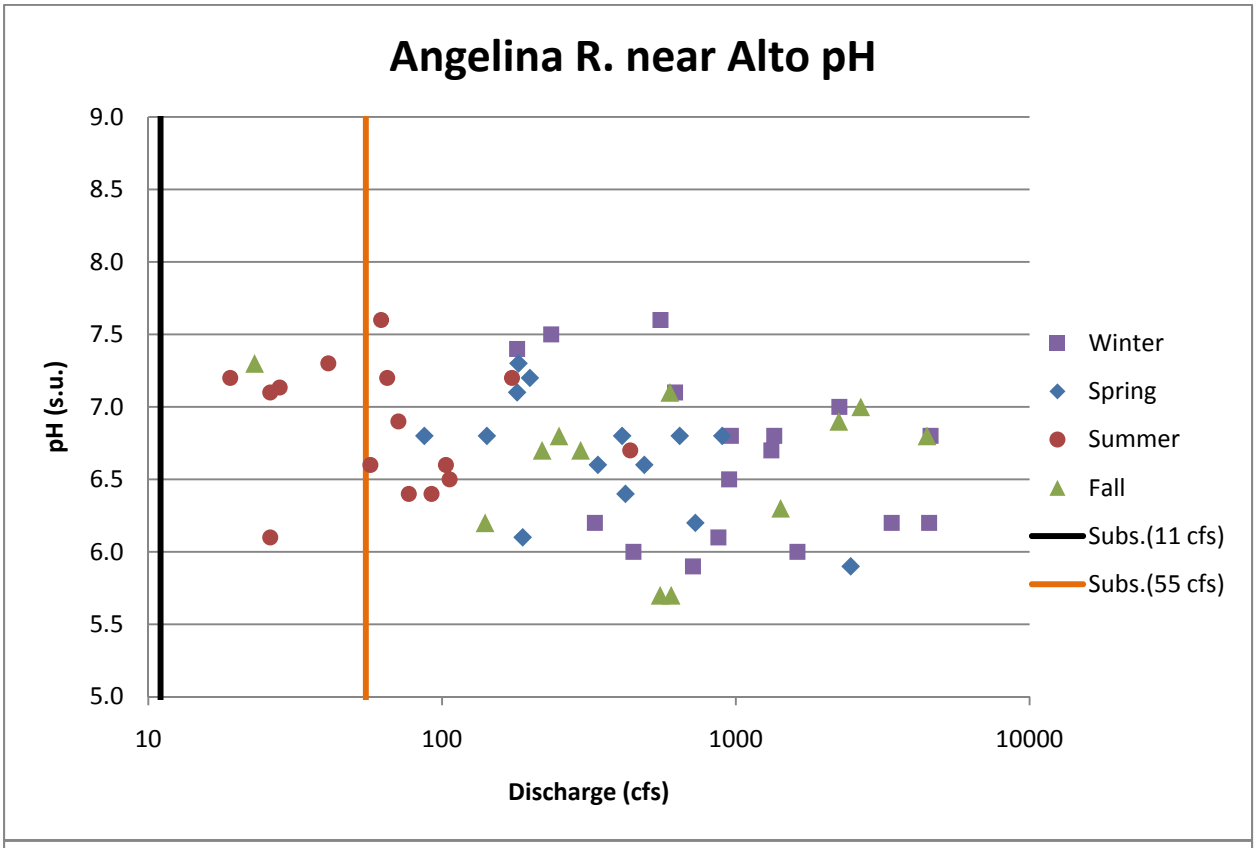

Attoyac Bayou near Chireno Temperature
Temperature (C)
35
30
25
20
15
10
5
0
1
10
100
1000
10000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(10 cfs)
Subs.(29 cfs)

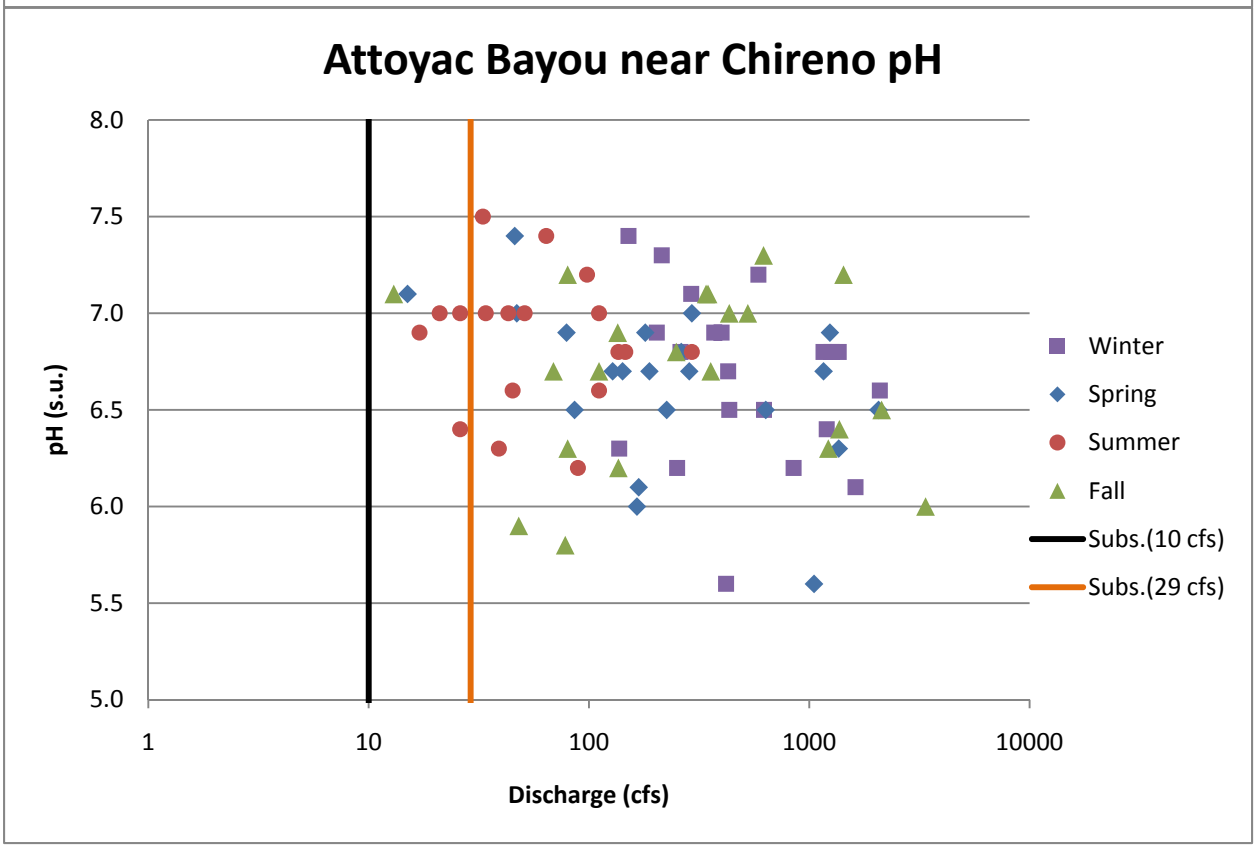

Neches R. near Evadale Temperature
Temperature (C)
35
30
25
20
15
10
5
0
100
1000
10000
100000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(228 cfs)
Subs.(266 cfs)

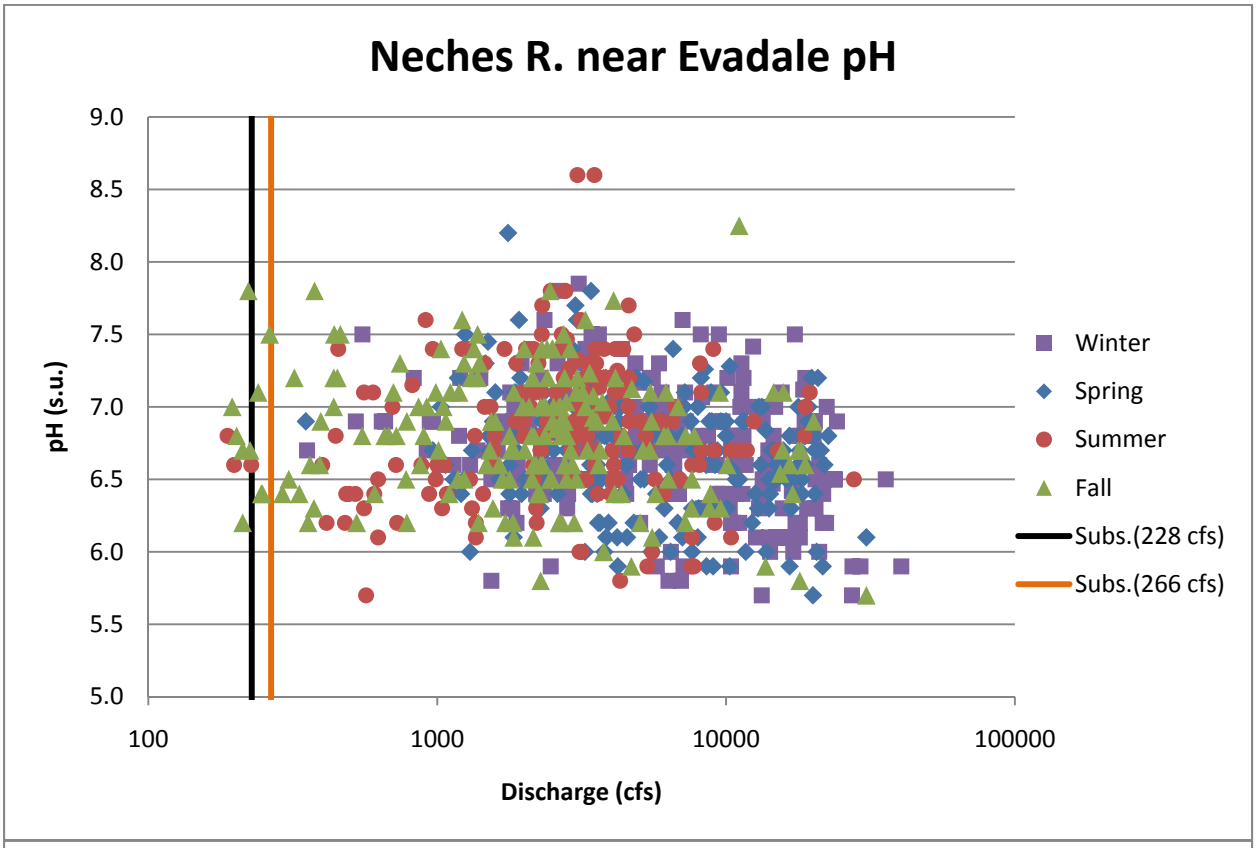

Village Creek near Kountze Temperature
Temperature (C)
40
35
30
25
20
15
10
5
0
10
100
1000
10000
100000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(41 cfs)
Subs.(83 cfs)

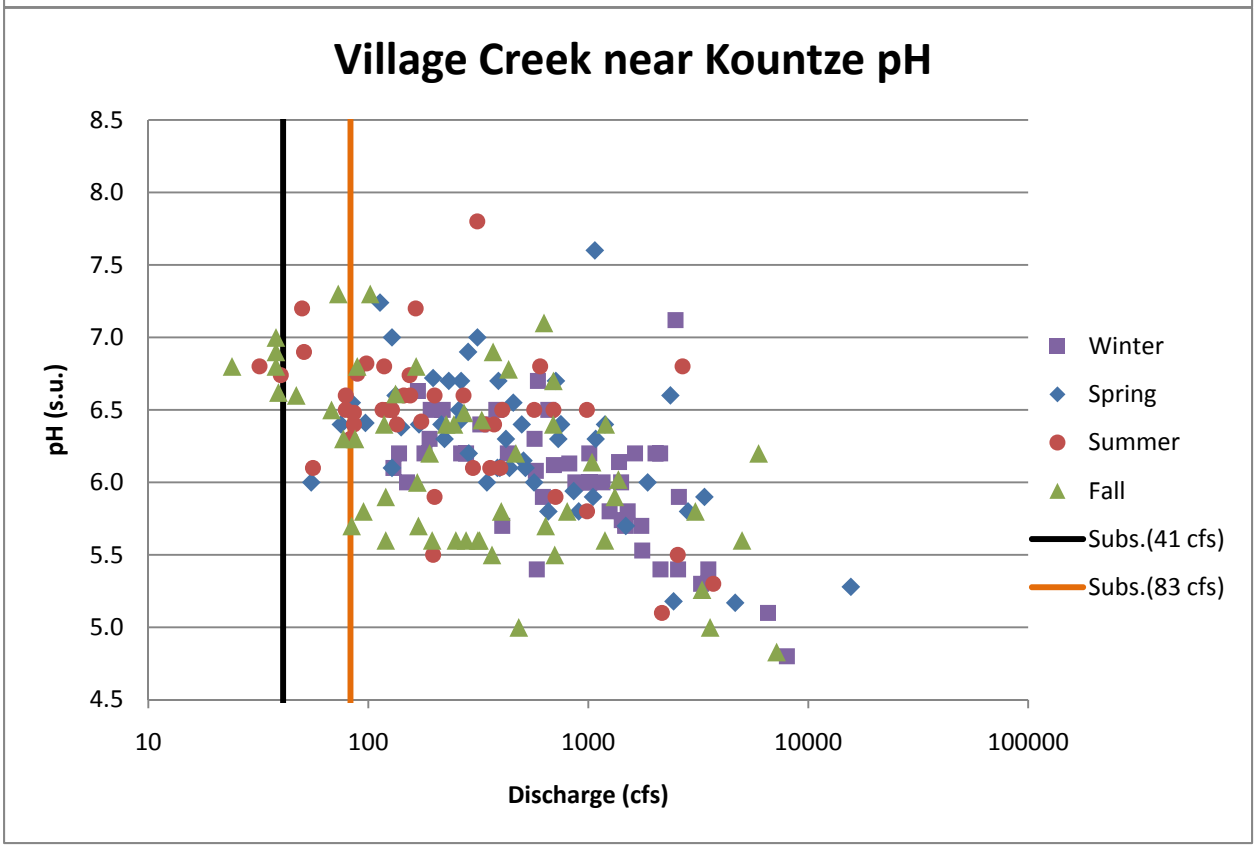

Neches R. near Neches pH
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
pH (s.u.)
10
100
1000
10000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(12 cfs)
Subs.(51 cfs)

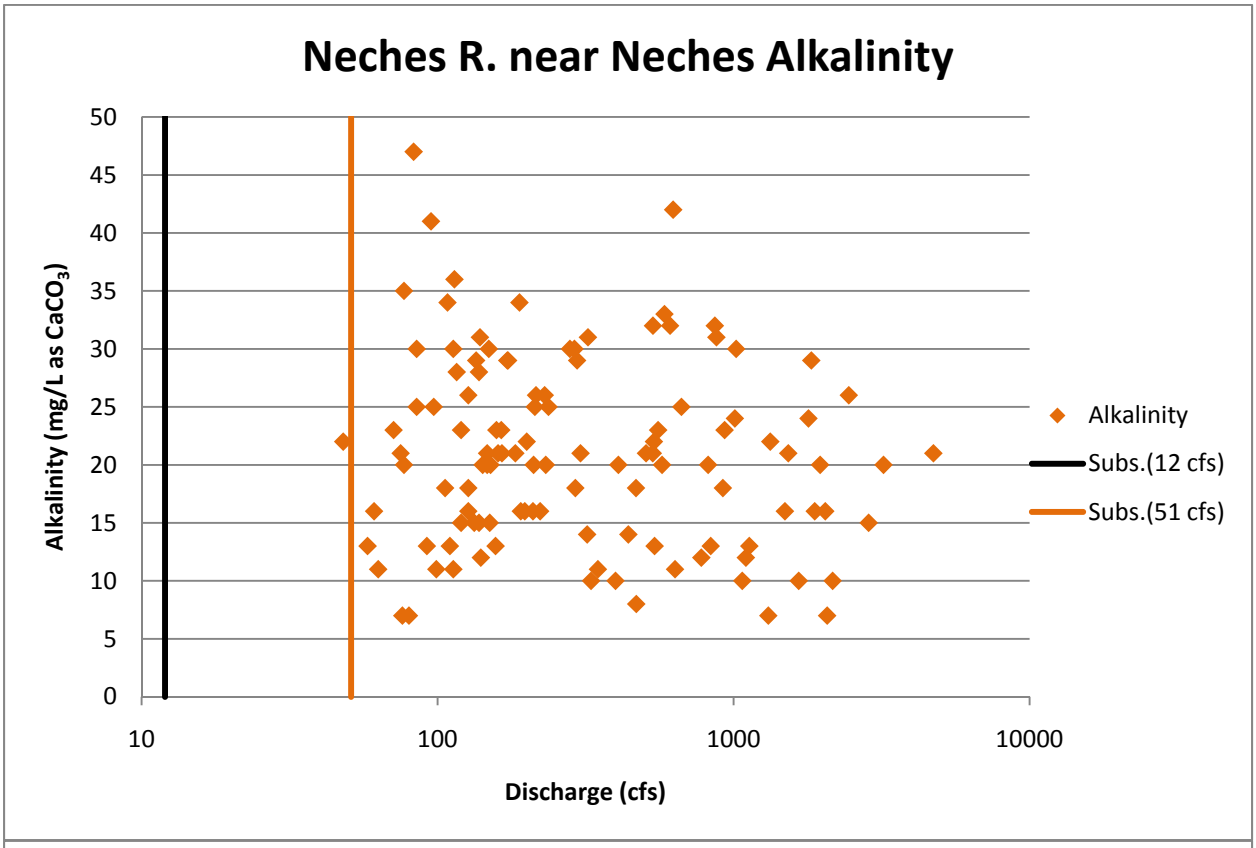

Neches R. near Rockland pH
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
pH (s.u.)
10
100
1000
10000
100000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(21 cfs)
Subs.(67 cfs)

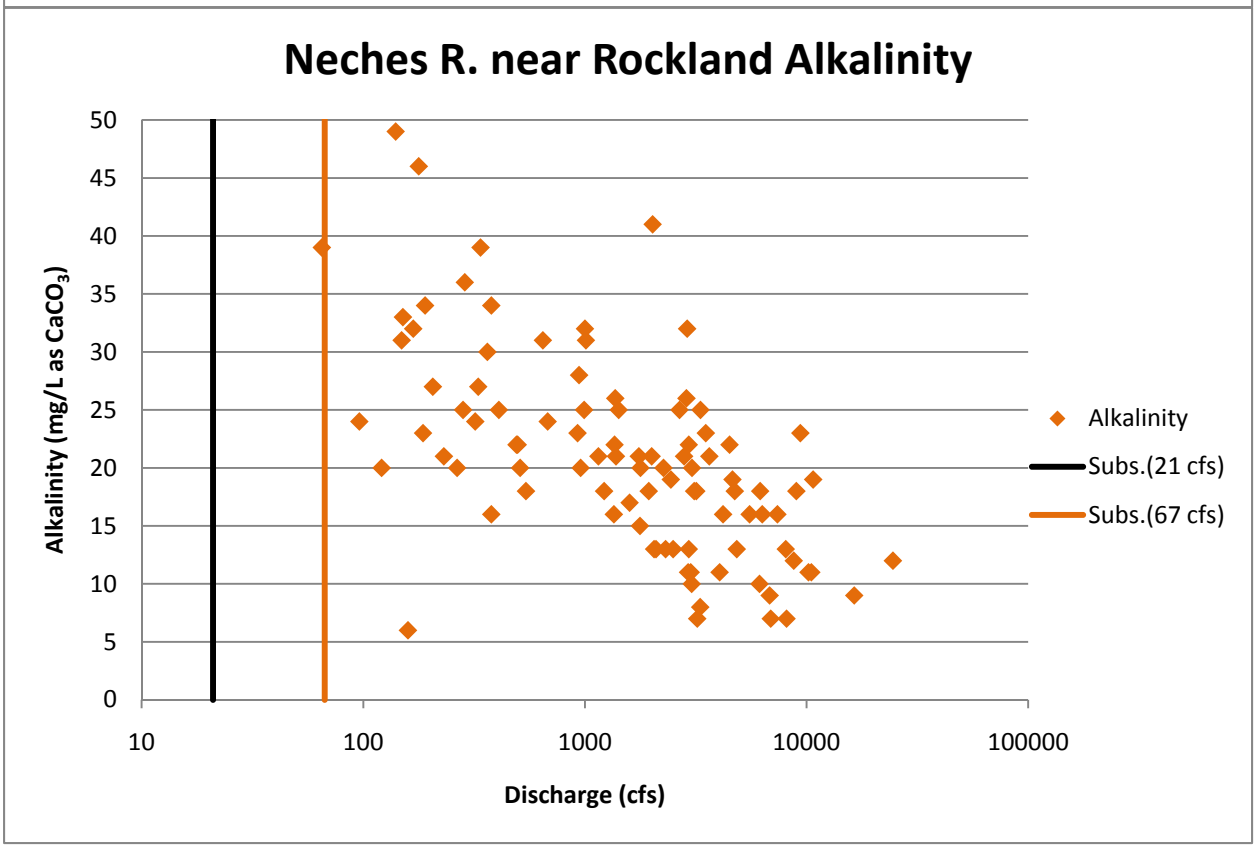

Angelina R. near Alto pH
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
pH (s.u.)
10
100
1000
10000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(11 cfs)
Subs.(55 cfs)

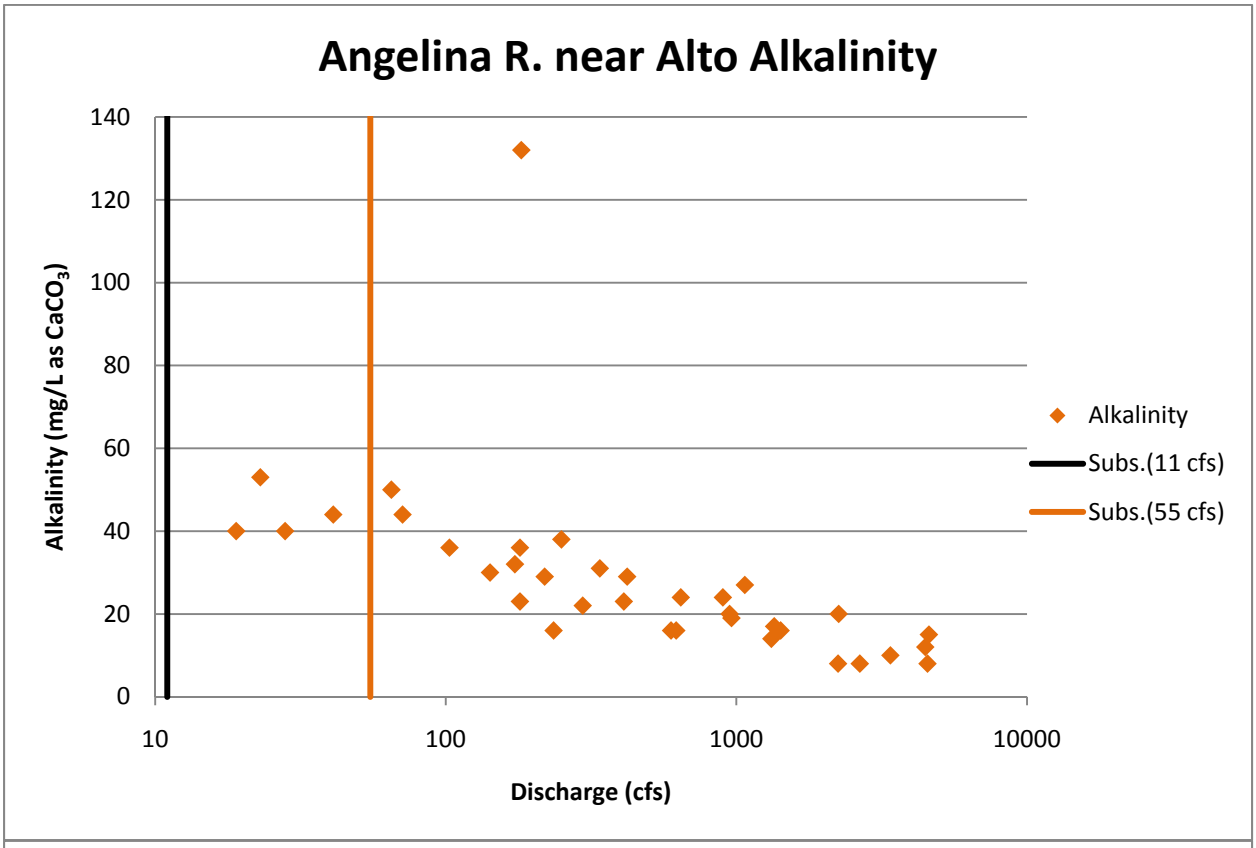

Attoyac Bayou near Chireno pH
8.0
7.5
7.0
6.5
6.0
5.5
5.0
pH (s.u.)
1
10
100
1000
10000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(10 cfs)
Subs.(29 cfs)

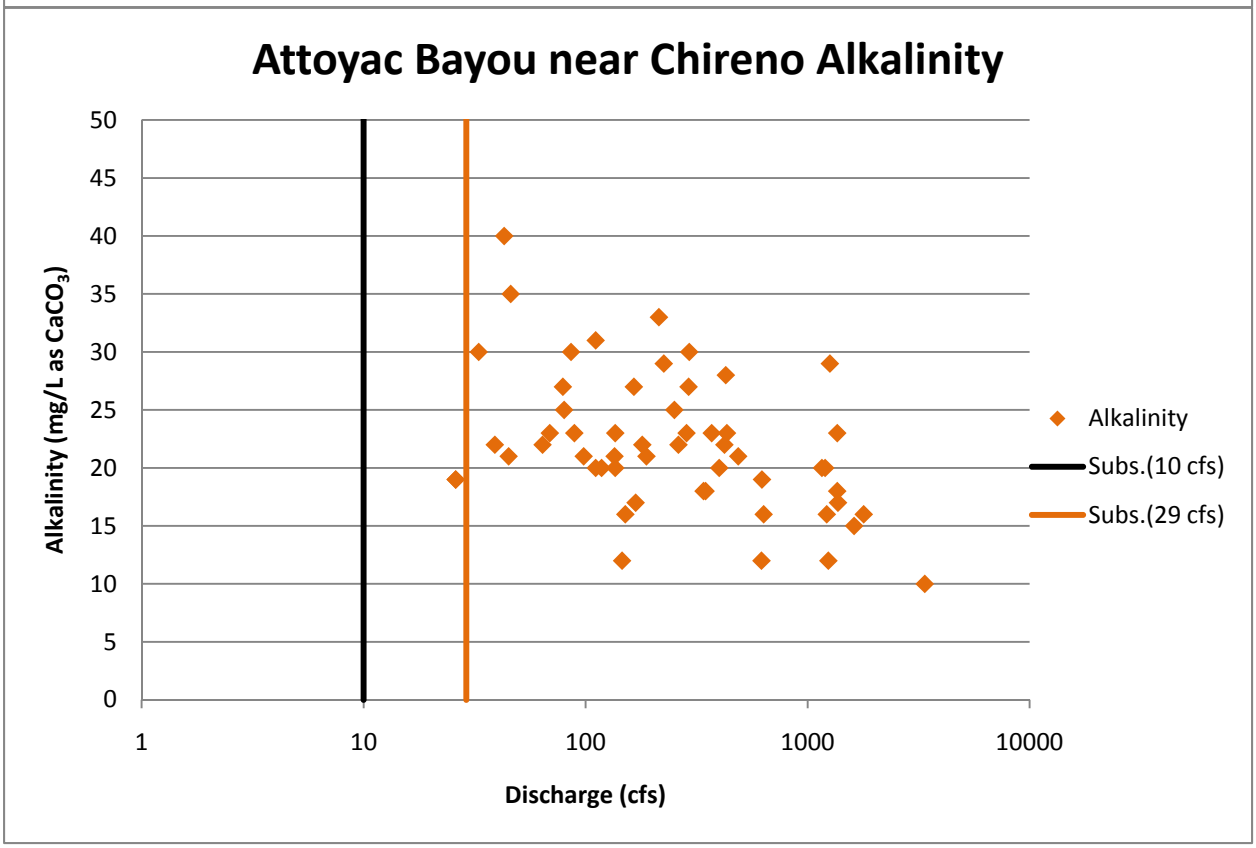

Neches R. near Evadale pH
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
pH (s.u.)
100
1000
10000
100000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(228 cfs)
Subs.(266 cfs)

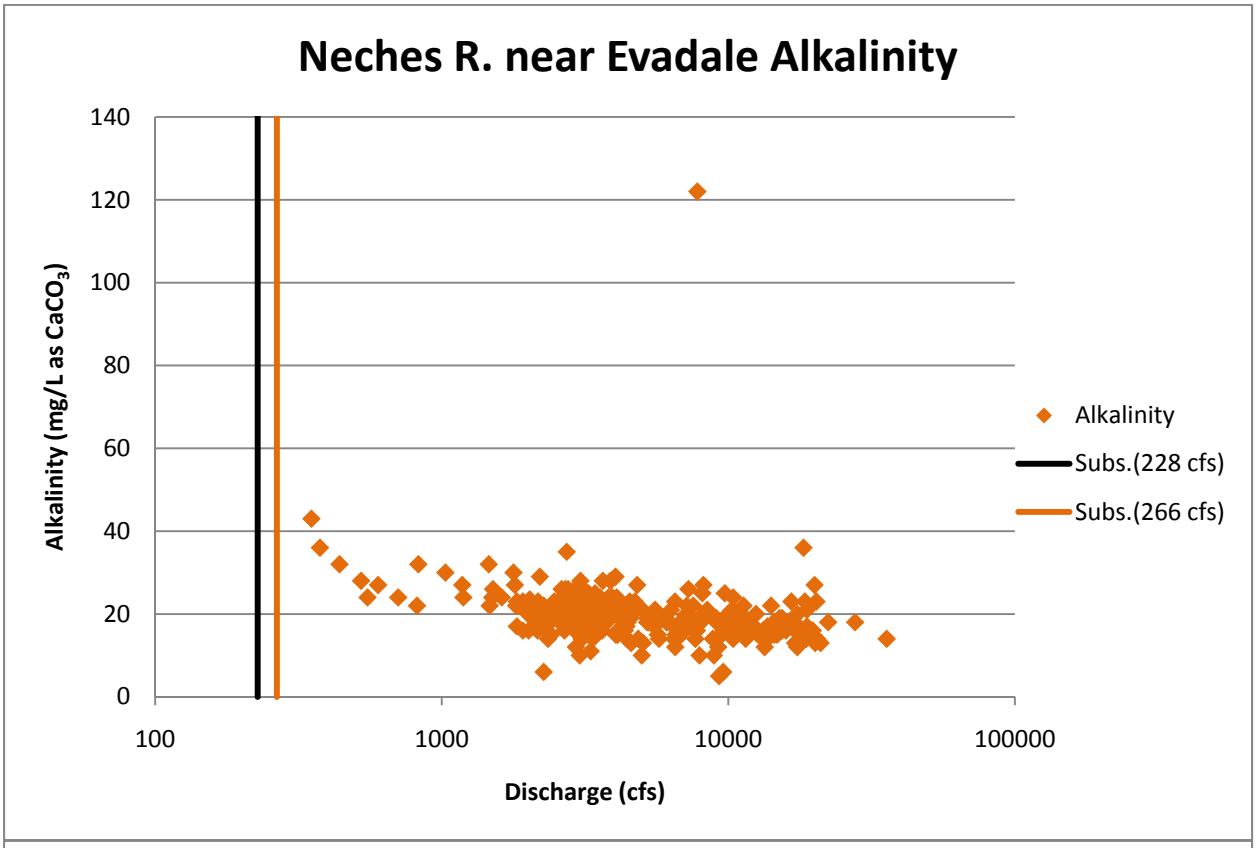

Village Creek near Kountze pH
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
pH (s.u.)
10
100
1000
10000
100000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(41 cfs)
Subs.(83 cfs)

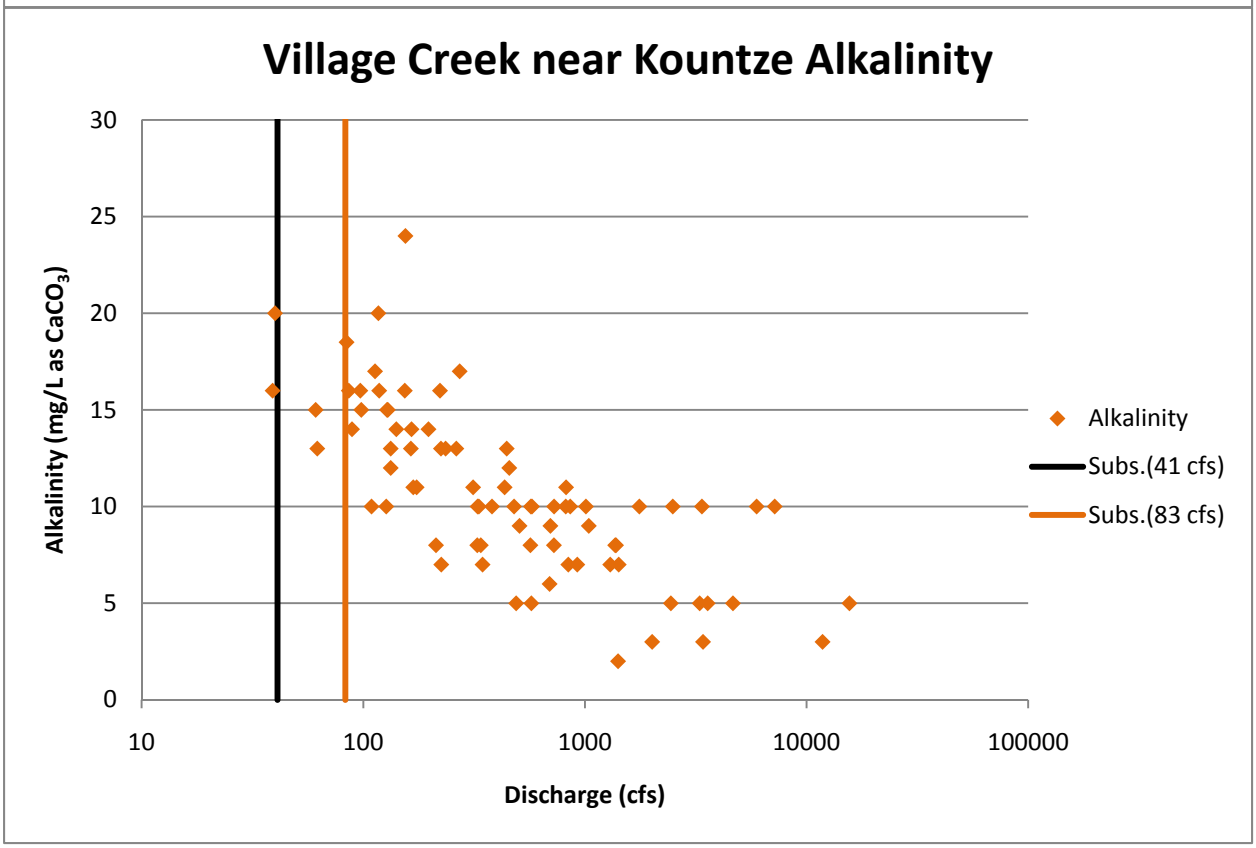

Neches R. near Neches Alkalinity
Alkalinity (mg/L as CaCO3)
50
45
40
35
30
25
20
15
10
5
0
10
100
1000
10000
Discharge (cfs)
Alkalinity
Subs.(12 cfs)
Subs.(51 cfs)

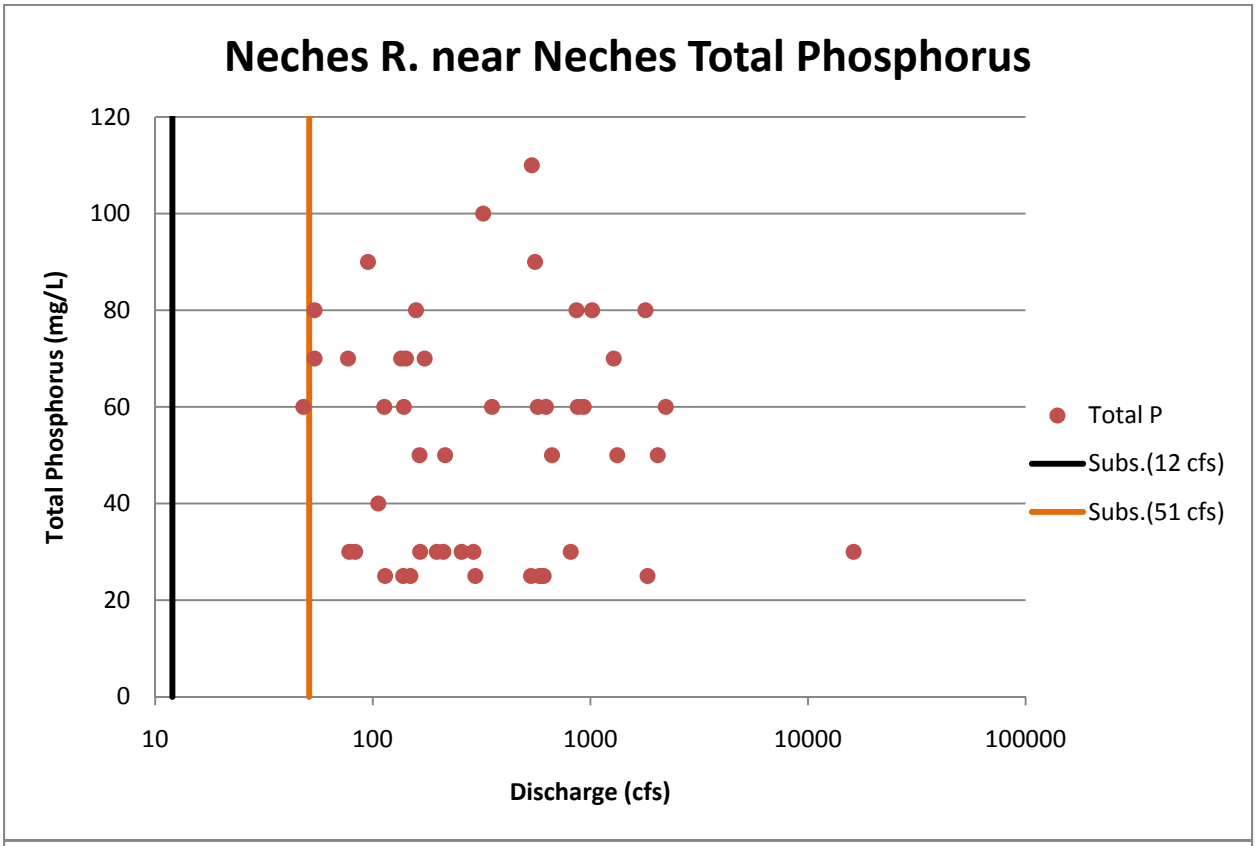

Neches R. near Rockland Alkalinity
Alkalinity (mg/L as CaCO3)
50
45
40
35
30
25
20
15
10
5
0
10
100
1000
10000
100000
Discharge (cfs)
Alkalinity
Subs.(21 cfs)
Subs.(67 cfs)

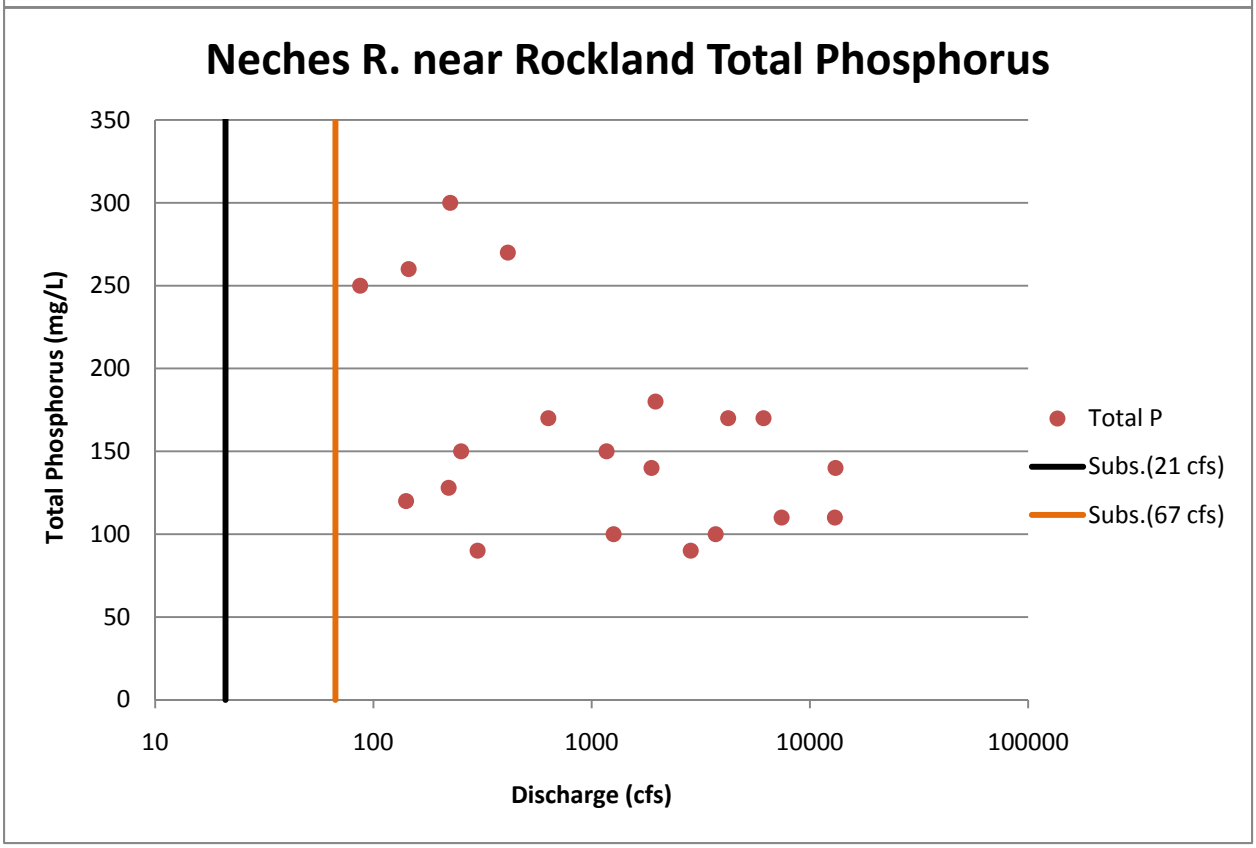

Angelina R. near Alto Alkalinity
Alkalinity (mg/L as CaCO3)
140
120
100
80
60
40
20
0
10
100
1000
10000
Discharge (cfs)
Alkalinity
Subs.(11 cfs)
Subs.(55 cfs)

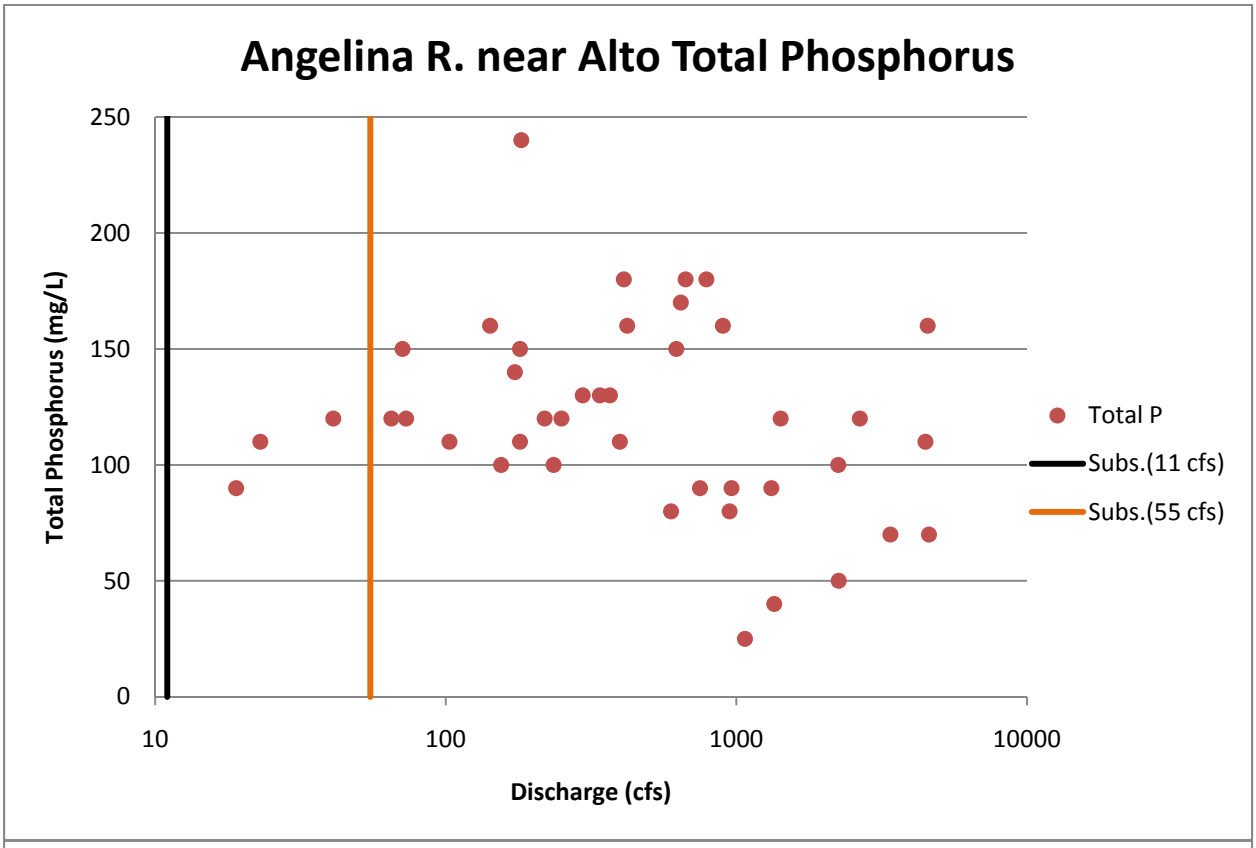

Attoyac Bayou near Chireno Alkalinity
Alkalinity (mg/L as CaCO3)
50
45
40
35
30
25
20
15
10
5
0
1
10
100
1000
10000
Discharge (cfs)
Alkalinity
Subs.(10 cfs)
Subs.(29 cfs)

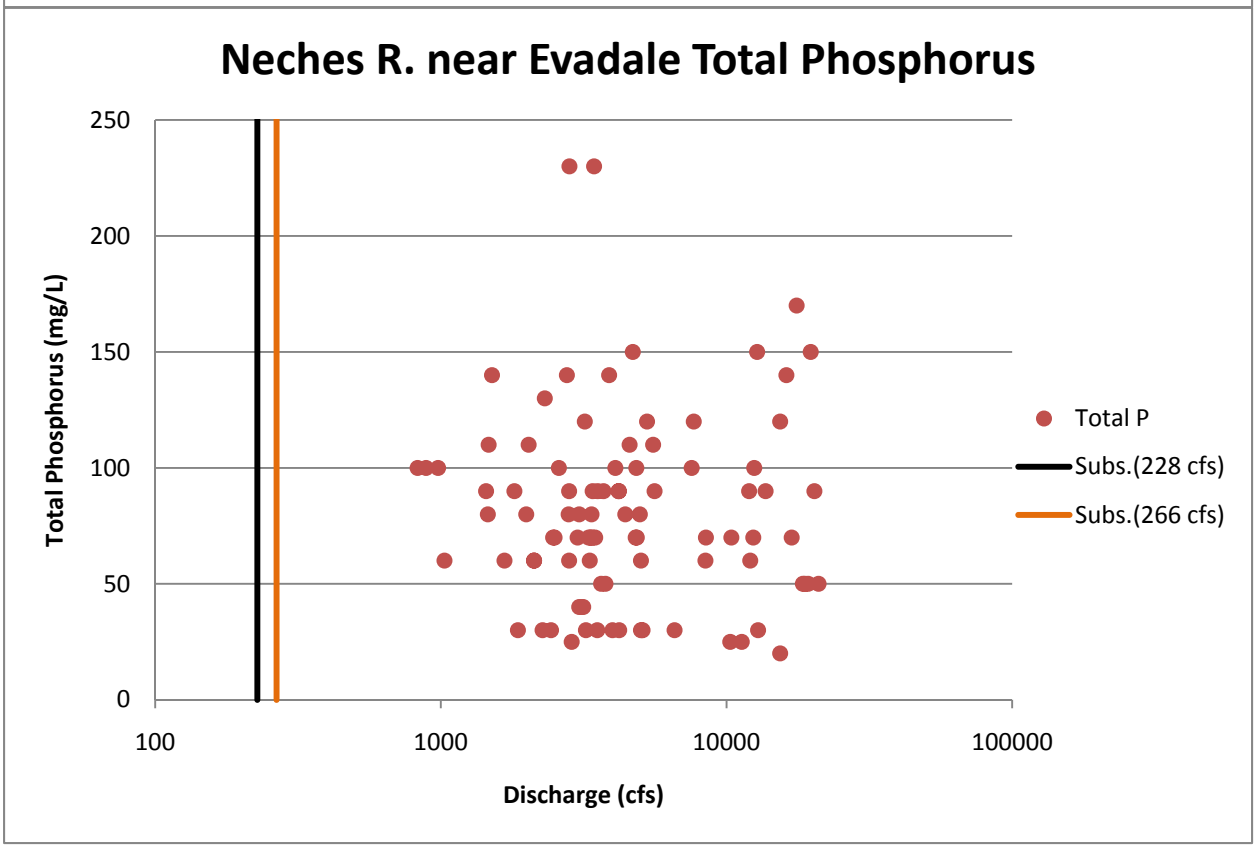

Neches R. near Evadale Alkalinity
Alkalinity (mg/L as CaCO3)
140
120
100
80
60
40
20
0
100
1000
10000
100000
Discharge (cfs)
Alkalinity
Subs.(228 cfs)
Subs.(266 cfs)

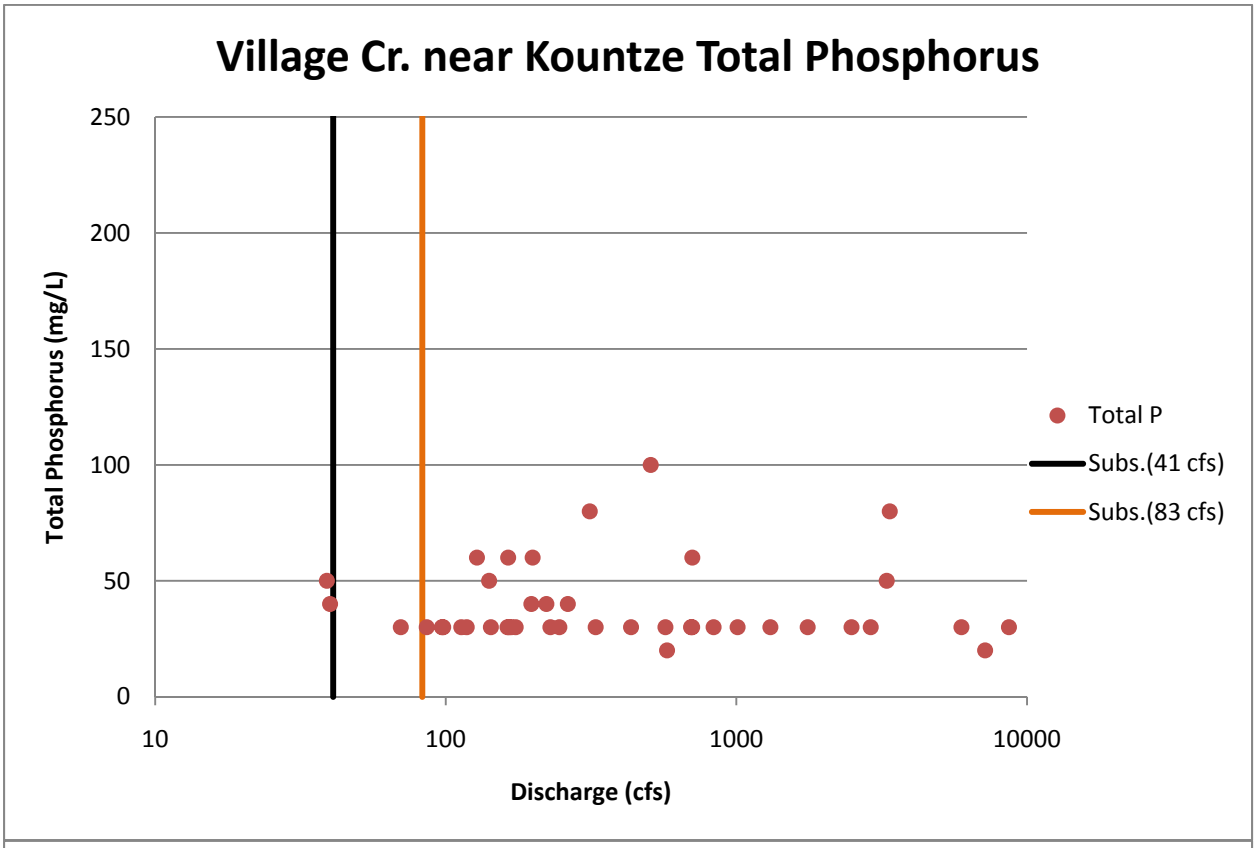

Village Creek near Kountze Alkalinity
Alkalinity (mg/L as CaCO3)
30
25
20
15
10
5
0
10
100
1000
10000
100000
Discharge (cfs)
Alkalinity
Subs.(41 cfs)
Subs.(83 cfs)

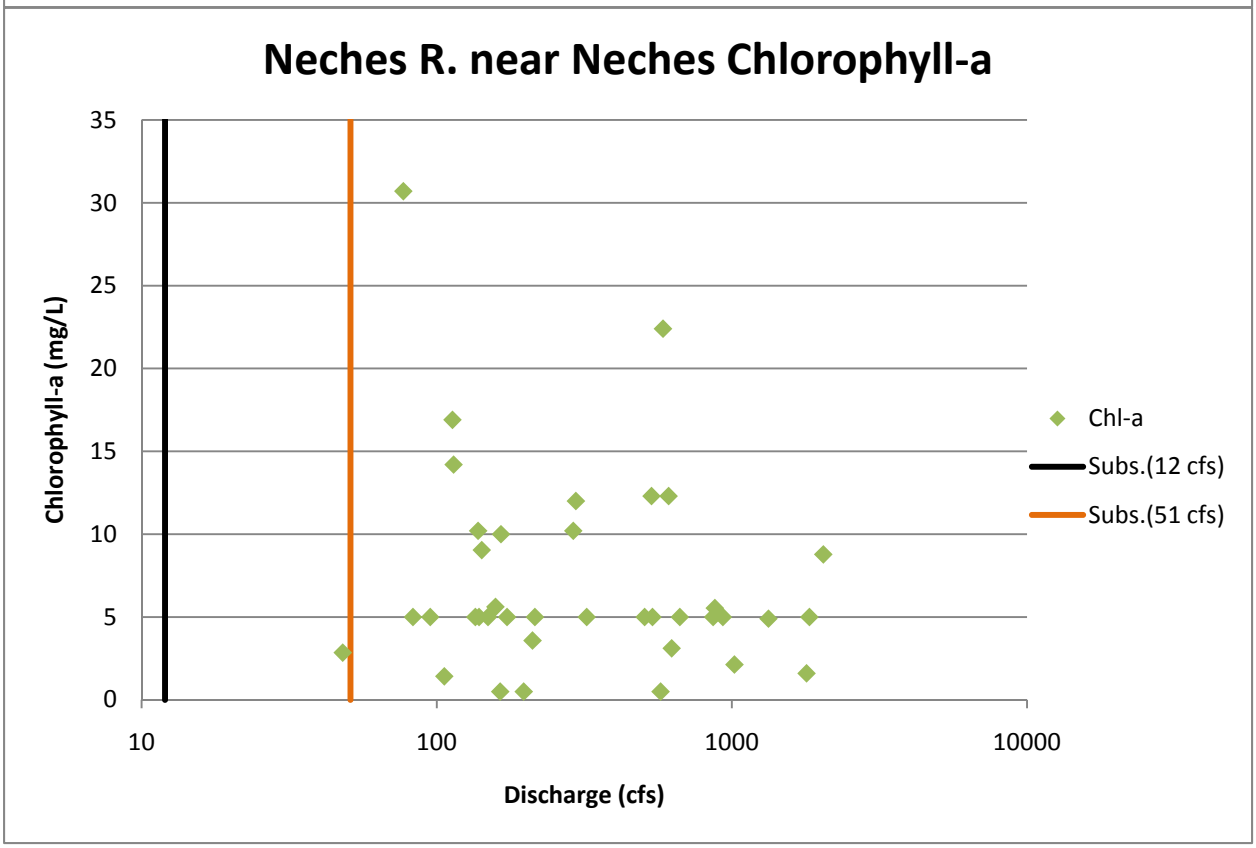

Neches R. near Neches Total Phosphorus
Total Phosphorus (mg/L)
120
100
80
60
40
20
0
10
100
1000
10000
100000
Discharge (cfs)
Total P
Subs.(12 cfs)
Subs.(51 cfs)

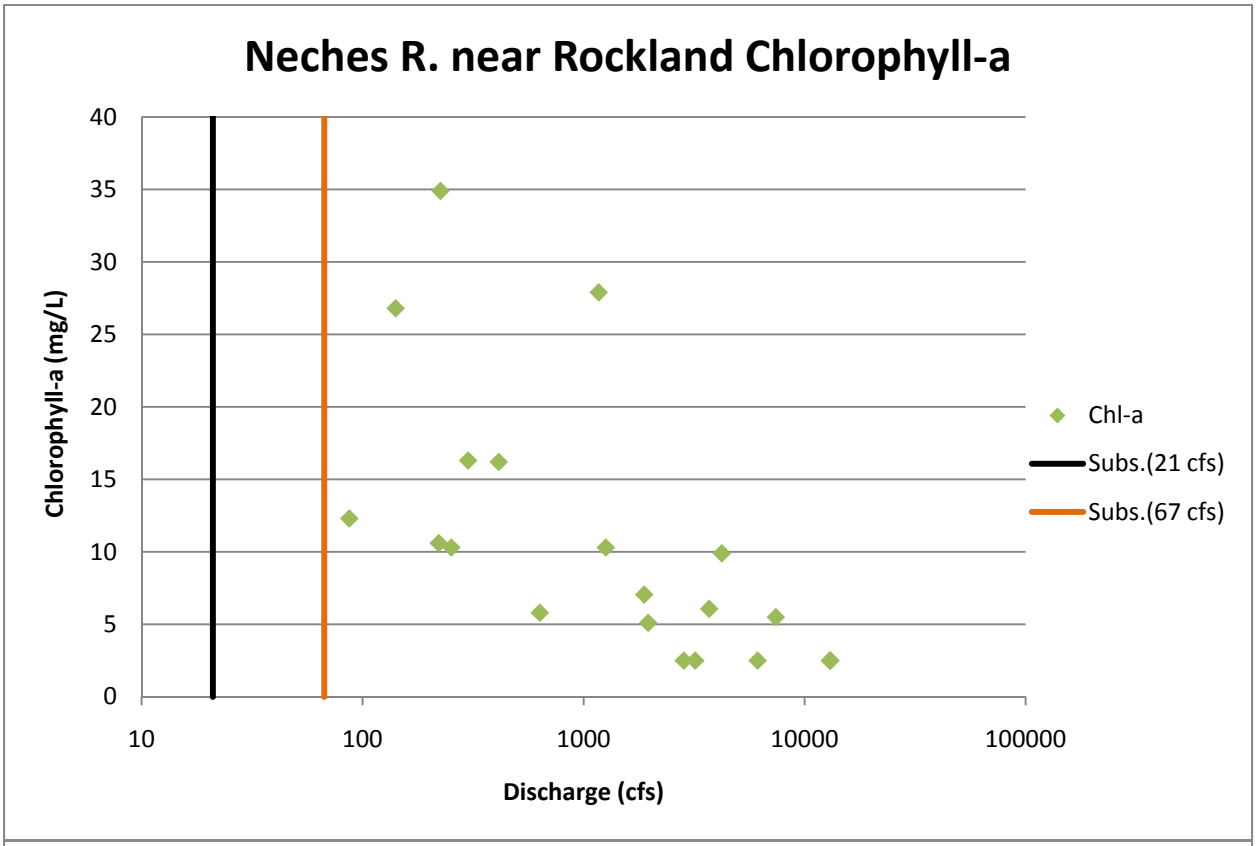

Neches R. near Rockland Total Phosphorus
Total Phosphorus (mg/L)
350
300
250
200
150
100
50
0
10
100
1000
10000
100000
Discharge (cfs)
Total P
Subs.(21 cfs)
Subs.(67 cfs)

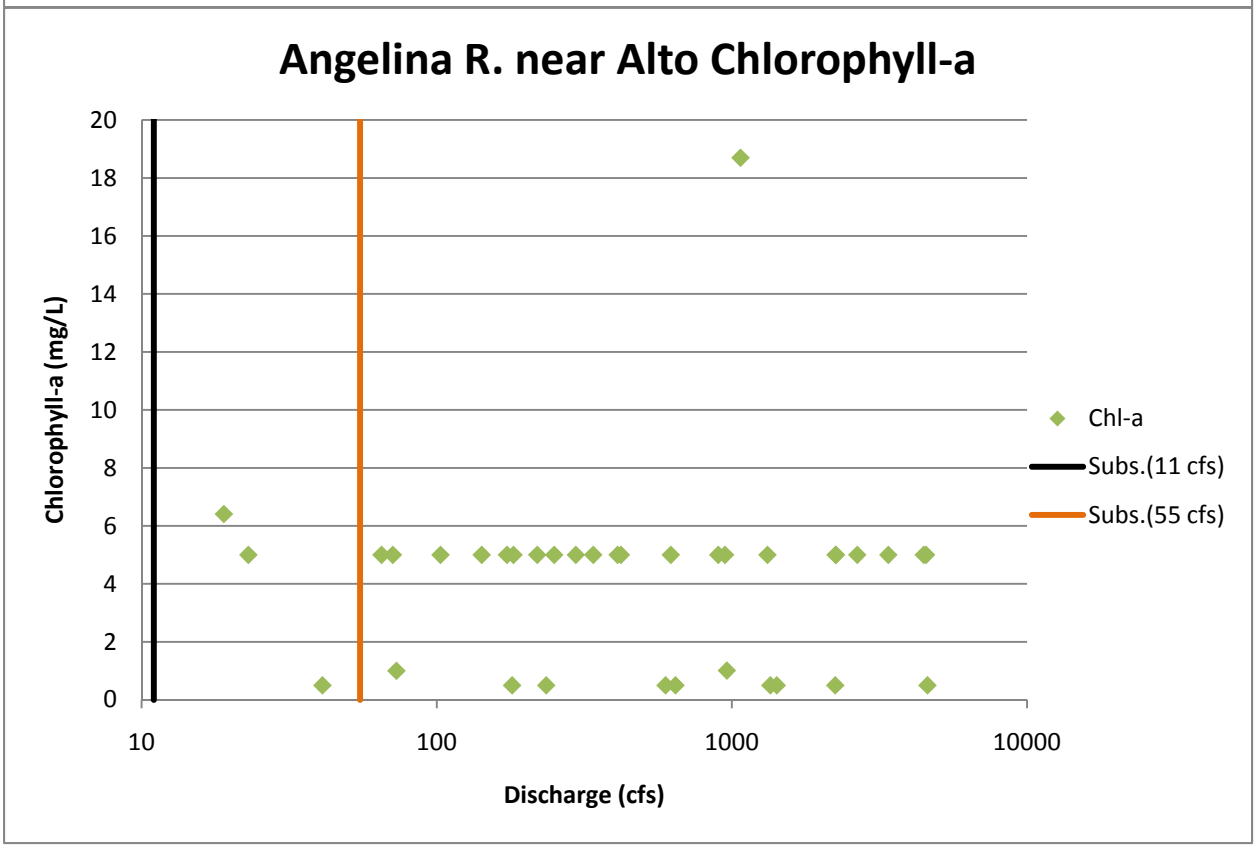

Angelina R. near Alto Total Phosphorus
Total Phosphorus (mg/L)
250
200
150
100
50
0
10
100
1000
10000
Discharge (cfs)
Total P
Subs.(11 cfs)
Subs.(55 cfs)

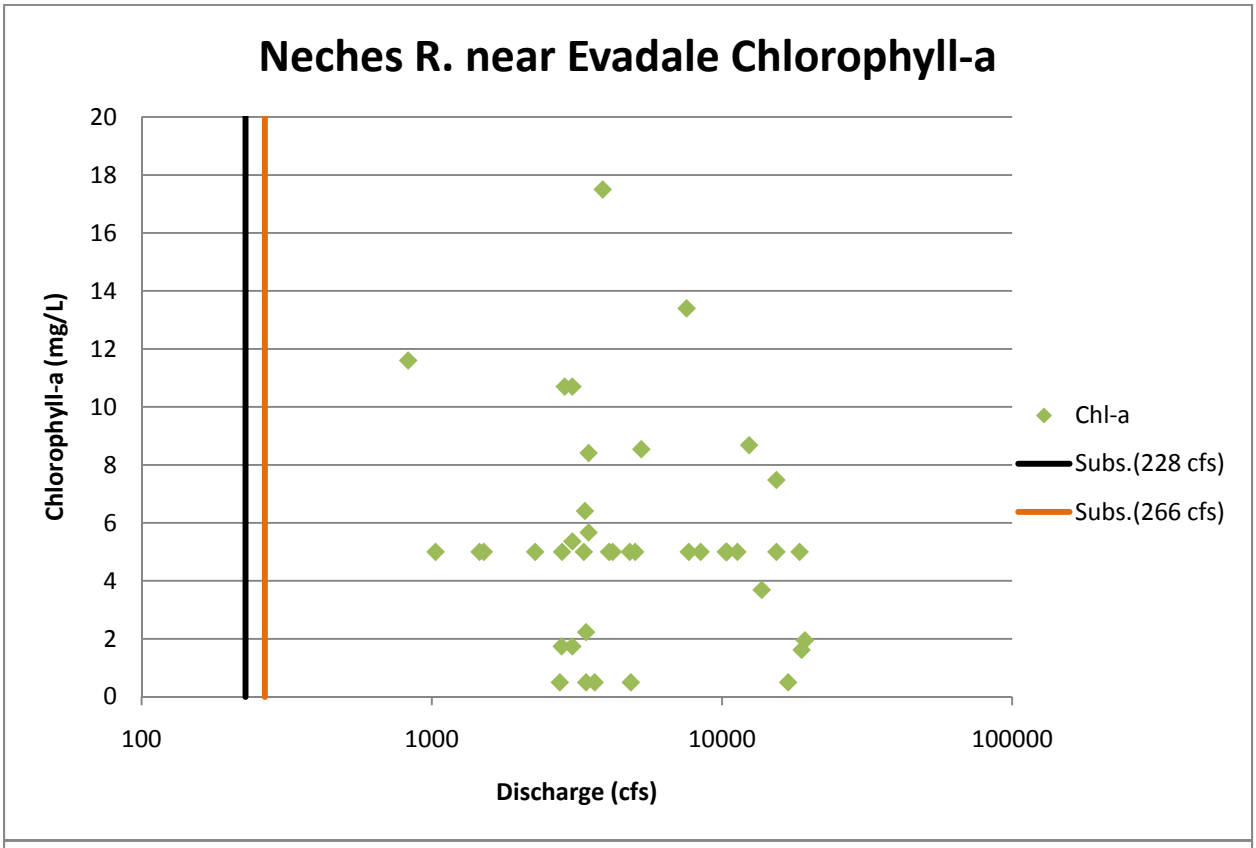

Neches R. near Evadale Total Phosphorus
Total Phosphorus (mg/L)
250
200
150
100
50
0
100
1000
10000
100000
Discharge (cfs)
Total P
Subs.(228 cfs)
Subs.(266 cfs)

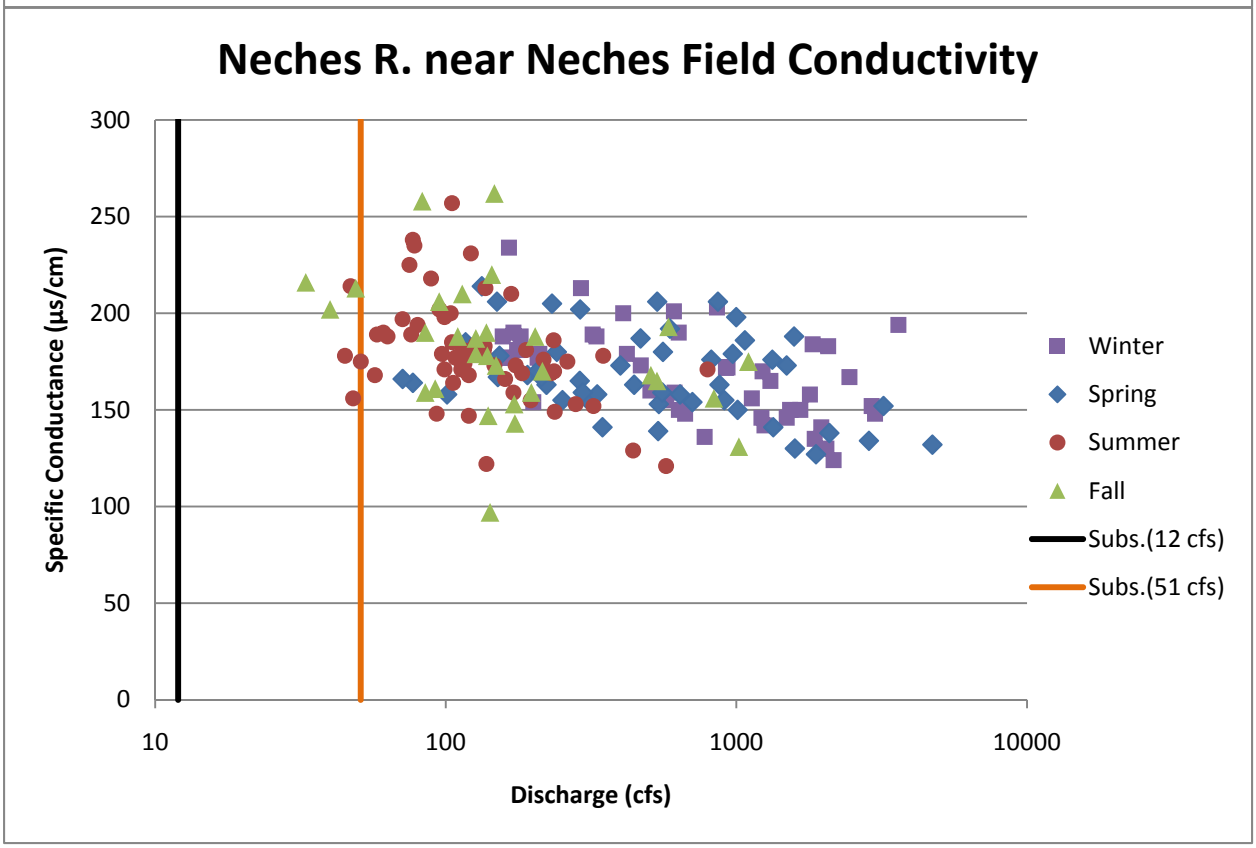

Village Cr. near Kountze Total Phosphorus
Total Phosphorus (mg/L)
250
200
150
100
50
0
10
100
1000
10000
Discharge (cfs)
Total P
Subs.(41 cfs)
Subs.(83 cfs)

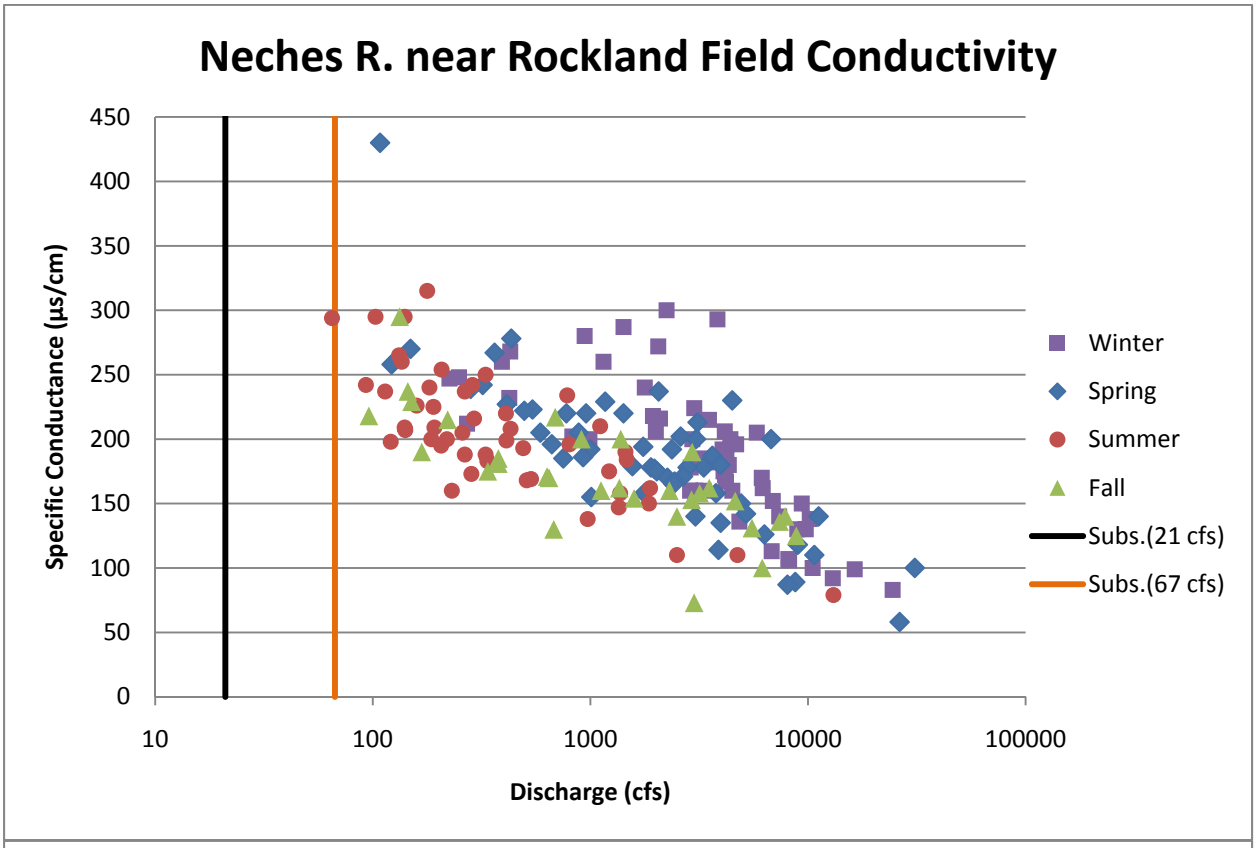

Neches R. near Neches Chlorophyll-a
Chlorophyll-a (mg/L)
35
30
25
20
15
10
5
0
10
100
1000
10000
Discharge (cfs)
Chl-a
Subs.(12 cfs)
Subs.(51 cfs)

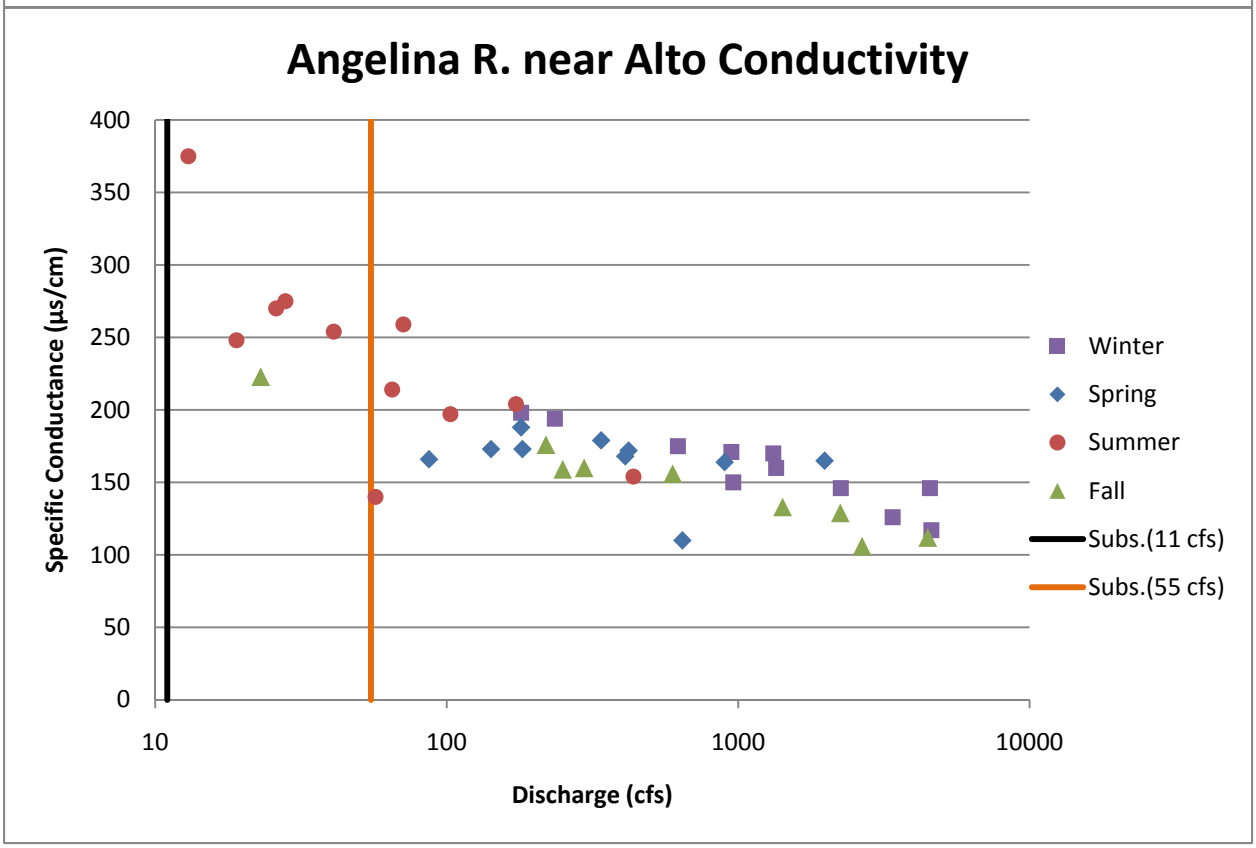

Neches R. near Rockland Chlorophyll-a
Chlorophyll-a (mg/L)
40
35
30
25
20
15
10
5
0
10
100
1000
10000
100000
Discharge (cfs)
Chl-a
Subs.(21 cfs)
Subs.(67 cfs)

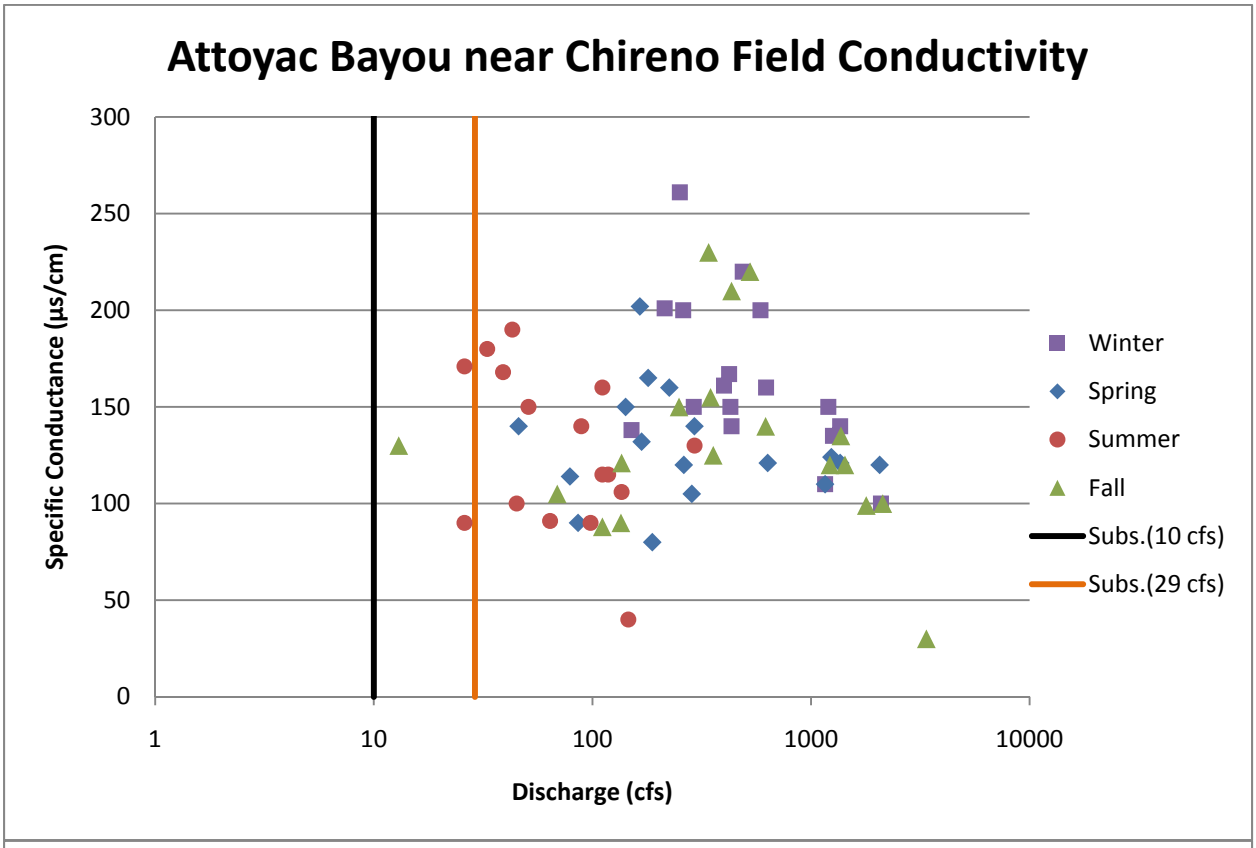

Angelina R. near Alto Chlorophyll-a
Chlorophyll-a (mg/L)
20
18
16
14
12
10
8
6
4
2
0
10
100
1000
10000
Discharge (cfs)
Chl-a
Subs.(11 cfs)
Subs.(55 cfs)

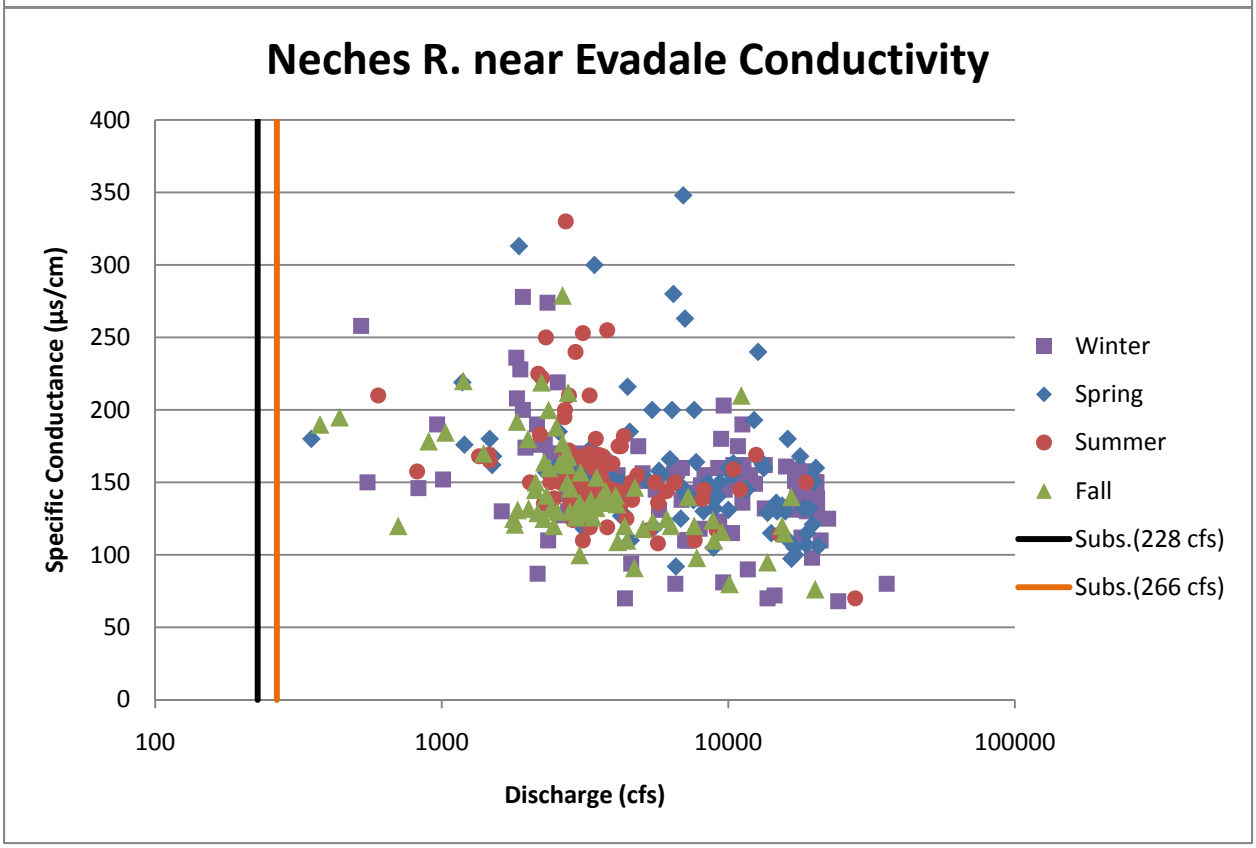

Neches R. near Evadale Chlorophyll-a
Chlorophyll-a (mg/L)
20
18
16
14
12
10
8
6
4
2
0
100
1000
10000
100000
Discharge (cfs)
Chl-a
Subs.(228 cfs)
Subs.(266 cfs)

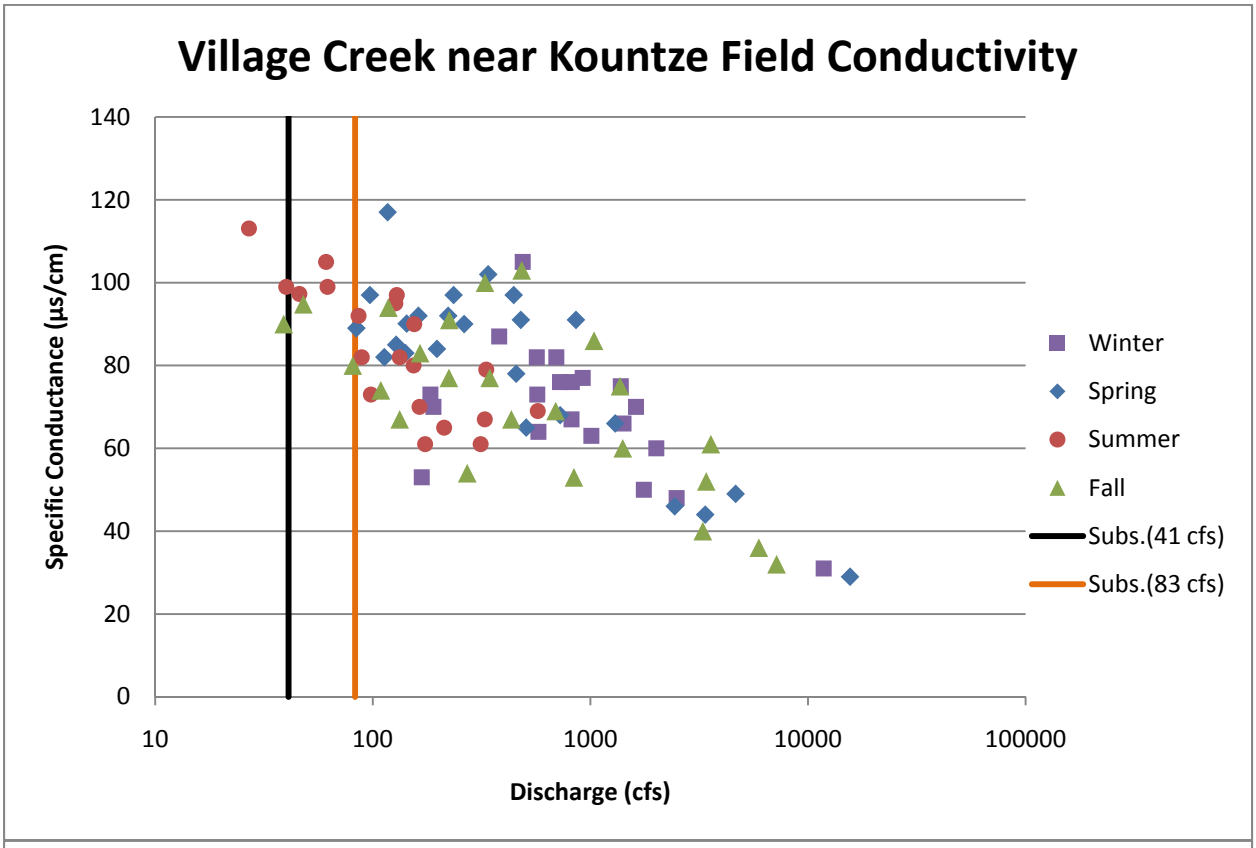

Neches R. near Neches Field Conductivity
Specific Conductance (µs/cm)
300
250
200
150
100
50
0
10
100
1000
10000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(12 cfs)
Subs.(51 cfs)

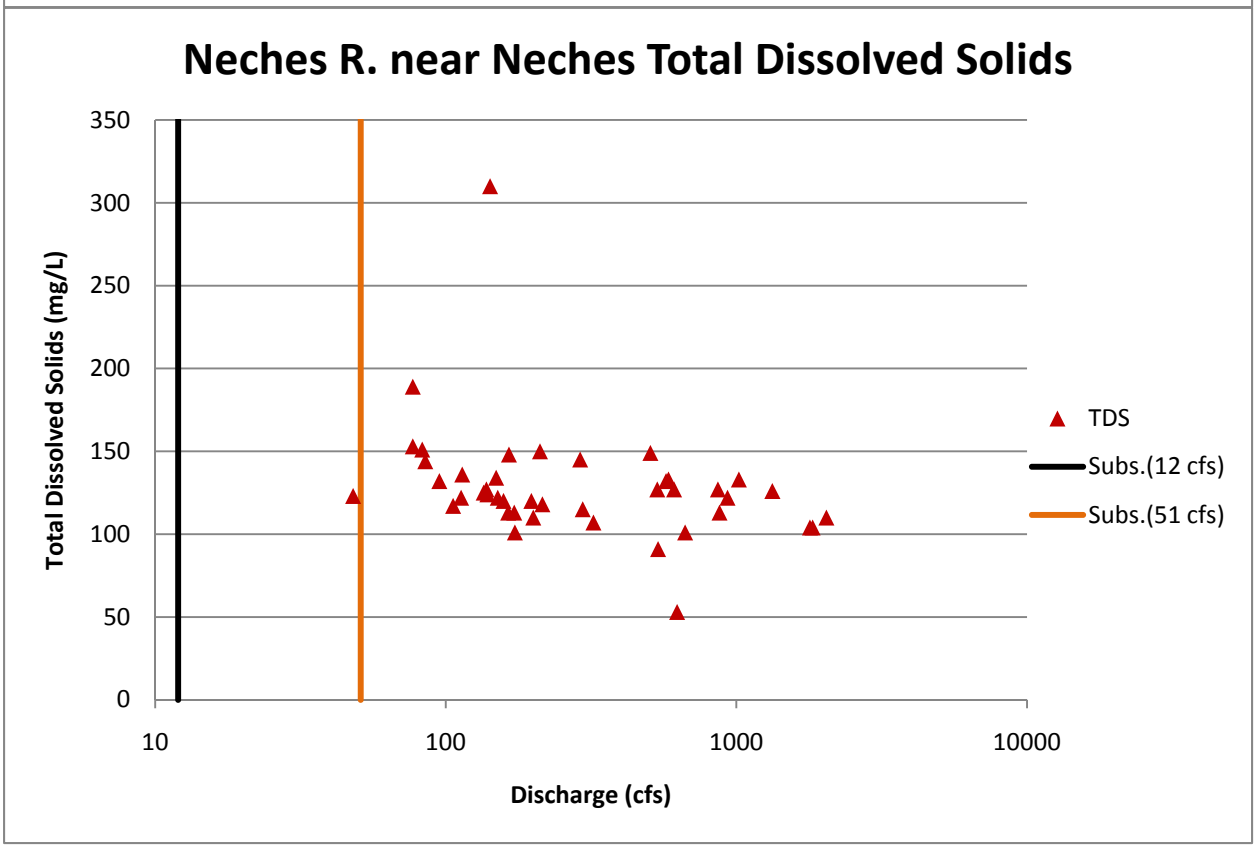

Neches R. near Rockland Field Conductivity
Specific Conductance (µs/cm)
450
400
350
300
250
200
150
100
50
0
10
100
1000
10000
100000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(21 cfs)
Subs.(67 cfs)

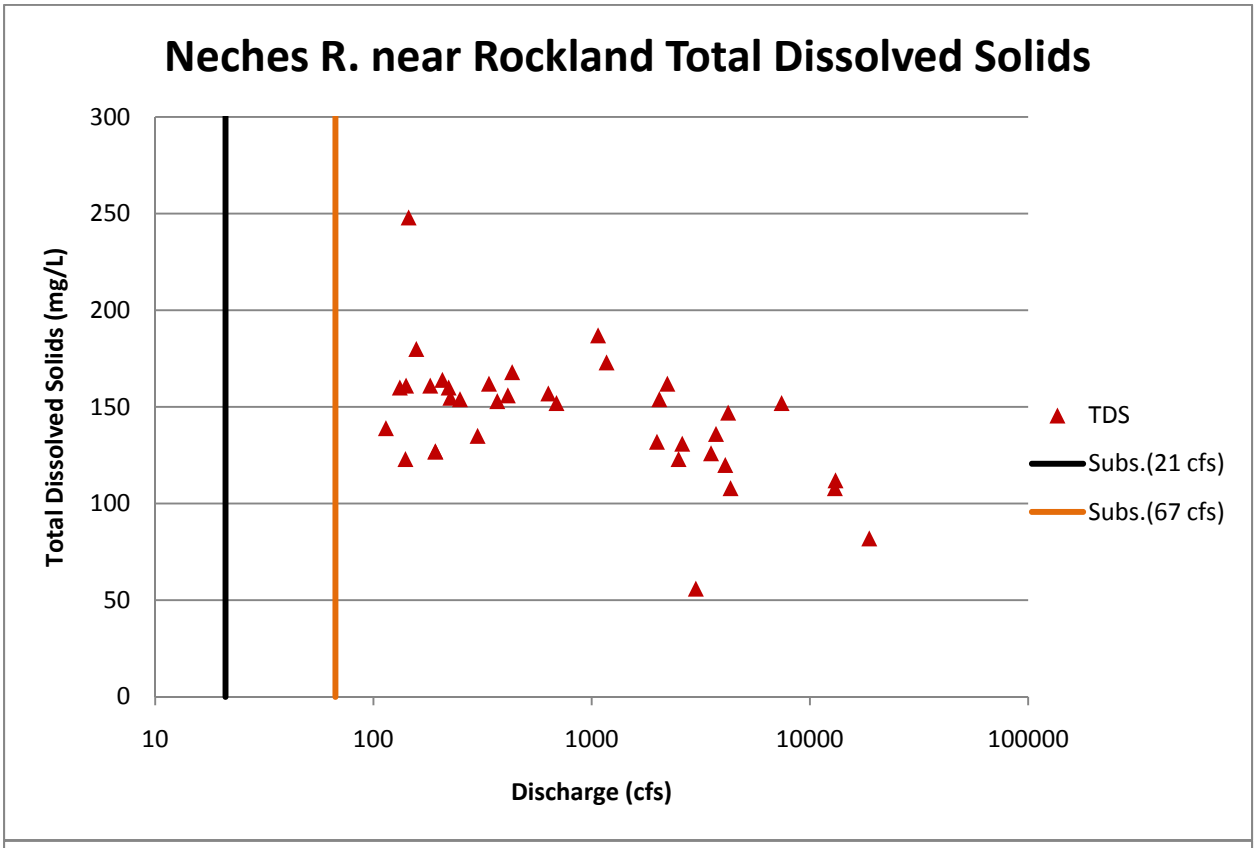

Angelina R. near Alto Conductivity
Specific Conductance (µs/cm)
400
350
300
250
200
150
100
50
0
10
100
1000
10000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(11 cfs)
Subs.(55 cfs)

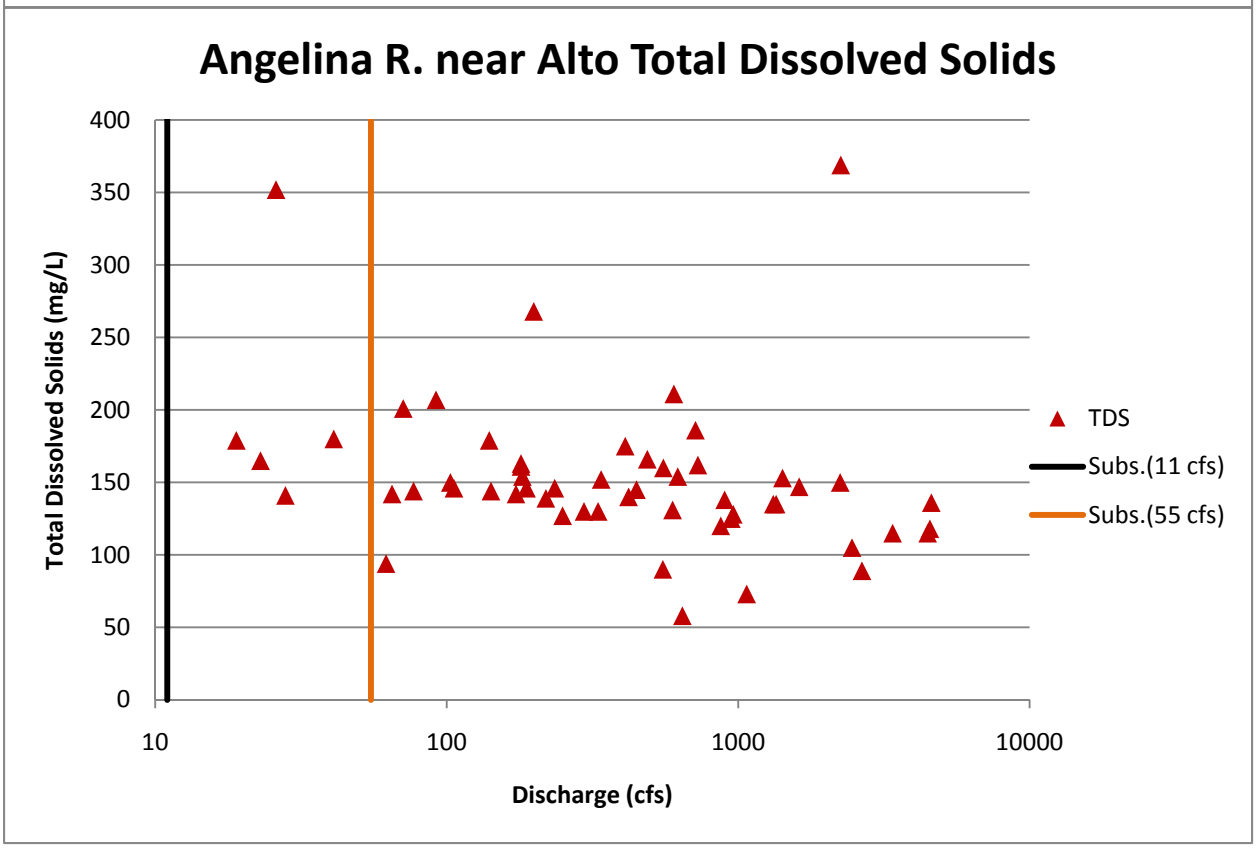

Attoyac Bayou near Chireno Field Conductivity
Specific Conductance (µs/cm)
300
250
200
150
100
50
0
1
10
100
1000
10000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(10 cfs)
Subs.(29 cfs)

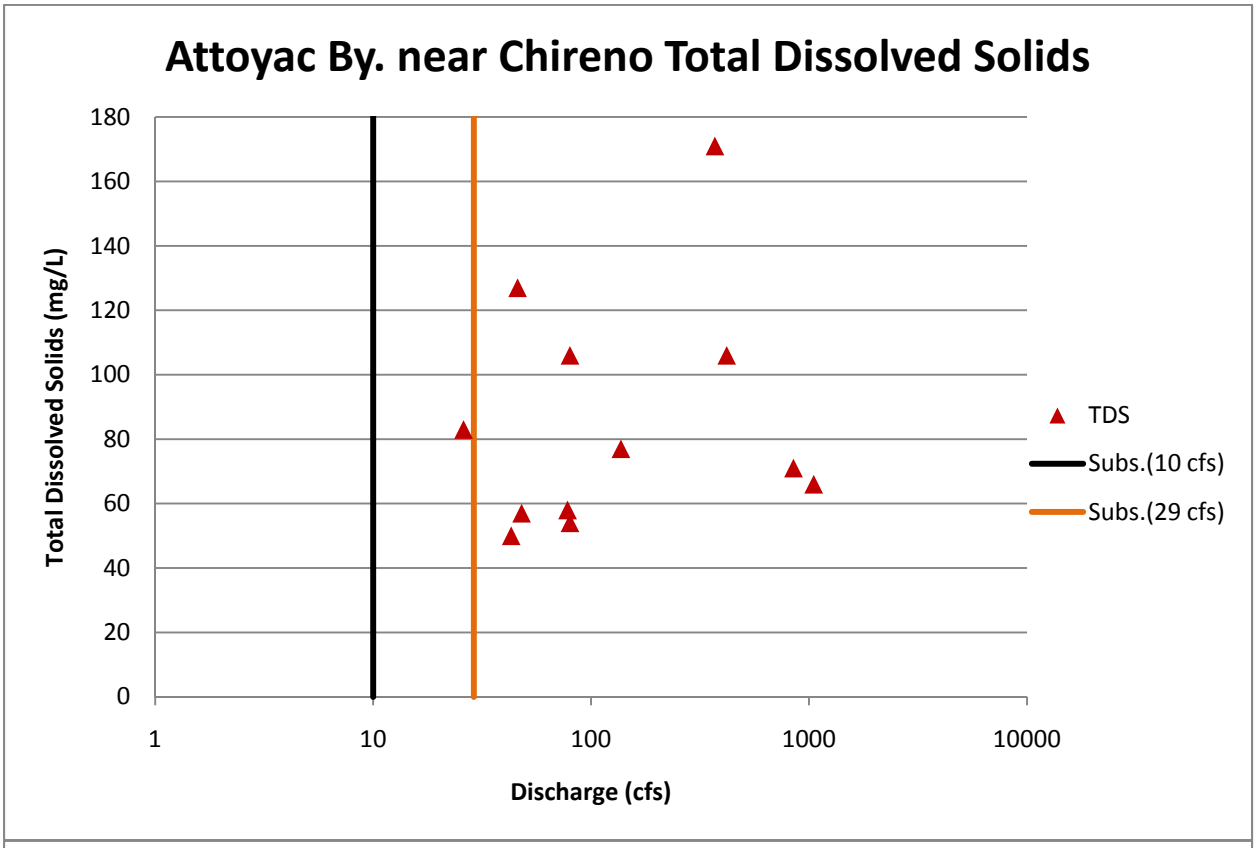

Neches R. near Evadale Conductivity
Specific Conductance (µs/cm)
400
350
300
250
200
150
100
50
0
100
1000
10000
100000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(228 cfs)
Subs.(266 cfs)

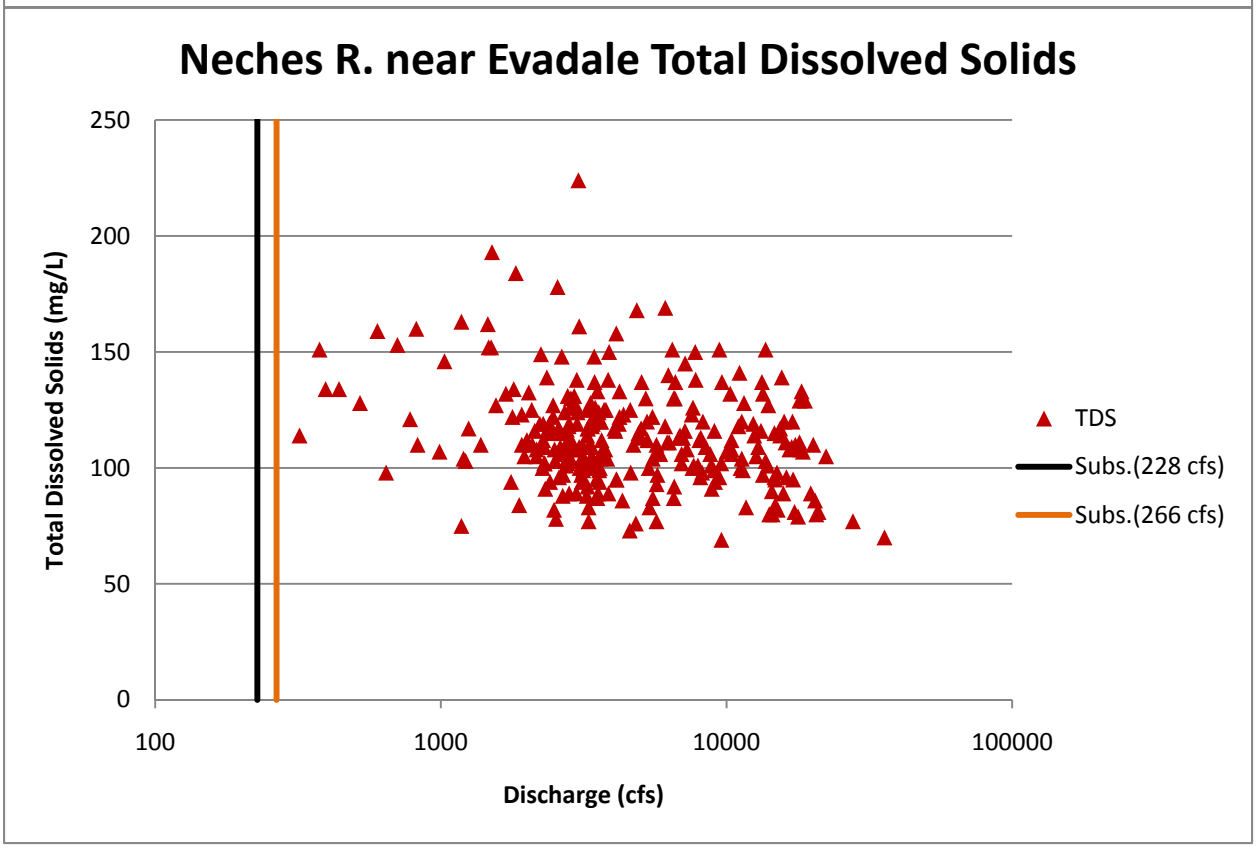

Village Creek near Kountze Field Conductivity
Specific Conductance (µs/cm)
140
120
100
80
60
40
20
0
10
100
1000
10000
100000
Discharge (cfs)
Winter
Spring
Summer
Fall
Subs.(41 cfs)
Subs.(83 cfs)

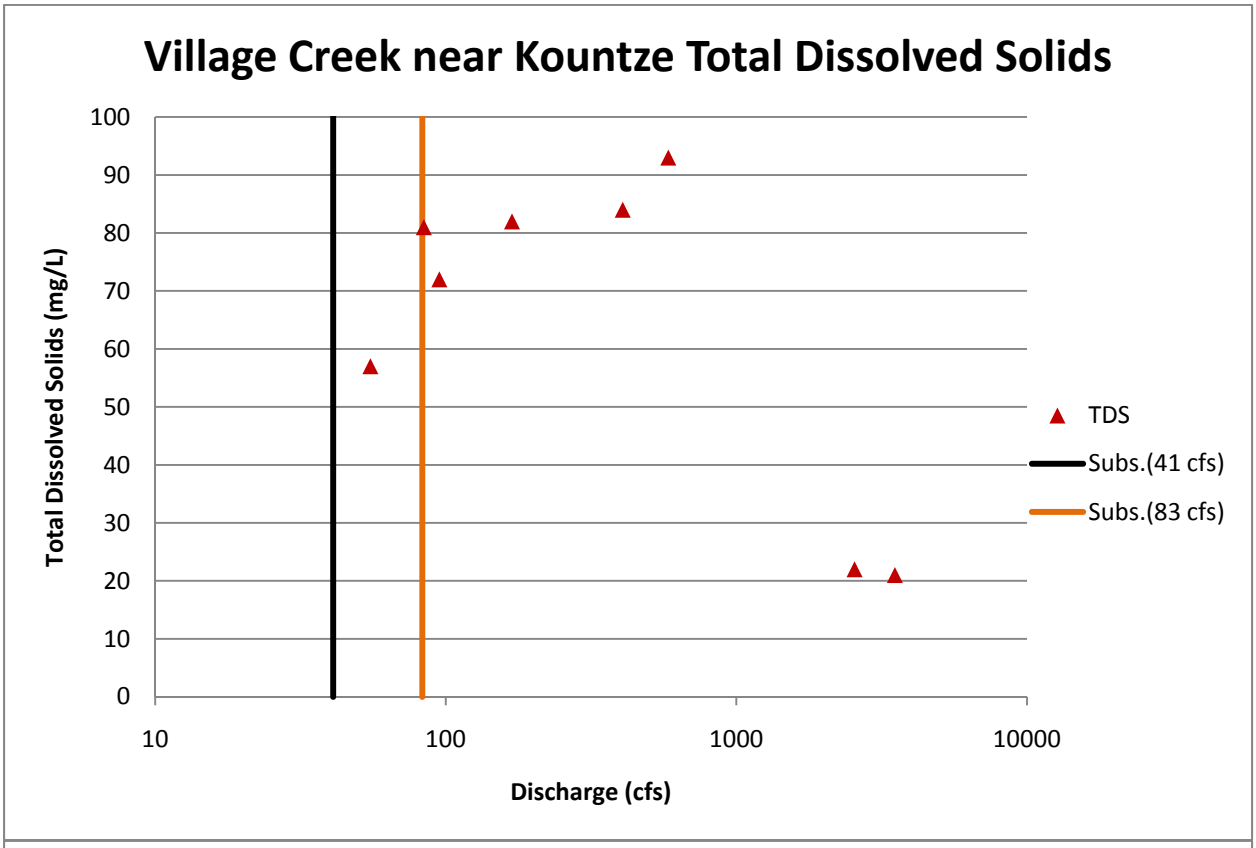

Neches R. near Neches Total Dissolved Solids
Total Dissolved Solids (mg/L)
350
300
250
200
150
100
50
0
10
100
1000
10000
Discharge (cfs)
TDS
Subs.(12 cfs)
Subs.(51 cfs)

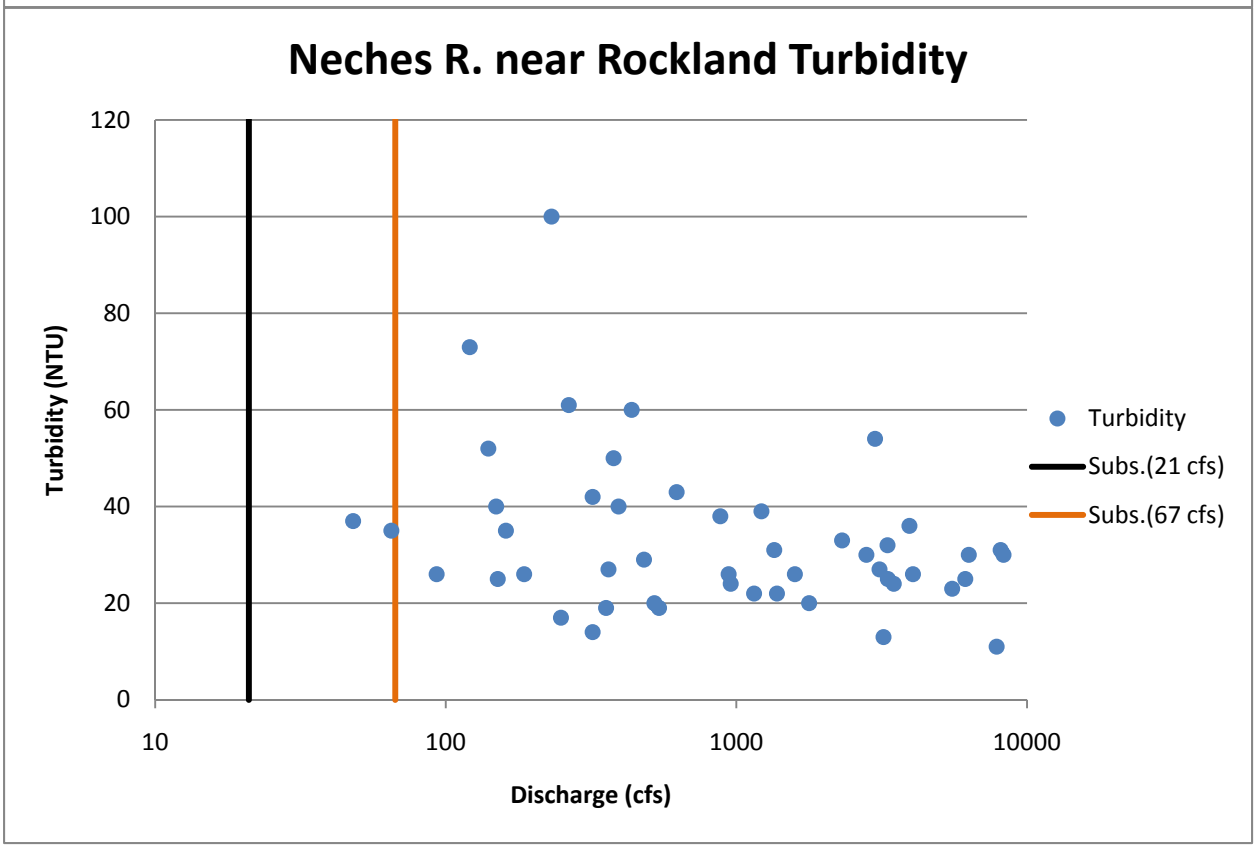

Neches R. near Rockland Total Dissolved Solids
Total Dissolved Solids (mg/L)
300
250
200
150
100
50
0
10
100
1000
10000
100000
Discharge (cfs)
TDS
Subs.(21 cfs)
Subs.(67 cfs)

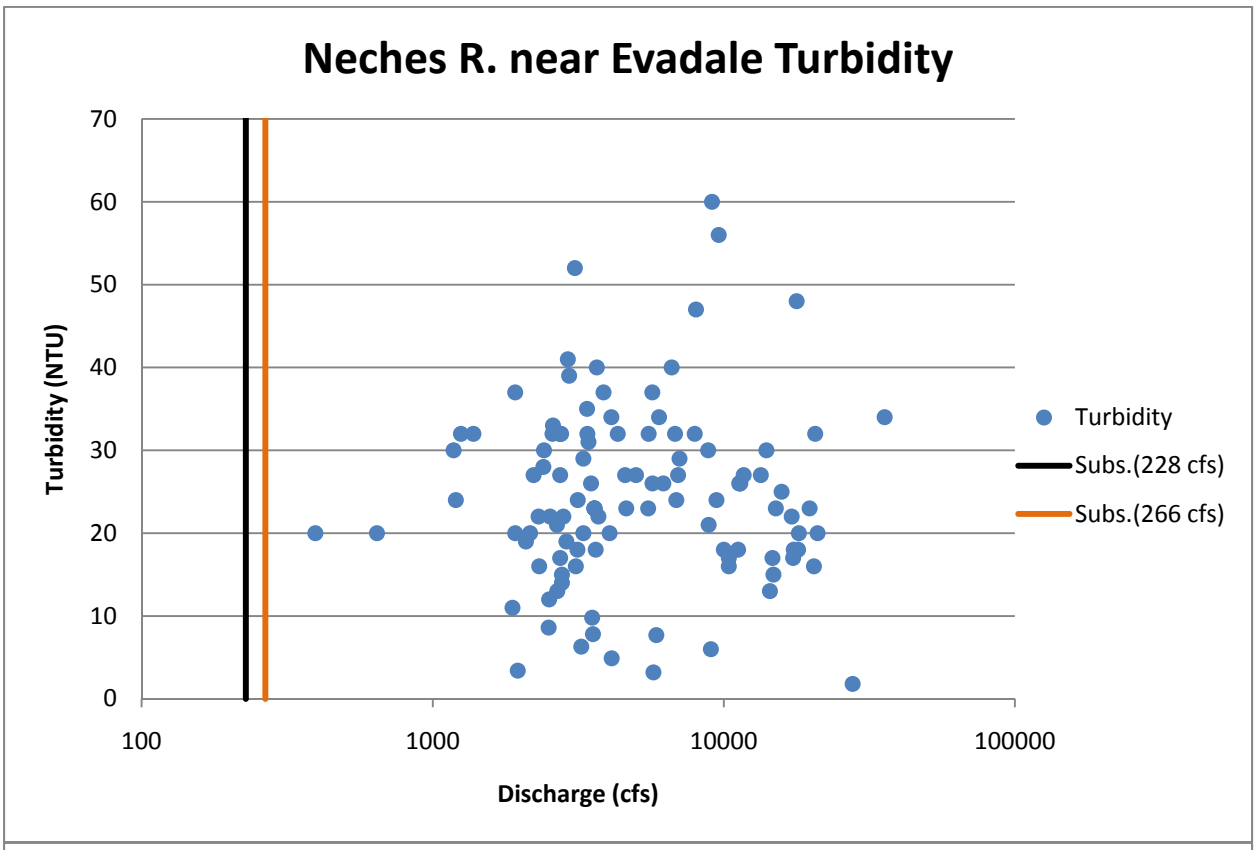

Angelina R. near Alto Total Dissolved Solids
Total Dissolved Solids (mg/L)
400
350
300
250
200
150
100
50
0
10
100
1000
10000
Discharge (cfs)
TDS
Subs.(11 cfs)
Subs.(55 cfs)

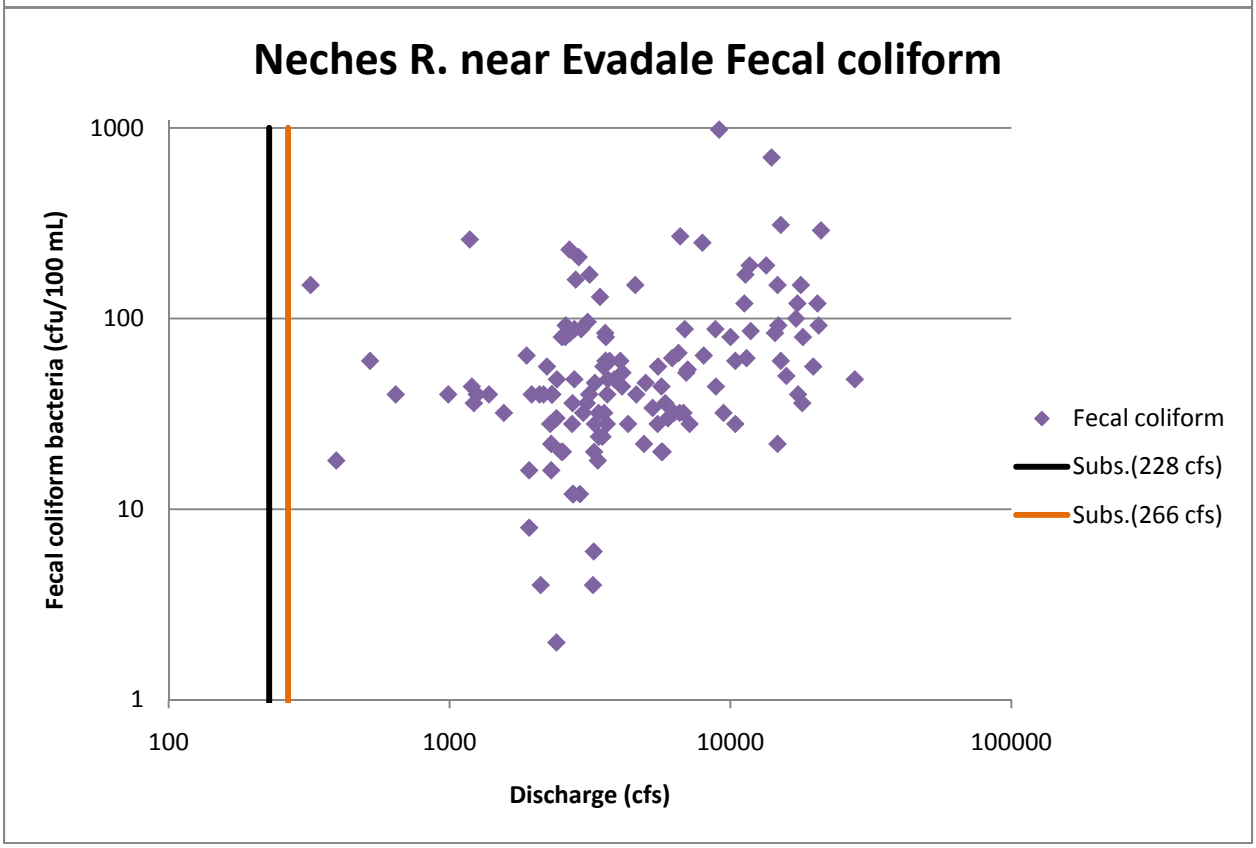

Attoyac By. near Chireno Total Dissolved Solids
Total Dissolved Solids (mg/L)
180
160
140
120
100
80
60
40
20
0
1
10
100
1000
10000
Discharge (cfs)
TDS
Subs.(10 cfs)
Subs.(29 cfs)


Neches R. near Evadale Total Dissolved Solids
Total Dissolved Solids (mg/L)
250
200
150
100
50
0
100
1000
10000
100000
Discharge (cfs)
TDS
Subs.(228 cfs)
Subs.(266 cfs)


Village Creek near Kountze Total Dissolved Solids
Total Dissolved Solids (mg/L)
100
90
80
70
60
50
40
30
20
10
0
10
100
1000
10000
Discharge (cfs)
TDS
Subs.(41 cfs)
Subs.(83 cfs)


Neches R. near Rockland Turbidity
Turbidity (NTU)
120
100
80
60
40
20
0
10
100
1000
10000
Discharge (cfs)
Turbidity
Subs.(21 cfs)
Subs.(67 cfs)


Neches R. near Evadale Turbidity
Turbidity (NTU)
70
60
50
40
30
20
10
0
100
1000
10000
100000
Discharge (cfs)
Turbidity
Subs.(228 cfs)
Subs.(266 cfs)


Neches R. near Evadale Fecal coliform
Fecal coliform bacteria (cfu/100 mL)
1000
100
10
1
100
1000
10000
100000
Discharge (cfs)
Fecal coliform
Subs.(228 cfs)
Subs.(266 cfs)

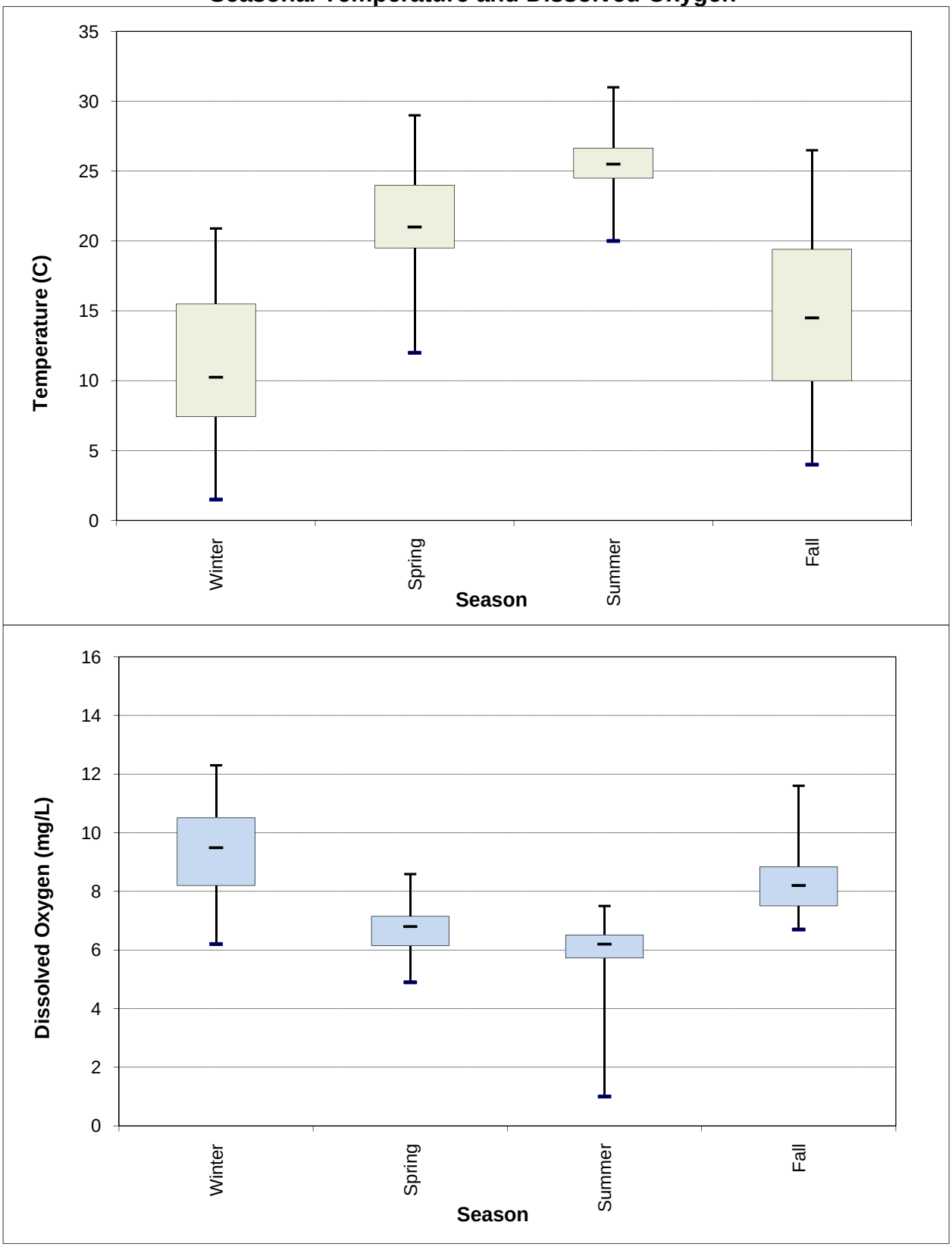
APPENDIX XII-3

SEASONAL WATER QUALITY ASSESSMENT

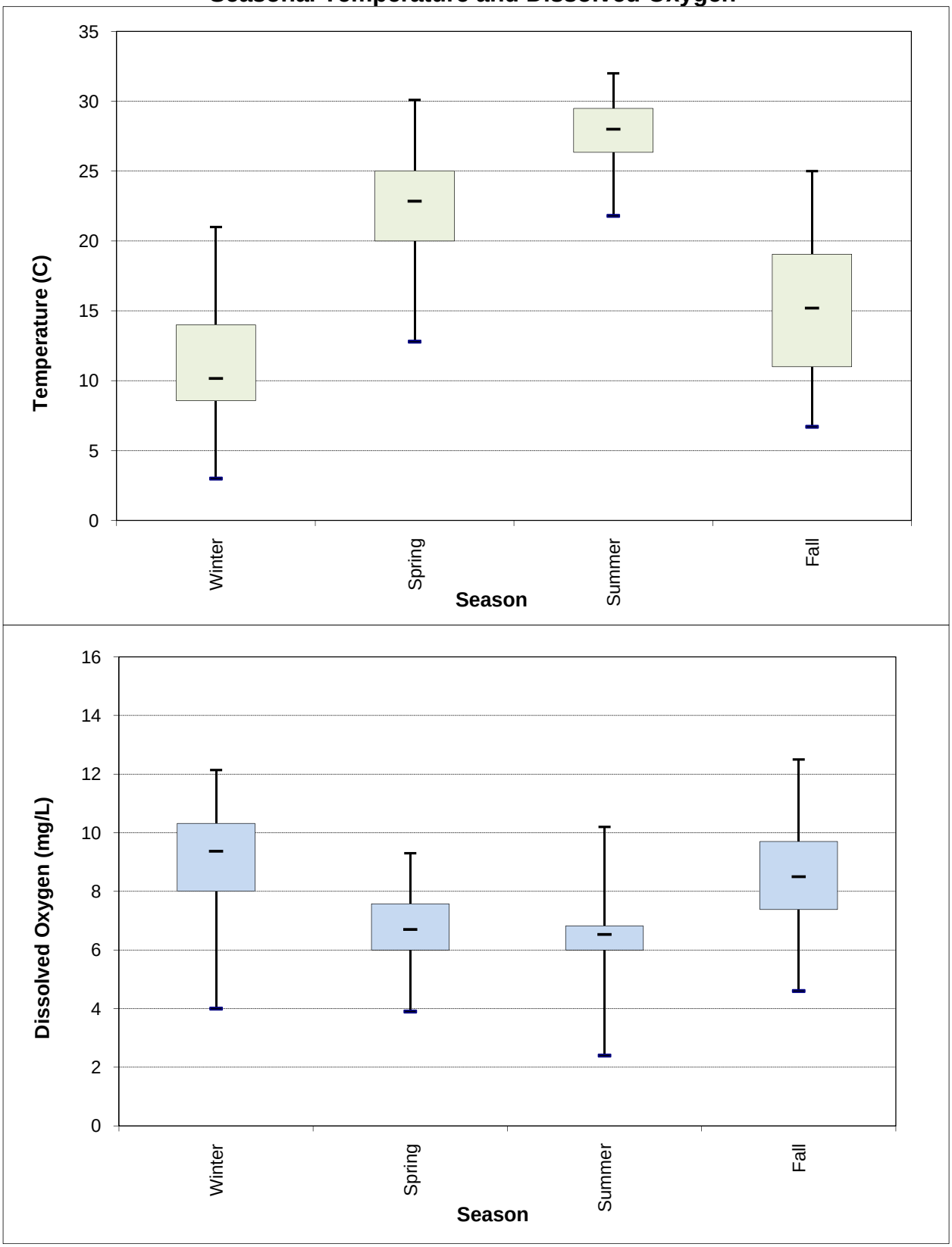
Temperature and dissolved oxygen (DO) data from selected USGS gages were used to assess seasonal trends. Periods of record were not equal for temperature and DO at all gages, but ranged from as early as 1960 to 2009. The graphs included herein display temperature and DO summarized by season in box and whisker plots. Each plot identifies, from top to bottom, the seasonal maximum, 75th percentile, median (50th percentile), 25th percentile, and minimum value recorded during the respective season.

Seasonal temperature and DO generally exhibited inverse relationships. Temperature was lowest in winter and fall and highest in spring and summer, whereas DO was highest during winter and fall and lowest during spring and summer. As discussed in Appendix XII-2, temperature and DO were both within acceptable ranges except for a few outliers at some of the gages.

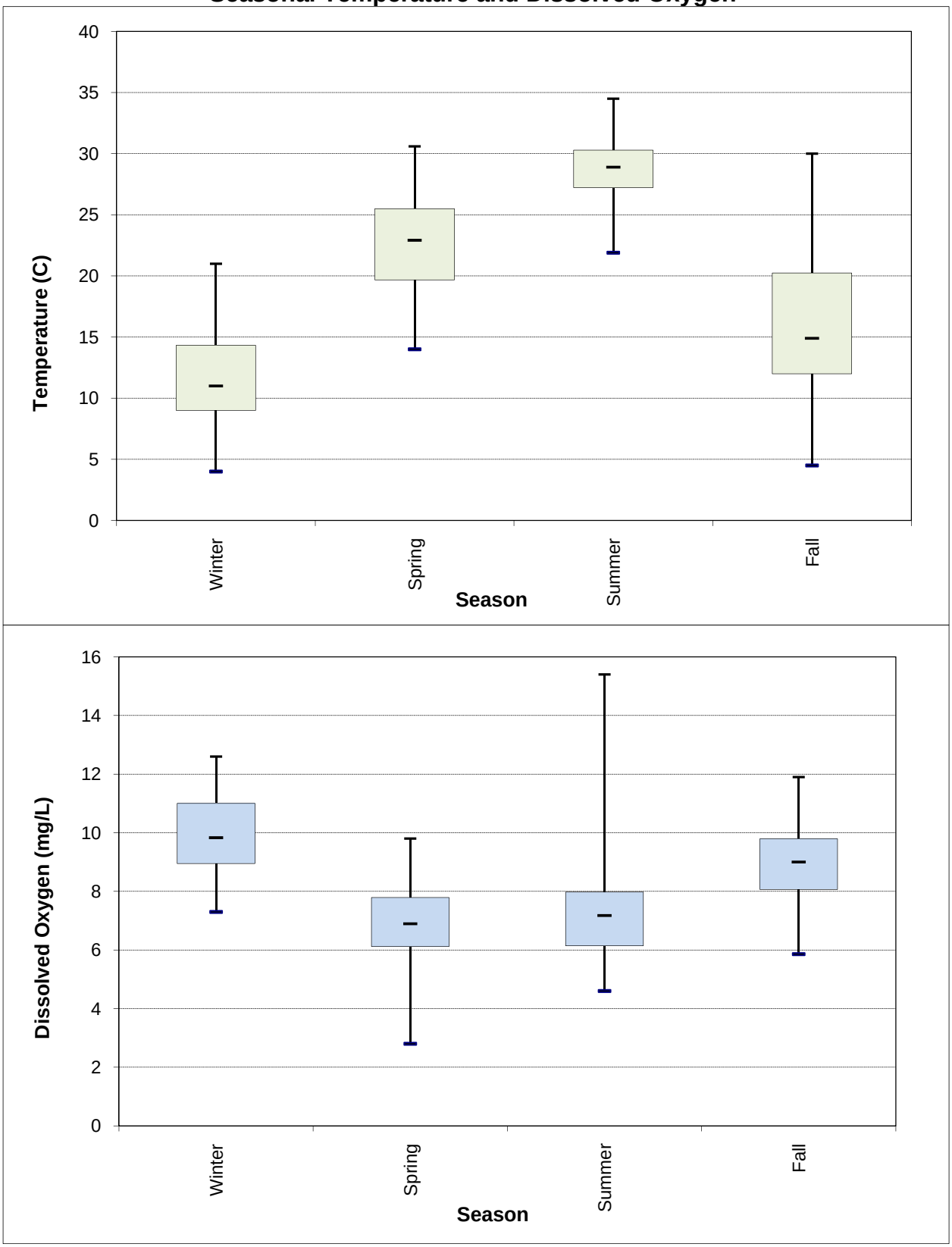
Big Sandy Creek Near Big Sandy
Seasonal Temperature and Dissolved Oxygen



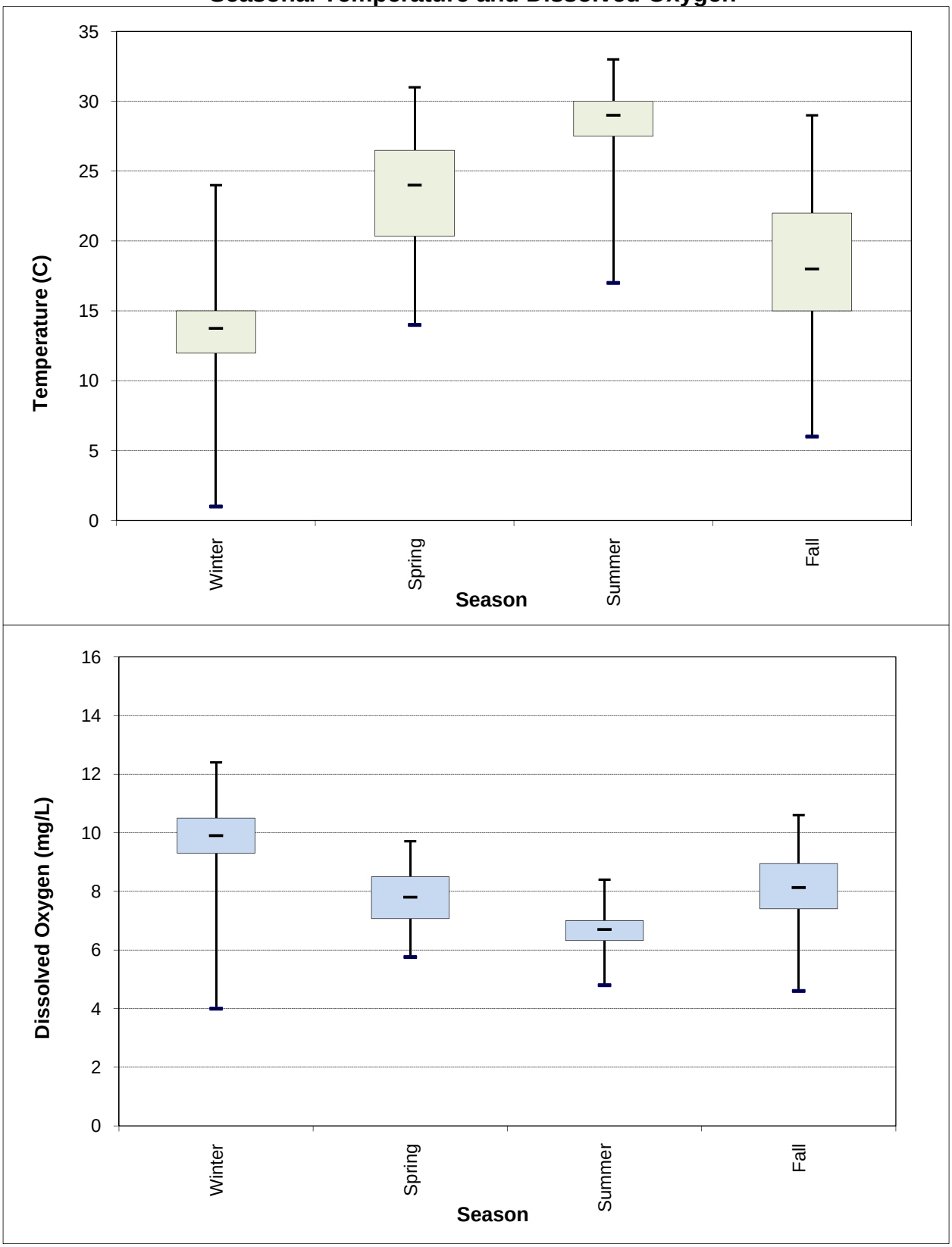
Sabine River Near Gladewater
Seasonal Temperature and Dissolved Oxygen



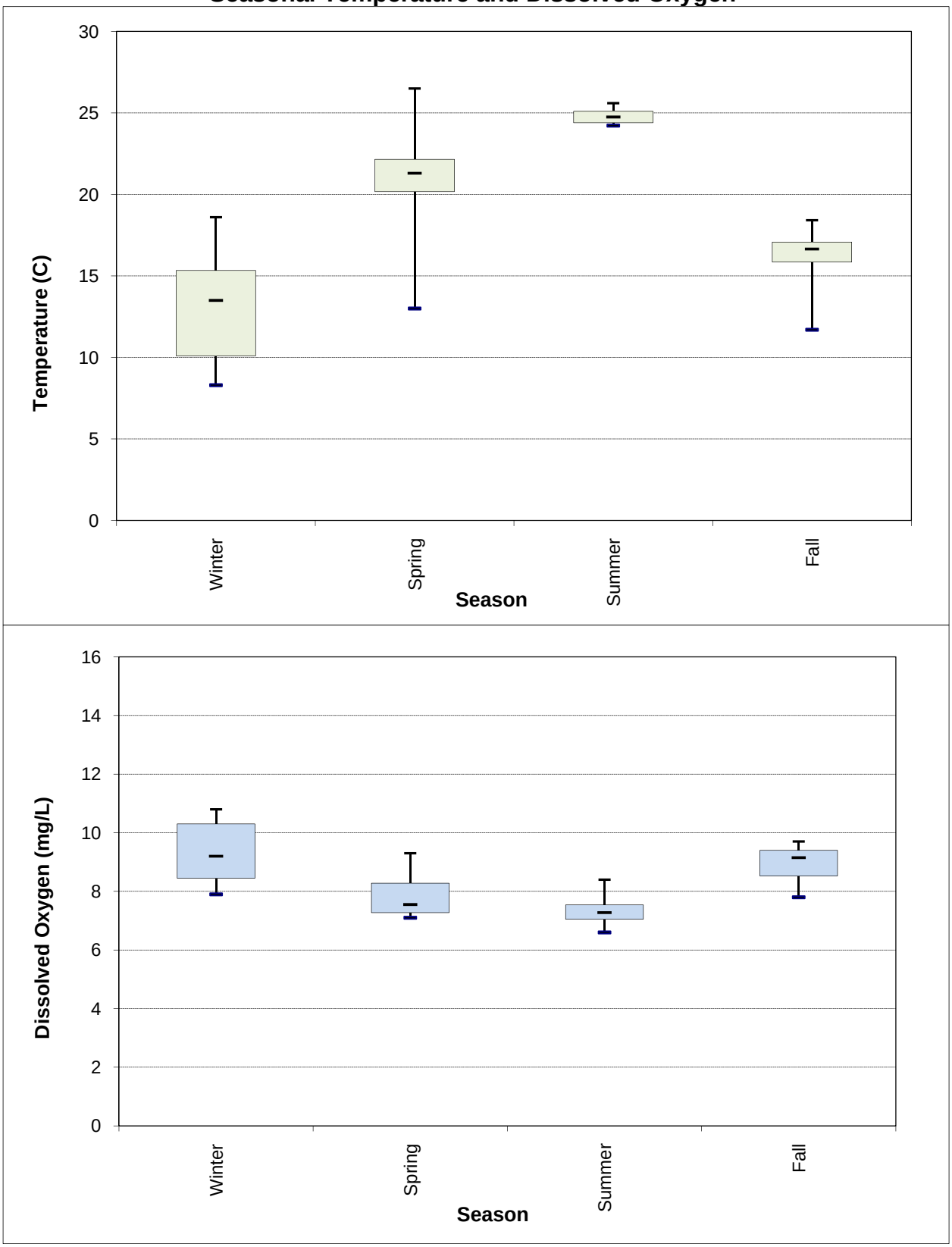
Sabine River Near Beckville
Seasonal Temperature and Dissolved Oxygen



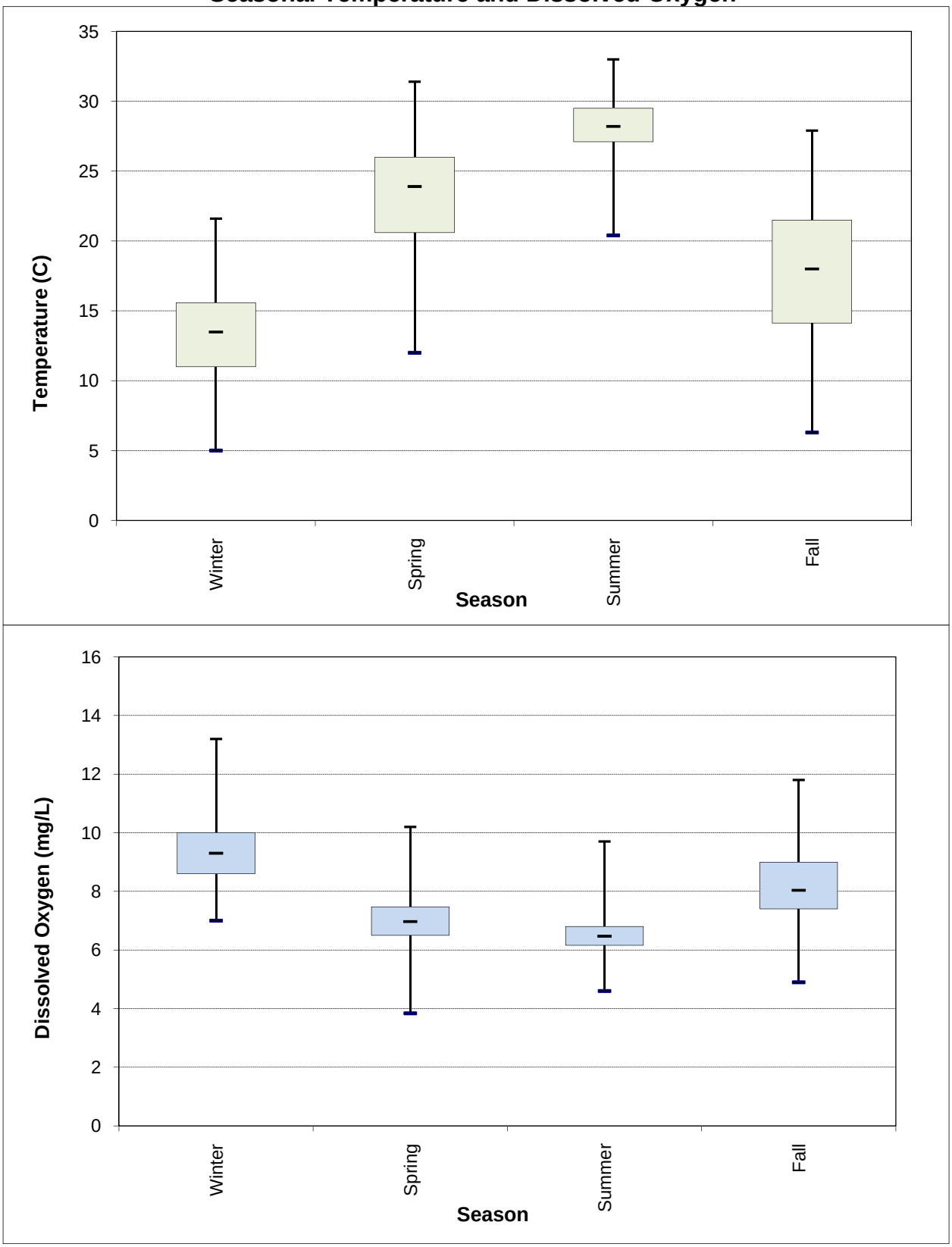
Sabine River Near Bon Wier
Seasonal Temperature and Dissolved Oxygen



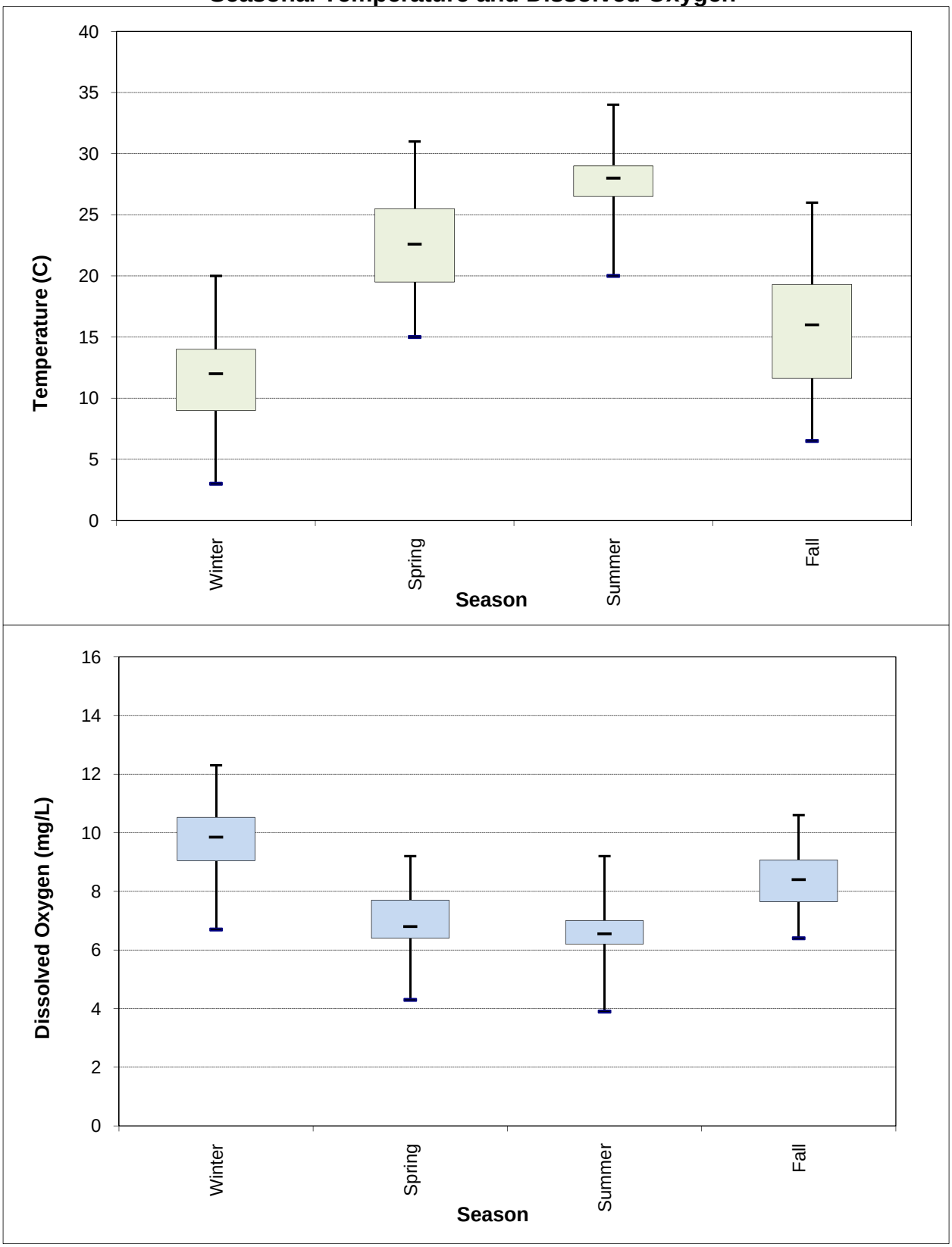
Big Cow Creek Near Newton
Seasonal Temperature and Dissolved Oxygen



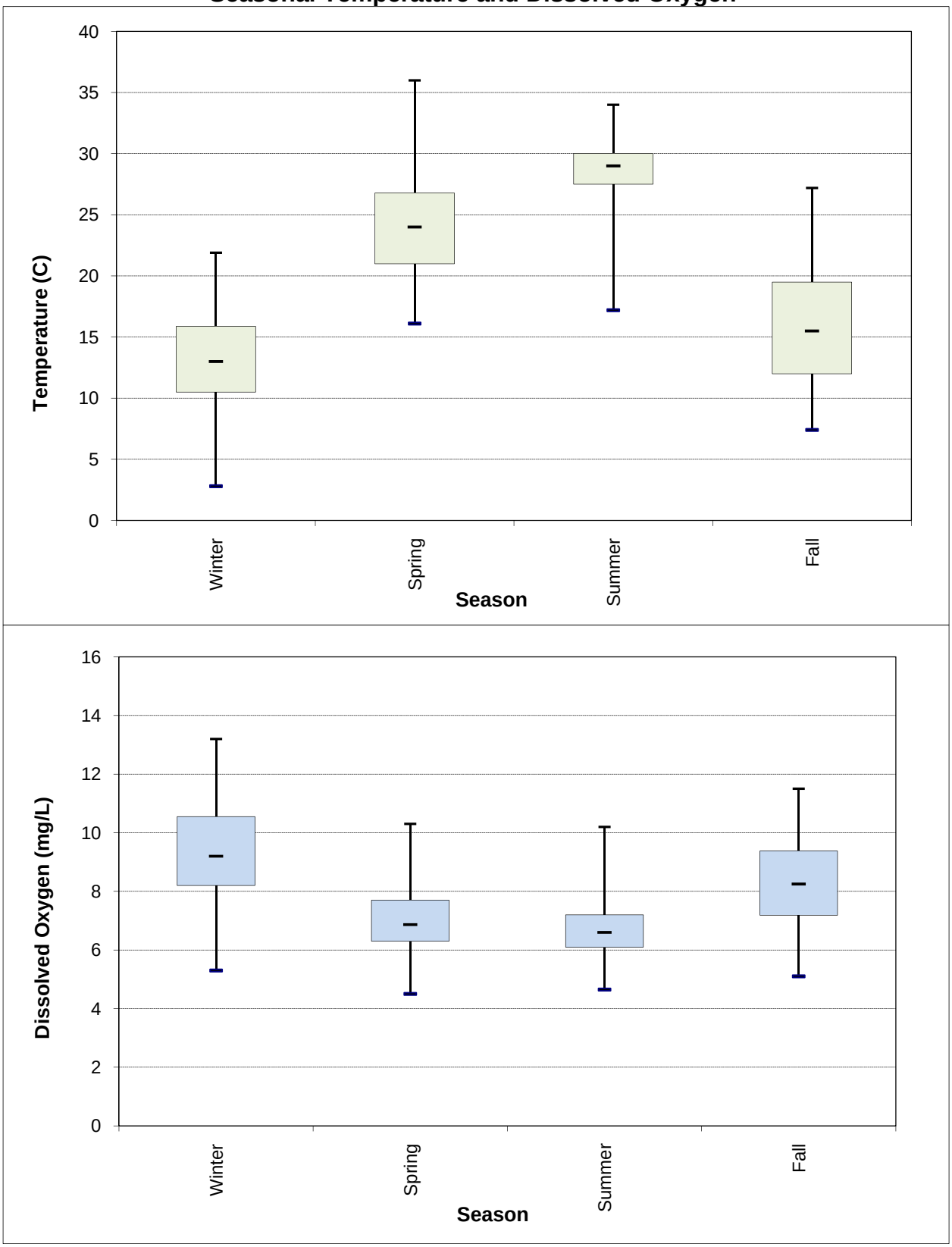
Sabine River Near Ruliff
Seasonal Temperature and Dissolved Oxygen



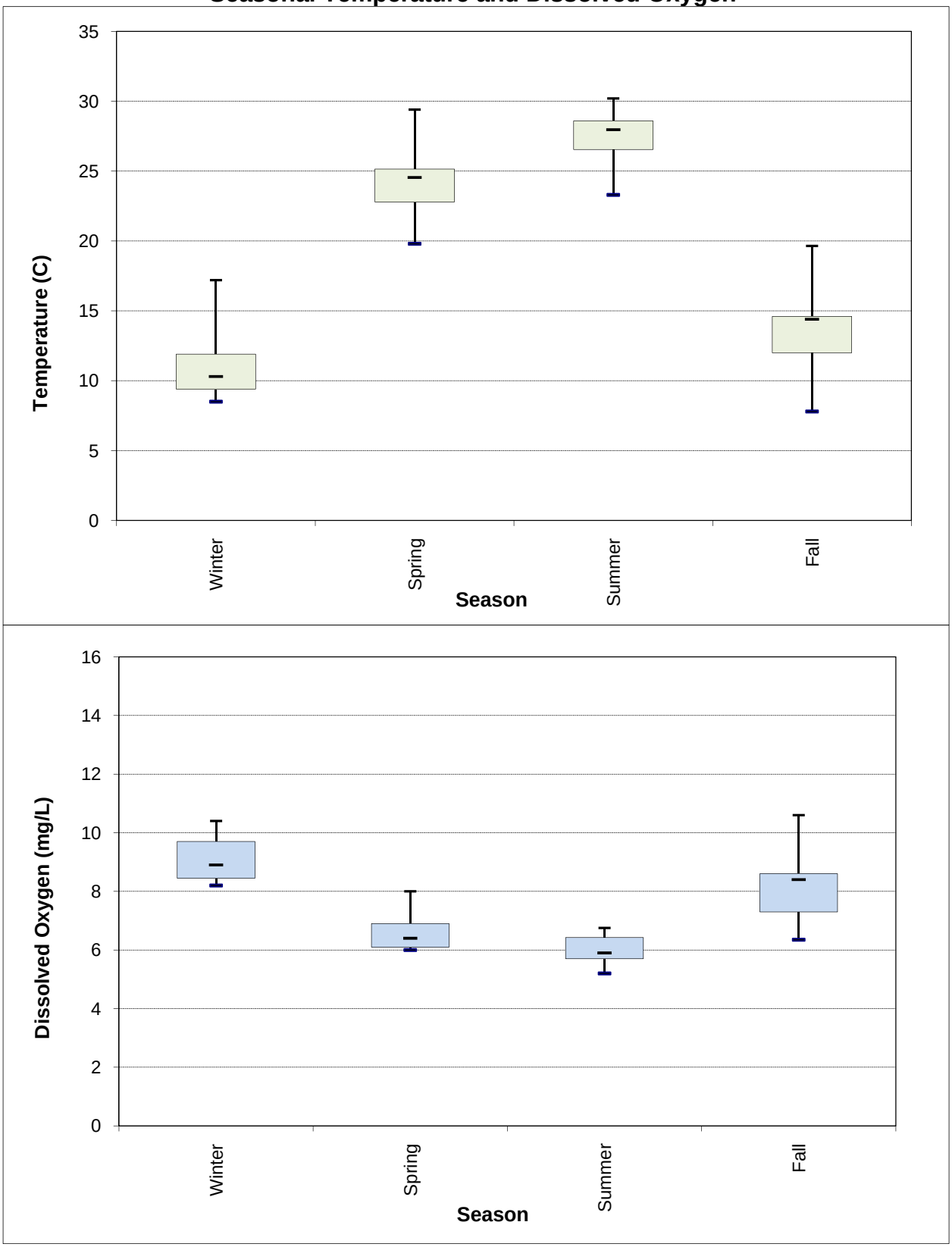
Neches River Near Neches
Seasonal Temperature and Dissolved Oxygen



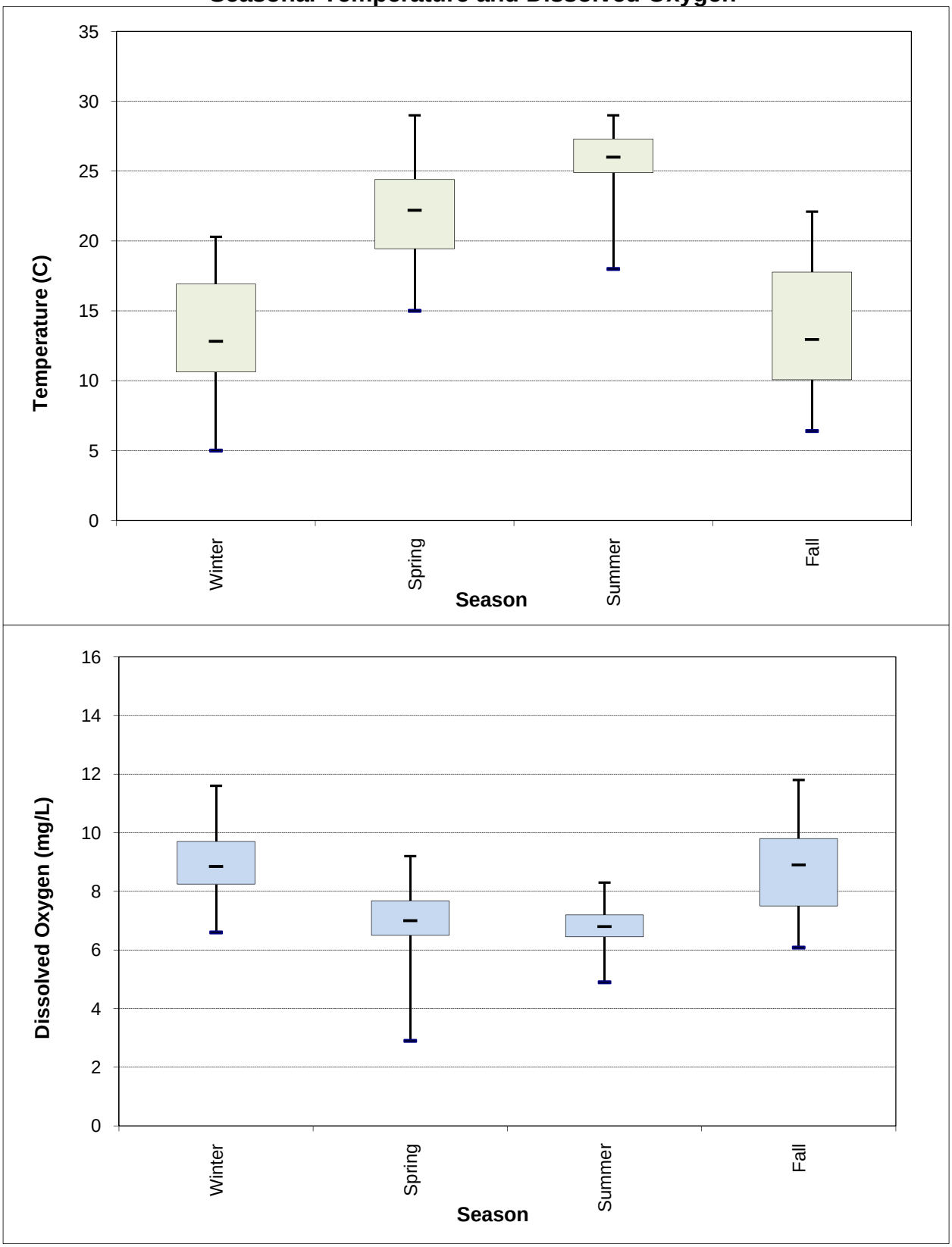
Neches River Near Rockland
Seasonal Temperature and Dissolved Oxygen



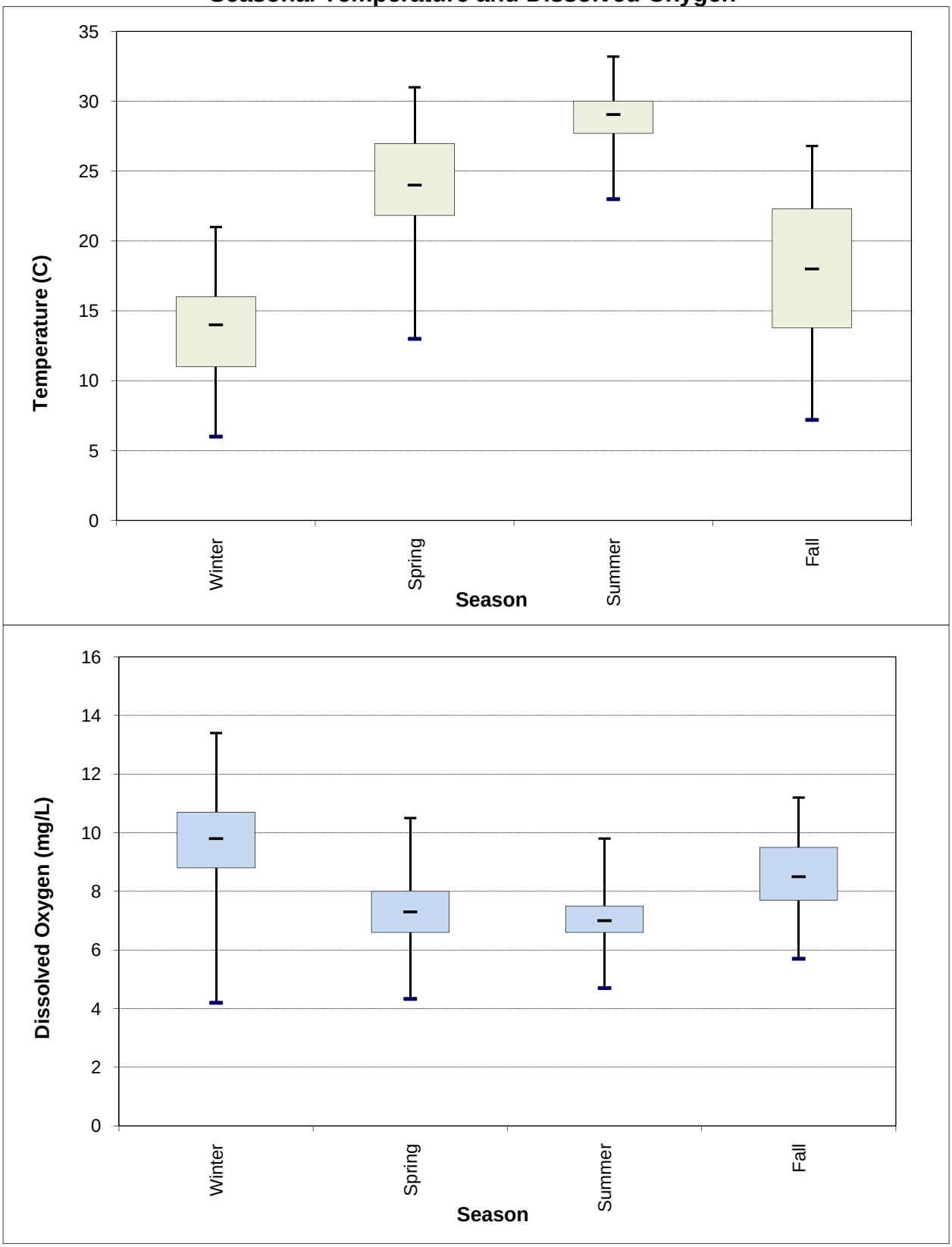
Angelina River Near Alto
Seasonal Temperature and Dissolved Oxygen



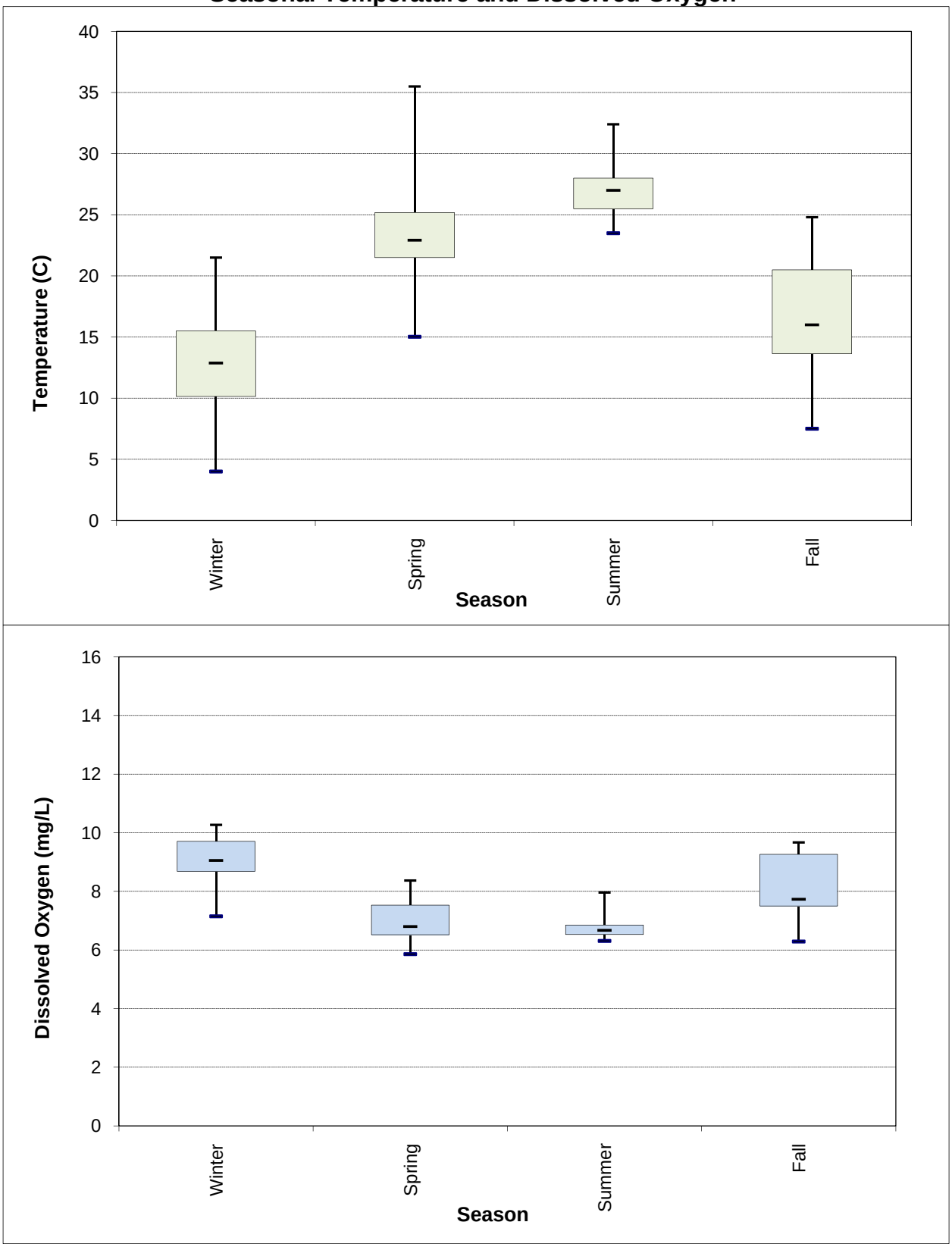
Attoyac Bayou Near Chireno
Seasonal Temperature and Dissolved Oxygen



Neches River at Evadale
Seasonal Temperature and Dissolved Oxygen



Village Creek Near Kountze
Seasonal Temperature and Dissolved Oxygen



Sabine/Neches BBEST Biological Overlay Approach
November 30, 2009

Fluvial Ecosystem Realm –

For determining environmental flow recommendations for the fluvial realm of the Sabine and Neches river basins (tributary streams and mainstem rivers), our BBEST's biological overlays subcommittee adopted the basic approach recommended by the state's Environmental Flows Science Advisory Committee (SAC. Aug. 31, 2009. Essential Steps for Biological Overlays in Developing Senate Bill 3 instream flow recommendations. Report # SAC-2009-05, Appendix I[1]) which involves defining and estimating subsistence flow, base flow, high flow pulses, and overbanking flow pulses. A brief outline of this approach, include excerpts from the SAC guidance document, and descriptions with justifications of the Sabine/Neches BBEST's analyses leading to its recommendations for environmental flows are presented in this document.

SAC Recommended Procedure for Biological Overlays

STEP 1. Establish clear, operational objectives for support of a sound ecological environment and maintenance of the productivity, extent, and persistence of key aquatic habitats in and along the affected water bodies.

The Sabine/Neches BBEST adopted the definition proposed by the SAC:

A sound ecological environment is one that:

- sustains the full complement of native species in perpetuity,
- sustains key habitat features required by these species,
- retains key features of the natural flow regime required by these species to complete their life cycles, and
- sustains key ecosystem processes and services, such as elemental cycling and the productivity of important plant and animal populations.

STEP 2. Compile and evaluate readily available biological information and identify a list of focal species.

Our BBEST extensively reviewed available information for ecosystems and important species in the basins of interest. Early in this process, a list of focal species was identified, and these species were the main focus of the biological overlays. We also relied on ecological studies from other major Texas river systems (i.e., Brazos, Colorado), as well as inferences based on life history information compiled from the literature, and reliance on general habitat suitability criteria developed for species from

[1] Appendix references are to the Sabine-Neches BBEST Recommendations Report (November 2009) Appendices, available at http://www.sratx.org/BBEST/RecommendationsReport/index.html.

multiple regions. BIO-WEST was contracted to provide synopses of our focal species for both fluvial and estuarine systems (BIO-WEST 2009a, 2009b, attached as Appendix X).

STEP 3. Obtain and evaluate geographically-oriented biological data in support of a flow regime analysis.

Following initial reviews and deliberations and in consultation with our hydrological analysis contractor (Freese and Nichols, memo to BBEST, subject: Analysis of BBEST Stream Gages, Sept. 8, 2009, Appendix IX), 12 gages were selected with sufficient historical flow records to provide broad geographic coverage within the two basins. Reports were obtained for studies of historical records of fishes in the Sabine Basin (Bonner and Runyan 2007 Bart 2008) and historical records of freshwater mussel collections in the Sabine and Neches basins were reported by Howells (2002). An analysis of wetland and riparian vegetation communities was performed by the National Wildlife Federation (NWF) and Greater Edwards Aquifer Alliance (GEAA) (Appendix XVII), and our analysis of this information appears below in the section addressing flow pulses.

STEP 4. Parameterize the flow regime hydrological analysis using ecological and biological data.

Due to severe time constraints, little biological information was used to set or modify default parameters for both the hydrographic separation method (MBFIT) and the HEFR analysis.

STEP 5. Evaluate and refine the initial flow matrix.

The flow regime matrix produced by the HEFR hydrological analysis was evaluated to ensure that the ecological needs of the major components of the biological system, their water quality requirements, and geomorphic processes that create and maintain their habitats are maintained. According to the SAC Biological Overlay Guidance document, this final step is perhaps the most critical one in the environmental flow evaluation process. Three multidisciplinary integration workshops were convened to evaluate and refine the flow regime matrix (two held in Beaumont and one in College Station). The SAC recommended use of a flow regime framework consisting of subsistence flows, base flows, high flow pulses, and overbanking flows.

The Sabine-Neches Fluvial Ecosystems – Current Conditions and Responses of Focal Species to Flow Components –

Subsistence Flows –

Subsistence flows represent the minimum flow requirement to maintain populations during periods of severe and prolonged drought. Subsistence flows thus should be viewed as the emergency ration of water required to prevent local extirpation of aquatic

and riparian species (Acreman and Dunbar 2004, Richter et al. 2003, 2006, and references therein). Subsistence flows provide minimal yet sufficient habitat of sufficient quality such that populations can rebound upon reestablishment of base flow conditions. Thus, subsistence flow conditions are infrequent.

The concept of subsistence flow represents the lowest threshold that defines periods when certain flow diversions would be reduced or in some cases halted as conditions degrade in response to drought. Two of the key objectives in identifying subsistence flows are ensuring that water quality is maintained and key habitats are available and accessible by focal species and/or guilds. Data from water quality monitoring programs at the gages selected were compared to flows established through hydrologic analysis (Sabine-Neches BBEST Environmental Flows Recommendation Report and Appendix XII, Water Quality Overlay Appendices). Water quality can become an issue during periods of severe drought, but we obtained little evidence that this is a significant problem in streams and rivers of east Texas (It must be noted that little water quality data exist for flows in the subsistence flow ranges generated from our HEFR hydrological analysis). This may be due to the fact that east Texas is dominated by sandy soils and the streams carry relatively low loads of suspended particulate organic matter, and thus may have relatively low biological oxygen demand. Water quality and flow relationships are discussed in more detail in the water quality overlay section of this report.

During subsistence flow conditions, larger fishes (e.g., channel and blue catfish, smallmouth buffalo, blue sucker, gars, freshwater drum, largemouth and spotted bass) refuge in the deeper and larger pools of the main channel and side channels (anastomoses) of the lower reaches. Some floodplain aquatic habitats may dry up completely, but deeper oxbows may support populations of bass, gars, crappies, sunfishes, and small fishes (e.g., pugnose minnows, blackstripe top minnows). Under subsistence flow conditions in tributary streams, fishes may be forced to occupy isolated pools within reaches of the main channel. During these periods when fishes are concentrated at high per-unit-area densities in reduced volumes of habitat with reduced flow and connectivity, predation is more intense, and populations become reduced. Only a few of the fish species attempt reproduction under these conditions (e.g. Sabine shiner, ironcolor shiner, western mosquitofish), but even for these species with relatively high and continuous reproductive effort, recruitment success is very low in the crowded biotic communities.

Specific habitat area-streamflow relationships and the underlying modeling should be evaluated to construct new recommendations and refinements to hydrologically derived subsistence flows. This kind of analysis was performed for the lower Colorado River in Texas (BIO-WEST 2008a). The goal of the refinement to the subsistence flow recommendation was to reduce risks that any given fish habitat guild (each representative of multiple species) would be without essential habitat during periods of subsistence flow.

Few site-specific studies have been performed in the Sabine and Neches river basins to inform our recommendations for subsistence flows. Werner (1982a, 1982b) performed

an analysis of hydraulic habitat in the lower Sabine River and lower Neches River reaches. For both systems, he employed the Physical Habitat Simulation (PHABSIM) component of the Instream Flow Incremental Methodology (Bovee and Milhous 1978) to estimate habitat available for life stages of focal fish species under a range of discharge levels. Werner relied on literature-based suitability curves rather than developing site-specific indices. By weighting the results to reflect the needs of the most habitat-restricted life stages and species, he derived recommended "maintenance flow" for two segments of each river. Werner's maintenance flows are defined in a manner that blends elements of what are now defined as subsistence flows and base flows. Thus, it is difficult to make a direct comparison of his flow recommendations with those derived by our BBEST from HEFR analysis of hydrological data. Nonetheless, Werner's findings are valuable for comparison with our flow value ranges for subsistence and dry-year base flows, and for examination of estimates of weighted usable habitat area for various species under different flow levels. In addition, Werner provided recommended flows during periods of drought, and these would be equivalent to what we now refer to as subsistence flows. In general, Werner's recommendations for drought/maintenance flows are significantly higher than the values obtained by our HEFR hydrological analysis.

Although no other specific instream flow studies have been completed in our basins, our evaluation of biological/ecological responses to flow variation was greatly aided by data collected over broader spatial and temporal scales (e.g., Evans and Noble 1979, Moriarty and Winemiller 1997, Bonner and Runyan 2007, Bart 2008, and see other studies summarized in BIO-WEST 2009a). No species of fishes, mussels, or wetland/floodplain plants appear to have been extirpated from the basins due to severe reductions in subsistence flows during drought periods. Due to summertime hydropower releases (when energy demand is high), the lower reaches of the mainstem Sabine and Neches rivers has higher flows during exceptionally dry summers compared to what occurred under these conditions historically. Major changes in minnow communities in the lower Sabine River documented by both Bart (2008) and Bonner and Runyan (2007) appear to be due to altered hydrology and a reduction in delivery of fine sediments and reduced turbidity that favored species associated with clear-water conditions (e.g. *Cyprinella venusta*) and simultaneously resulted in reductions of minnows preferring turbid waters and fine bottom sediments (e.g. *Cyprinella lutrensis, Notropis buchanani*). Long-term trends in subsistence flows in the unregulated upper reaches of tributaries are not apparent, and available evidence suggests that no native faunal or floral elements have been extirpated from the basins. In streams such as Village Creek, the fish fauna and riparian vegetation community seem to be in good condition. The Texas Parks and Wildlife Department (TPWD) document, Ecologically Significant River & Stream Segments of Region I (East Texas) Regional Water Planning Area (2005) provides a good overview of the current state of many of these tributaries.

Reduction and possible extirpation of naturally reproducing populations of paddlefish (*Polyodon spathula*) in the two mainstem rivers likely was caused by 1) blockage of migration routes in the mainstem rivers, 2) elimination of shoals used for spawning, and/or 3) disruption of the natural high flow pulse regime by dams (Pitman 1991). Elimination of appropriate late-winter to early spring high flow pulses interferes with

spawning cues, access and/or availability of spawning habitats (shoals located in upper reaches of the mainstems), transport of fertilized and eggs and larvae, and connectivity of the river channel with productive backwater habitats used for zooplankton feeding by juveniles and adults. For lack of specific studies to address the subsistence flow component, our ecological analysis began with the HEFR subsistence estimates from each gage. These were compared with recorded minimum flows, percentiles of seasonal flows, the 5th percentile of all flows, the current flow standard used by state and federal agencies for water quality risk assessment under severe low-flow conditions (7Q2, 7Q10), as well as Werner's (1982a, 1982b) findings and recommendations. These steps leading to our BBEST consensus recommendations appear below.

Base Flows –

Ecological roles of base flows include providing suitable habitat, maintaining habitat diversity, and supporting the survival, growth, and reproduction of aquatic organisms. Base flows are also important for riparian areas (Reference Table 1 in the SAC Biological Overlays Guidance document). Information on focal species (i.e., species that indicate the needs for a group of species with similar ecological requirements) can be used to confirm and refine base flow estimates. Flow-ecology relationships discovered in literature reviews were used to guide our interpretations of likely species responses to flow variation in the east Texas basins. Qualitative life history information and conceptual models of focal species' life cycles were used (see Section 2, Development of Information for Biological Overlay, of SAC 2005-05, Appendix I, and BIO-WEST 2009a, Appendix IX). For example, data on fish spawning seasons was used to evaluate the timing of higher base flows and other flow components. Information on basic habitat use for different life stages of a species indicates the pattern and range of flows needed across seasons. Our suite of focal species was evaluated in this and other ways to establish patterns for evaluating hydrologically derived base-flow estimates during different seasons and across dry, average, and wet years.

Habitat-flow assessments produce a measure of habitat such as weighted usable area or diversity as a function of stream flow and may be useful in evaluating hydrology-derived base flows. Such tools can be used to compare habitat time series using different HEFR settings, hydrologic records, and algorithms. The only site-specific studies from the Neches and Sabine basins available to our BBEST were those of Werner (1982a, 1982b), and these are discussed below in the context of base and subsistence flow recommendations. Extensive and detailed habitat-hydrology research and modeling was performed recently for the lower Colorado River in Texas (BIO-WEST 2008a), and many of the fish species in that system are shared by the lower Neches and Sabine rivers. According the SAC, information from instream flow assessments on nearby systems or similar river types can be evaluated to ascertain if similar habitat-flow relationships would be expected.

The studies by Werner (1982) are the only known site-specific, quantitative studies from the two basins that directly address base flows, but again, his focus on maintenance flows blended together the modern concept of subsistence and base flow components. To guide

inferences about required base flows during dry, average, and wet years, we examined the findings from the extensive research conducted by BIO-WEST (2008a, 2008b). We know that some degree of inter-annual variation in base flows is natural, and very necessary to maintain a balance of aquatic species belonging to different habitat guilds. This is because some fish guilds will have more habitat available to them during dry-year conditions and others will have less (Figure 1). The relative availability of habitat types generally undergoes a shift with a transition to average and wet year conditions (BIO-WEST 2008a, 2009a). This shifting in the amount of instream habitat during years with different amounts of rainfall is important for maintaining secure populations of all the species characteristic of the region's rivers and streams. In other words, if base flows were to be held at the dry-year level on a chronic basis, significant reductions in populations of species belonging to certain guilds would be expected, and with time, these species would be generally replaced by species associated with the predominant habitat categories under this human imposed dry-year regime.

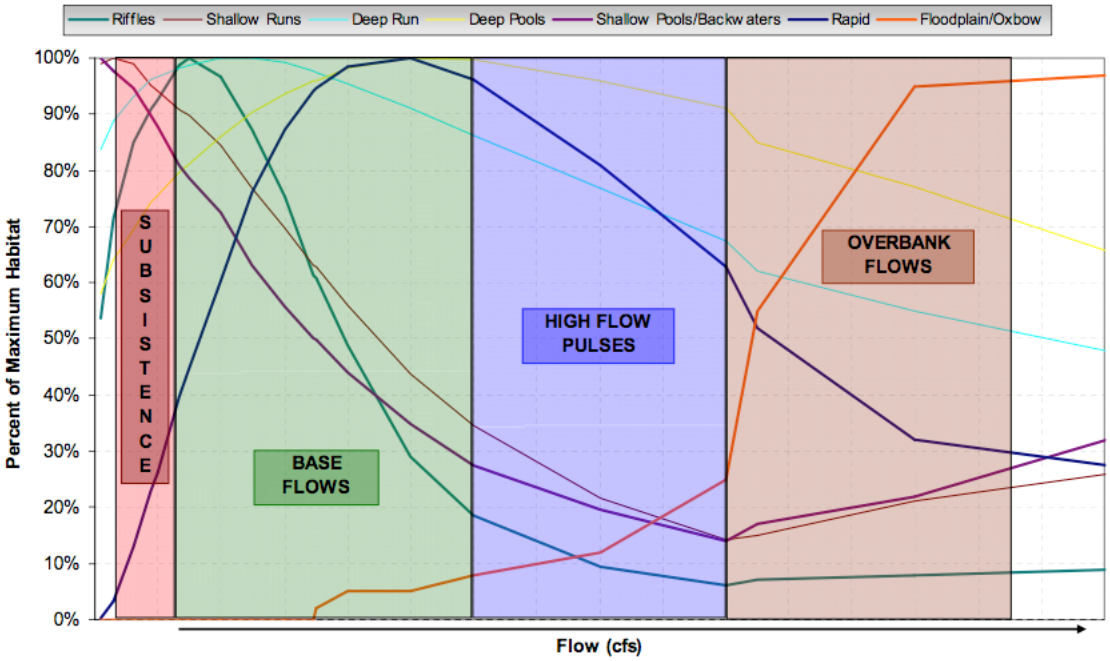


Figure 1. Habitat availability curves for seven fish habitat guilds in the lower Colorado River, Texas derived from recent instream flows research by BIO-WEST (2008a).

Studies modeling hydraulic habitat in other rivers, including the lower Colorado River in Texas, have estimated the shifting availability of habitats for fish guilds under different annual conditions (BIO-WEST 2008a, Figure 1). For example, riffle habitat was maximized at relatively low base flows while deep run habitat was maximized at relatively high base flows. These studies provide a strong conceptual framework for inferring the requirement for inter-annual variation in base flow levels for the Sabine and Neches rivers since many fish species including our focal species are shared by the Colorado, Neches, and Sabine rivers.

Periods of prolonged and stable base flow, especially during the summer-fall, can be beneficial for many species in terms of feeding interactions. Predatory fishes can exploit prey populations that are at higher per-unit-area densities during periods of low flow. For sight-oriented predators, water generally is more transparent during these periods when prey populations are more concentrated. Mussels can filter feed on higher densities of water-column food resources (phytoplankton and derived fine particulate organic detritus) during periods of extended base flow (Rypel et al. 2009). Also, sediments become more stable, which is beneficial for many mussel species (Vaughn and Taylor 1999, Strayer 2008). Certain minnow species spawn and may have better recruitment during prolonged periods of stable base flow during summer (e.g., ironcolor shiner). Base flow conditions also are important for survival of riparian plants that obtain groundwater from the hyporheic zone during periods of low rainfall (Rypel et al. 2009).

High Flow Pulses –

High flow pulses shape physical habitat of the river channel, contribute to sediment transport and flushing of silt and fine particulate matter and provide other geomorphic and water quality functions. Biological roles include providing spawning cues and habitat for some species of fish and facilitating connectivity to oxbows and other wetlands. The timing of high flow pulses may be critical for triggering spawning migrations or actual spawning events. The magnitude and duration of high flow pulses can also be double checked with known life history requirements. An example, well documented in Mosier and Ray (1992) and BIO-WEST (2008a), involves blue sucker *Cycleptus elongatus* spawning on the Colorado River, Texas. Information from these studies was used in assessments on the lower Colorado River but also can be used to inform flow requirements in other river systems, such as the lower Neches and Sabine rivers, where blue sucker currently exist (recently confirmed in the Sabine, and likely are present in the Neches).

The role of high flow pulses for supporting aquatic and riparian/floodplain plants and animals has been discussed extensively by river scientists (Junk et al. 1989, Poff et al. 1997, Winemiller et al. 2000, Lytle and Poff 2004, Richter et al. 1997, 2003, 2006, Zeug et al. 2005, 2009, Zeug and Winemiller 2007, 2008), and this evidence was summarized in the SAC Biological Overlays Guidance Document (SAC 2009-05, Appendix I). High flow pulses provide environmental cues that elicit reproductive behavior (migration, spawning), produce lateral connectivity allowing movement of organisms between the main channel and off-channel aquatic habitats (floodplain lakes, oxbows, sloughs, ephemeral ponds), and foraging opportunities in newly flooded riparian habitats (e.g., Kwak 1988).

The evaluation of the benefits to the biota of high pulses must focus on two components: time (or more accurately—the timing and duration of the pulse in relation to the requirements for spawning cues, feeding opportunities of juveniles, etc.) and space (or more accurately—how the rise in water level interacts with local landscape topography/geomorphology to produce connections with and enhancement of marginal

and off-channel aquatic habitats. In evaluating the spatial aspects of high flow pulses, various kinds of maps are extremely useful (topographic, digital elevation, wetlands, vegetation categories, etc.) We relied on NWS estimates of overbank flooding and a specific analysis by the National Wildlife Federation and the Greater Edwards Aquifer Alliance.

Responses of aquatic focal species to high flow pulses –

Tributaries: Although lateral connectivity to off-channel floodplain habitats is relatively less important in smaller headwaters and tributaries (e.g. Angelina River, Village Creek) than larger mainstem reaches located downstream, it is still critical, from an ecological standpoint, to have periodic high flow pulses to permit organisms to occupy marginal habitats for feeding and/or reproduction (connected backwaters, sloughs, etc.).

Spotted bass feed opportunistically in flooded marginal and off-channel habitats—juveniles in particular. Like other sunfishes (family Centrarchidae), this species is a substrate nester and requires relatively stable flows during spring (stable high or low flows) during the 1-3 weeks the male guards the nest (nesting period—Feb-May).
For the sabine shiner and ironcolor shiner, most reproduction takes place during spring when high pulses likely stimulate spawning; all size classes likely exploit terrestrial-derived food resources in flooded marginal areas during any time of the year, but late spring to fall probably is the most significant period in this respect.

The flathead catfish (juveniles), dusky darter, harlequine darter, and freckled madtom probably do not respond to high pulses by entering marginal or off-channel habitats, however they feed on drifting invertebrates, and during flow pulses they probably receive increased food resources in the form of dislodged aquatic macroinvertebrates and terrestrial insects.

During early spring (late Feb-early March), white bass migrate upstream in schools and enter tributary streams where they spawn in flowing waters in small groups. The largest populations reside in reservoirs during other times of the year, a few individuals also inhabit larger pools of lower river mainstems during the non-reproductive period. Higher flows stimulate larger migrations that penetrate further upstream. High pulse flows also enhance passive transport of the eggs and larvae of these broadcast spawners, maintain dissolved oxygen levels during development, and probably allow juveniles to move into and out of marginal lentic habitats where they feed on abundance food resources. Winemiller et al. (2000) captured juvenile white bass from oxbow lakes in the floodplain of the Brazos River.

Mainstem river/floodplains: A great deal of ecological literature demonstrates that paddlefish, alligator gar, flathead catfish, blue sucker, and other species characteristic of large mainstem rivers have major requirements for high flow pulses. Spawning is episodic during early spring, and eggs are scattered and drift some distance to settle into habitats where they larvae develop and then feed on zooplankton. In the case of alligator gars, spawning takes place over submerged vegetation of perhaps sticks. In the case of

paddlefish and suckers, spawning takes place in the main channel and eggs drift into pools. In all three species, the larval and early juvenile stages probably require lentic backwaters for feeding and survival. High flow pulses provide more of this habitat. It is unknown to what extent juveniles move into off-channel habitats, but likely this is very important for young paddlefish and alligator gar. Flood pulses also are needed during other times of the year to connect off-channel habitats with the channel so that adult paddlefish and alligator gar can move in and out for feeding (Robertson et al. 2008). Oxbows and sloughs have much greater aquatic primary and secondary productivity than main-channel habitats (Winemller et al. 2000).

As described above for white bass, high flow pulses cue and enhance spawning migrations during early spring. As described above for spotted bass, some degree of stability in flow pulses is beneficial for substrate nesting/guarding centrarchids. High flow pulses during spring are most beneficial for spotted bass and other sunfishes when they have a duration of 3 weeks, because this provides these fishes sufficient time to construct a nest, spawn, and guard the eggs and lavae until they are large enough to swim effectively.

Based on research on the Brazos River that focused on flows and connections between the river channel and oxbow lakes (Zeug and Winemiller 2005), it is clear that white crappie prosper greatly within the lentic and highly productive environment of oxbows. It should be noted that several other common species have the similar requirements (e.g shads), but crappies are a highly suitable indicator species for this particular function.

The shoal chub, ghost shiner and emerald shiner are minnows characteristic of large mainstem rivers. Shoal chubs and ghost shiners require broad sandbanks for foraging; the availability of submerged bank habitats increases during high flows, and high flows transport eggs/larvae of these broadcast spawners. Responses to flow pulses by populations of the dusky darter, harlequine darter, and freckled madtom (also juvenile flathead catfish) within the mainstems of the lower river reaches would likely be similar to those described above for tributary and headwater stream populations.

Sabine/Neches Fish Species with Spawning Synchronized to Flow Pulses During Late Winter–Spring (Feb–June)

Within-channel, water-column spawners (N= 26)

S/N BBEST FOCAL SPECIES: Paddlefish, blue sucker, white bass, shoal chub, emerald shiner, sabine shiner

OTHER Sabine/Neches SPECIES: gizzard shad, threadfin shad, cypress minnow, Mississippi silvery minnow, pallid shiner, ribbon shiner, redfin shiner, silver chub, golden shiner, blackspot shiner, ghost shiner, silverband shiner, weed shiner, mimic shiner, river carpsucker, smallmouth buffalo, spotted sucker, blacktail redhorse, yellow bass, freshwater drum

Spawning in submerged river margins* (eggs scattered on vegetation, rocks or other submerged structure, or nest constructed) (N=18)

S/N BBEST FOCAL SPECIES: Alligator gar, black crappie, white crappie, spotted bass, harlequin darter

OTHER Sabine/Neches SPECIES: Longnose gar, spotted gar, red shiner, blacktail shiner, fathead minnow, bullhead minnow, creek chub, creek chubsucker, lake chubsucker, yellow bullhead, blue catfish, channel catfish, redfin pickerel

This list only includes fish species that are strongly responsive to high flow pulses, usually moving into newly submerged littoral habitats or littoral habitats that become deeper with more suitable hydraulics (e.g., slow back eddies) to spawn or nest. This list does not include other species that spawn or nest in littoral habitats even without springtime cues provided by high flow pulses (e.g., the various sunfish species, darters, and topminnows).

Overbanking Flows –

As discussed in the SAC Biological Overlays Guidance Document, overbanking flows are important for moving coarse woody debris and sediments, scouring deep pools and depositing sediments to form sandbanks, and allowing aquatic organisms to colonize ephemeral aquatic floodplain habitats. The inundation of floodplains allows seeds of bottomland hardwood tree species to disperse or germinate following flood subsidence. Our terrestrial focal species having aspects of their life cycle dependent on periodic high flood pulses are the overcup oak and water tupelo. These bottomland hardwood tree species require periodic flooding for successful germination, seedling recruitment, and elimination of upland plant species that are competitively superior on well-drained soils (Sharitz and Mitsch 1993). When viewed over longer time scales, overbanking flows are critical for the sediment dynamics and geomorphic changes of the landscape needed to maintain riparian forest diversity (Shankman 1993, Meitzen 2009).

In addition to supporting major geomorphic processes (SAC-2009-05, Appendix I), overbank flows provide lateral connectivity for aquatic organisms to floodplain areas and maintain the balance and diversity of riparian zones. Assessments of lateral connectivity include reviewing available life history information of aquatic and riparian species, constructing conceptual models depicting flow-ecology relationships and needs, and evaluating the performance of overbank flow estimates in meeting those needs. Studies of fish assemblages using floodplain habitat such as oxbow lakes for different life stages are available for some Texas rivers (e.g., Winemiller et al. 2004, and see discussion below). Information on the hydraulic conditions needed to spill onto the floodplain can be derived from field based or desktop hydraulic assessments or by using flood stages identified by the National Weather Service, for example. Desktop approaches using digital elevation models have been used to relatively quickly develop relationships between magnitude and inundated floodplain area. Hydraulic information coupled with life history information for riparian species and their inundation characteristics (timing, duration, frequency, etc.) can be used to check and refine hydrology-derived characteristics of overbank flows.

Overbanking flows are a natural but relatively infrequent occurrence in east Texas. Unusual weather patterns, such as extended periods of high precipitation or hurricanes and tropical storms, can produce floods of variable magnitude and duration with greater frequency. Most "overbanking flows" do not result in extensive inundation of floodplain terrains, but instead water moves into bottomland wetlands, first in the lowest areas, such as oxbows and sloughs, and moving into wetlands with slightly higher elevations as flows inch upward. This pattern of variable flooding with variable flows is a natural consequence of landscape heterogeneity in floodplains.

Among alligator gars and other gar species (longnose and spotted gars), both adults but especially juveniles commonly move onto flooded plains to feed opportunistically on insects, amphibians, and other fish species that also exploit temporarily abundant food resources (Robertson et al. 2008). Many small fishes also use temporarily flooded riparian habitats to feed in terrestrial and soil invertebrates (Kwack 1988). In some cases, fishes may become stranded and perish when floodwater recede. However, it is assumed that most of the fish species that exploit flooded habitats find their way back to the main channel or permanent water bodies in the floodplain, and thus there is a net gain in fish biomass in response to the flood pulse.

The overbanking flow components of a flow matrix (as derived from our HEFR analysis) thus have important functions for the ecological system, and for some species this component is critical for completion of the life cycle (i.e., bottomland hardwood tree species) and/or support of significant population abundance (e.g., white and black crappies, gizzard shad). It is essential to recognize that overbanking flows are a part of the natural flow regime that maintains the native biodiversity of the two basins.

BBEST Subsistence Flow Recommendations –

As explained in the *Hydrological Analysis Section* of this report, HEFR outputs were used to estimate subsistence flows based historical streamflow data and manipulation of the MBFIT option. For our ecological analysis, the HEFR subsistence estimates for each season from each gage were compared with: 1) the recorded minimum flows, 2) percentiles of seasonal flows, 3) the 5th percentile of all flows, 4) 7Q2 and 7Q10 values which are a standard used by the state and federal agencies for water quality risk assessment under severe low-flow conditions (Tables 4 and 5, Freese and Nichols, HEFR analysis memo, Sept. 17, 2009), and Werner's (1982a, 1982b) drought flow recommendations based on PHABSIM/IFIM analysis (the latter only available for the lower Neches and Sabine segments).

Initially, the BBEST considered use of the lowest seasonal subsistence flow from MBFIT/HEFR analysis for the subsistence flow recommendation. The reasoning here was that if no fish populations are known to have been lost from the rivers and streams over the past 50 years of hydrological records and biological surveys, then this is evidence that the local biodiversity (populations of plants and animals) are able to recover and persist when faced with these severe reductions in flow. Next, the BBEST discussed problems with this reasoning. First, it is important to consider the frequency of occurrence and duration of these low flow events. By definition, subsistence flows are intended to be severe but infrequent events of low flow. The risk of setting subsistence flows too low is that aquatic and riparian populations of plants and animals might experience stressful environmental conditions, included crowding that leads to increased predation mortality, for unusually long periods with excessive frequency. In most cases, adoption of the lowest seasonal subsistence flow from HEFR (usually summer) for the entire year resulted in seasonal flows well below levels ever recorded for the segment. This was especially true for winter, the season when flows tend to be higher naturally. Second, adoption of the lowest seasonal subsistence flow level for all seasons resulted in many seasonal values that were significantly below 7Q2, 7Q10, and values recommended by Werner for the two lower river segments. Third, it seemed possible that although responses of water quality factors during Winter may not appear to be as potentially impactful as during Summer and early Fall, unforseen ecological factors (e.g., those related to metabolism of ecothermic organisms at low winter temperatures) may result in negative influences on aquatic and riparian systems if Winter flows were permitted to fall to levels never before observed in the ecosystems.

Some members of the biological overlay subcommittee supported use of the 5th percentile as the subsistence flow criterion, because there appears to be growing support for its adoption within the environmental flows literature, especially in the absence of site-specific findings from research on habitat availability, habitat connectivity, and water quality. Through a consensus workshop approach, Acreman et al. (2006) established the Q_{95} (5th percentile) as the hands-off (emergency low flow) criterion for regulatory standards to ensure ecological protection for rivers and lakes in the United Kingdom. Acreman et al. (2006) concluded that the "Q_{95} marks a significant point where below which conditions in the river change rapidly and hence the river is more sensitive to flow change." Citing this and other work, Hardy et al. (2006) used the monthly Q_{95} in the Klamath River in California as the ecological base flow (= subsistence flow)

recommendation. In Texas, BIO-WEST (2008a) used the 5th percentile flow as a starting point for evaluating subsistence flow recommendations in the lower Colorado River. BIO-WEST evaluated this flow level and found only a few instances where individual habitat categories went to 0 or below 5% of the available habitat in a given reach (BIO-WEST 2008a). Although extreme, these conditions when considered with monthly variation were deemed appropriate for an initial subsistence flow recommendation. Subsistence levels for the lower Colorado River were then modified (in some cases up and in some down) based on specific results from water quality modeling and reach-specific species requirements (BIO-WEST 2008a). Preliminary subsistence flow guidelines for the lower San Antonio River identified by BIO-WEST (2008b) were also compared to 5th percentile flows. Although field investigations were performed, the preliminary subsistence flow values proposed were conservatively higher than the historical 5th percentile (through 1971).

Next, our BBEST re-examined the issue of setting a single subsistence threshold versus separate seasonal thresholds. There is extensive support within the instream flow literature for adoption of monthly or seasonal subsistence flow recommendations. As a result, our BBEST ultimately decided to make subsistence flow recommendations on a seasonal basis. This also allowed our BBEST to avoid making untenable recommendations for flows intended for environmental protection during the most stressful periods that would be less than levels ever recorded for a gage/segment. The major hydrological evidence considered and our BBEST's final biological overlay adjustments for subsistence flows are described below for each stream/river segment.

As a result of deliberations by the BBEST biological overlays subcommittee (Oct. 15-25, 2009) and by the full membership of the BBEST (Oct. 27-28, 2009), a series of adjustments were made to the subsistence flow estimates from the MBFIT/HEFR hydrological analysis. ***Our BBEST recommends adoption of the seasonal subsistence flows from MBFIT/HEFR, unless 1) the seasonal value is less than the summer value in which case the summer value is adopted by default, and 2) MBFIT/HEFR failed to calculate a value (this occurred usually for winter) in which case the lowest recorded flow value for that season at that gage was adopted by default.***

Big Sandy Creek near Big Sandy –

- The minimum value for subsistence flow derived from HEFR/MBFIT was 8 cfs, which corresponded with the Summer period.
- For all flows, 8 cfs represents the 1.9 percentile – an extremely low value.
- Flows during Summer months were greater than 7 cfs 95% of the days.
- Flows during Fall months were greater than 7 cfs 99% of the days.
- Flows during Winter months were greater than 20 cfs 99% of the days.
- Flows during Spring months were greater than 11 cfs 99% of the days
- 12 cfs is the 5th percentile for all flows; 12.4 cfs is the 7Q2

Biological Recommendation: For Big Sandy Creek***, subsistence flows of 9 cfs during Spring and 8 cfs during Summer and Fall*** are recommended for maintenance of minimal habitat and environmental conditions for aquatic life during infrequent periods of severe and prolonged drought. ***For the Winter season, 20 cfs*** should be considered the subsistence benchmark, because the ecosystem has never experienced flows less than this during Winter.

Sabine River near Gladewater –

- The minimum value for subsistence flow derived from HEFR/MBFIT was 14 cfs, which corresponded with the Summer period.
- Recorded flows during the Winter and Spring months have never been as low as 14 cfs; the lowest flow ever recorded during the Winter was 45 cfs and for Spring 22 cfs.
- Summer flows have been greater than 14 cfs 96% of the days.
- Fall flows have been greater than 14 cfs 99 % of the days.
- For all flows, 14 cfs represents the 1.0 percentile; 32 cfs is the 5th percentile of all flows; the 7Q2 flow is 46.4 cfs.

Biological Recommendation: For the Sabine River reach near Gladwater, ***subsistence flows of 32 cfs during Spring, 14 cfs during Summer and 17 cfs during Fall*** are recommended for maintenance of minimal habitat and environmental conditions for aquatic life during infrequent periods of severe and prolonged drought. ***For the Winter season, 45 cfs*** should be considered the subsistence benchmark, because the ecosystem has never experienced flows less than this during Winter.

Sabine River near Beckville –

- The minimum value for subsistence flow derived from HEFR/MBFIT was 22 cfs, which corresponded with the Summer period.
- Recorded flows in the Winter and Spring months have never been as low as 22 cfs; the lowest flow ever recorded during the Winter was 66 cfs and for Spring 27 cfs.
- Summer flows have been greater than 22 cfs 96% of the days; Fall flows have been greater than 22 cfs more than 98% of the days.
- For all flows, 22 cfs represents the 1.3 percentile; 52 cfs is the 5th percentile of all flows; the 7Q2 flow is 75.9 cfs.
- 51 cfs is the Summer dry base flow value derived from MBFIT

Biological Recommendation: For the Sabine River near Beckville, ***subsistence flows of 28 cfs for Spring and 22 cfs for Summer and Fall*** are recommended for maintenance of minimal habitat and environmental conditions for aquatic life during infrequent periods of severe and prolonged drought. ***For the Winter season, 66 cfs*** should be considered should be considered the subsistence benchmark, because the ecosystem has never experienced flows less than this during Winter.

Sabine River near Bon Wier –

- The minimum value for subsistence flow derived from HEFR/MBFIT was 241 cfs, which corresponded with the Summer period.
- Recorded flows in the Winter and Spring months have never been as low as 241 cfs; the lowest flow ever recorded during the Winter was 479 cfs and for Spring 251 cfs.
- Summer flows have been greater than 241 cfs more than 97% of the days; Fall flows have been greater than 241 cfs more than 98% of the days.
- For all flows, 241 cfs represents the 1.1 percentile; 415 cfs is the 5th percentile of all flows; the 7Q2 flow is 703 cfs (this value is highly influenced by hydropower operations); the 7Q10 flow is 371 cfs.
- The lowest Summer flow recorded during the modern period (1971-2008) is 350 cfs.

Biological Recommendation: For the Sabine River near Bon Wier, ***subsistence flows of 279 cfs for Spring, 241 cfs for Summer and Fall*** are recommended for maintenance of minimal habitat and environmental conditions for aquatic life during infrequent periods of severe and prolonged drought. ***For the Winter season, 479 cfs*** should be considered the subsistence benchmark, because the ecosystem has never experienced flows less than this during Winter.

Big Cow Creek near Newton –

- The minimum value for subsistence flow derived from HEFR/MBFIT was 20 cfs, which corresponded with the Summer period.
- Recorded flows in the Winter months have never been as low as 20 cfs; the lowest flow ever recorded during the Winter was 28 cfs.
- Summer flows have been greater than 20 cfs about 96% of the days; Fall flows have been greater than 20 cfs about 97.5% of the days; Spring flows have been greater than 20 cfs more than 98% of the days.
- For all flows, 20 cfs represents the 2.2 percentile; 24 cfs is the 5th percentile of all flows; the 7Q2 flow is 30 cfs.

Biological Recommendation: For Big Cow Creek, ***subsistence flows of 20 cfs*** for Spring, Summer and Fall are recommended for maintenance of minimal habitat and environmental conditions for aquatic life during infrequent periods of severe and prolonged drought. ***For the Winter season, 28 cfs*** should be considered the subsistence benchmark, because the ecosystem has never experienced flows less than this during Winter.

Sabine River near Ruliff –

- The minimum value for subsistence flow derived from HEFR/MBFIT was 396 cfs, which corresponded with the Summer period.

- Recorded flows in the Winter and Spring months have never been as low as 396 cfs; the lowest flow ever recorded during the Winter was 949 cfs and for Spring 431 cfs.
- Summer and Fall flows have been greater than 396 cfs more than 97% of the days.
- For all flows, 396 cfs represents the 1.2 percentile; 662 cfs is the 5th percentile of all flows; the 7Q2 flow is 1121.3 cfs (although this value is likely influenced by hydropower operations); the 7Q10 flow is 584 cfs.
- The lowest Summer flow recorded during the modern period (1971-2008) is 456 cfs.

Biological Recommendation: For the Sabine River near Ruliff, ***subsistence flows of 436 cfs for Spring and 396 for Summer and Fall*** are recommended for maintenance of minimal habitat and environmental conditions for aquatic life during infrequent periods of severe and prolonged drought. ***For the Winter season, 949 cfs*** should be considered the subsistence benchmark, because the ecosystem has never experienced flows less than this during Winter.

Neches River at Neches – The minimum value for subsistence flow derived from HEFR/MBFIT was 12 cfs, which corresponded with the Summer period.

- Recorded flows in the Winter and Spring months have never been 12 cfs; the lowest flow ever recorded during the Winter was 51 cfs and for Spring 15 cfs.
- Summer flows have been greater than 12 cfs about 95% of the days; Fall flows have been greater than 12 cfs more than 98% of the time.
- For all flows, 12 cfs represents the 1.8 percentile; 26 cfs is the 5th percentile of all flows; the 7Q2 flow is 70.7 cfs.

Biological Recommendation: For the Neches River near Neches, ***subsistence flows of 21 cfs for Spring, 12 cfs for Summer, and 13 cfs for Fall*** are recommended for maintenance of minimal habitat and environmental conditions for aquatic life during infrequent periods of severe and prolonged drought. ***For the Winter season, 51 cfs*** should be considered the subsistence benchmark, because the ecosystem has never experienced flows less than this during Winter.

Neches River at Rockland – The minimum value for subsistence flow derived from HEFR/MBFIT was 21 cfs, which corresponded with the Summer period.

- Recorded flows in the Winter months have never been as low as 21 cfs; the lowest flow ever recorded during the Winter was 67 cfs.
- Summer flows have been greater than 21 cfs 97% of the days; Spring flows have been greater than 21 cfs about 99.9% of the days; Fall flows have been greater than 21 cfs about 98% of the days.
- For all flows, 21 cfs represents the 1.2 percentile; 58 cfs is the 5th percentile of all flows; 111.7 cfs is the 7Q2 flow.

Biological Recommendation: For the Neches River near Rockland, ***subsistence flows of 29 cfs for Spring and 21 cfs for Summer and Fall*** are recommended for maintenance of minimal habitat and environmental conditions for aquatic life during infrequent periods of severe and prolonged drought. ***For the Winter season, 67 cfs*** should be considered the subsistence benchmark, because the ecosystem has never experienced flows less than this during Winter.

Angelina River near Alto –

- The minimum value for subsistence flow derived from HEFR/MBFIT was 11 cfs, which corresponded with the Summer period.
- Recorded flows in the Winter and Spring months have never been as low as 11 cfs; the lowest flow ever recorded during the Winter was 55 cfs; the lowest flow recorded during the Spring is 12 cfs.
- Summer flows have been greater than 11 cfs more than 95% of the days; Fall flows have been greater than 11 cfs more than 99% of the days.
- For all flows, 11 cfs represents the 1.2 percentile; 29 cfs is the 5th percentile of all flows; 37.7 cfs is the 7Q2 flow.

Biological Recommendation: For the Angelina River near Alto, ***subsistence flows of 18 cfs for Spring, 11 cfs for Summer, and 16 cfs for Fall*** are recommended for maintenance of minimal habitat and environmental conditions for aquatic life during infrequent periods of severe and prolonged drought. ***For the Winter season, 55 cfs*** should be considered the subsistence benchmark, because the ecosystem has never experienced flows less than this during Winter.

Attoyac Bayou near Chireno – The minimum value for subsistence flow derived from HEFR/MBFIT was 10 cfs, which corresponded with the Summer period.

- Recorded flows in the Winter and Spring months have never been as low as 10 cfs; the lowest flow ever recorded during the Winter was 29 cfs and the lowest flow recorded during the Spring is 13 cfs.
- Summer flows have been greater than 10 cfs more than 95% of the days; Fall flows have been greater than 10 cfs more than 99% of the days.
- For all flows, 10 cfs represents the 2.0 percentile; 17 cfs is the 5th percentile of all flows; 25.6 cfs is the 7Q2 flow.

Biological Recommendation: For the Attoyac Bayou near Chireno, ***subsistence flows of 10 cfs for Spring, Summer, and Fall*** are recommended for maintenance of minimal habitat and environmental conditions for aquatic life during infrequent periods of severe and prolonged drought. ***For the Winter season, 29 cfs*** should be considered the subsistence benchmark, because the ecosystem has never experienced flows less than this during Winter.

Neches River at Evadale –

- The minimum value for subsistence flow derived from HEFR/MBFIT was 228 cfs, which corresponded with the Summer period.
- Recorded flows in the Spring months have never been as low as 228 cfs; the lowest flow ever recorded during the Spring was 266 cfs.
- Summer flows have been greater than 228 cfs more than 97% of the days, more than 95% of the days in the Fall, and more than 99% of the days in the Winter months.
- For all flows, 228 cfs represents the 1.7 percentile; 370 cfs is the 5th percentile of all flows; the 7Q2 flow is 1838.6 cfs (although this value is likely influenced by hydropower operations); the 7Q10 flow is 361 cfs.

Biological Recommendation: For the Neches River near Evadale, ***subsistence flows of 266 cfs for Spring and 228 cfs for Winter, Summer, and Fall*** are recommended for maintenance of minimal habitat and environmental conditions for aquatic life during infrequent periods of severe and prolonged drought.

Village Creek near Kountze –

- The minimum value for subsistence flow derived from HEFR/MBFIT was 41 cfs, which corresponded with the Summer/Fall period.
- Recorded flows in the Winter and Spring months have never been as low as 41 cfs; the lowest flow ever recorded during the Winter was 83 cfs and the lowest flow recorded during the Spring is 44 cfs.
- Summer flows have been greater than 41 cfs more than 96% of the days; Fall flows have been greater than 41cfs more than 97% of the days.
- For all flows, 41 cfs represents the 1.6 percentile; 61 cfs is the 5th percentile of all flows; 78.9 cfs is the 7Q2 flow.

Biological Recommendation: For the Village Creek near Kountze, ***subsistence flows of 49 cfs for Spring and 41 cfs for Summer and Fall*** are recommended for maintenance of minimal habitat and environmental conditions for aquatic life during infrequent periods of severe and prolonged drought. ***For the Winter season, 83 cfs*** should be considered the subsistence benchmark, because the ecosystem has never experienced flows less than this during Winter.

BBEST Base Flow Recommendations –

For our ecological analysis, the HEFR base flows for dry-year, average-year, and wet-year estimates from each gage were compared with our information on the ecology of focal species (BIO-WEST 2009a) and, when appropriate, findings from the BIO-WEST instream flow study of fishes in the lower Colorado River (BIO-WEST 2008a). With only one minor exception (Sabine River near Beckville), base flow estimates from the HEFR analysis were deemed ecologically suitable. Adoption of base flow benchmarks for dry years (low precipitation years when reservoir pools are low), average years, and wet years (high precipitation years when reservoir pools are high) was deemed critical for

protecting populations of aquatic organisms within the various diverse habitat guilds. It is important to note that base flow benchmarks represent a lower threshold (floor) which flows should not fall below unless it has been determined from independent data sources that the region has entered into a prolonged, severe drought.

Big Sandy Creek near Big Sandy – The following base flows derived from HEFR analysis are recommended for maintenance of native biota and its associated ecological processes:

- Base flow, Winter, Dry year: 66 cfs
- Base flow, Winter, Average year: 106 cfs
- Base flow, Winter, Wet year: 163 cfs
- Base flow, Spring, Dry year: 30 cfs
- Base flow, Spring, Average year: 51 cfs
- Base flow, Spring, Wet year: 111 cfs
- Base flow, Summer, Dry year: 14 cfs
- Base flow, Summer, Average year: 18 cfs
- Base flow, Summer, Wet year: 26 cfs
- Base flow, Fall, Dry year: 20 cfs
- Base flow, Fall, Average year: 36 cfs
- Base flow, Fall, Wet year: 63 cfs

Sabine River near Gladewater – The following base flows derived from HEFR analysis are recommended for maintenance of native biota and its associated ecological processes:

- Base flow, Winter, Dry year: 277 cfs
- Base flow, Winter, Average year: 472 cfs
- Base flow, Winter, Wet year: 836 cfs
- Base flow, Spring, Dry year: 119 cfs
- Base flow, Spring, Average year: 283 cfs
- Base flow, Spring, Wet year: 664 cfs
- Base flow, Summer, Dry year: 34 cfs
- Base flow, Summer, Average year: 46 cfs
- Base flow, Summer, Wet year: 78 cfs
- Base flow, Fall, Dry year: 49 cfs
- Base flow, Fall, Average year: 105 cfs
- Base flow, Fall, Wet year: 232 cfs

Sabine River near Beckville – The following base flows derived from HEFR analysis are recommended for maintenance of native biota and its associated ecological processes:

- Base flow, Winter, Dry year: 438 cfs
- Base flow, Winter, Average year: 807 cfs
- Base flow, Winter, Wet year: 1580 cfs

- Base flow, Spring, Dry year: 232 cfs
- Base flow, Spring, Average year: 526 cfs*
- Base flow, Spring, Wet year: 1260 cfs
- Base flow, Summer, Dry year: 52 cfs
- Base flow, Summer, Average year: 74 cfs
- Base flow, Summer, Wet year: 122 cfs
- Base flow, Fall, Dry year: 75 cfs
- Base flow, Fall, Average year: 141 cfs
- Base flow, Fall, Wet year: 356 cfs

*Note: In this instance, the base flow for dry periods will be 52 cfs (the 5th percentile of all days), the only instance in our gage analysis in which the base flow estimate equals subsistence flow estimate.

Sabine River near Bon Wier – The following base flows derived from HEFR analysis are recommended for maintenance of native biota and its associated ecological processes:

- Base flow, Winter, Dry year: 1460 cfs
- Base flow, Winter, Average year: 5870 cfs
- Base flow, Winter, Wet year: 15400 cfs
- Base flow, Spring, Dry year: 857 cfs
- Base flow, Spring, Average year: 1590 cfs
- Base flow, Spring, Wet year: 6680 cfs
- Base flow, Summer, Dry year: 478 cfs
- Base flow, Summer, Average year: 656 cfs
- Base flow, Summer, Wet year: 1120 cfs
- Base flow, Fall, Dry year: 478 cfs
- Base flow, Fall, Average year: 615 cfs
- Base flow, Fall, Wet year: 1110 cfs

Big Cow Creek near Newton – The following base flows derived from HEFR analysis are recommended for maintenance of native biota and its associated ecological processes:

- Base flow, Winter, Dry year: 56 cfs
- Base flow, Winter, Average year: 78 cfs
- Base flow, Winter, Wet year: 106 cfs
- Base flow, Spring, Dry year: 38 cfs
- Base flow, Spring, Average year: 52 cfs
- Base flow, Spring, Wet year: 74 cfs
- Base flow, Summer, Dry year: 28 cfs
- Base flow, Summer, Average year: 36 cfs
- Base flow, Summer, Wet year: 48 cfs
- Base flow, Fall, Dry year: 36 cfs
- Base flow, Fall, Average year: 46 cfs

- Base flow, Fall, Wet year: 64 cfs

Sabine River near Ruliff – The following base flows derived from HEFR analysis are recommended for maintenance of native biota and its associated ecological processes:

- Base flow, Winter, Dry year: 1520 cfs
- Base flow, Winter, Average year: 2565 cfs
- Base flow, Winter, Wet year: 5063 cfs
- Base flow, Spring, Dry year: 1208 cfs
- Base flow, Spring, Average year: 1795 cfs
- Base flow, Spring, Wet year: 3035 cfs
- Base flow, Summer, Dry year: 670 cfs
- Base flow, Summer, Average year: 870 cfs
- Base flow, Summer, Wet year: 1430 cfs
- Base flow, Fall, Dry year: 735 cfs
- Base flow, Fall, Average year: 970 cfs
- Base flow, Fall, Wet year: 1400 cfs

Neches River at Neches – The following base flows derived from HEFR analysis are recommended for maintenance of native biota and its associated ecological processes:

- Base flow, Winter, Dry year: 178 cfs
- Base flow, Winter, Average year: 408 cfs
- Base flow, Winter, Wet year: 814 cfs
- Base flow, Spring, Dry year: 87 cfs
- Base flow, Spring, Average year: 194 cfs
- Base flow, Spring, Wet year: 524 cfs
- Base flow, Summer, Dry year: 42 cfs
- Base flow, Summer, Average year: 73 cfs
- Base flow, Summer, Wet year: 108 cfs
- Base flow, Fall, Dry year: 73 cfs
- Base flow, Fall, Average year: 104 cfs
- Base flow, Fall, Wet year: 172 cfs

Neches River at Rockland – The following base flows derived from HEFR analysis are recommended for maintenance of native biota and its associated ecological processes:

- Base flow, Winter, Dry year: 548 cfs
- Base flow, Winter, Average year: 1390 cfs
- Base flow, Winter, Wet year: 2500 cfs
- Base flow, Spring, Dry year: 382 cfs
- Base flow, Spring, Average year: 1020 cfs
- Base flow, Spring, Wet year: 2160 cfs
- Base flow, Summer, Dry year: 61 cfs

- Base flow, Summer, Average year: 88 cfs
- Base flow, Summer, Wet year: 151 cfs
- Base flow, Fall, Dry year: 82 cfs
- Base flow, Fall, Average year: 168 cfs
- Base flow, Fall, Wet year: 381 cfs

Angelina River near Alto – The following base flows derived from HEFR analysis are recommended for maintenance of native biota and its associated ecological processes:

- Base flow, Winter, Dry year: 252 cfs
- Base flow, Winter, Average year: 581 cfs
- Base flow, Winter, Wet year: 971 cfs
- Base flow, Spring, Dry year: 82 cfs
- Base flow, Spring, Average year: 206 cfs
- Base flow, Spring, Wet year: 518 cfs
- Base flow, Summer, Dry year: 36 cfs
- Base flow, Summer, Average year: 48 cfs
- Base flow, Summer, Wet year: 69 cfs
- Base flow, Fall, Dry year: 47 cfs
- Base flow, Fall, Average year: 92 cfs
- Base flow, Fall, Wet year: 176 cfs

Attoyac Bayou near Chireno – The following base flows derived from HEFR analysis are recommended for maintenance of native biota and its associated ecological processes:

- Base flow, Winter, Dry year: 107 cfs
- Base flow, Winter, Average year: 188 cfs
- Base flow, Winter, Wet year: 339 cfs
- Base flow, Spring, Dry year: 49 cfs
- Base flow, Spring, Average year: 96 cfs
- Base flow, Spring, Wet year: 178 cfs
- Base flow, Summer, Dry year: 20 cfs
- Base flow, Summer, Average year: 28 cfs
- Base flow, Summer, Wet year: 48 cfs
- Base flow, Fall, Dry year: 34 cfs
- Base flow, Fall, Average year: 65 cfs
- Base flow, Fall, Wet year: 122 cfs

Neches River at Evadale – The following base flows derived from HEFR analysis are recommended for maintenance of native biota and its associated ecological processes:

- Base flow, Winter, Dry year: 1760 cfs
- Base flow, Winter, Average year: 2590 cfs
- Base flow, Winter, Wet year: 4980 cfs

- Base flow, Spring, Dry year: 1553 cfs
- Base flow, Spring, Average year: 3070 cfs
- Base flow, Spring, Wet year: 3868 cfs
- Base flow, Summer, Dry year: 471 cfs
- Base flow, Summer, Average year: 2140 cfs
- Base flow, Summer, Wet year: 3210 cfs
- Base flow, Fall, Dry year: 438 cfs
- Base flow, Fall, Average year: 1280 cfs
- Base flow, Fall, Wet year: 2630 cfs

Village Creek near Kountze – The following base flows derived from HEFR analysis are recommended for maintenance of native biota and its associated ecological processes:

- Base flow, Winter, Dry year: 240 cfs
- Base flow, Winter, Average year: 424 cfs
- Base flow, Winter, Wet year: 672 cfs
- Base flow, Spring, Dry year: 106 cfs
- Base flow, Spring, Average year: 189 cfs
- Base flow, Spring, Wet year: 335 cfs
- Base flow, Summer, Dry year: 70 cfs
- Base flow, Summer, Average year: 91 cfs
- Base flow, Summer, Wet year: 135 cfs
- Base flow, Fall, Dry year: 89 cfs
- Base flow, Fall, Average year: 138 cfs
- Base flow, Fall, Wet year: 236 cfs

BBEST High Flow Pulses and Overbank Flow Recommendations –

For our ecological analysis, the HEFR pulse flows were evaluated in the context of ecological information compiled for our focal species (BIO-WEST 2009a and sources cited therein). For the issue of lateral connectivity of aquatic habitats, we also relied on ecological inferences derived from research findings on the ecological dynamics of the lower Brazos River by Winemiller and colleagues (Winemiller 2000, Zeug et al. 2005, 2009, Zeug and Winemiller 2007, 2008, Robertson et al. 2008). Protection of high flow pulses during late winter and early spring is essential for providing spawning cues and environmental conditions required for successful spawning and early life stage survival for a great many fish species in the streams and rivers of the region. High flow pulses during other times of the year are important for inducing varying degrees of lateral aquatic habitat connectivity which provides for movement between the main channel and backwater/off-channel habitats.

To quantify the extent of lateral connectivity of aquatic habitats during high flow pulses, we also examined the percent flooding of wetland and bottomland hardwood vegetation zones in several of our reaches (this information was provided by the National Wildlife

Federation (NWF) and the Greater Edwards Aquifer Alliance (GEAA); Reference Appendix XVII). High flow pulse values generated from the HEFR outputs were evaluated for the total area of Pineywoods Riparian Ecotones identified in the NWF/GEAA inundation flows analysis. Determining the amount of riparian area inundated by the recommended high flow pulses and overbank flows is not only important in evaluating if riparian needs are being meet, but will also help evaluate other important aspects of high flow pulses such as channel maintenance, lateral floodplain connectivity, and migratory and spawning cues. Data from the NWF/GEAA analysis was used to develop a relationship between flow and the percent total area of Pineywoods Riparian Ecotones inundated. The analysis was set up as such:

- Data were obtained from the NWF Overbank Analysis Excel spreadsheet.
- Only gages with more than two observations were used (valid observations were those that were indicated as being used in the "BH Inflows Analysis").
- A best fit trend line was applied to the data (linear or logarithmic).
- The percentage of the total wetland/riparian vegetation community zone inundated was determined for each high flow pulse category.

Results of the regression models developed between flow and percent area of inundation are shown in Figure 2. Only four gages had sufficient data to develop models (Big Sandy, Ruliff, Neches, Evadale) and the R^2 values for all four models were high. The model equations developed for each of the four gages were then applied to the HEFR high flow pulses, including the 1-per-year overbanking flow, to predict the percent total area of the pineywoods wetland/riparian zones inundated (Table 1). Results of this analysis are shown in each of the gages HEFR version 2 outputs (Figures 3 – 6).

HEFR-derived high flow pulses of 2-per-season and 1-per-season plus overbanking pulses of 1-per-2 years in the upper basin gages (Neches and Big Sandy) provide good levels of riparian zone inundation. For the lower basin gages (Evadale and Ruliff), overbanking (1-per-2 year) flow outputs provide sufficient riparian inundation (100% inundation for both gages), but the smaller 2-per-season and 1-per-season high flow pulses do not appear to be sufficient for providing a degree of lateral connectivity and flooding of the pineywoods wetland/riparian zones on an annual basis (0% inundation for all high flow pulses at the Evadale gage, and only up to 25% inundation for the 1-per-season flows and 0% inundation for all 2-per-season flows).

Flow versus percent-area-of-inundation relationships were only possible for 4 gages, nonetheless a trend is observed geographically. It appears that the HEFR high flow pulse and the 1-per-2 year overbanking flows may be sufficient to maintain riparian habitats and lateral connectivity for both of the upper basin gages in the Neches and Sabine rivers. The two seasonal categories of HEFR high flow pulses (2-per-season, 1-per-season) for the three lower-reach gages are not sufficient to inundate riparian areas on an annual basis in both the lower Sabine River and lower Neches River. Given this trend, we recommend a 1-per-year high flow pulse for all three of lower basin gages (all located below reservoirs) to ensure that sufficient riparian inundation, lateral connectivity, and

channel maintenance flows are attained. These flows also would facilitate migration and spawning of river fishes if provided during the months of February-May.

	Overbank		**High Flow Pulse**					
	1 per 2 years		**1 per year**		**2 per 3 years**		**2 per year**	
	Flow (cfs)	Predicted % Area Inundated	Flow (cfs)	Predicted % Area Inundated	Flow (cfs)	Predicted % Area Inundated	Flow (cfs)	Predicted % Area Inundated
Big Sandy	2930	83.38%	1920	65.50%	1420	56.65%	1170	52.23%
Ruliff	41300	100%	29000	100%	22700	82.46%	16800	55.91%
Neches	7280	61.49%	4880	56.25%	3430	51.64%	2440	47.18%
Evadale	26800	100%	19500	70.69%	15800	49.39%	13000	29.64%

Table 1. Predicted percent area of inundation for overbanking flows and high flow pulses derived from our HEFR frequency-based analysis using the full period of record.

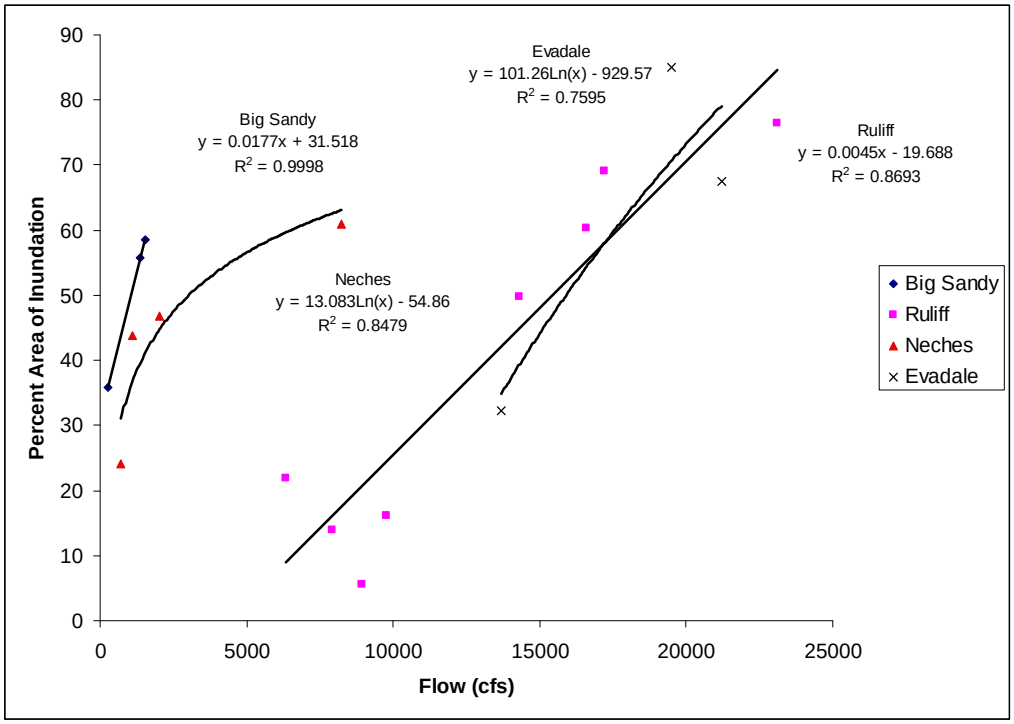


Figure 2. Relationship between observed flow and percent total area of Pineywoods Riparian Ecotones (wetlands and bottomland hardwood vegetation communities) inundated using NWF/GEAA overbanking flows analysis for the maintenance of bottomland hardwoods.

Overbank Flows	Qp: 2,930 cfs with Frequency 1 per 2 years Percent Area of Inundation = 83.38%			
High Flow Pulses				
	Qp: 942 cfs with Frequency 1 per season Percent Area of Inundation = 48.19%	Qp: 950 cfs with Frequency 1 per season Percent Area of Inundation = 48.33%	Qp: 132 cfs with Frequency 1 per season Percent Area of Inundation = 33.85%	Qp: 367 cfs with Frequency 1 per season Percent Area of Inundation = 38.01%
	Qp: 358 cfs with Frequency 2 per season Percent Area of Inundation = 37.85%	Qp: 313 cfs with Frequency 2 per season Percent Area of Inundation = 37.06%	Qp: 50 cfs with Frequency 2 per season Percent Area of Inundation = 32.40%	Qp: 130 cfs with Frequency 2 per season Percent Area of Inundation = 33.82%

Figure 3. Percent area of inundation predicted for HEFR v2 overbank and high flow pulses for Big Sandy.

Overbank Flows	Qp:41,300 cfs with Frequency 1 per 2 years Percent Area of Inundation =100%			
High Flow Pulses				
	Qp: 9,880 cfs with Frequency 1 per season Percent Area of Inundation = 24.77%	Qp: 9,880 cfs with Frequency 1 per season Percent Area of Inundation = 24.77%	Qp: 6,600 cfs with Frequency 1 per season Percent Area of Inundation = 10.01%	Qp: 6,030 cfs with Frequency 1 per season Percent Area of Inundation = 7.45%
	Qp: 1,600 cfs with Frequency 2 per season Percent Area of Inundation = 0%	Qp: 3,250 cfs with Frequency 2 per season Percent Area of Inundation = 0%	Qp: 3,380 cfs with Frequency 2 per season Percent Area of Inundation = 0%	Qp: 2,020 cfs with Frequency 2 per season Percent Area of Inundation = 0%

Figure 4. Percent area of inundation predicted for HEFR v2 overbank and high flow pulses for Ruliff.

Overbank Flows	Qp: 7,280 cfs with Frequency 1 per 2 years Percent Area of Inundation = 61.49%			
High Flow Pulses	Qp: 1,370 cfs with Frequency 1 per season Percent Area of Inundation = 39.63%	Qp: 1,370 cfs with Frequency 1 per season Percent Area of Inundation = 39.63%	Qp: 248 cfs with Frequency 1 per season Percent Area of Inundation = 17.27%	Qp: 782 cfs with Frequency 1 per season Percent Area of Inundation = 32.30%
	Qp: 833 cfs with Frequency 2 per season Percent Area of Inundation = 33.12%	Qp: 820 cfs with Frequency 2 per season Percent Area of Inundation = 32.92%	Qp: 113 cfs with Frequency 2 per season Percent Area of Inundation = 6.99%	Qp: 345 cfs with Frequency 2 per season Percent Area of Inundation = 21.59%

Figure 5. Percent area of inundation predicted for HEFR v2 overbank and high flow pulses for Neches.

Overbank Flows	Qp: 26,800 cfs with Frequency 1 per 2 years Percent Area of Inundation = 100%			
High Flow Pulses	Qp:8,700 cfs with Frequency 1 per season Percent Area of Inundation = 0%	Qp: 8,700 cfs with Frequency 1 per season Percent Area of Inundation = 0%	Qp: 3,390 cfs with Frequency 1 per season Percent Area of Inundation = 0%	Qp: 3,820 cfs with Frequency 1 per season Percent Area of Inundation = 0%
	Qp: 2,000 cfs with Frequency 2 per season Percent Area of Inundation = 0%	Qp: 3,440 cfs with Frequency 2 per season Percent Area of Inundation = 0%	Qp: 1,190 cfs with Frequency 2 per season Percent Area of Inundation = 0%	Qp: 1,150 cfs with Frequency 2 per season Percent Area of Inundation = 0%

Figure 6. Percent area of inundation predicted for HEFR v2 overbank and high flow pulses for Evadale.

Based on our analysis of these multiple sources of information, it was concluded that the following categories of flood pulses in our HEFR output matrix require protection: 2-per-season, 1-per-season, and 1-per-year (the latter for the three lower river segments only: Neches River at Evadale, Sabine River at Bon Wier, Sabine River at Ruliff) or 1-per-2 years (for the other 9 segments). Clearly, other high pulse categories would be beneficial for the ecosystems, both aquatic and riparian/wetland, but in our judgment and based on currently available information, these three are most essential for a sound ecological environment. It also is important to emphasize that the larger pulses (1-per-year; 1-per-2 years) are essential for the long-term maintenance of the biota and ecosystems, because these are, in addition to providing critical ecological functions, the flow levels that cause significant movement of bed materials, a process that creates both instream and floodplain aquatic habitat structure. This latter category also causes more extensive flooding in the lower reaches of the two rivers, which is critical for maintaining plant communities of wetlands and bottomland forests. The magnitudes of these 1-per-year and 1-per-2 years flows would inundate the lowest areas within floodplains– the areas associated with wetland and riparian vegetation communities. Nonetheless there also could be variable degrees of risk to certain economic activities in the floodplains, property, and public safety. *For this reason, our BBEST recognizes the ecological functions and benefits of these higher flow pulse categories, but we do not recommend actions be taken to produce such flows.* Normally, climatic conditions and events produce these levels of flow despite the best efforts to control and limit them.

Big Sandy Creek near Big Sandy – The following high flow pulses derived from HEFR analysis are recommended for maintenance of native biota and its associated ecological processes (volumes and durations are average values):

- 2-per-season, Winter: 358 cfs, volume 5,932, duration 10 days
- 2-per-season, Spring: 313 cfs, volume 5,062, duration 13 days
- 2-per-season, Summer: 50 cfs, volume 671, duration 6 days
- 2-per-season, Fall: 130 cfs, volume 2,189, duration 9 days
- 1-per-season, Winter: 942 cfs, volume 14,544, duration 16 days
- 1-per-season, Spring: 950 cfs, volume 12,852, duration 19 days
- 1-per-season, Summer: 132 cfs, volume 2,054, duration 11 days
- 1-per-season, Fall: 367 cfs, volume 6,055, duration 14 days
- *1-per-2 years: 2,930 cfs, volume 35,703, duration 30 days (not recommended, but ecological functions and benefits have been identified)*

Sabine River near Gladewater – The following high flow pulses derived from HEFR analysis are recommended for maintenance of native biota and its associated ecological processes:

- 2-per-season, Winter: 1,880 cfs, volume 48,599, duration 15 days
- 2-per-season, Spring: 1,580 cfs, volume 51,150, duration 16 days
- 2-per-season, Summer: 168 cfs, volume 2,752, duration 7 days
- 2-per-season, Fall: 380 cfs, volume 1,098, duration 11 days
- 1-per-season, Winter: 5,570 cfs, volume 194,743, duration 24 days

- 1-per-season, Spring: 5,070 cfs, volume 140,612, duration 25 days
- 1-per-season, Summer: 730 cfs, volume 13,480, duration 17 days
- 1-per-season, Fall: 2,240 cfs, volume 66,875, duration 21 days
- *1-per-2 years: 18,100 cfs, volume 483,275, duration 44 day (not recommended, but ecological functions and benefits have been identified)*

Sabine River near Beckville – The following high flow pulses derived from HEFR analysis are recommended for maintenance of native biota and its associated ecological processes:

- 2-per-season, Winter: 2,900 cfs, volume 84,998, duration 15 days
- 2-per-season, Spring: 2,160 cfs, volume 72,092, duration 15 days
- 2-per-season, Summer: 285 cfs, volume 5,436, duration 6 days
- 2-per-season, Fall: 628 cfs, volume 7,245, duration 9 days
- 1-per-season, Winter: 7,200 cfs, volume 302,174, duration 24 days
- 1-per-season, Spring: 7,030 cfs, volume 220,513, duration 27 days
- 1-per-season, Summer: 1,120 cfs, volume 19,863, duration 16 days
- 1-per-season, Fall: 3,250 cfs, volume 100,717, duration 21 days
- *1-per-2 years: 16,100 cfs, volume 541,644, duration 45 days (not recommended, but ecological functions and benefits have been identified)*

Sabine River near Bon Wier – The following high flow pulses derived from HEFR analysis are recommended for maintenance of native biota and its associated ecological processes:

- 2-per-season, Winter: 13,800 cfs, volume 421,966, duration 14 days
- 2-per-season, Spring: 6,700 cfs, volume 151,163, duration 12 days
- 2-per-season, Summer: 5,880 cfs, volume 132,571, duration 13 days
- 2-per-season, Fall: 2,590 cfs, volume 40,957, duration 7 days
- 1-per-season, Winter: 20,600 cfs, volume 690,800, duration 17 days
- 1-per-season, Spring: 16,500 cfs, volume 483,992, duration 21 days
- 1-per-season, Summer: 7,360 cfs, volume 175,009, duration 14 days
- 1-per-season, Fall: 8,960 cfs, volume 249,617, duration 17 days
- *1-per-year: 28,700 cfs, volume 931,140, duration 28 days (not recommended, but ecological functions and benefits have been identified)*

Big Cow Creek near Newton – The following high flow pulses derived from HEFR analysis are recommended for maintenance of native biota and its associated ecological processes:

- 2-per-season, Winter: 693 cfs, volume 4,911, duration 8 days
- 2-per-season, Spring: 350 cfs, volume 2,545, duration 7 days
- 2-per-season, Summer: 109 cfs, volume 873, duration 13 days
- 2-per-season, Fall: 322 cfs, volume 2,232, duration 7 days
- 1-per-season, Winter: 1,080 cfs, volume 7,387, duration 10 days
- 1-per-season, Spring: 862 cfs, volume 6,075, duration 10 days
- 1-per-season, Summer: 191 cfs, volume 1,447, duration 7 days
- 1-per-season, Fall: 790 cfs, volume 5,038, duration 9 days

- *1-per-2 years: 3,180 cfs, volume 18,325, duration 17 days (not recommended, but ecological functions and benefits have been identified)*

Sabine River near Ruliff – The following high flow pulses derived from HEFR analysis are recommended for maintenance of native biota and its associated ecological processes:

- 2-per-season, Winter: 1,600 cfs, volume 10,202, duration 3 days
- 2-per-season, Spring: 3,250 cfs, volume 42,883, duration 8 days
- 2-per-season, Summer: 3,380 cfs, volume 54,321, duration 11 days
- 2-per-season, Fall: 2,020 cfs, volume 17,662, duration 5 days
- 1-per-season, Winter: 9,880 cfs, volume 261,464, duration 22 days
- 1-per-season, Spring: 9,880 cfs, volume 253,851, duration 21 days
- 1-per-season, Summer: 6,600 cfs, volume 157,936, duration 19 days
- 1-per-season, Fall: 6,030 cfs, volume 110,471, duration 15 days
- *1-per-year: 29,000 cfs, volume 1,760,073, duration 60 days (not recommended, but ecological functions and benefits have been identified)*

Neches River at Neches – The following high flow pulses derived from HEFR analysis are recommended for maintenance of native biota and its associated ecological processes:

- 2-per-season, Winter: 833 cfs, volume 19,104, duration 10 days
- 2-per-season, Spring: 820 cfs, volume 20,405, duration 12 days
- 2-per-season, Summer: 113 cfs, volume 1,339, duration 4 days
- 2-per-season, Fall: 345 cfs, volume 5,391, duration 8 days
- 1-per-season, Winter: 1,370 cfs, volume 39,549, duration 13 days
- 1-per-season, Spring: 1,370 cfs, volume 31,846, duration 15 days
- 1-per-season, Summer: 248 cfs, volume 4,029, duration 7 days
- 1-per-season, Fall: 782 cfs, volume 19,996, duration 12 days
- *1-per-2 years: 7,280 cfs, volume 172,590, duration 38 days (not recommended, but ecological functions and benefits have been identified)*

Neches River at Rockland – The following high flow pulses derived from HEFR analysis are recommended for maintenance of native biota and its associated ecological processes:

- 2-per-season, Winter: 3,080 cfs, volume 82,195, duration 14 days
- 2-per-season, Spring: 1,720 cfs, volume 39,935, duration 12 days
- 2-per-season, Summer: 195 cfs, volume 1,548, duration 5 days
- 2-per-season, Fall: 515 cfs, volume 649, duration 8 days
- 1-per-season, Winter: 6,910 cfs, volume 256,523, duration 22 days
- 1-per-season, Spring: 5,600 cfs, volume 167,866, duration 23 days
- 1-per-season, Summer: 615 cfs, volume 13,365, duration 11 days
- 1-per-season, Fall: 2,240 cfs, volume 72,600, duration 17 days
- *1-per-2 years: 18,500 cfs, volume 661,717, duration 41 days (not recommended, but ecological functions and benefits have been identified)*

Angelina River near Alto – The following high flow pulses derived from HEFR analysis are recommended for maintenance of native biota and its associated ecological processes:

- 2-per-season, Winter: 1,620 cfs, volume 37,114, duration 13 days
- 2-per-season, Spring: 1,100 cfs, volume 24,117, duration 14 days
- 2-per-season, Summer: 146 cfs, volume 2,632, duration 8 days
- 2-per-season, Fall: 588 cfs, volume 12,038, duration 12 days
- 1-per-season, Winter: 3,530 cfs, volume 89,332, duration 18 days
- 1-per-season, Spring: 52,760 cfs, volume 59,278, duration 20 days
- 1-per-season, Summer: 397 cfs, volume 7,129, duration 13 days
- 1-per-season, Fall: 1,500 cfs, volume 34,291, duration 16 days
- *1-per-2 years: 9,690 cfs, volume 204,931, duration 29 days (not recommended, but ecological functions and benefits have been identified)*

Attoyac Bayou near Chireno – The following high flow pulses derived from HEFR analysis are recommended for maintenance of native biota and its associated ecological processes:

- 2-per-season, Winter: 837 cfs, volume 13,871, duration 10 days
- 2-per-season, Spring: 690 cfs, volume 10,618, duration 13 days
- 2-per-season, Summer: 146 cfs, volume 1,888, duration 7 days
- 2-per-season, Fall: 405 cfs, volume 6,353, duration 9 days
- 1-per-season, Winter: 1,200 cfs, volume 19,704, duration 12 days
- 1-per-season, Spring: 1,200 cfs, volume 18,062, duration 15 days
- 1-per-season, Summer: 390 cfs, volume 5,384, duration 12 days
- 1-per-season, Fall: 898 cfs, volume 16,133, duration 12 days
- *1-per-2 years: 7,520 cfs, volume 91,536, duration 27 days (not recommended, but ecological functions and benefits have been identified)*

Neches River at Evadale – The following high flow pulses derived from HEFR analysis are recommended for maintenance of native biota and its associated ecological processes:

- 2-per-season, Winter: 2,000 cfs, volume 21,702, duration 6 days
- 2-per-season, Spring: 3,440 cfs, volume 64,381, duration 12 days
- 2-per-season, Summer: 1,190 cfs, volume 15,630, duration 8 days
- 2-per-season, Fall: 1,150 cfs, volume 12,160, duration 6 days
- 1-per-season, Winter: 8,700 cfs, volume 255,138, duration 22 days
- 1-per-season, Spring: 8,700 cfs, volume 250,330, duration 23 days
- 1-per-season, Summer: 3,390 cfs, volume 64,197, duration 13 days
- 1-per-season, Fall: 3,820 cfs, volume 68,248, duration 13 days
- *1-per-year: 19,500 cfs, volume 1,242,210, duration 38 days (not recommended, but ecological functions and benefits have been identified)*

Village Creek near Kountze – The following high flow pulses derived from HEFR analysis are recommended for maintenance of native biota and its associated ecological processes:

- 2-per-season, Winter: 2,010 cfs, volume 36,927, duration 13 days
- 2-per-season, Spring: 1,380 cfs, volume 23,093, duration 13 days
- 2-per-season, Summer: 341 cfs, volume 6,159, duration 8 days
- 2-per-season, Fall: 712 cfs, volume 11,426, duration 9 days
- 1-per-season, Winter: 2,070 cfs, volume 38,134, duration 13 days
- 1-per-season, Spring: 2,070 cfs, volume 31,650, duration 15 days
- 1-per-season, Summer: 814 cfs, volume 11,418, duration 13 days
- 1-per-season, Fall: 2,070 cfs, volume 31,143, duration 13 days
- *1-per-2 years: 12,400 cfs, volume 170,313, duration 29 days (not recommended, but ecological functions and benefits have been identified)*

Estuarine Ecosystem Realm –

According to the SAC Guidance document for Estuarine Ecosystems (SAC 2009-04, Appendix IV), "the estuarine ecosystem is complex, comprised of many variables and their interactions." "Much of the complexity of estuaries derives from their nature as a transitional watercourse between freshwater and marine water. This is reflected in the multiple external forces controlling the estuary." "The exchange between estuary and sea is mainly affected by tides, gravity currents and meteorology (especially wind stress). Exchange between estuary and sea also manifests itself in the organisms, …. Many of the important estuarine animals, notably major fish and shellfish species, migrate between the sea and the estuary at various life-history stages. Most immigrate into the estuary from the sea as young, and mature in the estuary, taking advantage of sheltered, food-rich environments, then return to the sea as adults." "A direct measure of the physical exchange with the sea is the salinity distribution within the estuary. Salinity is the quintessential estuary parameter." "Most freshwater organisms cannot survive if salinity is too high, and most seawater organisms cannot survive if salinity is too low. An estuary is therefore an inhospitable environment for these "stenohaline" organisms. There are, however, "euryhaline" organisms that have a physiological capability to function—even thrive—in the intermediate and variable salinities of an estuary. The range and distribution of salinities can therefore be important demarcators of suitable habitat for estuarine species. The spatial estuarine gradient is fundamental for regulating differences in the functions, habitats, and integrity along the salinity gradient. Much is known about salinity gradients in estuaries and the average salinity over long time periods is an indicator of organisms' habitat." (SAC 2009-04, Appendix IV)

Estuarine ecosystems are spatially heterogeneous, physically and biologically dynamic, and highly complex owing to interactions among numerous environmental variables and diverse species spanning a range of salinity tolerances and ecological niches. Given these realities and complexities, the initial position examined by our BBEST was that the Sabine Lake estuary would receive the freshwater inflows that result from our HEFR-hydrological analysis and preliminary recommendations of flow components for the Sabine-Ruliff, Neches Evadale, and Village Creek gages. Once these volumes were calculated, we addressed the question: what are the likely responses of estuarine components? This was examined following two approaches. First, our BBEST contracted BIO-WEST to provide a literature review and

summary of focal species for the Sabine Lake ecosystem (BIO-WEST 2009b). Several plant, invertebrate, and fish species were selected to cover a range of population responses to salinity levels in Upper Gulf Coast estuaries. Second, our BBEST enlisted the help of the National Wildlife Federation (NWF) to analyze the potential responses of estuarine focal species to the salinity regimes resulting from the HEFR-derived freshwater inflows to the ecosystem. The NWF approach estimated habitat suitability within three zones of the estuary as a function of salinity regimes. Third, our BBEST examined (analysis performed under contract by Freese and Nichols) the relationship between the HEFR-derived freshwater inflows to Sabine Lake with inflow requirements estimated from the State Methodology for Estuarine (Kuhn and Chen 2005). We considered these two different approaches to be the best available science available for evaluating the suitability of freshwater inflows derived from our fluvial analysis for meeting the ecological needs of the estuarine ecosystem. Clearly, more research is needed and refinements to these analyses are warranted to reduce uncertainty. Nonetheless, these approaches, at present, provided us with the most feasible and robust means for independent assessment of environmental flows for the estuary. Both analyses supported the view that our fluvial-derived environmental flow recommendations fall within the range of values that should provide freshwater inflows sufficient to maintain a sound ecological environment within Sabine Lake under its current geomorphological configuration.

National Wildlife Federation (NWF) Analysis of Habitat Suitability for Key Estuarine Species under Alternative Flow Regimes

The recent SB 3 Science Advisory Committee report on methods for establishing an estuarine inflow regime (SAC, 2009-04, Appendix IV) recognizes a variety of potential approaches. The goal of these approaches is to link freshwater inflows, and its various attributes such as timing and volume, to the biologic response of the estuary. One of the principal methods for characterizing the biota of the estuary is the “Key Species” method. For the purposes of establishing an estuarine inflow regime, key species should exhibit sensitivity to inflow-controlled parameters, such as salinity or nutrient concentrations.

An analysis performed by NWF to assist the Sabine/Neches BBEST (Appendix XVI) focused on key species with specified salinity tolerance ranges (salinity suitability relationships) and used a variety of methods for coupling species’ biologic responses to the inflow-salinity patterns. The NWF analysis focused on a suite of four specific species and two marshland communities, all with well-established and published salinity tolerance (a.k.a. salinity suitability) information. These key species and communities are: *Rangia cuneata* larvae, blue crab juveniles, Olney bulrush (adults and seedlings), Intermediate Marsh, and Brackish Marsh. The bivalve mollusk *Rangia cuneata* (*Rangia* hereafter), blue crabs, oysters, and the Olney bulrush were recommended “focal species” in a previous report to the BBEST (BIO-WEST 2009b). The spatial extent and abundance of oyster and blue crabs are well known in Sabine Lake based on the Texas Parks and Wildlife Department’s long-term sampling program. The Olney bulrush was recommended by BIO-WEST (2009b, Appendix VII) due to its likely occurrence in the marsh types surrounding Sabine Lake.

The spatial extent and abundance of *Rangia* was not well established for Sabine Lake and thus an important preliminary undertaking was a field investigation with sonar imaging and field sampling. In summary, *Rangia* are widespread in the majority of Sabine Lake, approximately the upper three-fourths of the estuary. Thus *Rangia* is a very good key species for this estuary evaluation not only because of the well-defined salinity tolerance limits of the larvae (more below), but also due to the fact that they comprise a substantial benthic biomass in much of the estuary. The two marshland communities are widespread around the margins of Sabine Lake as indicated by Kuhn and Chen (2005).

There are well-established salinity suitability relationships for their focal species (e.g. 10-20 ppt is optimal for oysters) including relationships for particular life stages (*e.g*. for *Rangia*). For the marshland communities, the salinity suitability relationships are broad levels thought to support that particular community over a long-term.

The availability of a set of existing salinity-inflow regression equations at several points in the estuary facilitated the examination of how these species and communities are likely to respond to freshwater inflows and associated salinity patterns. The primary focus of these assessments is evaluation of the potential freshwater inflows that would result from fluvial environmental flow regimes recommended by the BBEST. However, their analysis also aimed to evaluate the levels of freshwater inflow that may be necessary to support these species and communities and thus protect a "sound ecological environment."

The flows passing through gages at Ruliff (Sabine), Evadale (Neches) and near Kountze (Village Creek) do not comprise all of the potential inflow to Sabine Lake. There are also contributions from other gaged watersheds (Pine Island Bayou and Cow Bayou) as well as ungaged areas below these gages or other wholly ungaged drainages. For these areas the Texas Water Development Board (TWDB) has estimates of inflows dating back to 1941 on a monthly basis. The TWDB also has records, or estimates, of diversions, return flows, direct precipitation onto Sabine Lake, and evaporation that must also be taken into account. Although these later components are generally minor compared to the mainstem river contributions they can be important for very low portions of the environmental flow regimes.

Their analysis focused on two of the four flow components because of their likely importance in the overall flow regimes and potential role in influencing the ecology of Sabine Lake. Time limitations prevented a more complete evaluation of the full spectrum of flow components. First, they focused on the "base average" condition flows because they may be in effect for a substantial portion of the time as these environmental flow regimes are implemented. However, because no attainment frequency for this component has been explicitly specified as of the time of their analysis, the precise percentage of time those conditions might be expected to pertain is unclear. Their second primary area of focus was "subsistence" flows. Flows of this low magnitude should be rare events, occurring only during very dry, near drought-of-record, periods (TIFP 2008). They focused on subsistence flows in order to assess their implications for Sabine Lake.

To assess the implications of adopting and implementing the proposed HEFR-derived flows, they used a procedure similar to that employed by the TWDB and TPWD in earlier salinity modeling of Sabine Lake (Kuhn and Chen 2005). The HEFR-derived flow values were substituted for the actual historic values at the three BBEST sites Sabine River at Ruliff, Neches River at Evadale, and Village Creek near Kountze. Other historic inflow contributions as reflected in TWDB records, including from other gaged watersheds (Pine Island Bayou and Cow Bayou) as well as ungaged areas below these gages and other wholly ungaged drainages, remained unchanged.

For the creation of the synthetic flows, several steps and a few assumptions were necessary:

1) for any flow component being evaluated, it was assumed that that flow level (e.g. base flow during an average year & high-tier seasonal pulse) was occurring at all three sites (Ruliff, Evadale, and Village Creek) simultaneously;
2) HEFR components that are depicted as flow rates in cubic feet per second (cfs) were converted to a volumetric value considering the number of applicable days in the month;
3) high flow pulses, expressed as a volume, are added to the converted base flows. However, due to the mechanics of the HEFR program, to avoid double counting volume, the duration of the pulse (days) was deducted from the applicable days of base flow;
4) for the "low-tier pulses" that occur twice per season it was assumed these occur in the first and second month of the season;
5) the higher tier pulses, occurring once per season, were assumed to occur in the middle month of the season; and
6) when assembling the synthetic subsistence inflow record it was assumed that the subsistence level of flows were imposed for the period of March-June, a duration of approximately 120 days, and this flow level was occurring at all three HEFR sites. For the remainder of the year historic inflows prevailed again.

For "average" conditions and the presumed occurrence of "base average" flows at the HEFR sites, they used all years in the 1941-2005 period in which the historic total inflows were between the 40th and 60th percentiles on an annual basis. To analyze "subsistence" conditions, they chose all years in which the historic total inflows were less than or equal to the 5th percentile on an annual basis.

After the synthetic inflow record is created with the HEFR-derived inflows, it is next necessary to predict the salinity response in the estuary. For this step we relied upon previously developed inflow – salinity regression equations as presented in Kuhn and Chen (2005). These equations were derived for three areas of Sabine Lake. Their regression equations and statistical r-squared values are:

Upper: $Sal = 41.7760 - 4.3824*\ln(Q1) - 0.9153*\ln(Q2)$ [$r^2=0.73$]
Middle: $Sal = 42.1146 - 4.6393*\ln(Q1) - 0.7225*\ln(Q2)$ [$r^2=0.71$]
Lower: $Sal = 61.2663 - 7.1793*\ln(Q1) - 0.0521*\ln(Q2)$ [$r^2=0.75$]

where Sal is predicted salinity, ppt; Q1 = cumulative inflow volume over previous 30 days, 1000 ac-ft; Q2 = cumulative inflow volume for previous 31-60 days, 1000 ac-ft.

These equations are based on inflows and salinity data for the 1977-97 period (Kuhn and Chen 2005).

Figures 7 and 8 illustrate the salinity response at the mid-estuary site for representative "average" and "very dry" years 1999 and 1996, respectively. For 1999 the salinities shown are those predicted with the salinity-inflow regression for both the historic inflows and the synthetic inflow record constructed with the HEFR-derived values at the "base average and high-tier seasonal pulse" levels at the Ruliff, Evadale, and Village Creek sites. Similarly, for the 1996 depictions, the regression-predicted salinity responses are shown for both the historic values and the synthetic inflow record, but here HEFR subsistence flows at the three sites are substituted in for the March-June period.

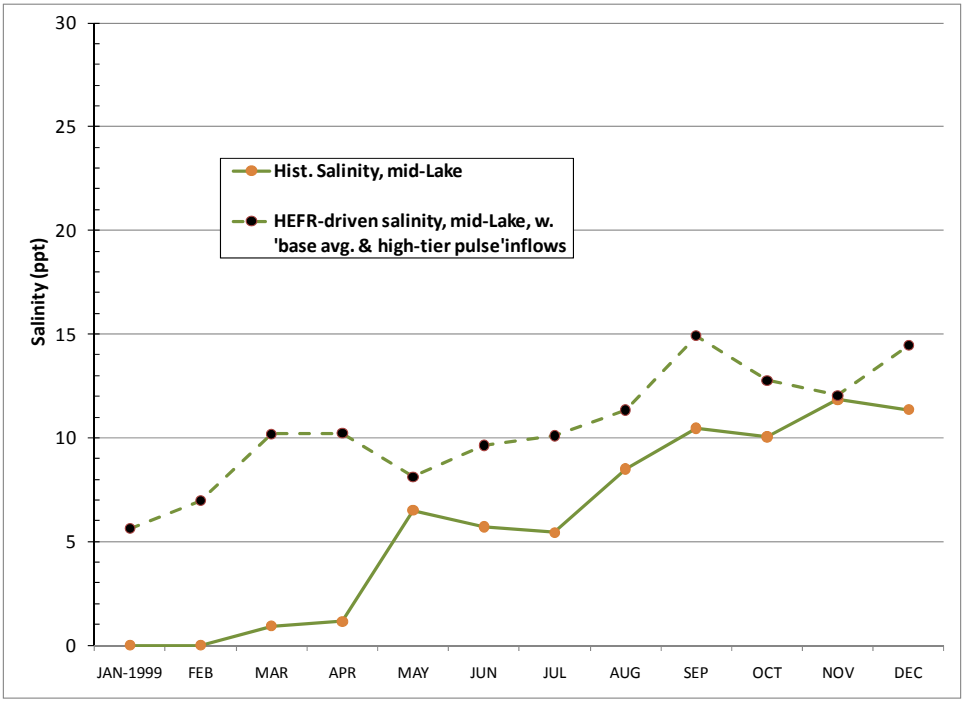


Figure 7. Predicted salinity in Sabine Lake under the original historic inflows for 1999 and with the synthetic inflow record of HEFR-derived values corresponding to "base average and high-tier seasonal pulse" for the sites at Ruliff, Evadale, and Village Creek.

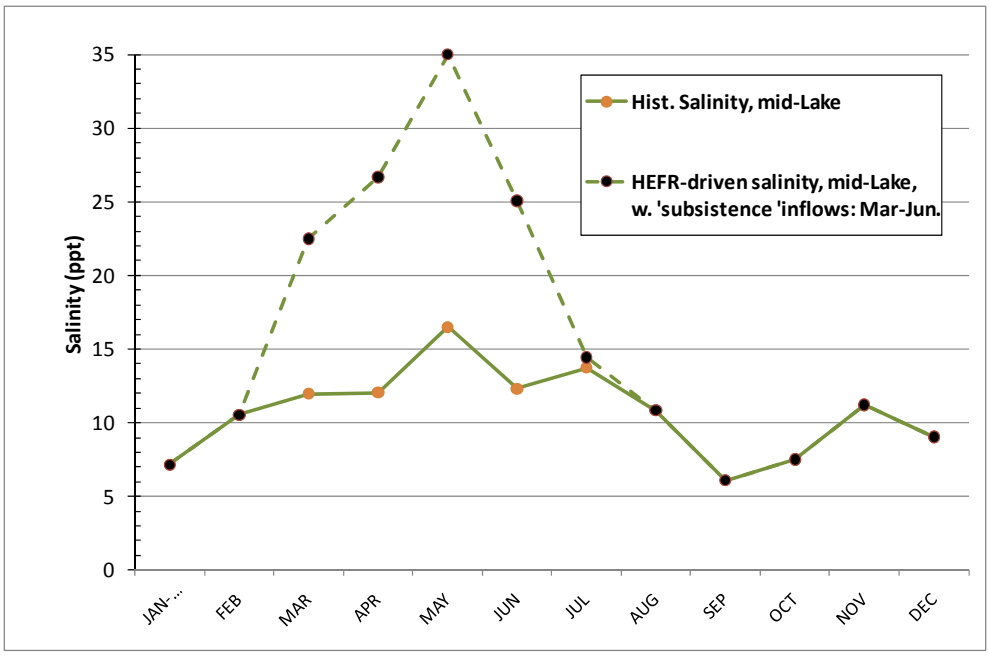


Figure 8 – Illustration of the predicted salinity in Sabine Lake under the original historic inflows for 1996 and with the synthetic inflow record of HEFR-derived values corresponding to "subsistence" levels for the March – June period at the sites at Ruliff, Evadale, and Village Creek.

Salinity Suitability of Key Species and Communities

Another essential element of the NWF analysis is the published salinity suitability information for the four key species (*Rangia cuneatea*, oysters, blue crab, and Olney bulrush) and two key marshland community types (intermediate and brackish). This information provides the critical link between freshwater inflows, the associated salinity patterns, and the ecological health of the biota in the estuary. With a salinity suitability relationship, as shown in Figure 9 for blue crabs, they were able to ascribe a relative level of significance for any given salinity for that species or community. With a suite of such relationships, a broad perspective was sought regarding the potential effects of salinity changes tied to freshwater inflow alterations.

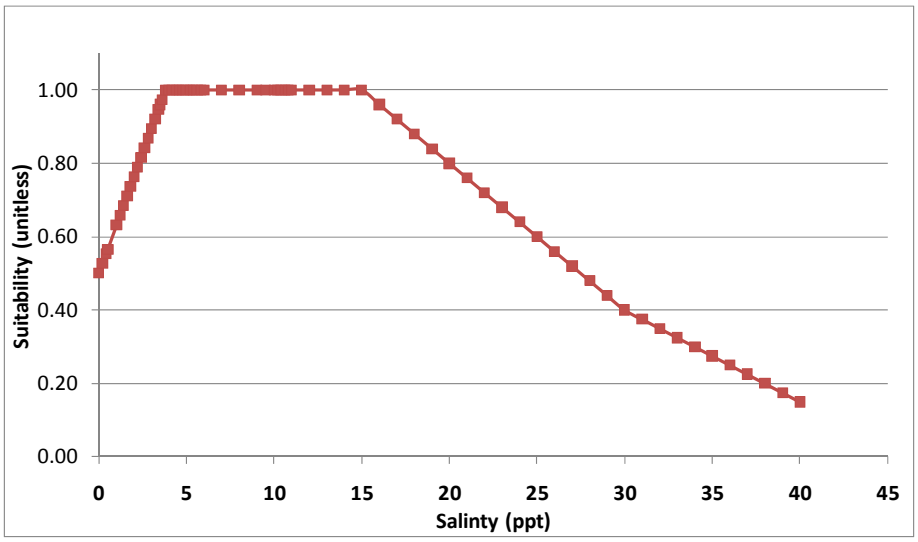


Figure 9. The salinity suitability relationship for blue crabs (based on the synthesis of literature from LCRA-SAWS (2007).

They also examined important seasonal considerations for each focal species. These are essentially the portions of the year in which the relationship of salinity to biologic health is thought to be most important. Figure 10 illustrates how the predicted salinities, salinity suitability curve, and the seasonal constraints (blue crabs as an example) were used in the analysis. On the bottom half of the figure are the salinity responses for historic inflows and the HEFR-derived "base average and high-tier seasonal pulse" inflows at the Ruliff, Evadale, and Village Creek sites. Appearing in the top half of the graph are the computed salinity suitability for both of the salinity traces. In the upper panel, only salinities for the period Feb.-July are used; for the remainder of the months, a default value of 0.0 is shown.

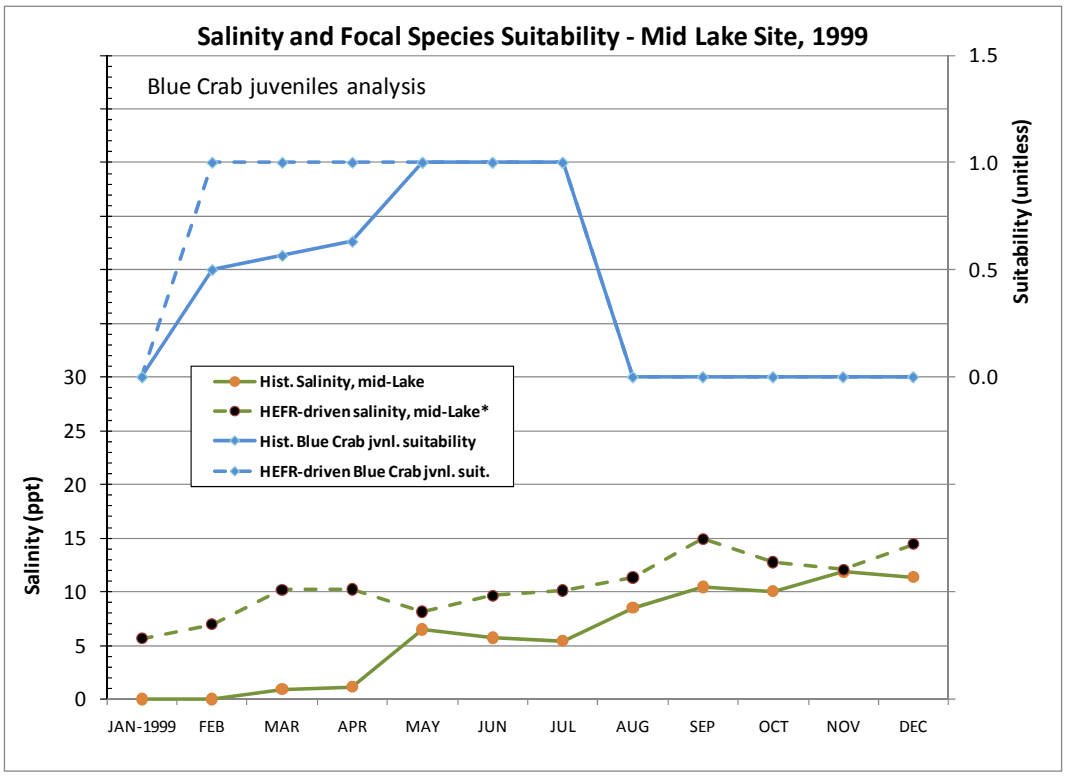


Figure 10. An illustration of how the salinity suitability relationship for blue crabs is combined with the predicted salinity values from the historic record and for HEFR-derived values. Salinities on the lower portion are for historic and HEFR-based "base average and high-tier seasonal pulse" inflows. Corresponding suitabilities for each month in the Feb-July period are in top panel.

Findings: Salinity Suitablilty Analysis of HEFR-derived Inflows

<u>Inflows at the "base average and high-tier seasonal pulse" level</u> – The Sabine River at Ruliff, Neches River at Evadale, and Village Creek near Kountze segments were assigned flows at the "base average and high-tier seasonal pulse" level for the whole year. 1980 was used as an example year since historic total inflows were at the 50th percentile of the historic record for 1941-2005. All other inflow contributions to Sabine Lake were maintained at their historic level during the year. Findings of habitat suitability analysis for several focal species are shown in Figure 11 a-f.

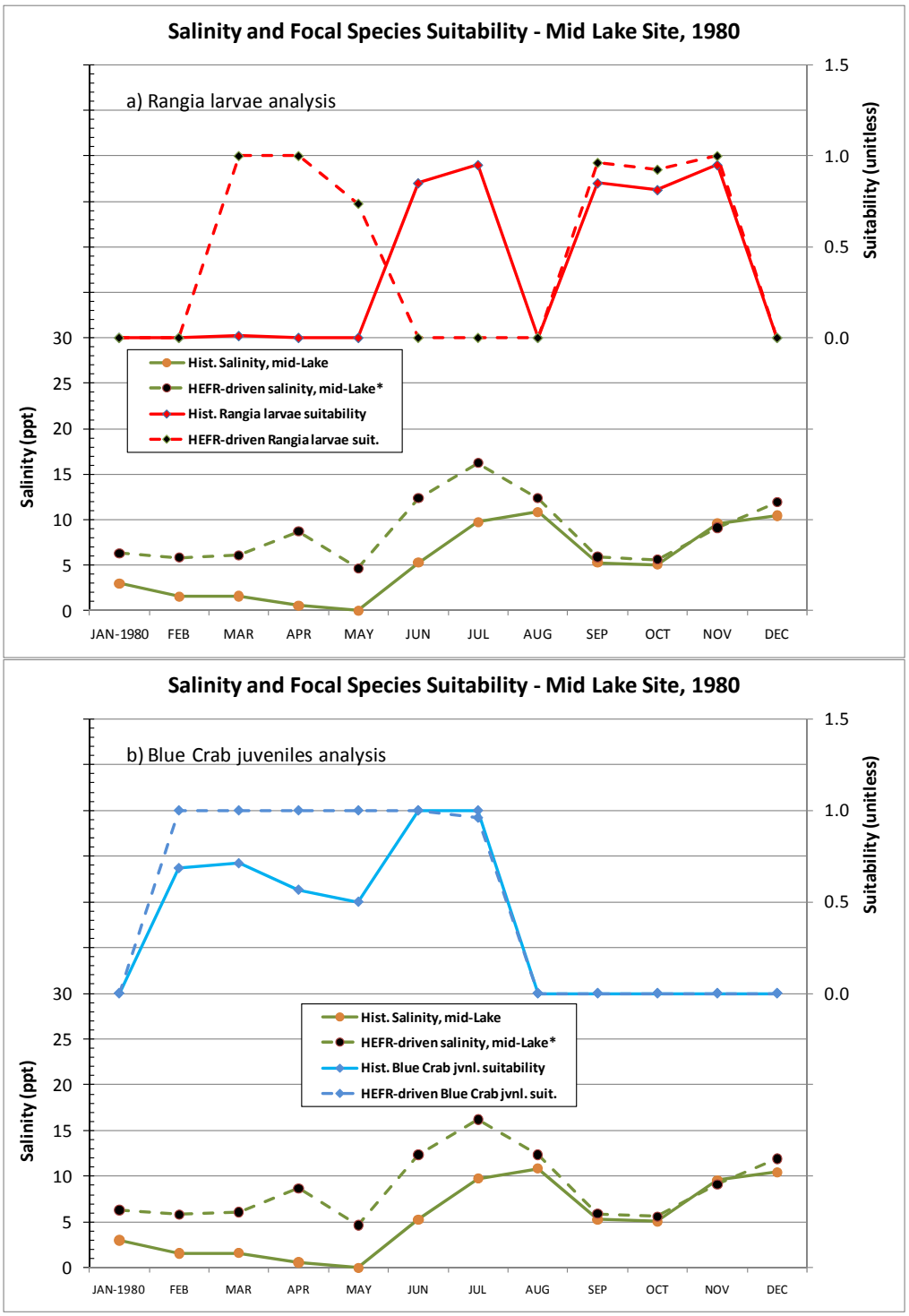
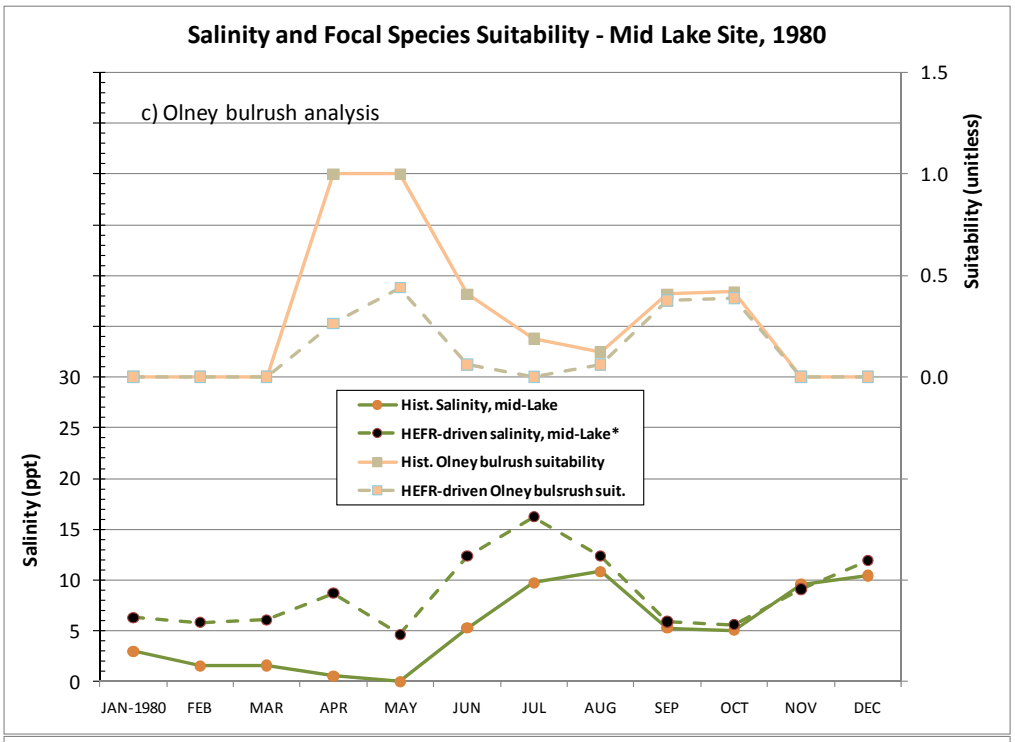

Salinity and Focal Species Suitability - Mid Lake Site, 1980
a) Rangia larvae analysis
Salinity (ppt)
Suitability (unitless)
Hist. Salinity, mid-Lake
HEFR-driven salinity, mid-Lake*
Hist. Rangia larvae suitability
HEFR-driven Rangia larvae suit.
JAN-1980
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
Salinity and Focal Species Suitability - Mid Lake Site, 1980
b) Blue Crab juveniles analysis
Salinity (ppt)
Suitability (unitless)
Hist. Salinity, mid-Lake
HEFR-driven salinity, mid-Lake*
Hist. Blue Crab jvnl. suitability
HEFR-driven Blue Crab jvnl. suit.
JAN-1980
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

Fig. 11 a, b


Salinity and Focal Species Suitability - Mid Lake Site, 1980
c) Olney bulrush analysis
Salinity (ppt)
Suitability (unitless)
Hist. Salinity, mid-Lake
HEFR-driven salinity, mid-Lake*
Hist. Olney bulrush suitability
HEFR-driven Olney bulsrush suit.
JAN-1980
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

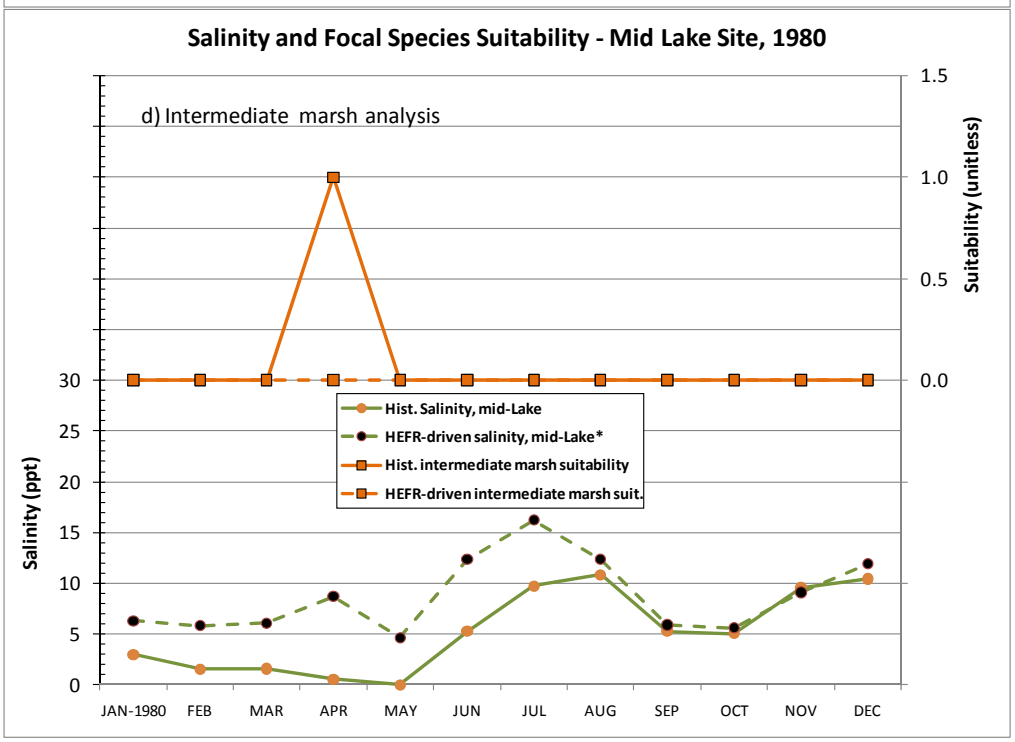
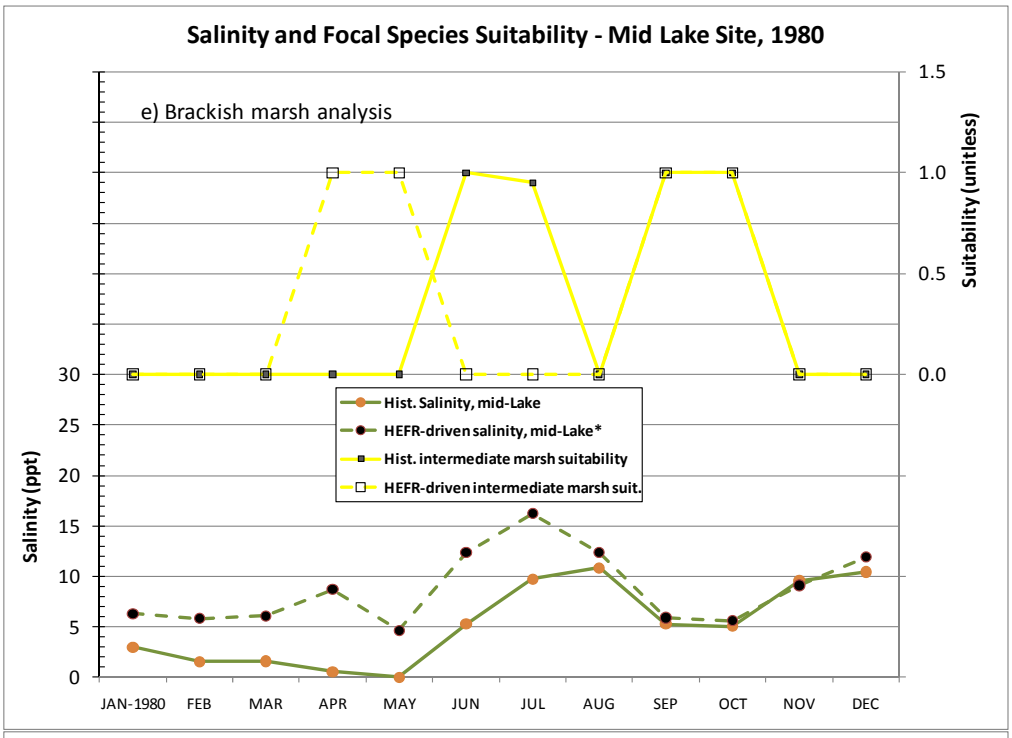

Salinity and Focal Species Suitability - Mid Lake Site, 1980
d) Intermediate marsh analysis
Salinity (ppt)
Suitability (unitless)
Hist. Salinity, mid-Lake
HEFR-driven salinity, mid-Lake*
Hist. intermediate marsh suitability
HEFR-driven intermediate marsh suit.
JAN-1980
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

Fig 11 c, d



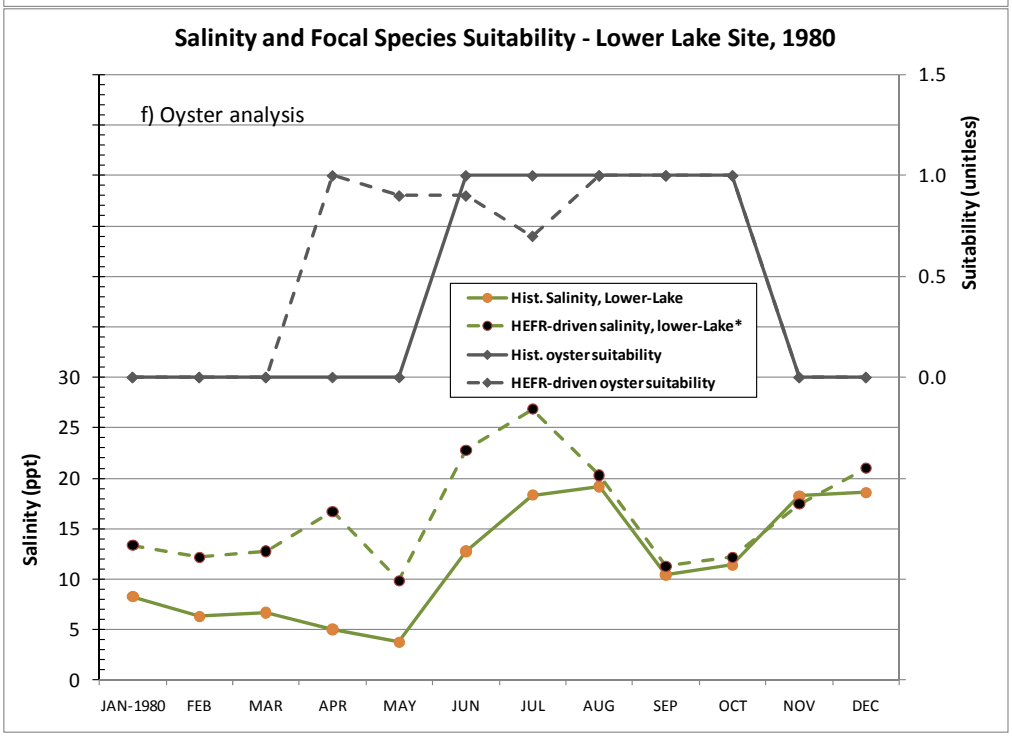


Fig. 11 e, f

Figure 11 (panels a-f). The predicted salinity and salinity suitability results of several key species and communities after substitution of the HEFR-derived instream flow "base average and high-tier seasonal pulse" values for the three BBEST sites (Sabine River at Ruliff, Neches River at Evadale, and Village Creek near Kountze) for 1980.

Inflows at the "subsistence" level – Figure 12a-e illustrates the results of inflows to Sabine Lake when the three BBEST sites Sabine River at Ruliff, Neches River at Evadale, and Village Creek near Kountze have flows at the "subsistence" level for the March-June period. 1967 was used as an example year since historic total inflows were at their lowest in the historic record for 1941-2005. During March-June, and for the remainder of the year, all other inflow contributions are maintained at their historic level. Each figure shows both the salinity response and individual key species and community salinity suitability for the year.

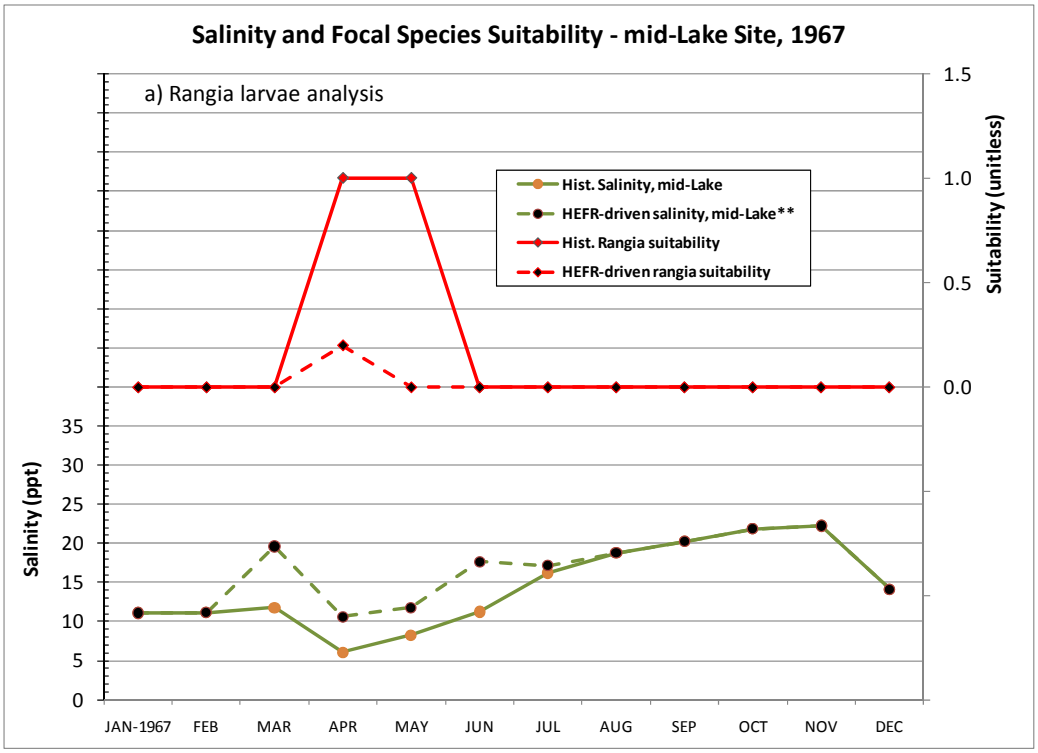
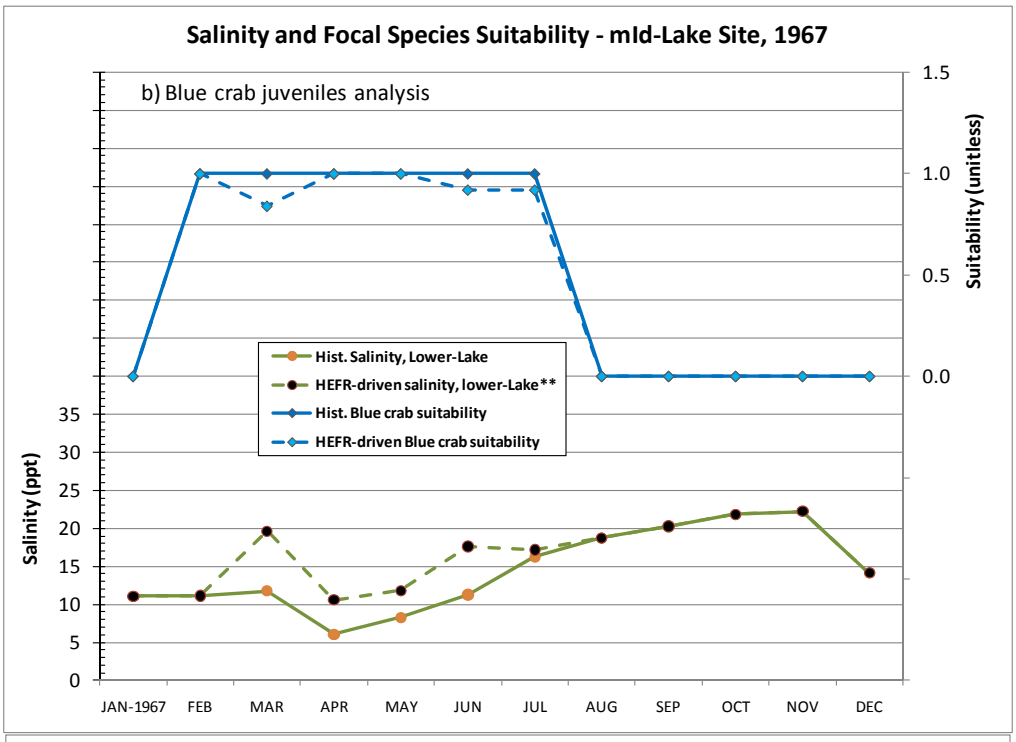


Fig. 12a


Salinity and Focal Species Suitability - mId-Lake Site, 1967
b) Blue crab juveniles analysis
Hist. Salinity, Lower-Lake
HEFR-driven salinity, lower-Lake**
Hist. Blue crab suitability
HEFR-driven Blue crab suitability
Salinity (ppt)
Suitability (unitless)
0
5
10
15
20
25
30
35
0.0
0.5
1.0
1.5
JAN-1967
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

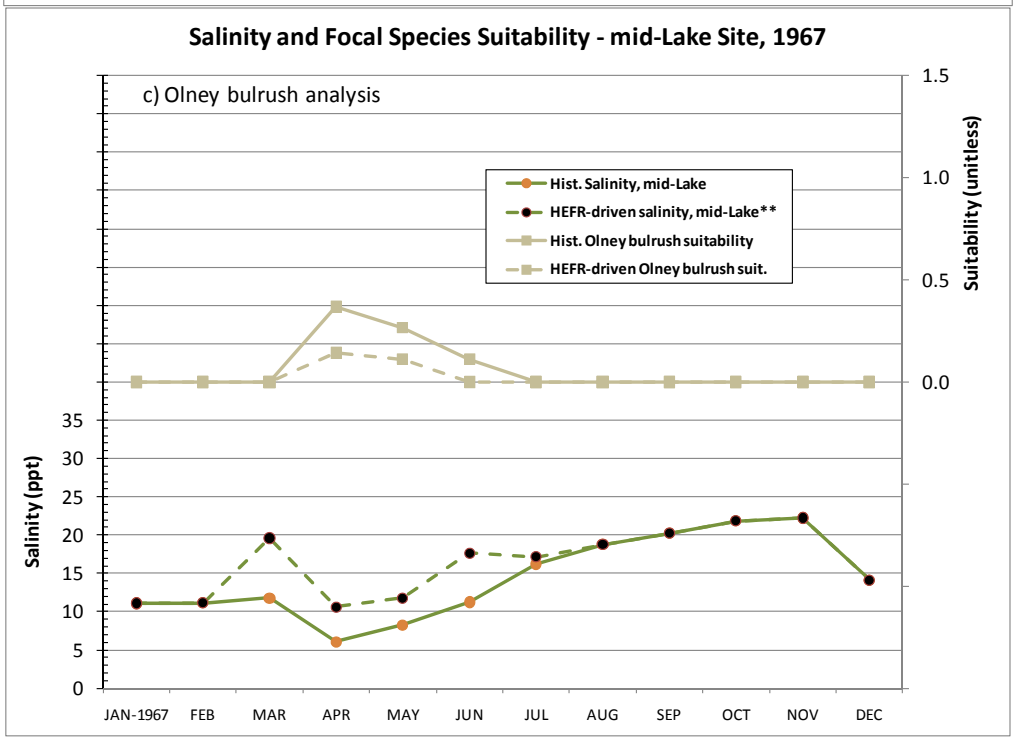
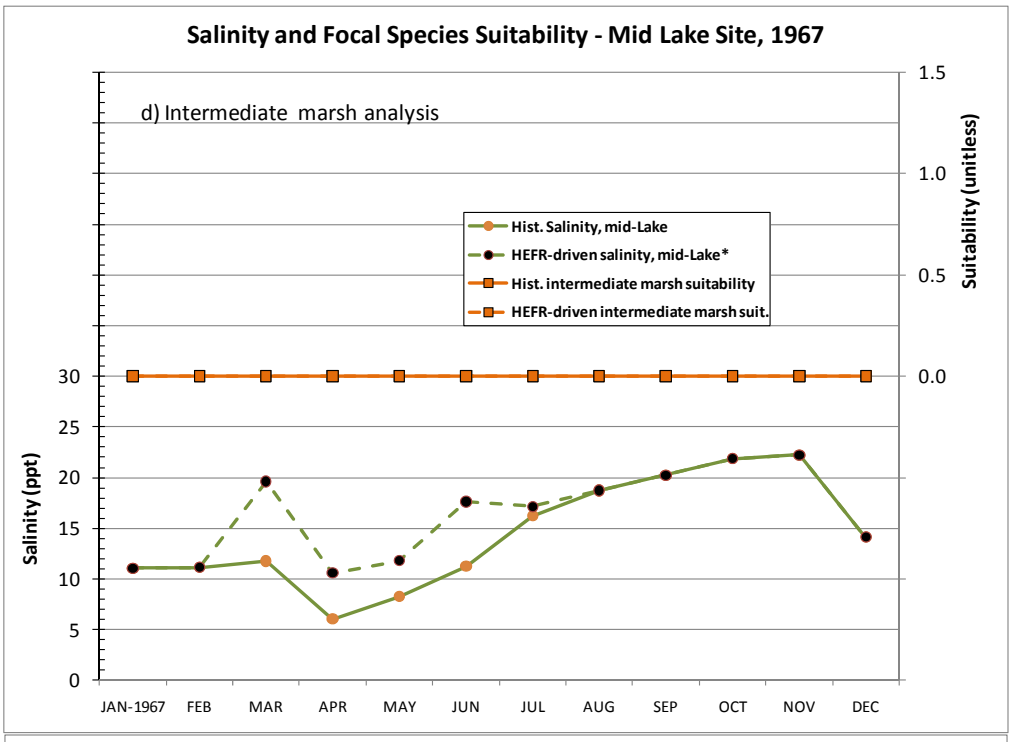

Salinity and Focal Species Suitability - mid-Lake Site, 1967
c) Olney bulrush analysis
Hist. Salinity, mid-Lake
HEFR-driven salinity, mid-Lake**
Hist. Olney bulrush suitability
HEFR-driven Olney bulrush suit.
Salinity (ppt)
Suitability (unitless)
0
5
10
15
20
25
30
35
0.0
0.5
1.0
1.5
JAN-1967
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

Fig. 12 b, c



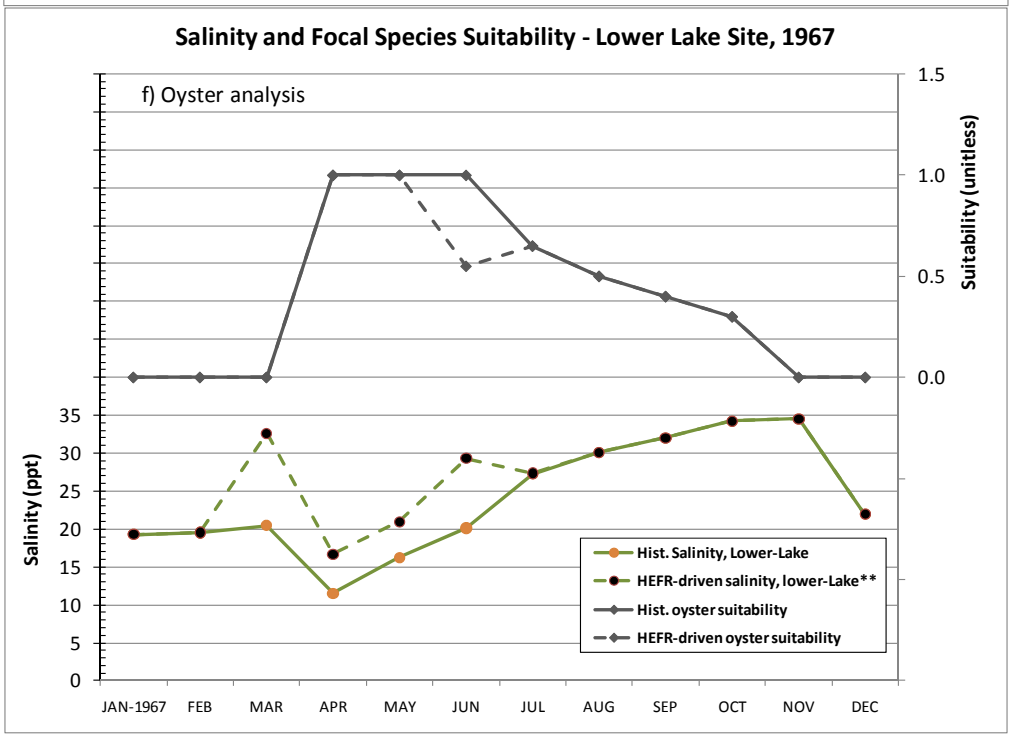


Fig. 12 d, f

Figure 12 (panels a-f). The predicted salinity and salinity suitability results of several key species and communities after substitution of the HEFR-derived instream flow "subsistence" values for the three BBEST sites Sabine River at Ruliff, Neches River at Evadale,and Village Creek near Kountze for 1967.

Discussion of Estuarine Inflow - Focal Species Findings

Generally, the base average conditions, represented here by the “base average and high-tier seasonal pulse” analyses, appear to be reasonable in terms of the average salinity suitability for *Rangia*, blue crabs, oysters, and brackish marsh. The average salinity suitability for these four key species and communities vary among years, but the overall average for the thirteen years are not greatly different when comparing the historical conditions to the HEFR-based conditions. In fact, conditions for blue crabs and oysters, both tolerant euryhaline species, might improve based on these analyses.

The most significant area of concern for the base average conditions was with the marshland species and community that are less salinity tolerant: the Olney bulrush and intermediate marsh. Both the upper- and mid-Sabine Lake areas showed significant reductions in salinity suitability on average for this species and the intermediate marsh community.

With subsistence flows for a four-month period, they concluded that there would be more potential for widespread deleterious impacts, although presumably on a less frequent basis. Since one assumes these very low inflows would occur in what is already a very dry year (e.g. one similar to 1967), essentially the HEFR-derived inflows amplify an already bad situation for most of the key species and communities. For instance *Rangia* suitability moved from an already poor value of about 0.2 to just 0.06 on average at the upper lake site for the 4 very dry years. Even for these four driest years of the historic record, there was some portion of the year in which *Rangia* reproduction (larval survival) was possible at the upper lake site. However, under the “subsistence” inflow scenario, three of the four years would lose even this limited suitability. A somewhat lesser, but still substantial, decline in *Rangia* suitability was evident at the mid-Sabine Lake site.

Unlike the analysis at “base average” conditions, “subsistence” inflows would be expected to result in a significant deleterious impact on the brackish marsh communities according to their analysis. Conditions for the less salinity tolerant Olney bulrush and intermediate marsh are already so poor, even under historic conditions in these very dry years, that the incremental effects of the “subsistence” inflows are small. Finally, under the “subsistence” inflow conditions, there were significant declines in salinity suitability conditions even for blue crabs and oysters.

THE STATE METHODOLOGY FOR ESTIMATING FRESHWATER INFLOW NEEDS OF BAYS AND ESTUARIES

General Procedure

The Texas Water Development Board (TWDB) and the Texas Parks and Wildlife Department (TPWD) are responsible for determining the total inflow to each bay necessary "...for the maintenance of productivity of economically important and ecologically characteristic sport

or commercial fish and shellfish species and estuarine life upon which such fish and shellfish are dependent," referred to as "beneficial inflows" [Texas Water Code §11.147]. The State Methodology is documented in an extensive report (Longley 1994), consisting of many components of study, data compilations and analyses, and modeling. The methodology arrives at a solution for a given estuary that is a sequence of monthly flows that will achieve a specified "goal". Central to the inflow determination are two sets of relationships: i) salinity at selected locations in the estuary as a function of inflow, and ii) abundances of several key species as a function of inflow. Both of these are determined by a statistical fit to data. For the salinity relation, a multivariate linear regression is used on two independent inflow variables, the monthly mean flows corresponding to, and preceding, the date of salinity measurement. More important is the relation between inflow and the abundance of key species.

For Sabine Lake, fisheries abundance is based upon the TPWD Coastal Fisheries database. The last substantial step of the State Methodology process is to employ the salinity and key species regressions in a sophisticated nonlinear multivariate optimization model, called TxEMP, to determine the distribution of monthly inflows that either maximizes or minimizes some variable, defined by a specific management "goal". The most important of such goals are:

MaxC, total annual harvest/abundance is maximized, subject to constraints on inflows

MinQ, total annual inflow is minimized, subject to the constraint that total annual harvest be no lower than 70% of its period-of-record average, and subject only to constraints on salinity

MinQsal, total annual inflow is minimized and subject only to constraints on salinity

In addition, solutions are sometimes provided for MaxQ and MinQ-sal, and additional potential goal formulations are given in Longley (1994). Figure 13 presents monthly MinQsal, MaxC, and MinQ flows for Sabine Lake. Although the State Methodology does not provide attainment frequencies for MinQsal, MinQ, and MaxC, it is understood that minimum attainment frequencies are part of an environmental flow recommendation. For example, the Region H Regional Water Plan, based on input from the Galveston Bay Freshwater Inflows Group, has identified attainment frequencies of 50%, 60% and 75% for MaxH/MaxC, MinQ and MinQsal, respectively.

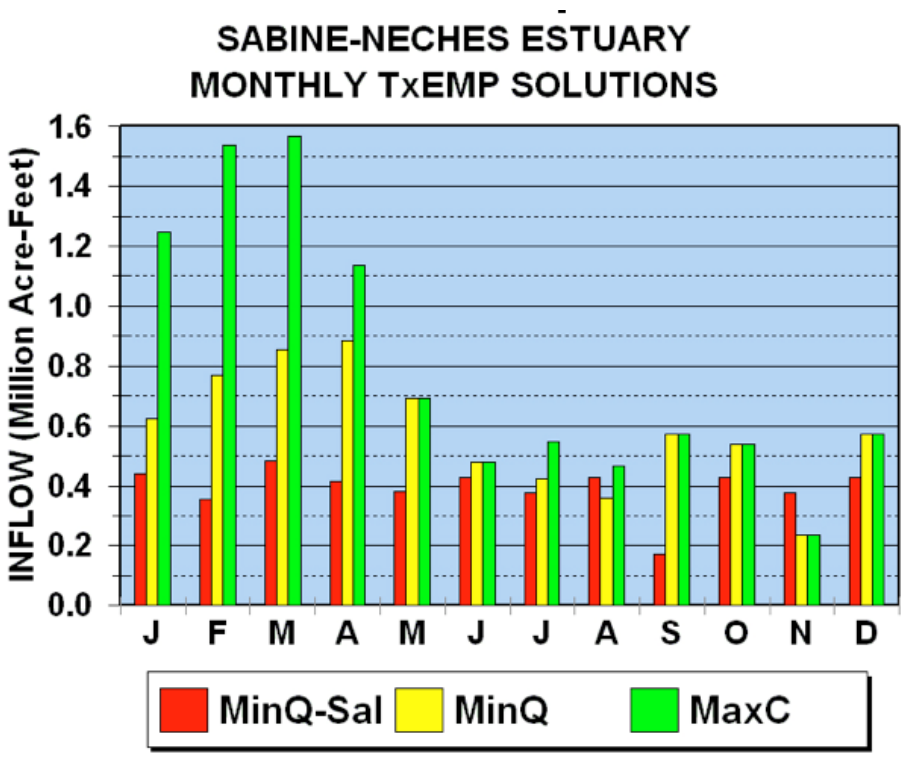


Figure 13. Comparison of monthly freshwater inflow requirements for Sabine Lake according to three different response variables from the state methodology.

Strengths of the State Methodology include:

- *Easily understood objectives* - The catch/abundance goal of maintaining a minimum abundance/catch as a fraction of the historical mean of "economically important and ecologically characteristic sport or commercial fish and shellfish" is clearly understood.
- *Sensible way to integrate disparate information* - TxEMP integrates management goals with hydrological and biological goals and constraints.
- *Attempts to make best use of flow resource* - TxEMP computes the minimum flows that meet goals and constraints.
- *Constraints keep solution "reasonable"* - Hydrological and biological constraints keep the solution "reasonable". Salinity zones are evaluated for important habitat areas as a final check. Although the optimization may be weak due to nature of catch-inflow equations, reasonableness of the solution is enforced by constraints.
- *Optimization model is objective* - Solution found after goals and constraints are set is objective.
- Solutions have been obtained for each of the major estuaries of the State and are available in an appendix to the TPWD verification reports.[2]

Weaknesses of the State Methodology include:

[2] Texas Water Development Board, Bays & Estuaries Program, http://midgewater.twdb.state.tx.us/bays_estuaries/b_nEpage.html#studies_done, retrieved 11/30/2009

• *Commercial harvest data subject to numerous sources of error and are affected by factors having no relation to abundance* - Fishing effort, reporting of catch, and other issues affect accuracy of reported harvest can undermine the use of harvest as a representation of abundance. Moreover, harvest may not have occurred in the system where it was sold at dockside.
• *Low predictive ability of catch- inflow equations* - Predictive ability of harvest/abundance equations is low, although this is not surprising due to the complexity of the ecological relationships between flow and harvest/abundance.
• *Species may not fully represent estuarine ecology* - Initial applications of the State Methodology focused exclusively on commercial species (mainly because harvest data records provided the only sufficient record of species information). As extended periods of TPWD fisheries independent data became available, more recent applications have included one or two species of ecological, but not commercial, significance.
• *Solution implies that flows must always be met* - While the goal of determining flows to meet targets is met by the State Methodology, the solution calls for the flow to always to be met. That is, there is no attainment strategy, such as a statistical frequency of occurrence. Moreover, the *maxC* and *minQ* patterns do not occur exactly in the historical inflow record to the estuary.
• *Does not address low flow needs explicitly*. This is because low flows do not arise as optimum solutions as long as there is a biological constraint, or biology is the objective function.
• *Does not provide an inflow regime consistent with the requirements of Senate Bill 3* that reflects seasonal and yearly fluctuations, including the required frequency of various inflow amounts or inflow patterns needed during very dry periods, as well as the frequency of higher inflows during wet years that help sustain a healthy bay and estuarine ecosystem.
• *The optimized solution is dominated by the constraints*, e.g. that each monthly or bimonthly flow must lie between the 10th percentile and median values, which are specified without scientific defense. While constraints are a necessary and important aspect of the optimization problem specification because they ensure that the solution is realistic, when the majority of the resulting monthly flows are the constraint values, these constraints are, in effect, the answer, and therefore the basis for their specification becomes central.

Comparison of HEFR-Generated Freshwater Inflows to Sabine Lake with Freshwater Inflow Requirements Based on the State Methodology

A HEFR hydrological analysis was performed on inflows into Sabine Lake was performed under contract with our BBEST by Freese and Nichols (HEFR memo to Sabine-Neches BBEST, Sept. 17, 2009). The flow data consisted of historical daily flows from BBEST gages Village Creek near Kountze, Neches River at Evadale and Sabine River near Ruliff, plus the USGS gages Pine Island Bayou near Sour Lake (08041700) and Cow Bayou near Mauriceville (08031000). The historical daily gage flows were added to estimated ungaged inflows obtained from the Texas Water Development Board (TWDB). The ungaged flows

consist of monthly data for the period from 1941 to 2005. These flows were distributed to daily using historical flow patterns from the Kountze gage. TWDB also has monthly estimates of diversions and return flows for the ungaged data. These data were distributed evenly throughout the each month and the diversions were subtracted and the return flows added to the daily flows. TWDB also has historical monthly precipitation and evaporation estimates for Sabine Lake. These data were not included in the inflows. The median net precipitation on Sabine Lake (precipitation – evaporation) for the 1941 to 2005 period averages about 49,000 acre-feet per year, which is less than 1 percent of the average annual flow into the Sabine Lake.

Table 2 compares the annual volume from the HEFR runs using the percentile-based approach for Sabine Lake to the annual volume for MinQ, MaxC and MaxQ[3] from the State Methodology for bay and estuary inflows. HEFR matrix volumes for each flow condition (25th percentile, median or 75th percentile) are shown for base flows only, base plus pulse flows and with the entire HEFR overbank event added to each condition. Subsistence flows have not historically occurred during the winter and spring months. In these months the fall HEFR result was used to calculated volumes.

Comparing HEFR-generated flow components to the State Methodology shows that the HEFR 25th percentile (dry) conditions are less than the MinQ unless an overbank event occurs during the year. Base + pulse flows for median (average) conditions are less than MinQ for the Full Period and Pre-dam time periods, but are more than MinQ for the Post-dam period. MaxC values are only exceeded for the median (average) condition if an overbank event occurs during the year. The 75th percentile (wet) condition is relatively close to the MaxQ even without the occurrence of an overbank flow.

Most of the volume entering Sabine Lake is included in the base flow component. The base flow by itself is about 70% of the Base + Pulse volume in the 25th percentile (dry) conditions and over 90% for 75th percentile (wet) condition. Post-dam HEFR results have higher volumes than the Full Period or Pre-dam results.

Figure 14 compares the seasonal distribution of the HEFR volumes to the seasonal distribution using the State Methodology. The monthly State Methodology values were summed by the same seasons used in the HEFR analysis. The distribution for the HEFR volumes without overbank flows is similar to the State Methodology, with the highest flows occurring during the winter months and the lowest during the summer months. The occurrence of an overbank flow can significantly alter the distribution, however. The HEFR volumes are for the Full Period of record. The Pre-Dam and Post-Dam periods have similar results.

Table 2. Comparison of HEFR-generated annual freshwater inflow volumes to freshwater inflow volumes recommended for Sabine Lake according to the State Methodology (values in acre-feet per year).

HEFR Annual Volumes	Full Period (41-05)	Pre-Dam (41-60)	Post-Dam (71-05)
Subsistence:	549,757	535,467	680,223
25th Percentile (Dry) Condition:			
Base Only:	2,243,997	2,316,804	3,306,215
Base + Pulse:	3,150,508	3,643,588	4,114,963
Base + Pulse + Overbank:	6,451,892	8,646,629	7,316,168
Median (Average) Condition:			
Base Only:	5,018,915	5,013,258	7,240,502
Base + Pulse:	6,380,477	6,325,716	8,234,125
Base + Pulse + Overbank:	9,467,182	10,719,867	11,271,050
75th Percentile (Wet) Condition:			
Base Only:	11,076,875	10,520,563	13,694,250
Base + Pulse:	11,986,199	11,300,553	14,298,506
Base + Pulse + Overbank:	14,266,063	14,416,682	16,359,393
State Methodology:			
MinQ:	7,114,000		
MaxC:	9,596,600		
MaxQ:	11,619,300		

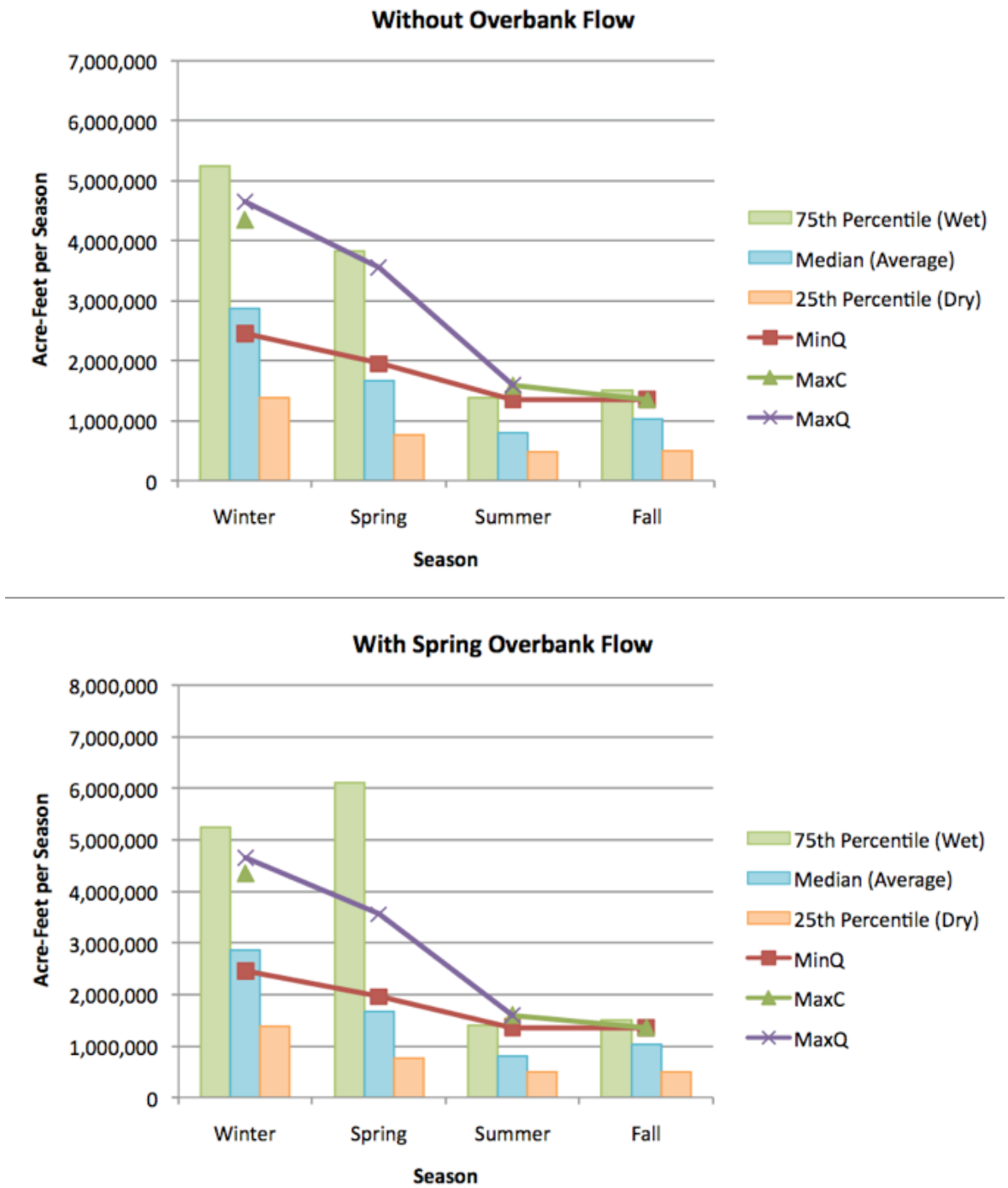


Figure 14. Comparison of seasonal flow volumes for full period HEFR and State Methodology for Sabine Lake, with and without overbank Flow (from Freese and Nichols, HEFR analysis memo to Sabine-Neches BBEST, Sept. 17, 2009).

Impacts of Oil and Gas Exploration and Ship Channel Dredging on Salinity and Ecological Dynamics in Sabine Lake and Fringing Wetlands –

Changes to the Sabine-Neches Estuary (Sabine Lake) began in the 1870's with navigation channels being cut through the offshore bar at the mouth of both Sabine Pass and Calcasieu Pass (Morton 1996; U.S. Army Corps of Engineers 2004). These navigation channels have been maintained and enlarged ever since. The current Sabine-Neches ship channel completed in 1972 consists of a 40-ft channel to the Port of Beaumont and a 30-ft channel to the Port of Orange. The Calcasieu Ship Channel is maintained at 40-ft depth and 400-ft width. The Gulf Intracoastal Waterway (GIWW) completed in 1933 (Sutherlin 1996) and other canals through the marsh have linked Sabine Lake to Calcasieu Lake in multiple locations (Paille 1996). Some of these connections have been plugged (rock weir control structures) by restoration efforts but the two systems are still linked.

Today the Sabine-Neches Estuary and the Calcasieu Estuary cannot be viewed separately. The system is a marsh at its center cut by an impressive network of canals and secondary channels with many open water areas therein, bracketed by deep water channels to the east and west, with a shallower channel cut through the north end (GIWW) and a chenier ridge to the south protecting it from the Gulf of Mexico. The Sabine National Wildlife Refuge occupies some 125,000 acres in the middle stretching from the east shore of Sabine Lake to the west shore of Calcasieu Lake, with three man-made impoundments totaling 33,000 acres (largest being 30,000 acres). The proximity of the channel to the east (Calcasieu Ship Channel) seems to have a greater effect on the marsh than the channel to the west (Sabine-Neches Waterway) which is protected somewhat by a spoil bank and Sabine Lake. This is evidenced by salinity data showing higher numbers on the east side of the marsh than the west (Paille 1996). These navigation channels affect the Sabine estuary in at least two ways. First during times of high tide they allow saltwater to intrude into the estuary and further upstream into the rivers, lakes, bayous, the GIWW and marshes. Secondly, during times of flooding they move fresh water out of the estuary more quickly reducing the amount of marsh land flooding; thereby, giving less retention time for fresh water flows and the accumulation of sediments in the marsh (Boesch, Josselyn et al. 1994, and references therein). The GIWW allows water to infiltrate the marsh through unprotected locations. At times of low flow and high tide, which in this area means a strong southerly wind, saline waters move up the deep channels of the SNWW and the Calcasieu Ship Channel and into the GIWW. Saline waters also flow into Sabine Lake through connections with the SNWW at the north and south ends of the Lake as well as the lower Sabine and Neches Rivers. This sometimes leaves the center of the lake fresher than either end. These saline waters then move into the marshes though canals and secondary channels from the GIWW, the Calcasieu Ship Channel and Sabine Lake. These canals dredged for the petroleum operations have had a devastating effect on the marsh by allowing saltwater intrusion into the marshes, these canals are a "source of erosive energy on the surrounding marsh" (Boesch, Josselyn et al. 1994, and references therein) with subsequent land subsidence in some areas, and resulted in loss of vegetation and erosion of organic soil. Open water lakes have formed in the marshes that have become increasingly unstable and continue to degrade into larger open-water areas under existing conditions (Boesch, Josselyn et al. 1994, and references therein; Tatum 2009). Today the amount of wetlands lost from

coastal Louisiana and Texas is staggering. These canals have been estimated to be responsible for the majority of this loss (Scaife, Turner et al. 1983).

During periods of normal and high flows, fresh water as expected freshens the rivers and Lakes but is expedited to the Gulf through the enlarged openings of both navigation channels. It is uncertain how much freshwater inflows affect the marshes other than freshening the canals. However, precipitation seems to contribute most of the fresh water to the marsh as shown by salinity data (Paille 1996).

Adaptive Management

SB 3 envisions an adaptive management process for revisiting the environmental flow standards and environmental flow set-asides derived through the TCEQ rulemaking procedure. The SB 3 adaptive management process envisions that additional data, information, and studies will be necessary in order to make informed decisions regarding future changes to environmental flow recommendations. The on-going Texas Instream Flow Program (TIFP) studies will provide useful information, but more research will likely be needed. In particular, dependence upon hydrology-based environmental flow recommendations, which may be largely required to meet the aggressive time frames specified in SB3, highlights the need for future adaptation of the adopted flow standards. While application of the pre- and post-biological overlay process can substantively improve the hydrology-based recommendations, future refinements and validation will accrue only from the use of new and better science developed through the adaptive management process.

We have identified several priority areas for research that would greatly assist in filling critical information gaps.

1. More data and improved knowledge of the ecological conditions and responses to flow variation are needed for the zone between the subsistence flow and dry base flow thresholds for each season. Field studies are needed in multiple stream and river segments of the basins to reveal relationships between key environmental parameters and biotic components during periods of low flow.

2. Additionally, more thought and deliberation are needed regarding alternative implementation guidelines (policies) for water diversions as flows change within the zone lying between the thresholds for subsistence and dry base flows. The concern here is that diversions under dry-year base flow conditions could drive flows to the subsistence flow threshold for long periods of time. The subsistence flow defines a very rare occurrence, on the order of the lowest 1-2 percentile of all recorded flows.

3. More research is needed to establish, with greater precision and accuracy, the relationships between discharge and inundation of riparian bottomland hardwood and wetland zones of the floodplain. We were only able to obtain data for a limited

number of our stream and river segments, but more aerial images may be available for analysis, and additional high quality images should be obtained in the future.

4. Research is needed to quantify relationships between flow pulses (timing, duration, frequency) and reproduction and recruitment of important fish populations, within mainstem and tributary segments of the basins. Research is needed for species that complete their life cycle within the main channel as well as those that use both channels and backwaters (aquatic floodplain habitats).

5. More research is needed to establish relationships between the freshwater inflows established under the fluvial environmental flow recommendations and biological components of Sabine Lake. Given the heterogeneity and diversity of the estuarine ecosystem, focal species should receive greatest attention.

6. Relationships between freshwater inflows and salinity in fringing marshes, especially in the northern regions of Sabine Lake are needed. The influence of wind, tides, and depth of human-constructed channels on salinity dynamics in these regions should be examined.

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Geomorphic Overlay for the Sabine-Neches BBEST

November 30, 2009

Purpose

The purpose of this analysis is to evaluate fluvial sediment transport as an overlay to instream flow recommendations for the Sabine and Neches River Basins. The Sabine Neches BBEST is in the process of considering recommendations based on the Hydrologic Environmental Flow Regime (HEFR) for 12 gages in the Sabine and Neches River Basins and this geomorphic overly analysis was prepared to assist in making these recommendations.

Effective Discharge

This report computes Effective Discharge using the procedures outlined in "Fluvial Sediment Transport as an Overlay to Instream Flow Recommendations for the Environmental Flows Allocation Process." This document is a guidance document provided by the Texas Environmental Flows Scientific Advisory Committee (SAC).[1]

Sediment transport is one of the many natural processes occurring within river systems. Rivers are in equilibrium when their transport capacities for water and sediment are equal to the rate of supply (Chang 1998). Rivers adjust their width, depth, velocity, and meander wavelength and bed-material discharge until a dynamic equilibrium is achieved (Chang 1988). Any imbalance in a river's sediment should cause a change in the morphology of the river in the form of either erosion or deposition (Biedenharn, et al. 2000). A sediment imbalance can be caused by climate changes, hydrologic changes, tectonic events, reservoir construction, and flow diversion into and out of rivers and streams.

Effective discharge is defined as the mean of the discharge increment that transports the largest fraction of the annual sediment load over a period of years (Andrews 1980). This definition of effective discharge incorporates the principle prescribed by Wolman and Miller (1960) that the channel-forming discharge is a function of both the magnitude of the event and its frequency of

[1] TCEQ Environmental Flow Resources, http://www.tceq.state.tx.us/permitting/water_supply/water_rights/eflows/resources.html, retrieved November 10, 2009. Also referenced as Sabine-Neches BBEST Environmental Flows Recommendation Report Appendix III.

occurrence. It is calculated by integrating the flow-duration curve and a bed-material-sediment rating curve. A graphical representation of the relationship between sediment transport, frequency of transport, and effective discharge is shown in Figure 1. The peak of curve III from Figure 1 marks the discharge which is most effective in transporting sediment and is therefore hypothesized to do the most work in forming the channel. (Copeland, et al. 2000)

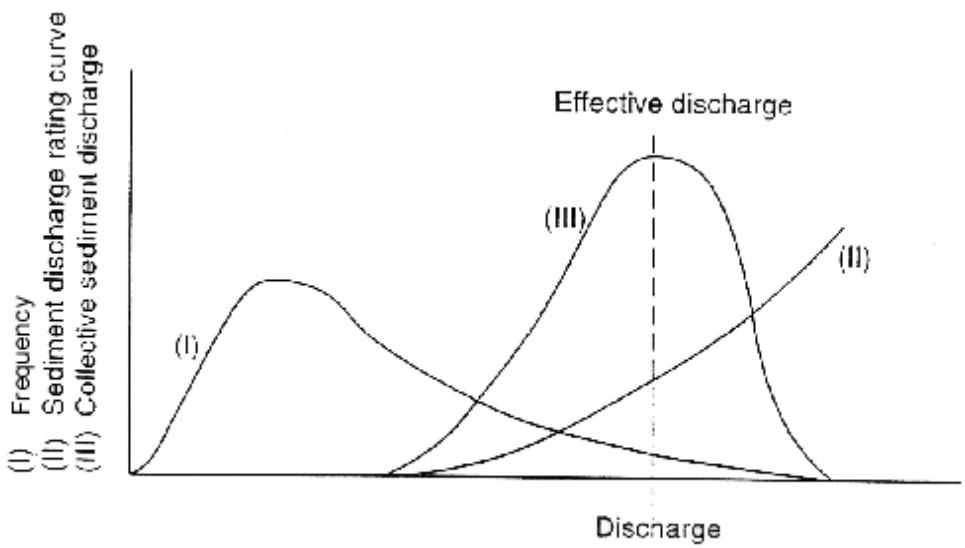

Figure 1 Derivation of total sediment load-discharge histogram (III) from flow frequency (I) and sediment load rating curves (II) (Copeland , et al. 2000)

Effective Discharge Calculations –Data Requirements and Sources

Due to lack of available time and data, seven of the twelve gages were selected for computation of the Effective Discharge. Because observed sediment measurements are not available, calculating the Effective Discharge at these seven gages in the Sabine and Neches River Basins required assembling data from four different sources as follows.

The first step in determining the Effective Discharge was development of a water stage–discharge curve (Rating Curve). The data to develop the stage-discharge curve was taken from USGS field measurements for the seven gages for the period of record for each gage. Cross-sections for the channel at each gaging station were developed from recent discharge measurements. The cross-

section used in the computations for the seven gage locations are shown in Figures 1E -7E of Appendix A. Historical field measurements were used to determine flow velocities and energy slopes needed to calculated a sediment rating curve at the each of the seven gages (see Step 2 below).

Step 2 of the process to develop each Effective Discharge was computation of sediment rating curves, which required the hydraulic properties developed in Step 1 and a bed-material gradation of the sediments in the bed of the stream at the gage location. Texas Water Development Board (TWDB) personnel visited each of the seven gage sites in August and September 2009 and collected bed material samples. These samples where analyzed and the sediment gradations of the bed material at each of the seven gages are provided in Appendix A, Figures 1F -7F.

Step 3 of the Effective Discharge computations was development of a daily hydrologic flow hydrograph. The hydrology used for this study was supplied by daily flows from the appropriate TCEQ Water Availability Model (WAM). One set of calculations was completed with daily flows from WAM Run 8, which represents existing infrastructure and present water use, including return flows from permitted water users. For a comparison to WAM Run 8 results and as an evaluation of possible future conditions, calculations were also completed with daily flows from WAM Run 3. WAM Run 3 is representative of full utilization of existing water right permits with no return flows. Daily flows from WAM Runs 3 and 8 were provided by the Sabine-Neches BBEST. Flow Duration Curves for the seven gage locations for WAM Runs 8 and 3 can be found in Appendix A, Figures 1C-7C, Figures 1D-7D, and Tables 1-7.

Results and Analysis

In a typical application, the Effective Discharge is calculated for both an existing condition and some expected future condition. In this analysis, daily flows from WAM Run 8 were used as being representative of the existing condition and from WAM Run 3 as a possible future condition.. At this time, no specific procedures are assumed for adjustment of future flows to reflect implementation of HEFR flow regime values.
However, in order to analyze the effects of the potential HEFR flow regime under consideration by the BBEST, a a comparison was made of the proposed High Flow Pulses and Overbank Flow to the Effective Discharge computed at each gage(shown in Table 1below). The High Flow

Pulses and Overbank Flow generally exceed the Effective Discharge at each gage location. As importantly, the durations of the High Flow Pulses and Overbank Flow also exceed the amount of duration that historical flows (as represented by WAM Run 8 daily flows) were in the Effective Discharge increment (sometimes referred to as the effective discharge bin). Because some of the flows included in the rising or falling limb of a High Flow Pulse or Overbank Flow event may be less that those included in the Effective Discharge increment, it is for the durations of these events to exceed the duration of the Effective Discharge increment.

WAM Run 3 is representative of full utilization of existing water rights permits with no return flows. Although already permitted and legally possible, this is considered an extreme future condition for the Sabine and Neches Basins and one that is not likely to occur for many decades. Daily flows from WAM Runs 3 were provided by the Sabine-Neches BBEST and were not adjusted to reflect implementation of the proposed HEFR flow regime for this analysis. Various data comparing the Effective Discharge for WAM Run 8 and WAM Run 3 can be found in Appendix A, Figures 1 A&B – 7 A&B. As shown in Table 2 and as expected, the annual water and sediment yield for Run 3 is less than for Run 8. Without detailed modeling and a precise description of how water and sediment yield would be reduced, it is very difficult to determine how the channel might respond to this change. In general, when a channel experiences a loss of both water and sediment, expected changes include some change in channel depth, a reduction in channel width, a decrease in channel width-depth ratio, and a tendency for the channel to become straighter, decreasing sinuosity (Schumm 1969). The differences between Run 8 and Run 3 are most pronounced in the lower reaches of the Sabine River (below Toledo Bend Reservoir) as further explained below.

The comparison of results from WAM Run 8 to WAM Run 3 shows a decrease in the volume of water and sediment that passes each of the gages in the Basin. At the Ruliff gage, the most downstream gage on the Sabine River used in this study, Run 3 water volume is about 66% of the Run 8 volume and the sediment load for Run 3 is about 50% less than Run 8 sediment load. The Effective Discharge at Ruliff remains about 21,000 cfs for both Run 3 and Run 8. This implies the channel may get smaller over time because of less flow in the channel. Depending on the how the flow and sediment diversions occur upstream of Ruliff, the channel could remain relative stable or become unstable with a tendency to incise and/or the meander wavelength could decrease, leading to bank caving and other channel instabilities. The Effective Discharge for Run 3 at Bon Weir is reduced by about 30%. This reduction should be expected to lead to losses in

channel width and depth, resulting in a smaller channel over time. Again, some incision and bank caving should be expected while the channel adjusts to the new flow regime. The rate of change for the flow regime will determine the severity of the projected channel instabilities. If the changes occur slowly over decades, instabilities will also occur slowly and will be very difficult to detect without detailed hydrographic surveys over that period. If the changes occur rapidly, as they would with the construction of large infrastructures such as a dam or major diversion, instabilities could require more management and mitigation to prevent basin wide channel effects.

The small differences between the Run 8 and Run 3 Effective Discharges and annual water and sediment yields at the other gage locations (Beckville and Gladewater on the Sabine River, Evadale and Rockland on the Neches River, and Chireno on Attoyac Bayou) do not indicate that significant changes in channel bathymetry would be likely to occur as a result of these changed conditions..

Conclusions

When comparing the Effective Discharge for WAM Run 8 to the Hydrologic Environmental Flow Regimes under consideration by Sabine-Neches BBEST, it appears that High Flow Pulses and Overbank Flows will provide sufficient flow to maintain the existing dynamic equilibrium of the rivers and streams in the two basins. In making this determination of the continued stability of channels, it is assumed that future permitting activities will protect the High Flow Pulses and Overbank Flows prescribed by the HEFR analysis at each gaging station.

	WAM Run 8 Effective Discharge in CFS	Number of Days Flow is in Effective Discharge Bin	Highest Seasonal High flow Pulse	Duration of Highest Seasonal High Flow Pulse	HEFR Overbank Flow	HEFR Overbank Flow Frequency	Annual Duration of HEFR Overbank Flow Frequency
			Sabine River Basin				
Ruliff	21,760	19	9,880	22	29,000	1 per year	60
Bon Weir	19,997	9	20,600	17	28,700	1 per year	28
Beckville	5,960	15	7,200	24	16,100	1 per 2 years	45
Gladewater	5,650	8	5,570	24	18,100	1 per 2 years	22
			Neches River Basin				
Evadale	17,622	5	8,700	22	19,500	1 per year	38
Rockland	5,500	12	6,910	22	18,500	1 per 2 years	41
Chireno	1,264	12	1,200	12	7,520	1 per 2 years	27

Table 1 Effectice Discharge and High Pulse Flows

Location	Run 8 Effective Discharge	WAM Run 8 Annual Water yield AC-FT	WAM Run 8 Annual Sediment Yield Tons	Run 3 Effective Discharge	WAM Run 3 Annual Water yield AC-FT	WAM Run 3 Annual Sediment Yield Tons	Sediment Function used
		Sabine River Basin					
Ruliff	21,760	6,146,000	284,688	21,065	4,222,000	144,000	ENGELUND -HANSEN
Bon Weir	19,997	4,919,000	81,674	13,812	3,066,000	43,643	YANG,D50
Beckville	5,960	1,731,000	111,579	5,961	1,393,000	81,675	ENGELUND -HANSEN
Gladewater	5,650	1,213,000	300,433	5,437	969,000	206,775	ENGELUND -HANSEN
		Neches River Basin					
Evadale	17,622	4,718,000	279,335	16,202	4,237,000	221,440	YANG,D50
Rockland	5,500	1,706, 000	154,333	5,406	1,469,000	130,108	YANG,D50
Chireno	1,264	314,000	12,510	*	*		YANG,D50

Table 2 Effective Discharge for RUN 8 and Run 3

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Geomorphic Overlay for the Sabine-Neches BBEST

Appendix A

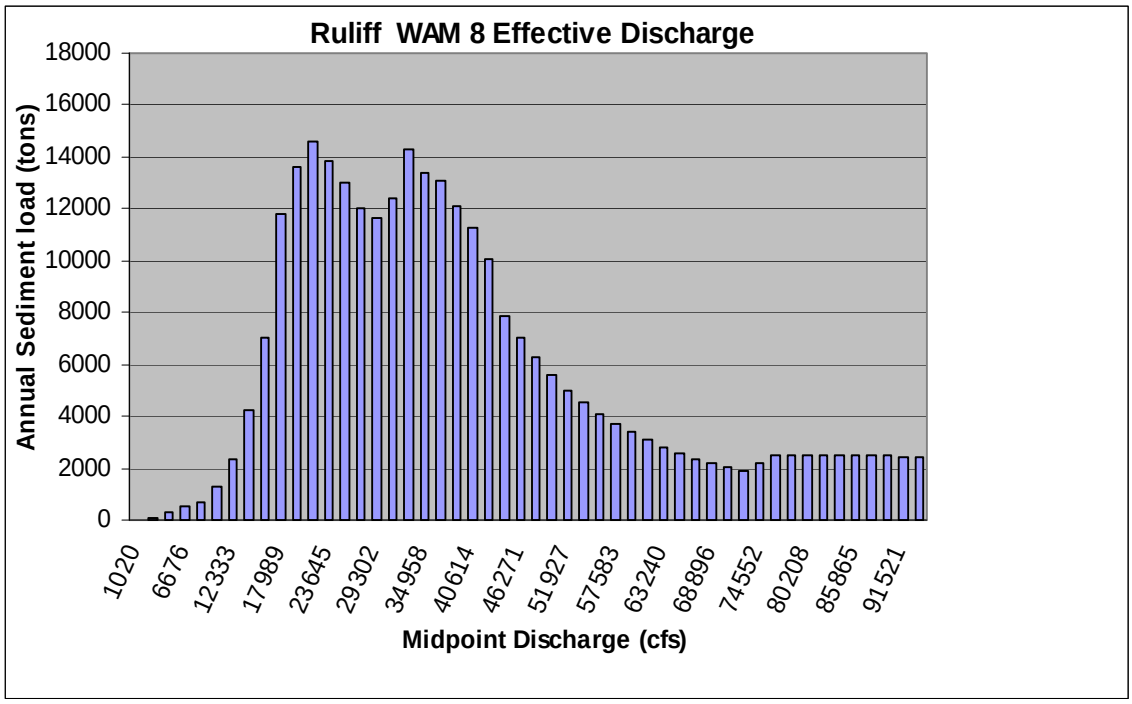


Figure 1A. Effective discharge WAM Run 8 for Ruliff.

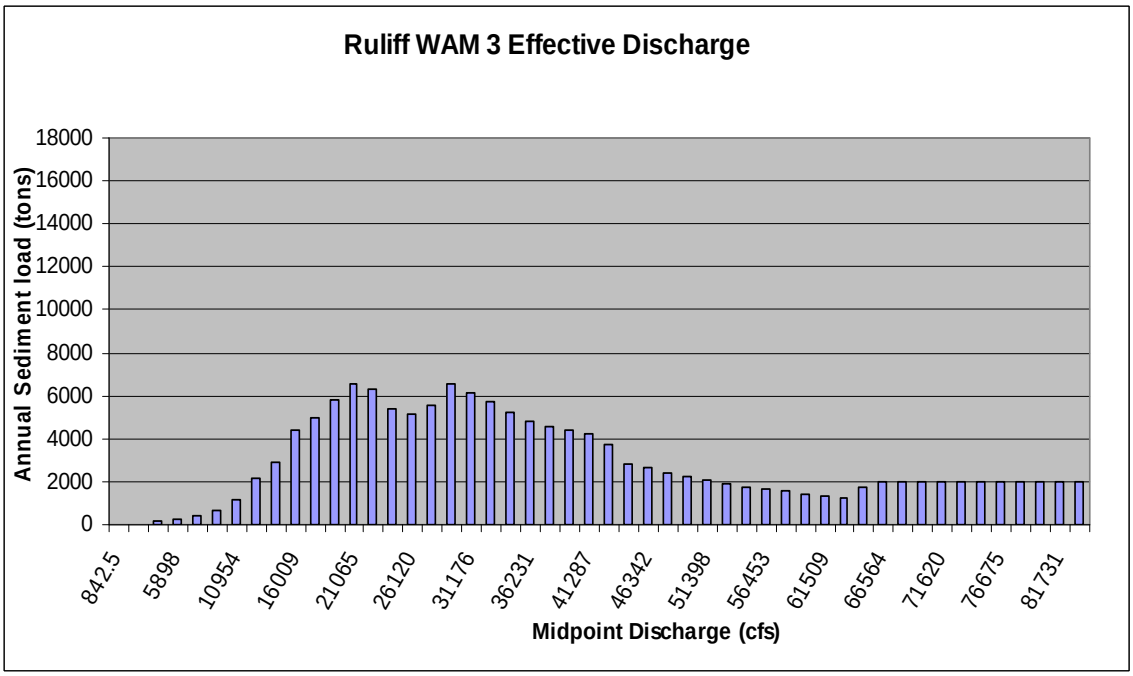


Figure 1B. Effective discharge WAM Run 3 for Ruliff.

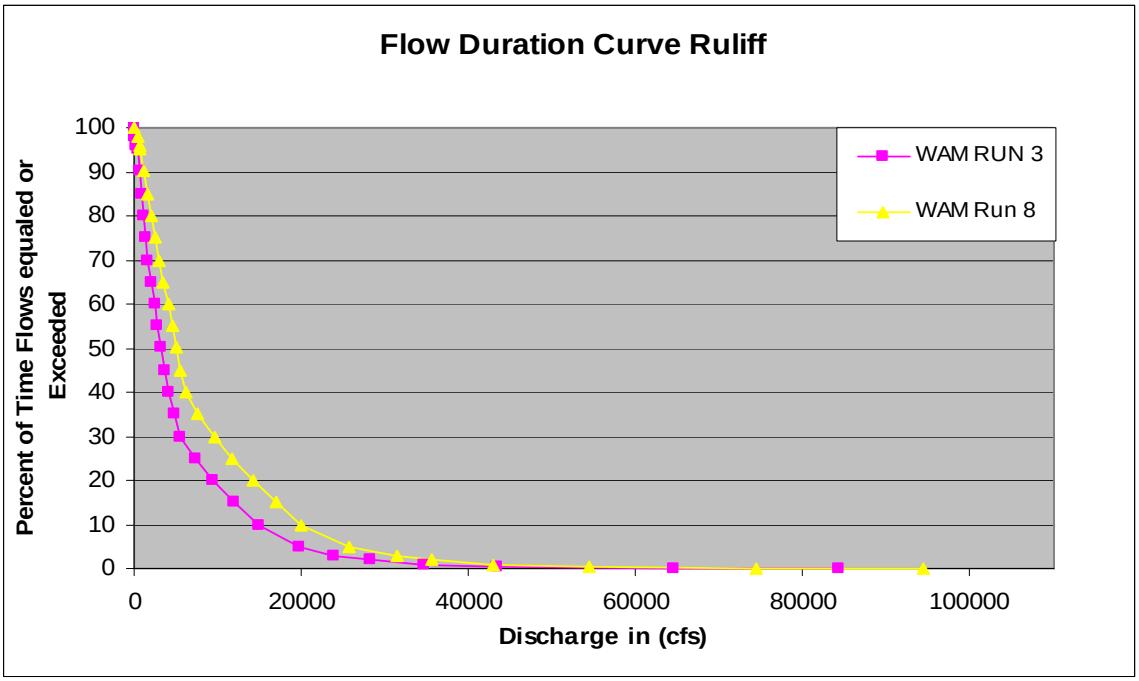


Figure 1C. Flow duration curve for Ruliff.

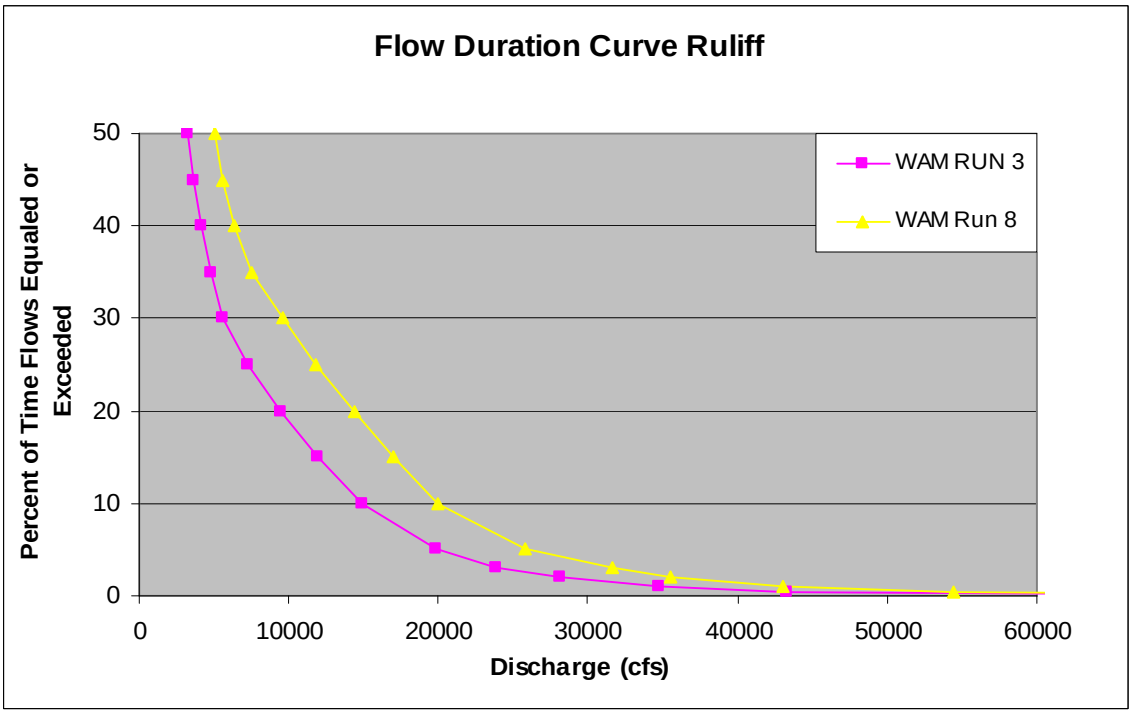


Figure 1D. Flow duration curve for Rullif.

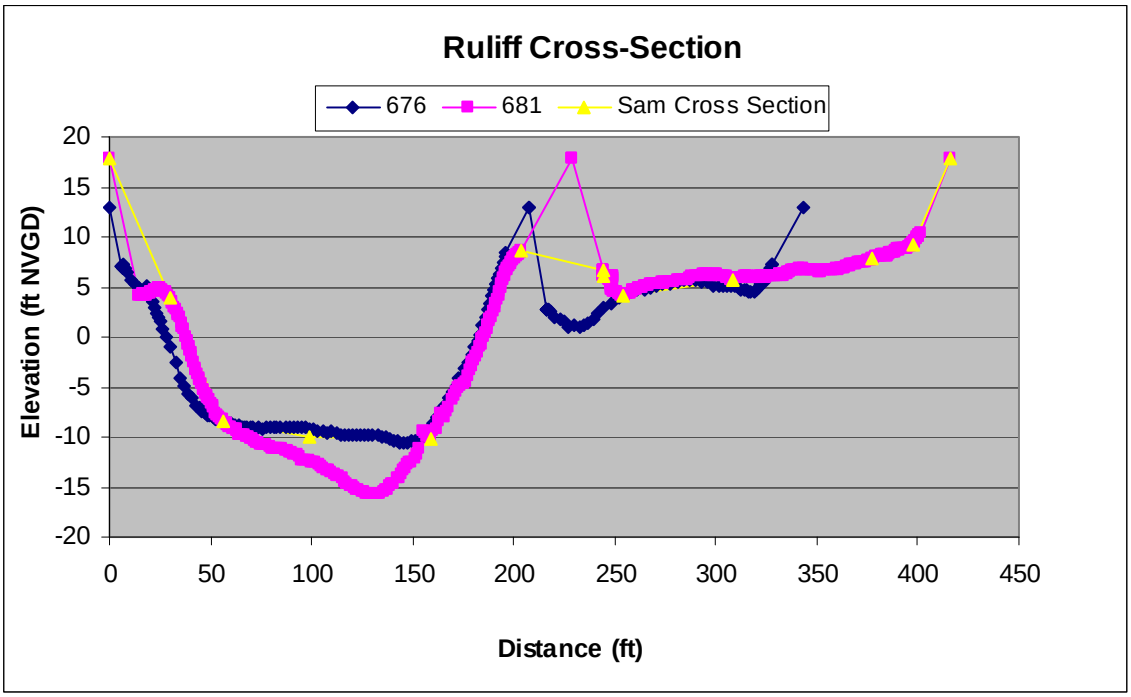


Figure 1E. Cross section for Ruliff.

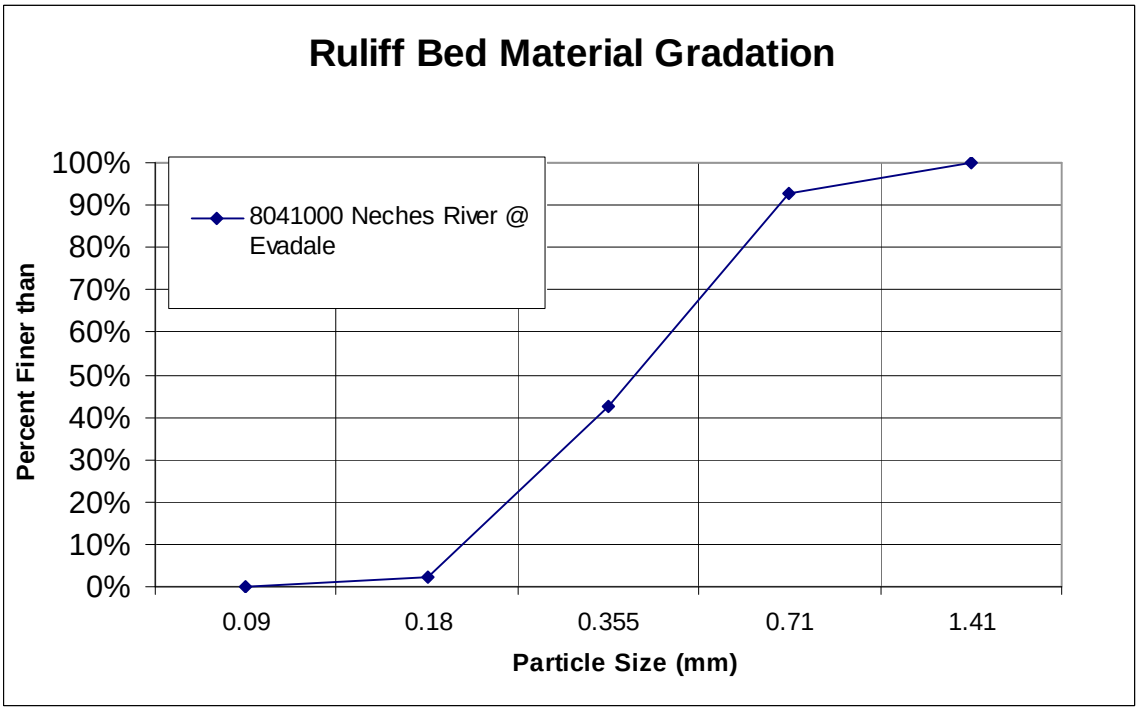
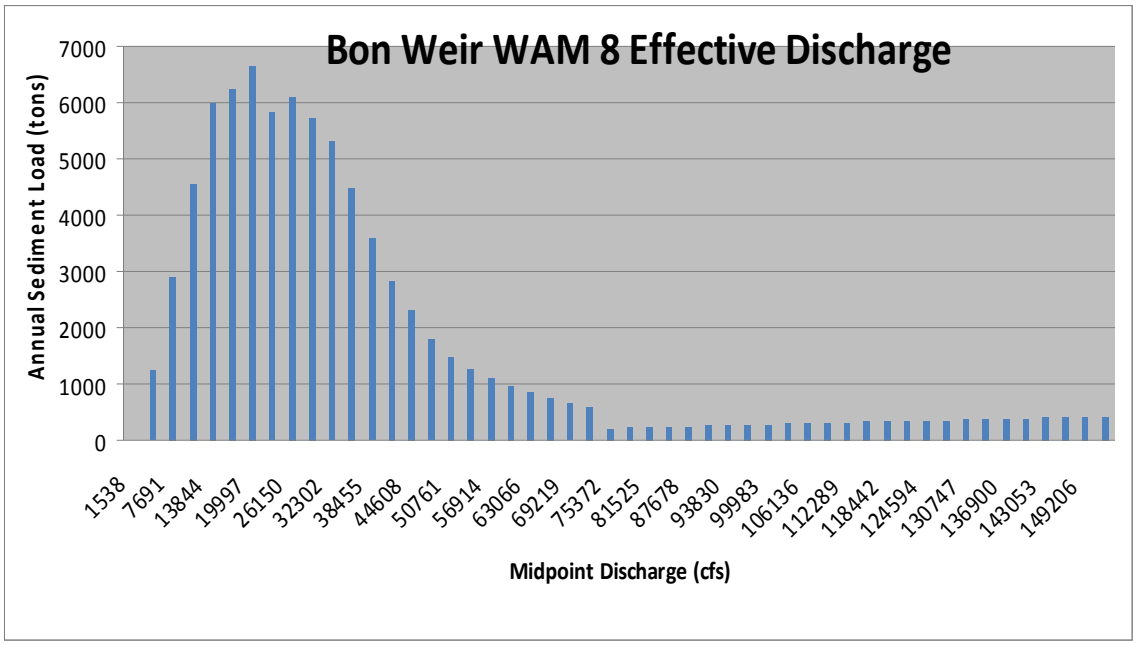


Figure 1F. Bed material gradation for Ruliff.



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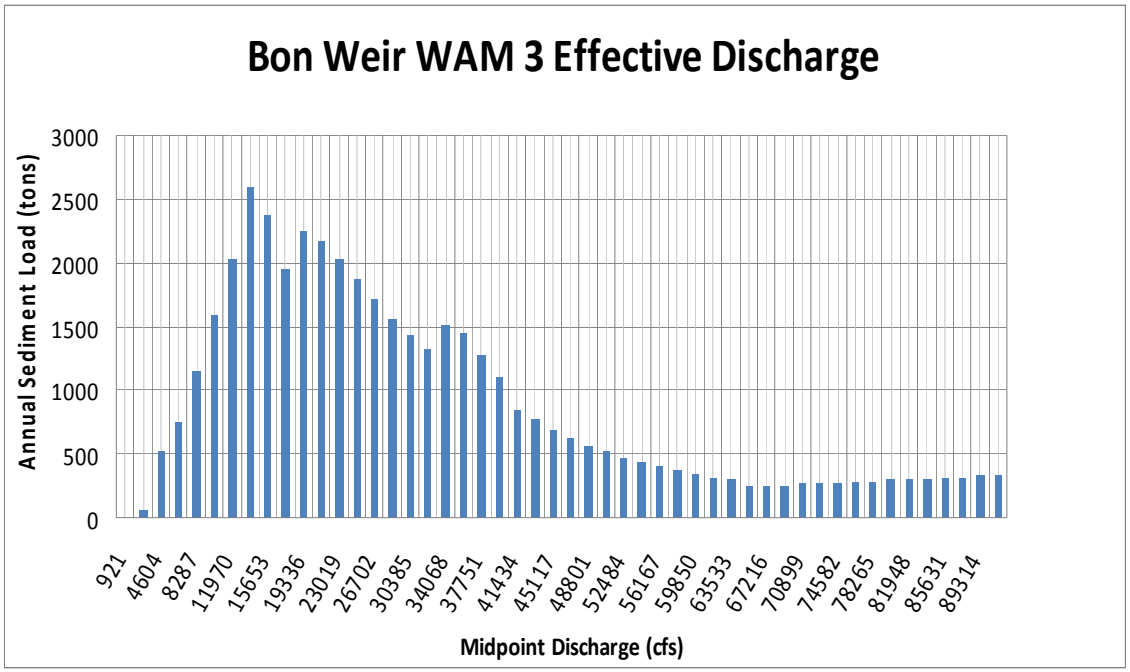

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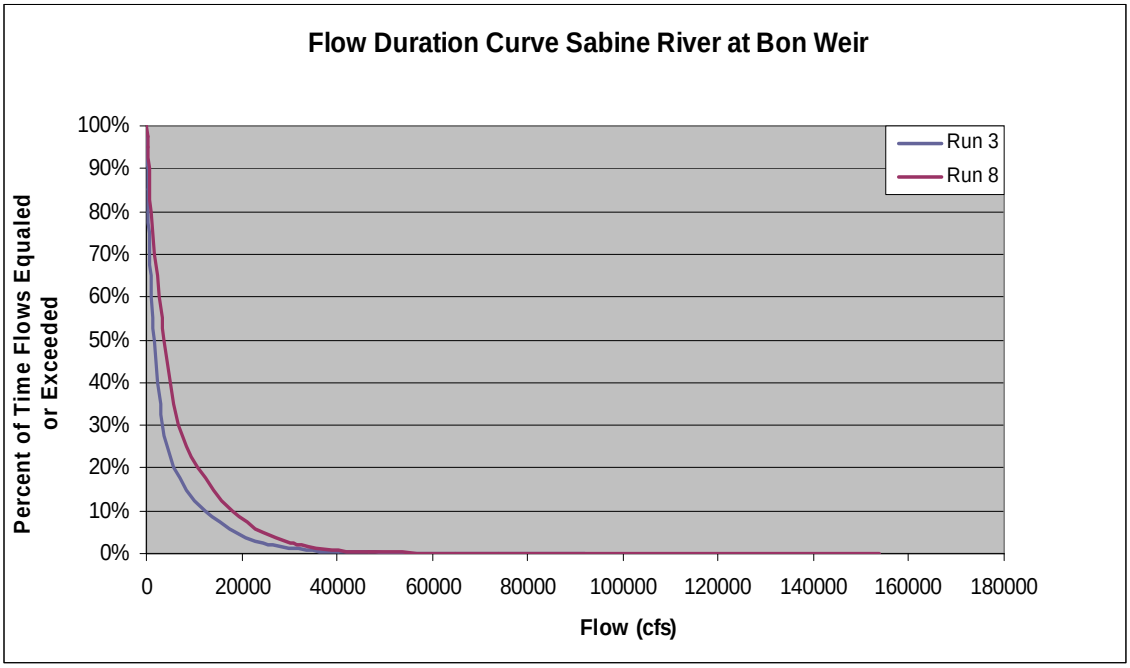

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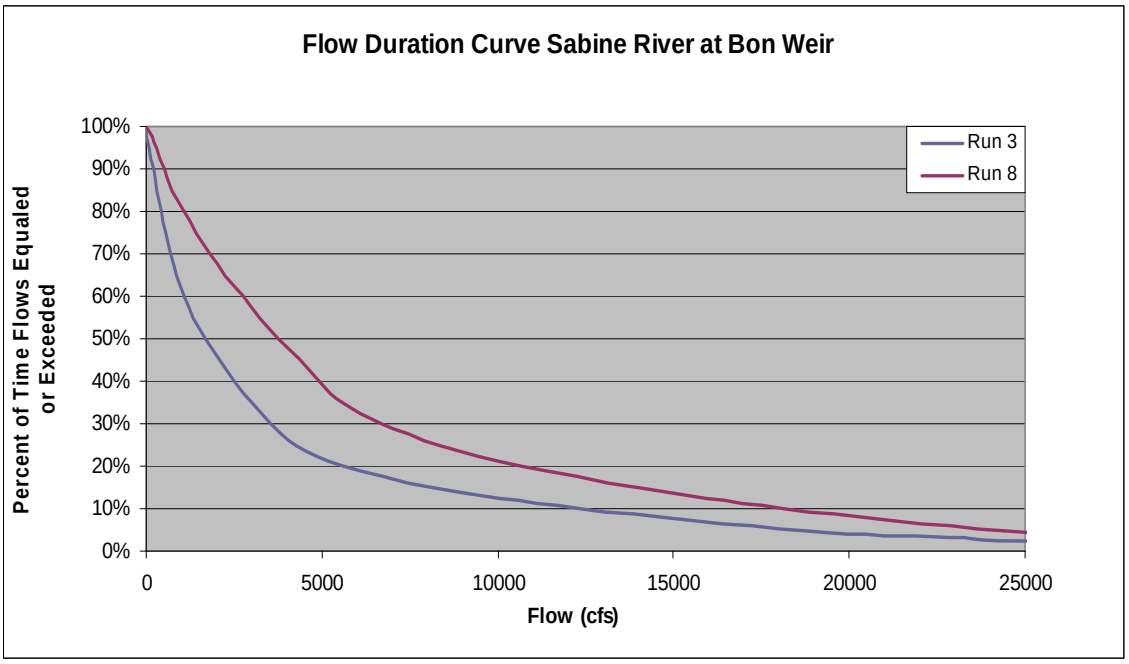

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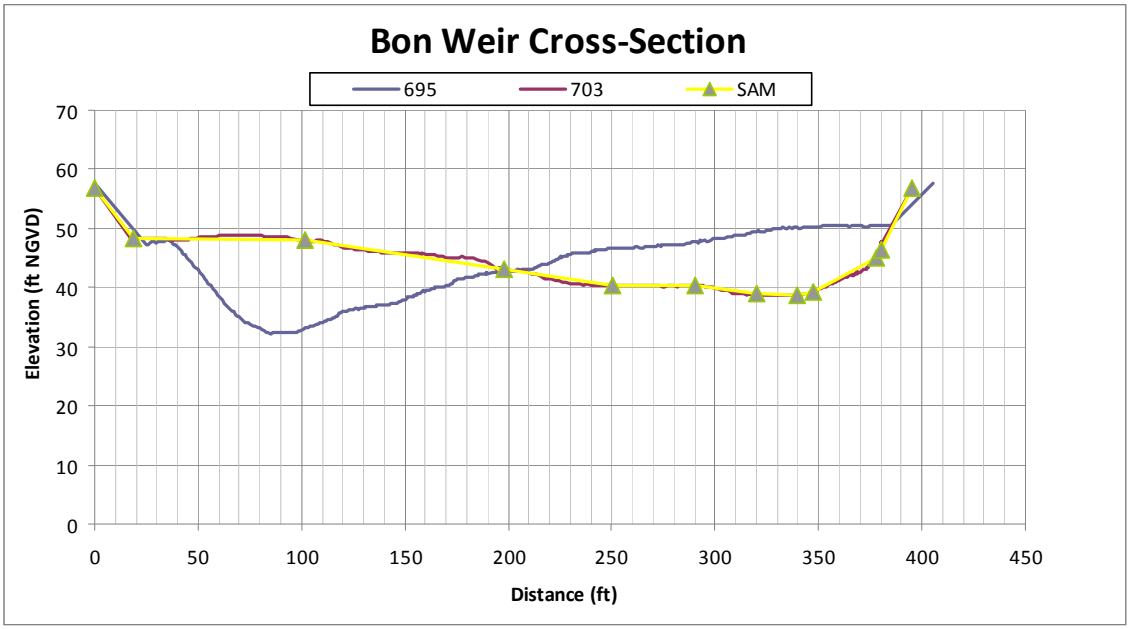

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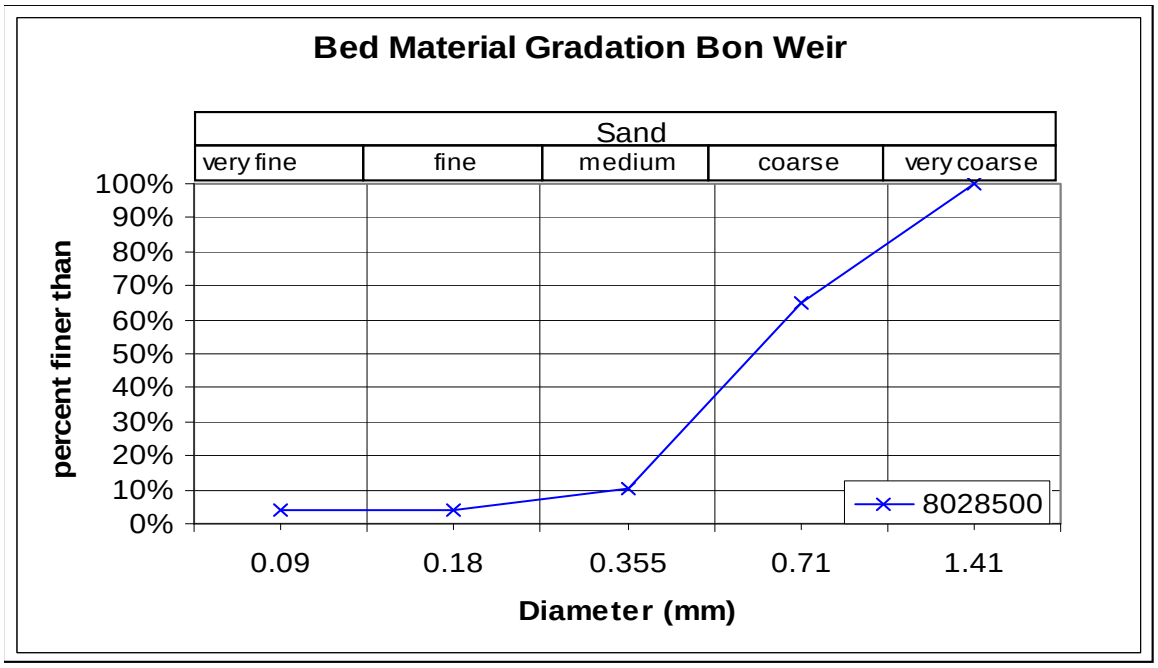

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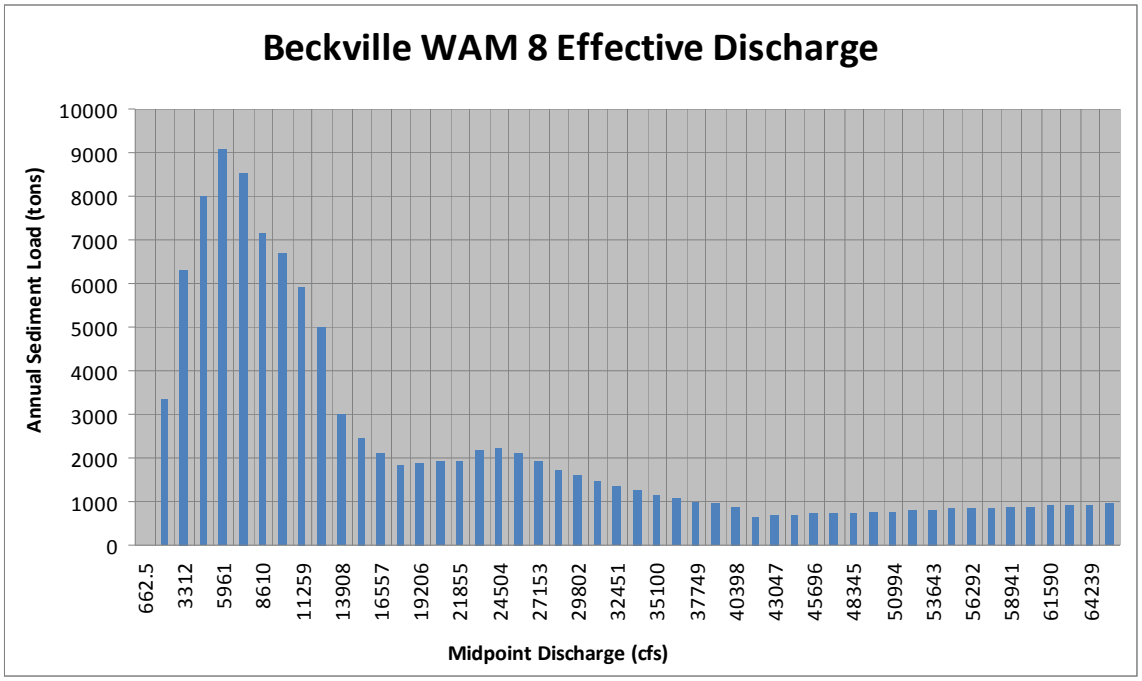

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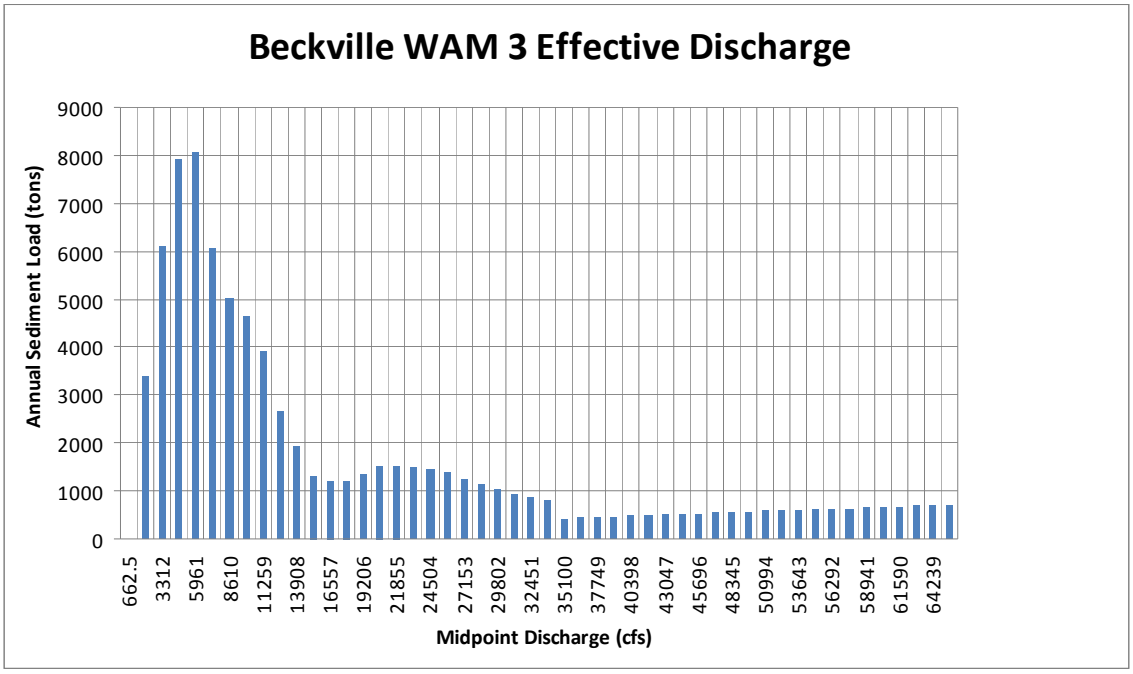

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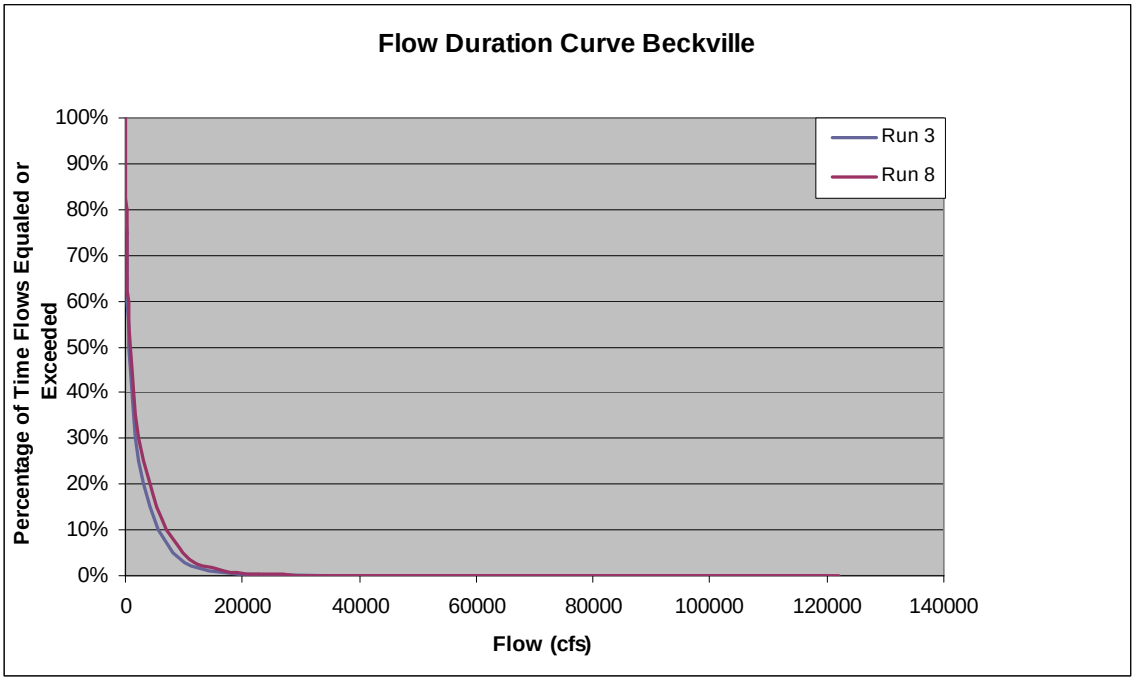

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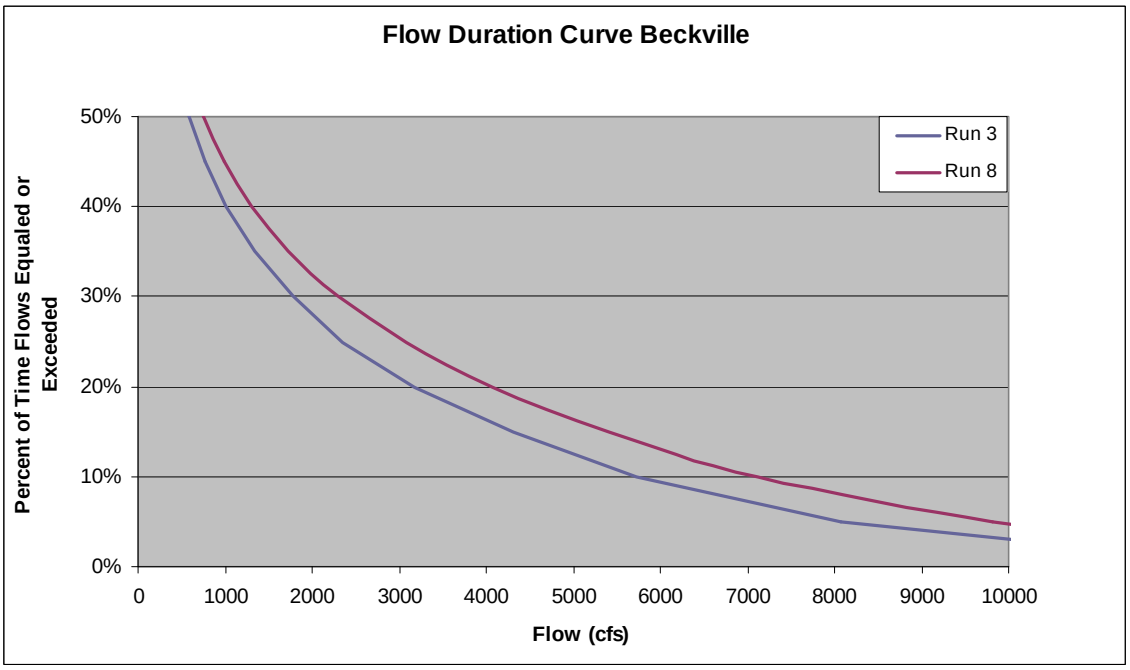

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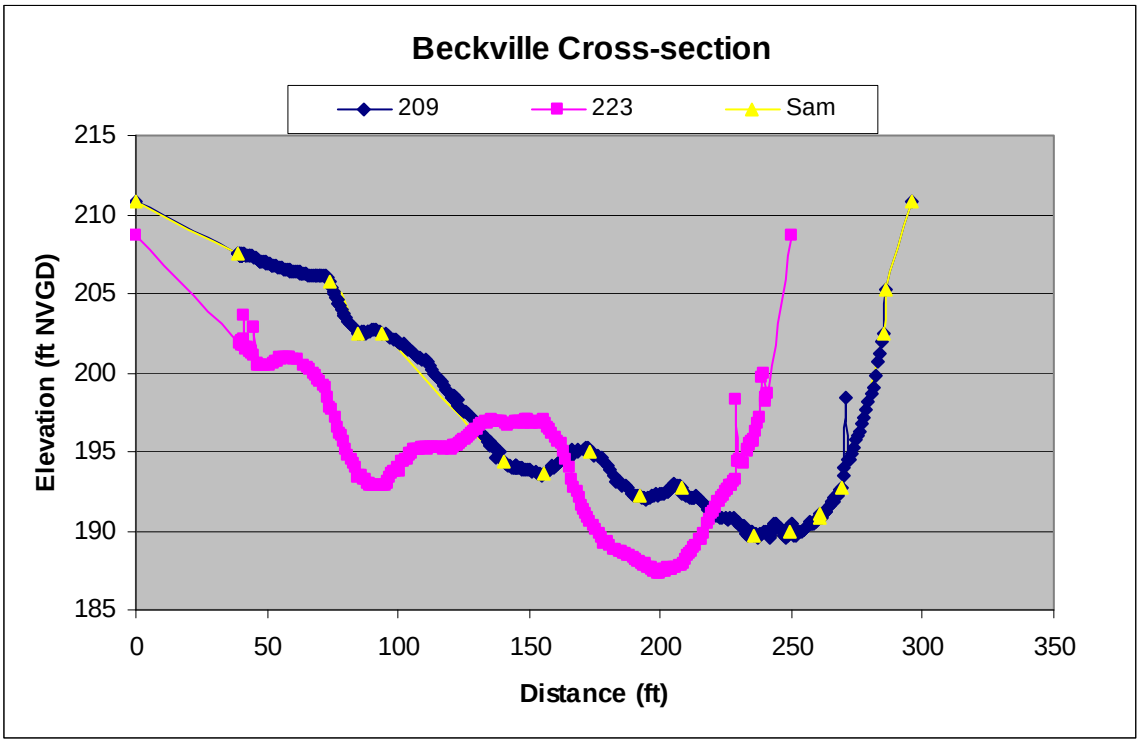

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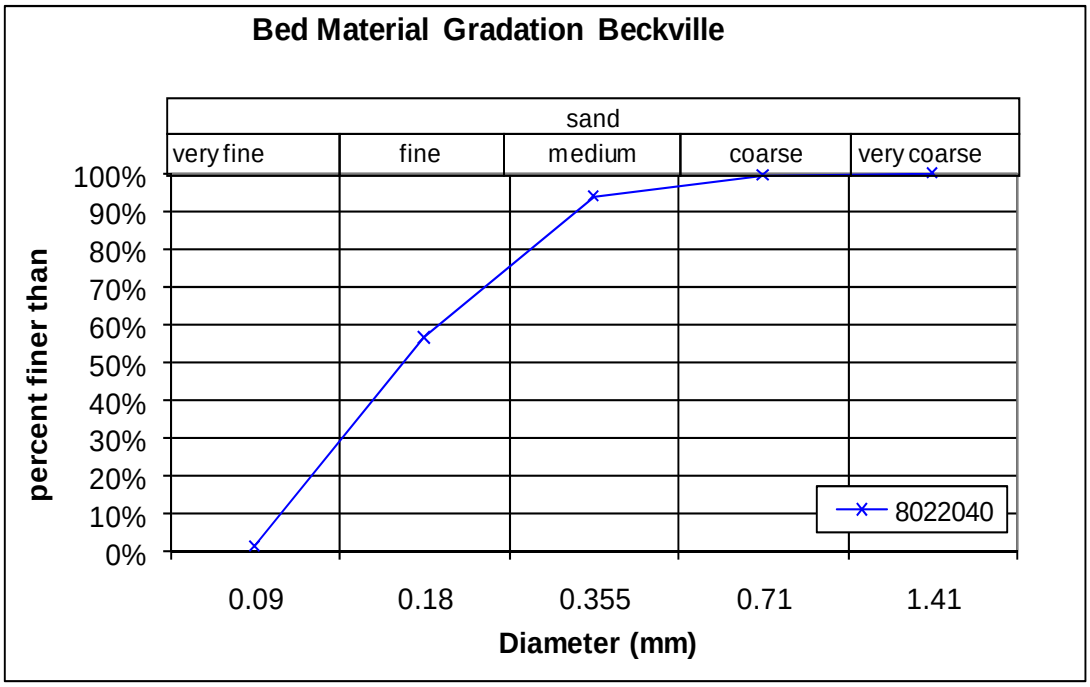

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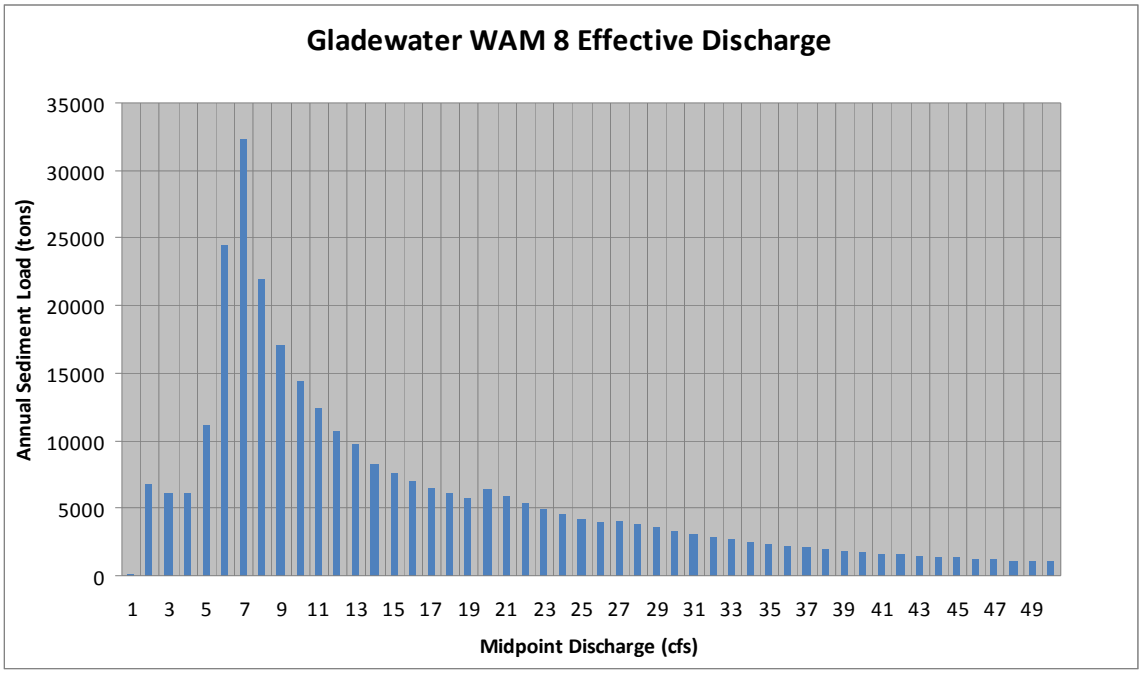

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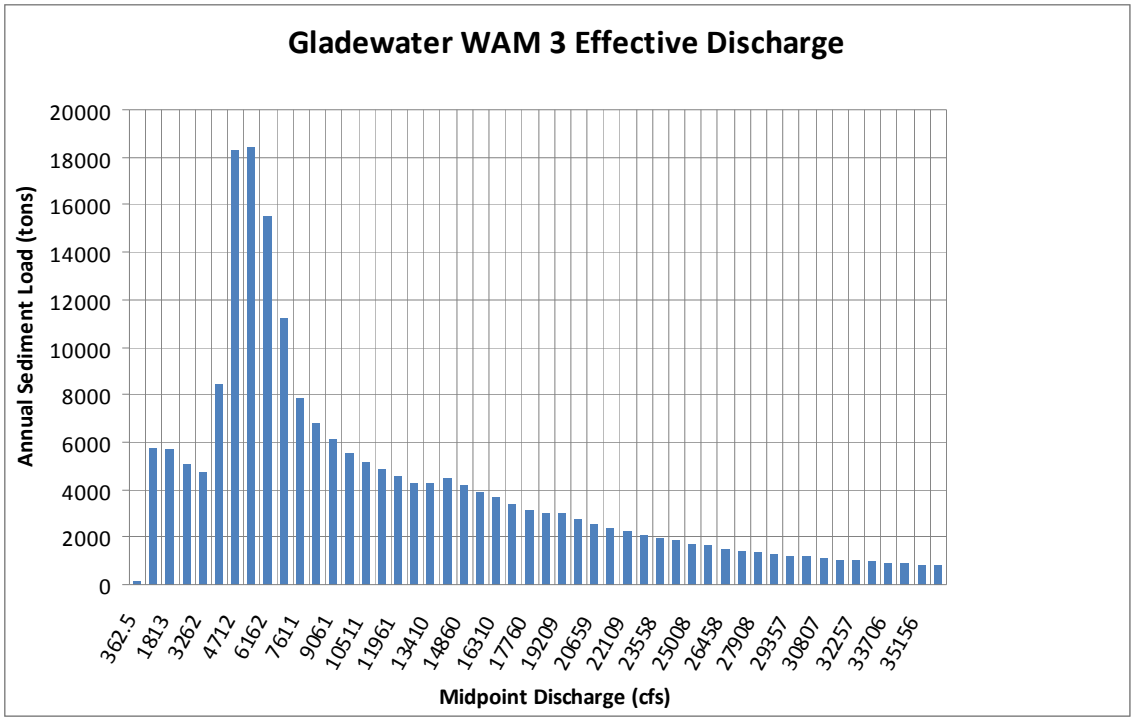

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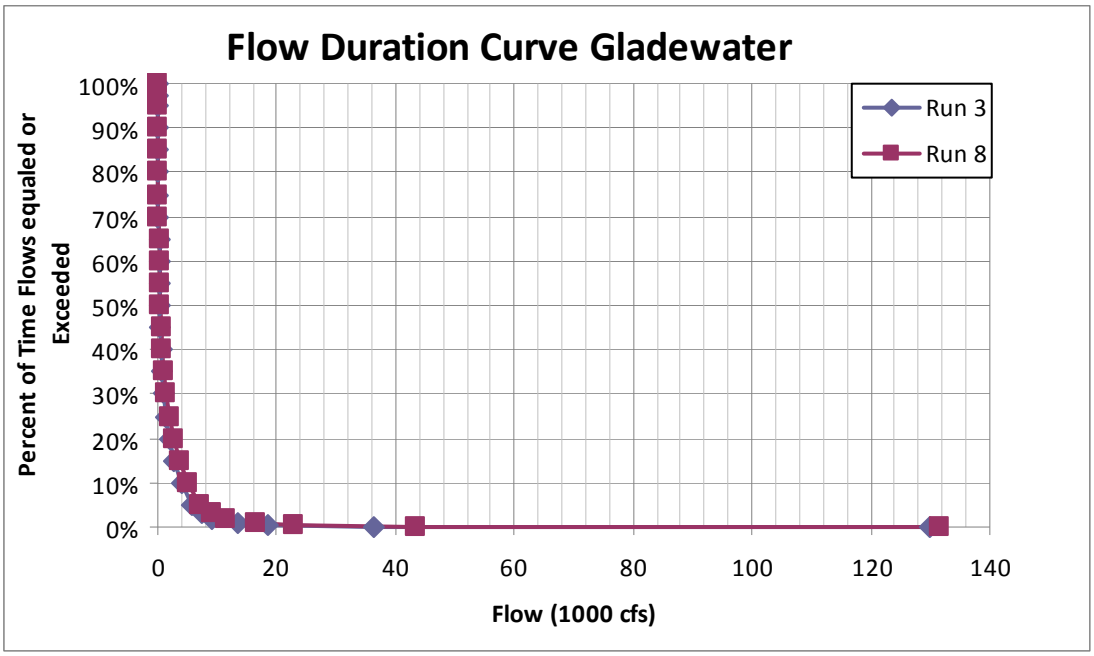
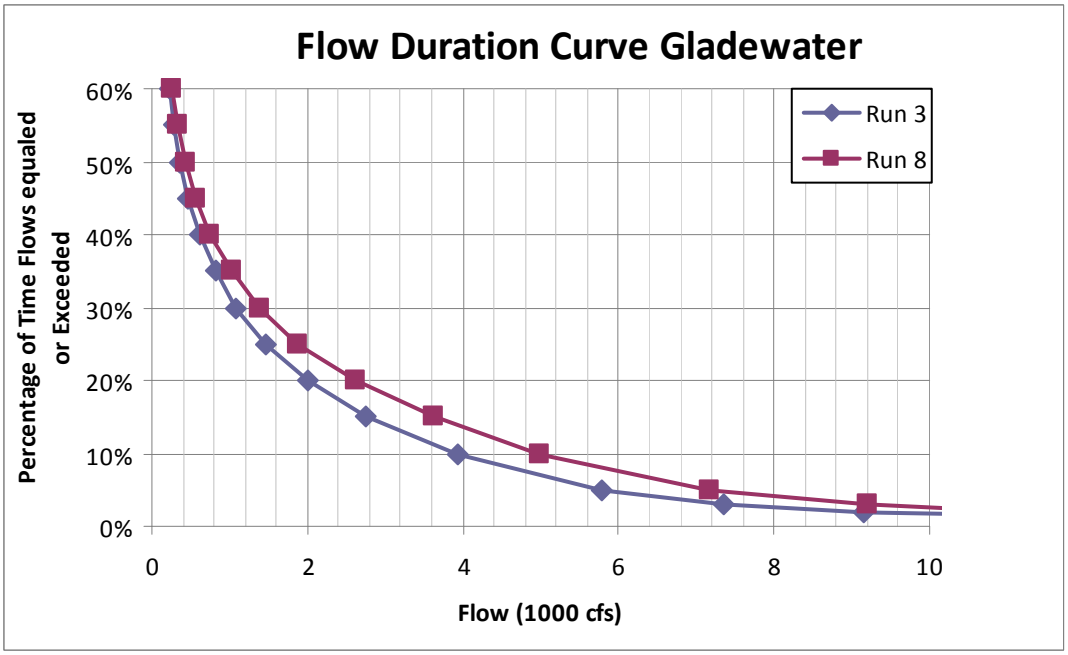


Figure 4C. Flow duration curve for Gladewater.



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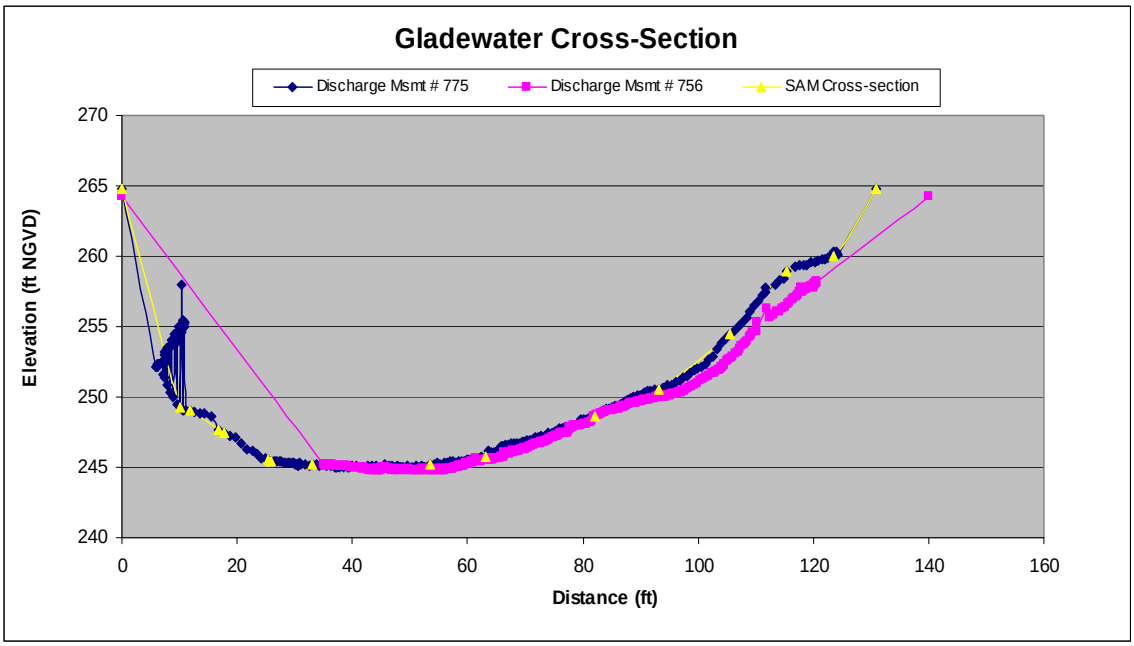

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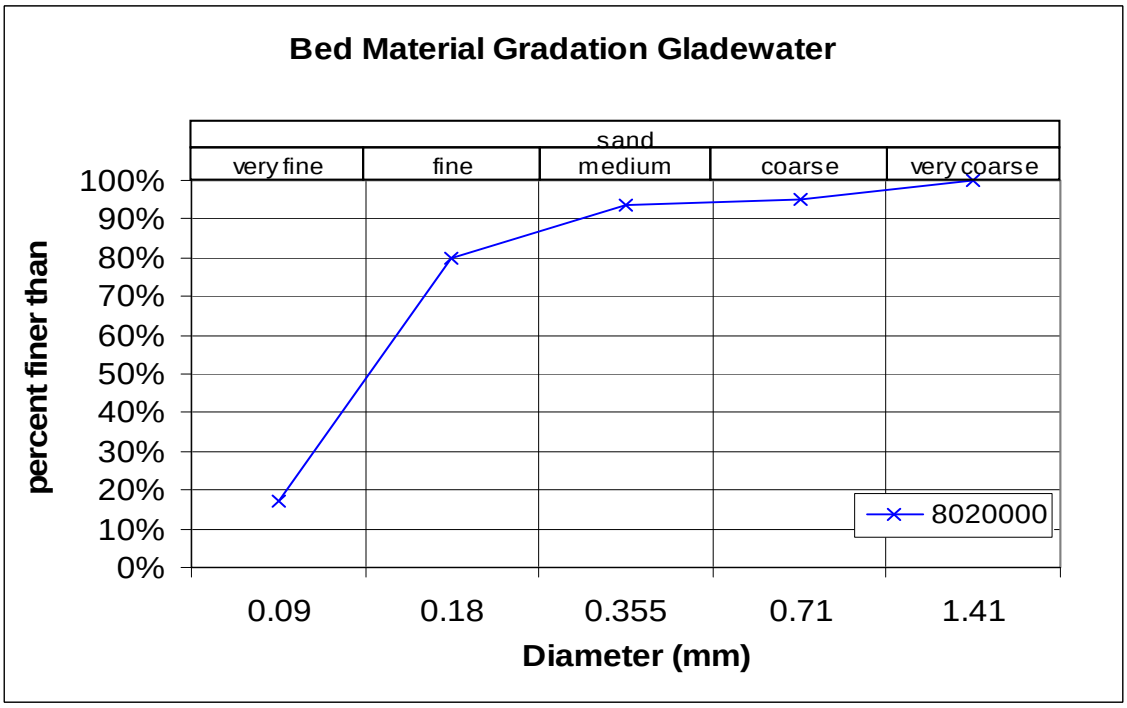

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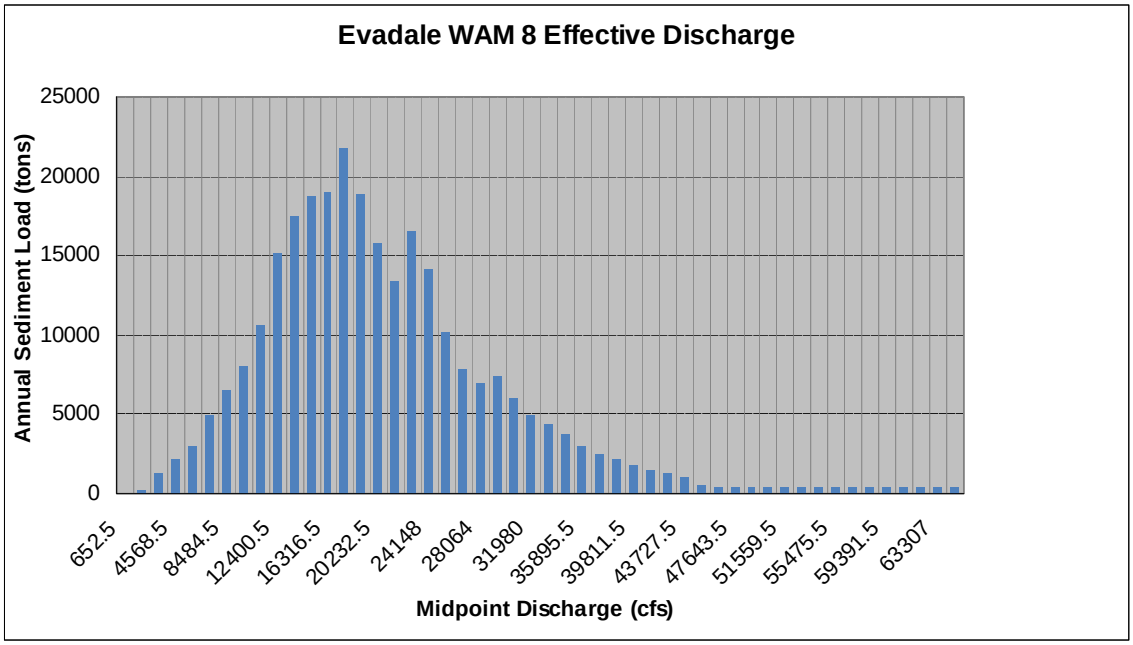

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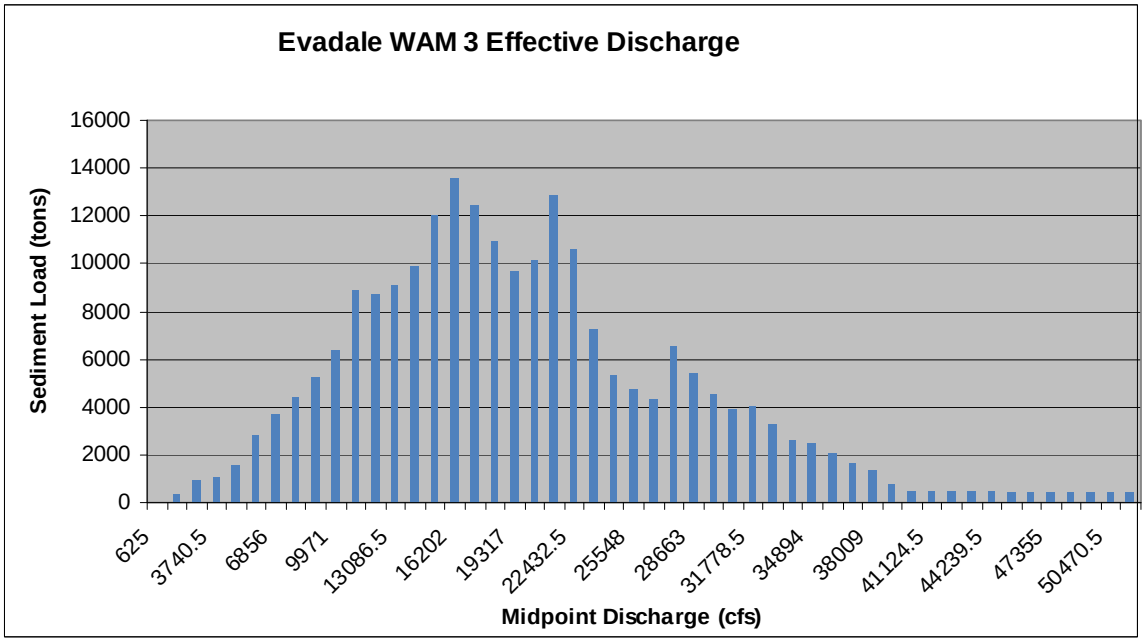

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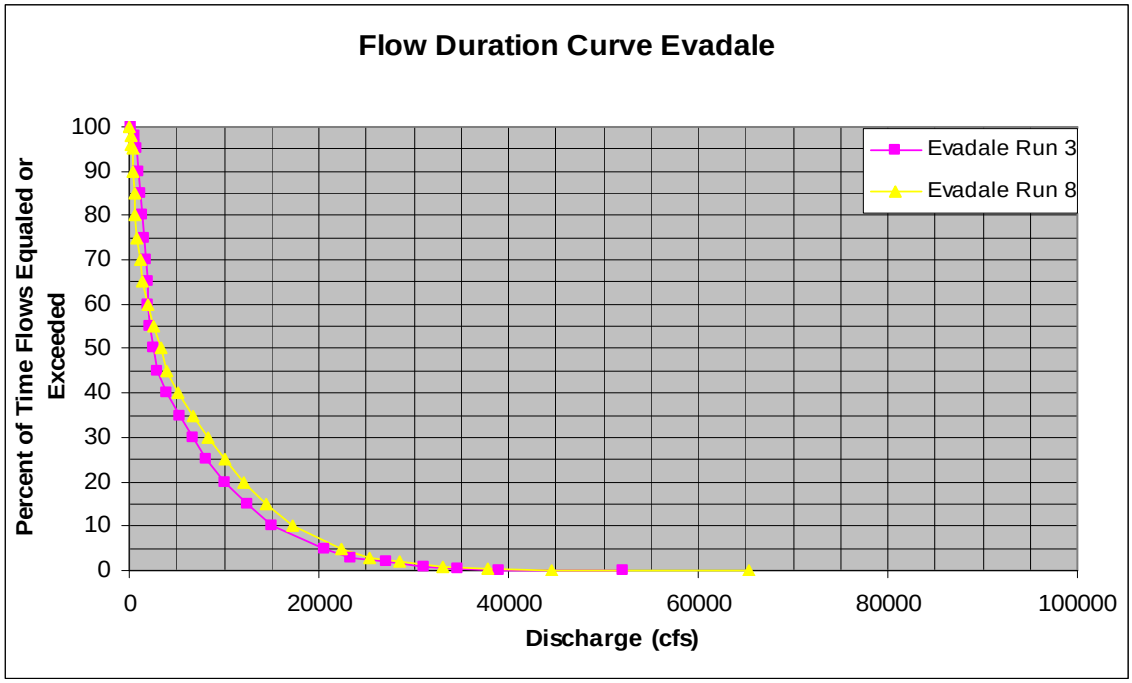
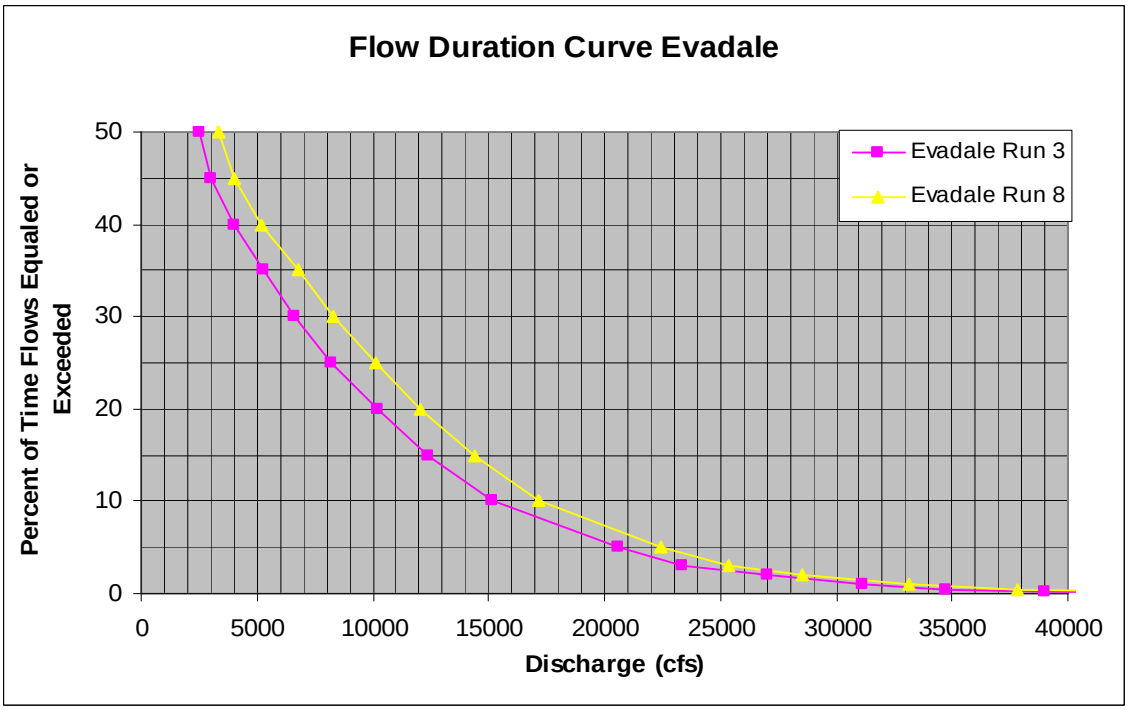


Figure 5C. Flow duration curve for Evadale.



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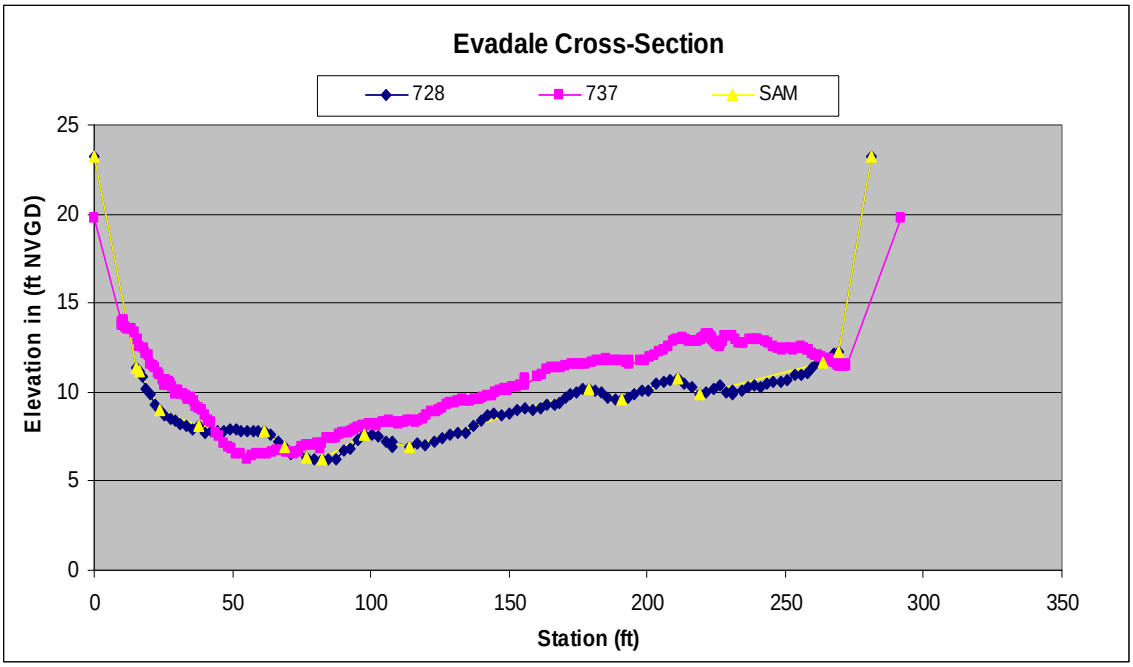

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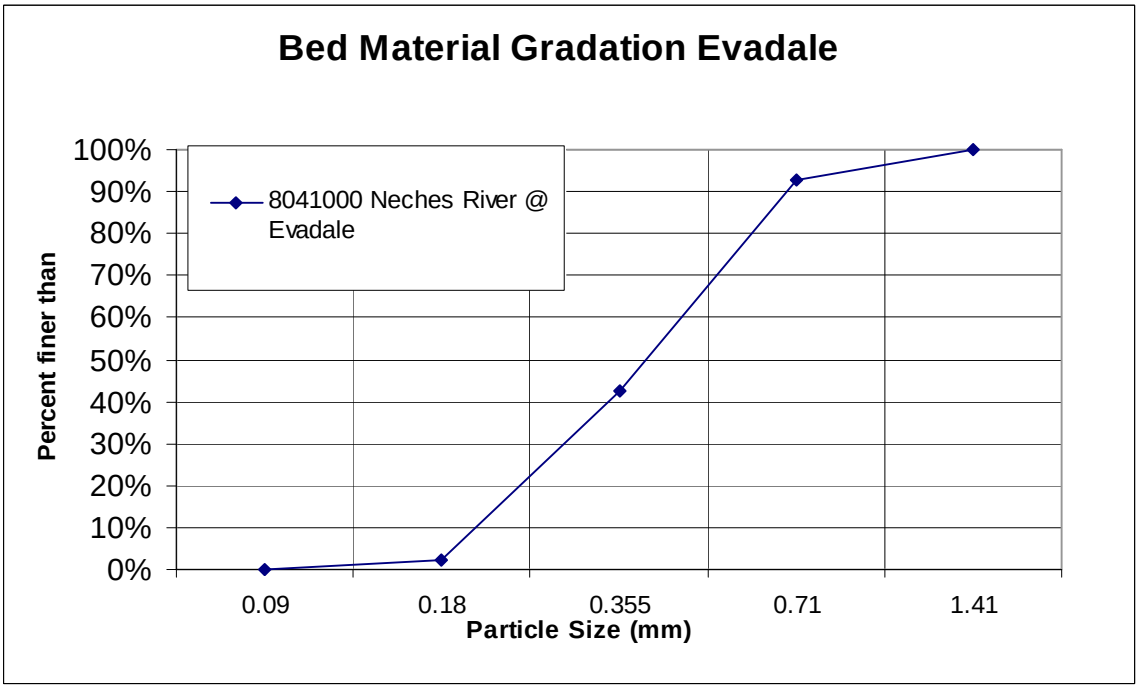

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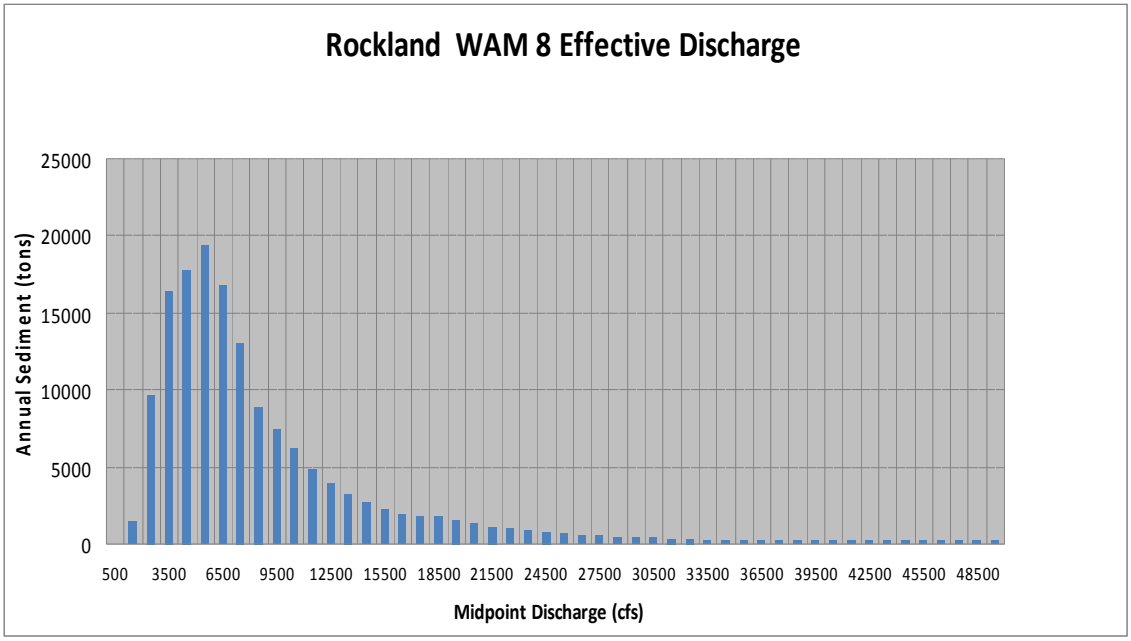

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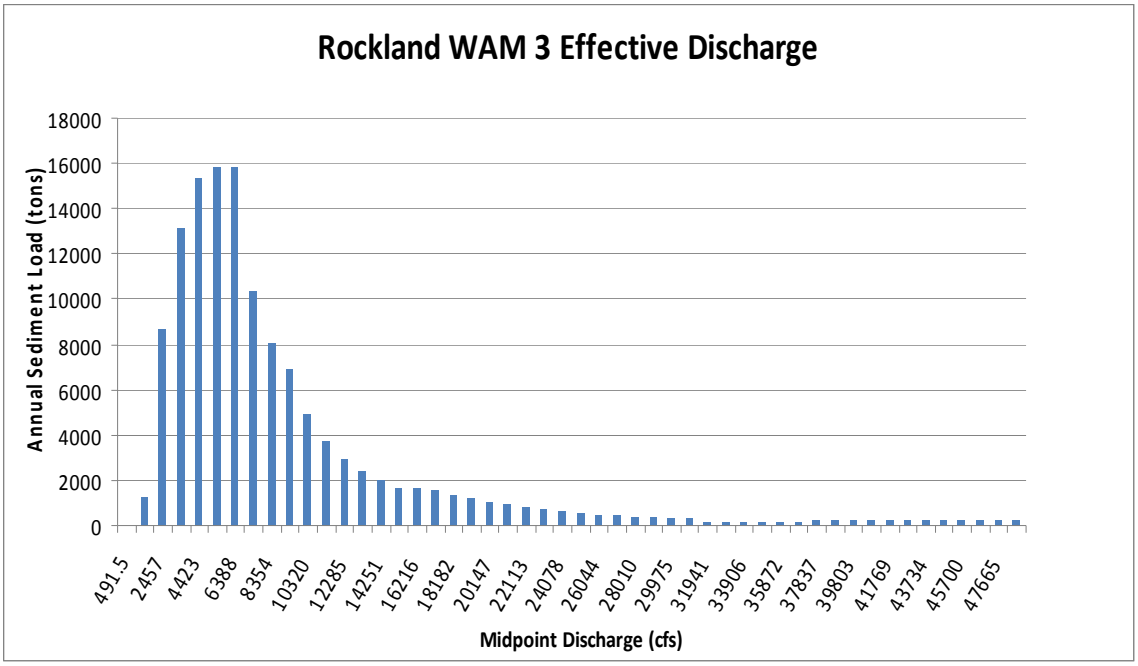

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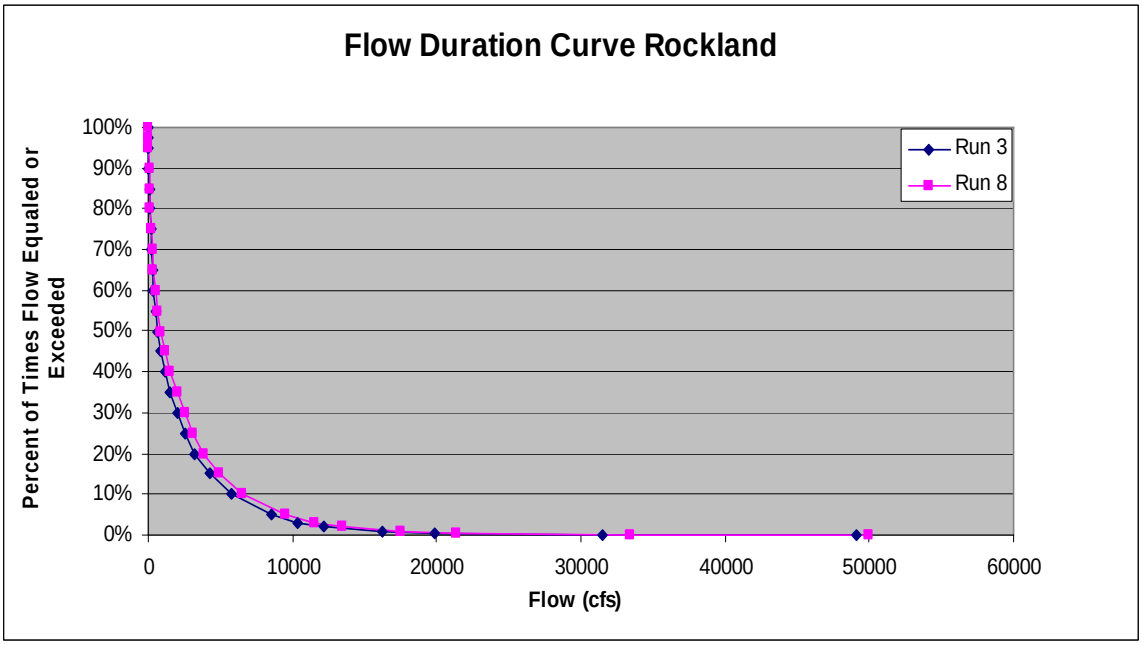

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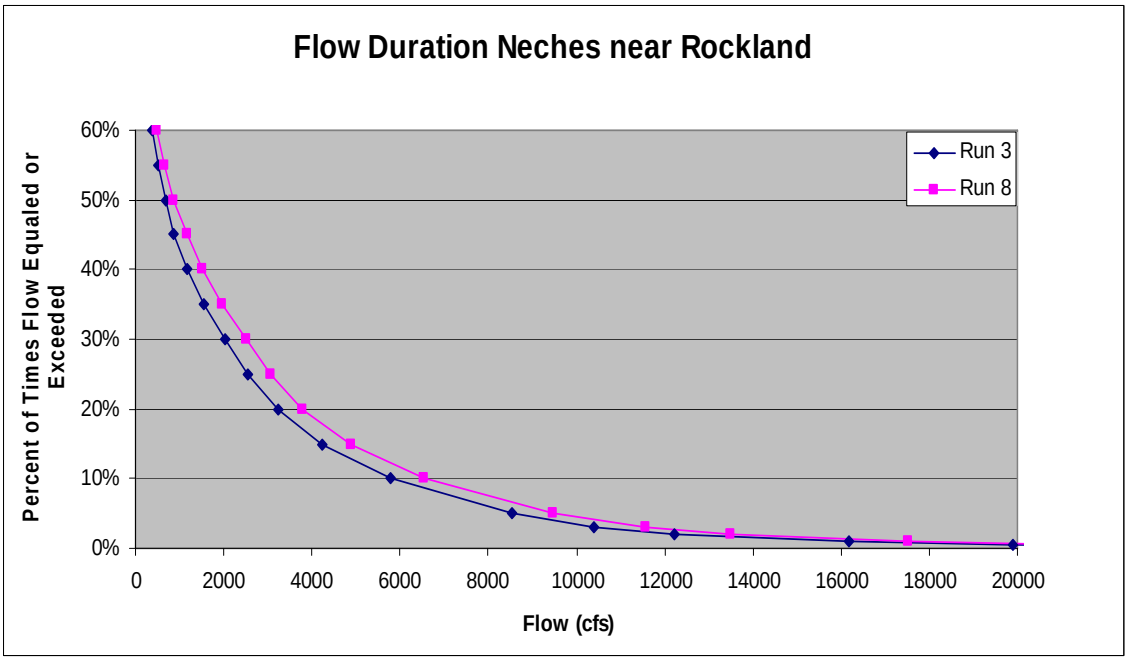

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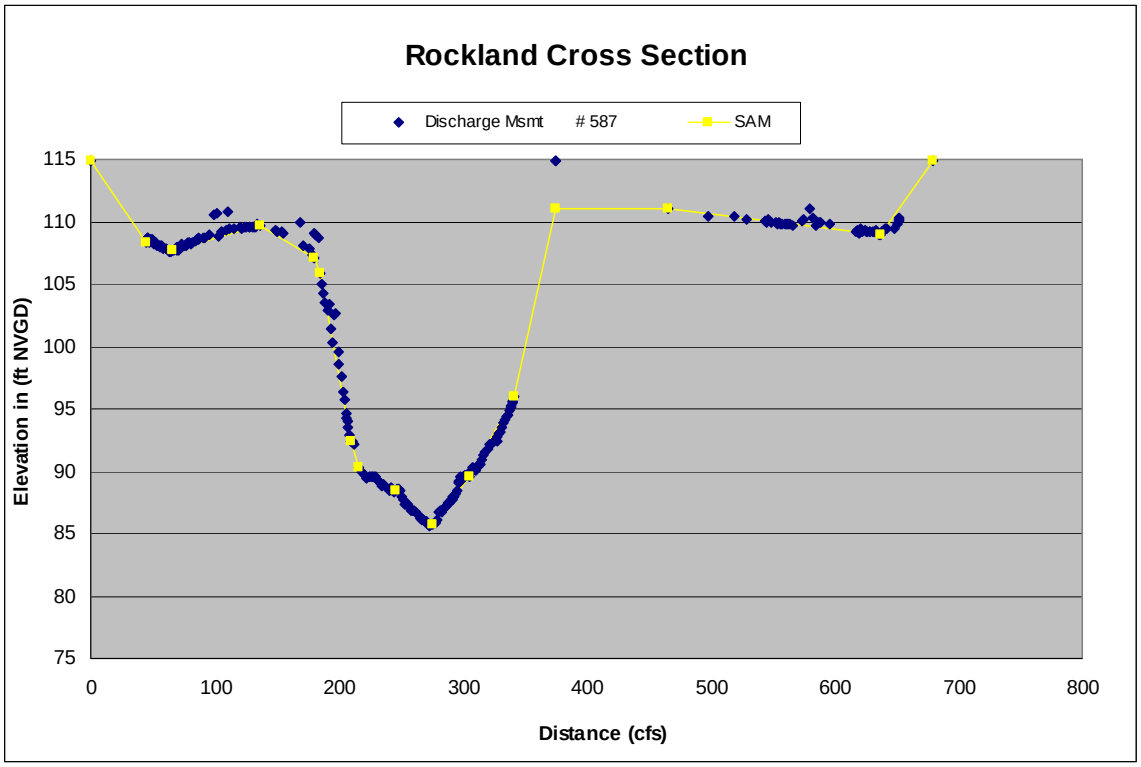

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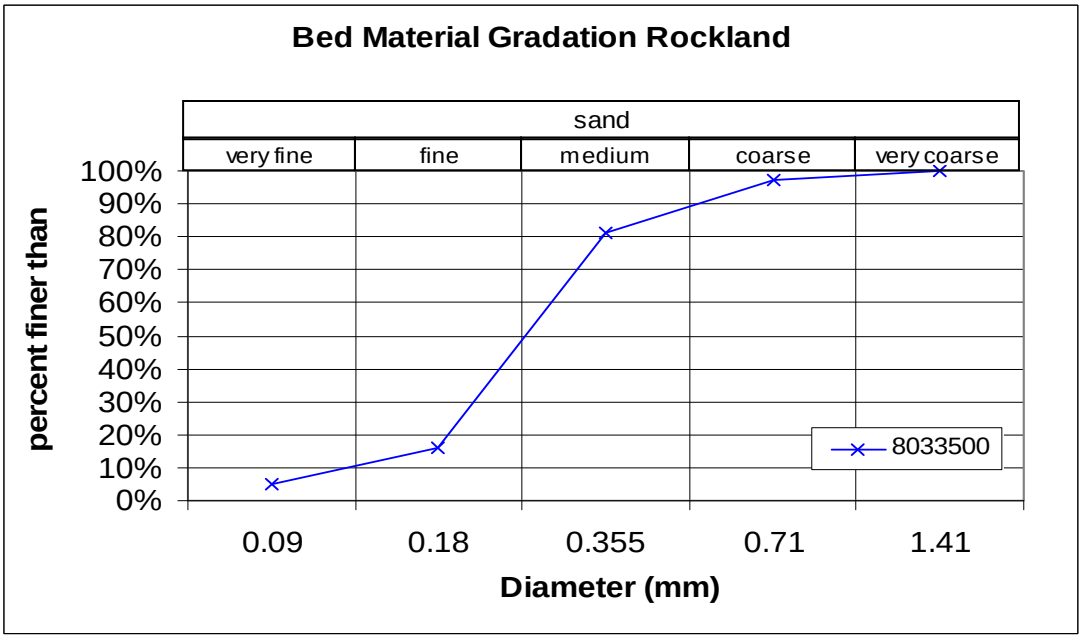

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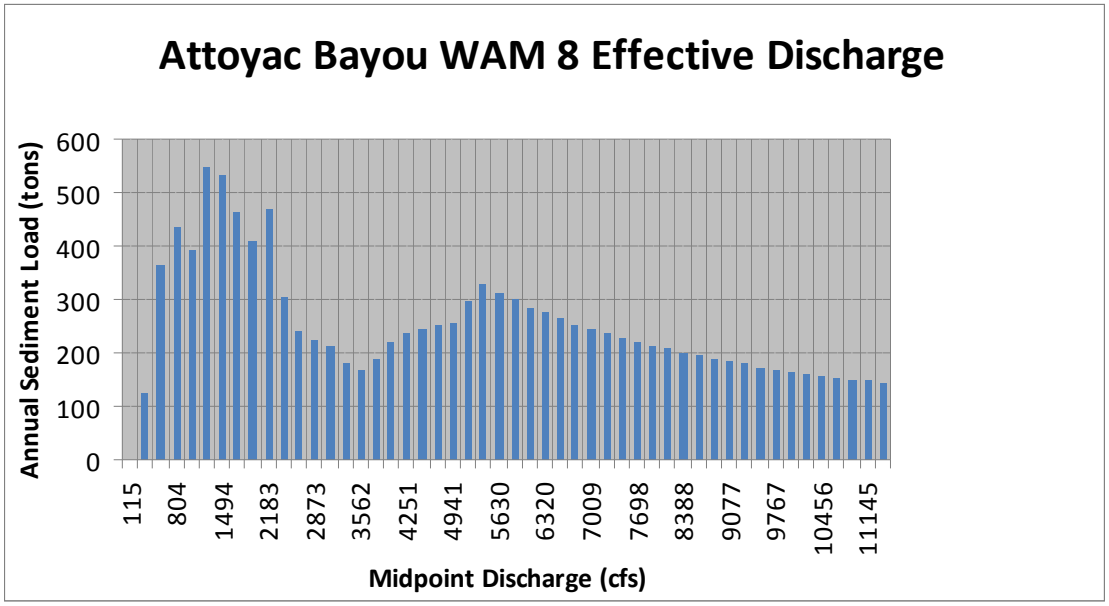

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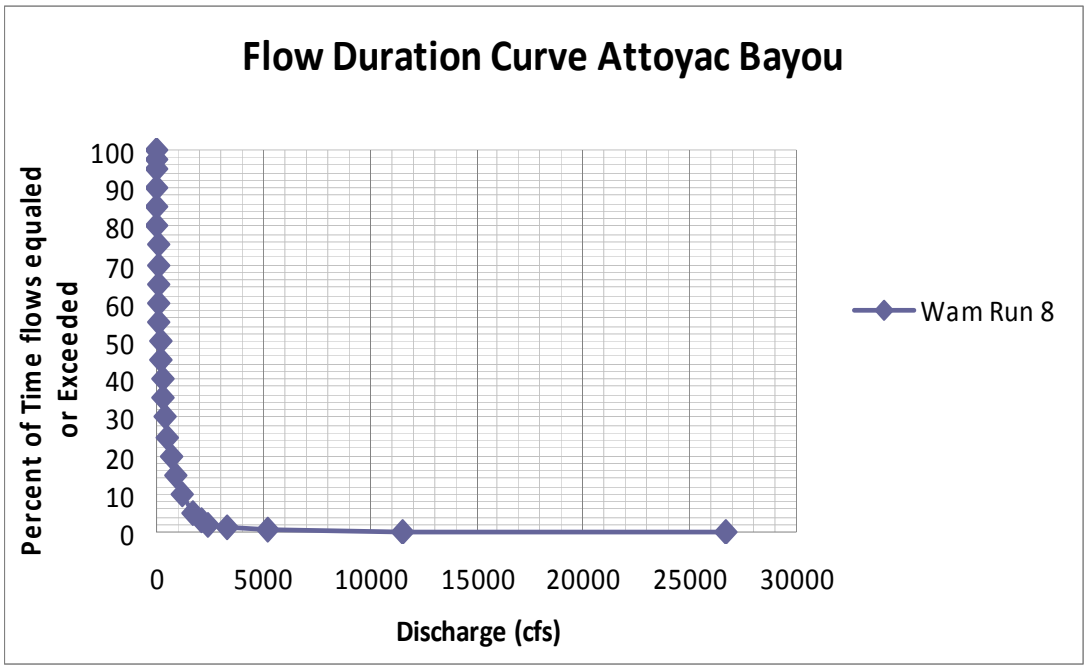

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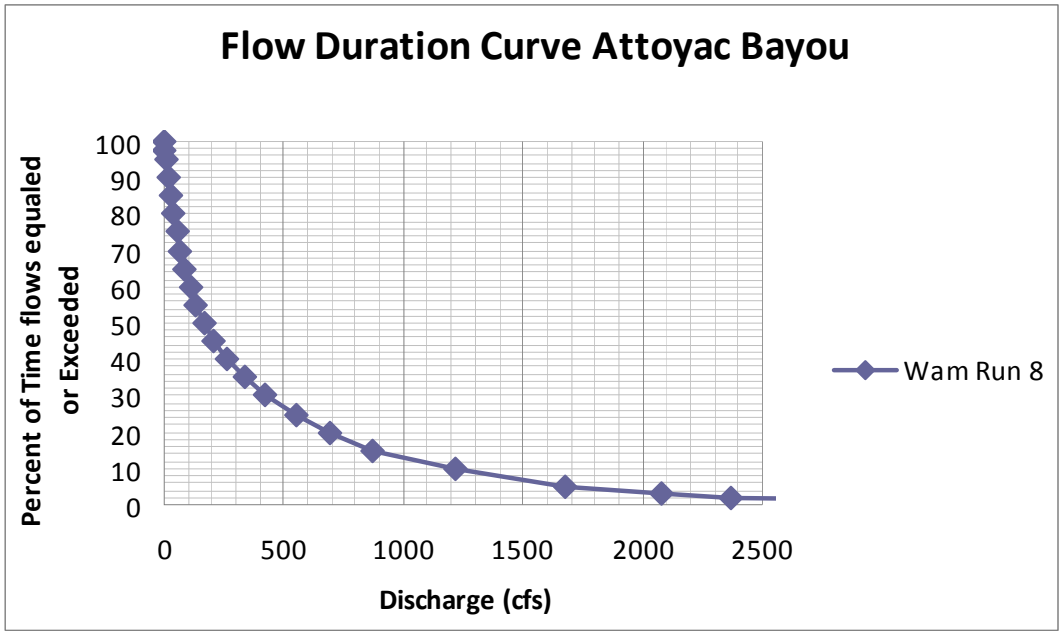
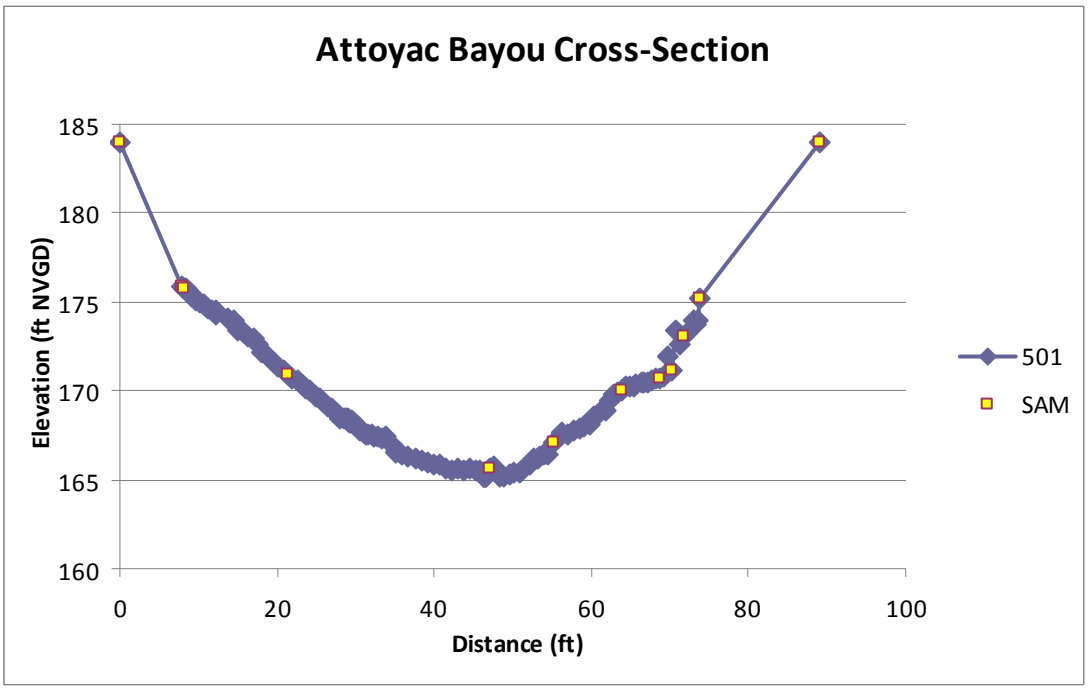


Figure 7C. Flow duration curve for Attoyac Bayou.



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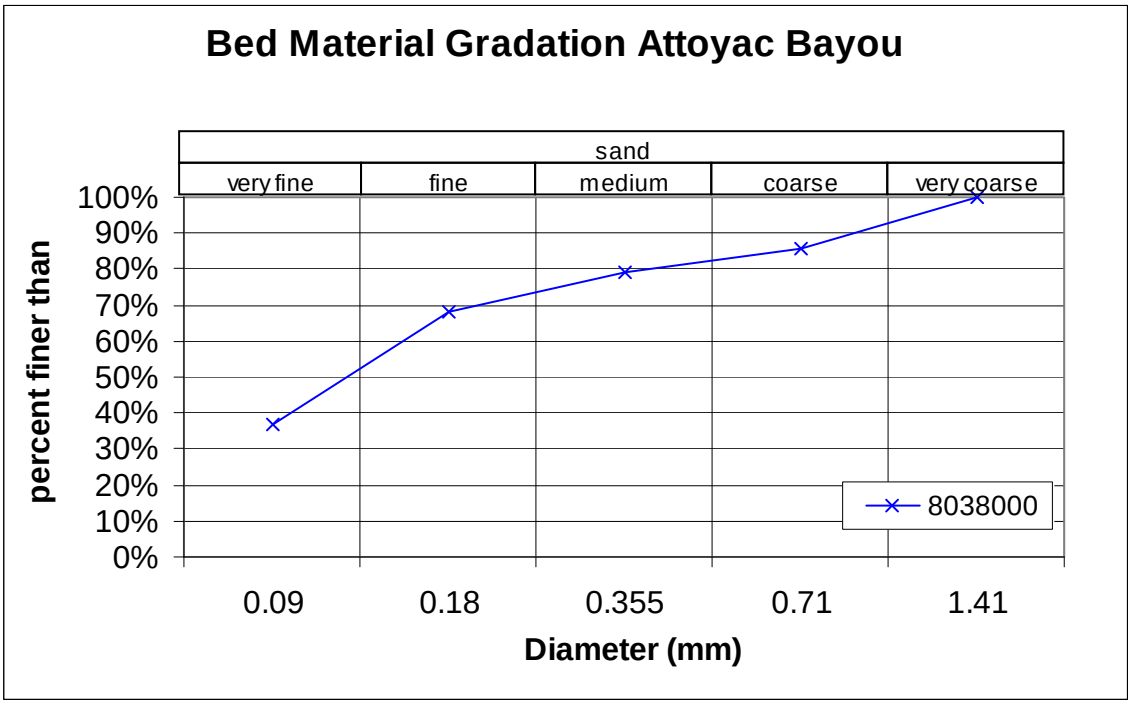

Figure 7E. Bed material gradation for Attoyac Bayou.

Geomorphic Units
Of the Lower Sabine River

Project Report for the Texas Water Development Board and Texas Instream Flow Program, TWDB contract number 0704830782

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FINAL REPORT
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Geomorphic Units of the Lower Sabine River: Chapter 1: Introduction and Overview

BACKGROUND AND PURPOSE

This report addresses the subreach-scale landforms of the lower Sabine River, Texas/Louisiana from Toledo Bend Dam to Sabine Lake. Building on previous work delineating geomorphic zones or reaches (river styles) and associated environmental controls and hydrologic and geomorphic processes (Phillips, 2008a; Phillips and Slattery, 2007a), this study addresses the characteristic landforms within those zones. The goals were to identify and describe the dominant (in terms of size, frequency of occurrence, and influence on hydrologic and ecological conditions) geomorphic units, to relate these to hydrologic and geomorphic processes and controls, and to link the geomorphic units (GUs) to the river styles zonation. A particular emphasis was placed on transverse bars. These (more-or-less cross-channel) sand bars are important bedforms and aquatic habitat elements in rivers.

The specific objectives of the study were to:

(1) Identify and describe major geomorphic units associated with the geomorphic zones identified in previous work (Phillips 2008a; Phillips and Slattery 2007a).

(2) Describe geomorphic units with respect to size, form, origin, longevity (e.g., typical time scales or persistence) and relationships to particular fluvial or ecological processes.

(3) Assess the geography of geomorphic units with respect to environmental settings, longitudinal (up-downstream) distribution, and association with geomorphic zones.

(4) Test a hypothesis regarding transverse bars. Some point bars in the Sabine show evidence of downstream translation. If the rate of such movements exceeds the rate of overall meander bend migration, then the extensions of the point bar into the channel (i.e., the transverse bar) should occur downstream of the bend apex. The hypothesis was that the sandy bars are mobilized at lower shear stresses than those required for bank erosion, and thus bar mobility occurs more often than cutbank erosion, which is required for migration of the meander as a whole.

Early results showed the hypothesis above to be false, and efforts were refocused on a general study of the occurrence and formation of cross-channel bars.

STUDY AREA

The study area encompasses the lower Sabine River from the Toledo Bend reservoir to the Sabine Lake estuary, along the border of Texas and Louisiana (Fig. 1). The Sabine River has a total drainage area of 25,267 km^2, of which 6,676 km^2 (26%) is downstream of the Toledo Bend dam. The area has a humid subtropical climate.

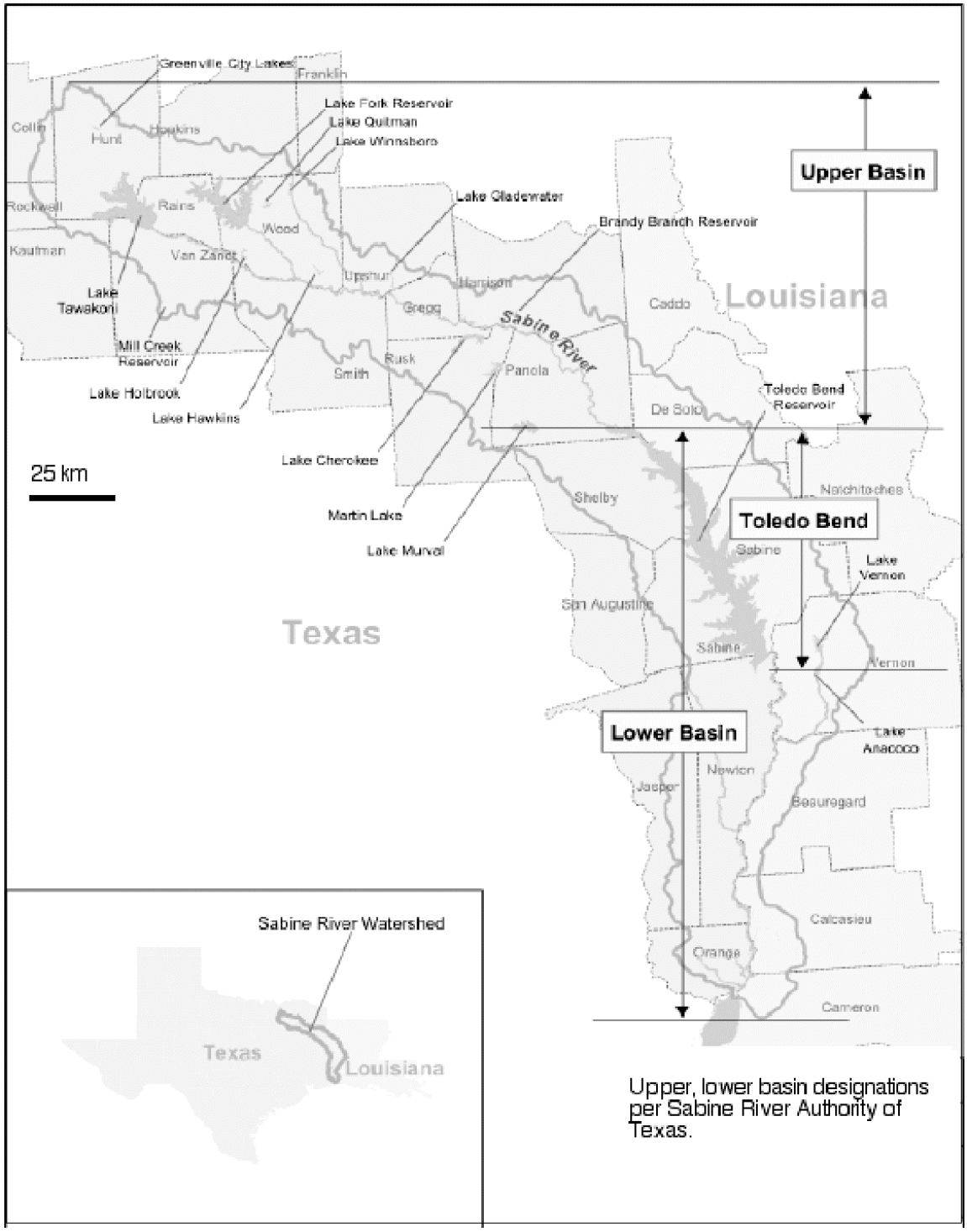

Figure 1. Sabine River drainage basin.

Toledo Bend reservoir, completed in 1967, has a surface area of about 735 km^2 and a capacity of > 5.5×10^9 m^3 at normal water levels. Toledo Bend is the largest and lowermost impoundment on the river. The primary purpose is hydropower generation, and it is not designed or operated as a flood control reservoir. Though a small constant flow-through release is maintained via a spillway, dam releases are highly pulsed in conjunction with power generation.

Channel and Valley Geomorphology

The lower Sabine is an active alluvial river. A scour zone exists downstream of the dam spillway, as is typical in such situations, with evidence of both post-dam channel widening and incision. However, the erosional effects of the dam are greatly diminished more than 24 km downstream of the dam (Phillips 2003; Phillips and Musselman 2003).

For more than 100 km downstream of the dam, the Sabine channel is a single-thread meandering channel with large, sandy point bars. Morphology, vegetation indicators, and historical comparisons all indicate a highly active channel (Phillips 2003; 2008a). Dominant forms of activity include point bar accretion and cutbank erosion, downstream migration of meanders, and other forms of lateral channel migration. Further downstream of Toledo Bend, sandy point bars are generally smaller, but the general indications of channel activity are the same. The numerous oxbows, meander scars, and sloughs on the floodplain indicate that the Sabine has been an active, meandering river throughout historical and Holocene times.

In the vicinity of Sudduth Bluff and the junction of Nicholls Creek (figure 2), the Sabine takes on a different character, with a wider floodplain, and a transition from a dominantly convergent to a dominantly divergent network. Rather than tributaries which normally flow into to the Sabine, connecting waterways are dominantly distributaries to which the Sabine contributes water (particularly at higher flows), or streams which may function as tributaries or distributaries, directing flow to or away from the main river channel. Major tributary mouths are also embayed.

The Sabine from Nicholls Creek to the Cutoff Bayou is, like the channel upstream, an actively meandering channel, with abundant field and aerial photographic evidence of recent point bar accretion and cutbank erosion, as well as point bar migration. Numerous oxbows and meander scars again testify to the historical and Holocene activity of the channel (Phillips 2003, 2008a). Unlike the upstream reaches, however, during flood events a number of distributary, yazoo, and tie channels are activated to convey the water downstream.

The junction of the Sabine River and Cutoff Bayou is about 180 km downstream of Toledo Bend. The majority of the flow (about 50 to nearly 80 percent, according to measurements from the Sabine River Authority of Texas) is diverted to the east toward the Old River channel. The Old River and Sabine channels are relatively stable in the sense of lacking evidence of recent erosion, infilling, or migration, with the exception of the Sabine in the vicinity of Jackson cutoff, where several oxbows occur. However, this reach of the valley is essentially an anastamosing system characterized by a dominant

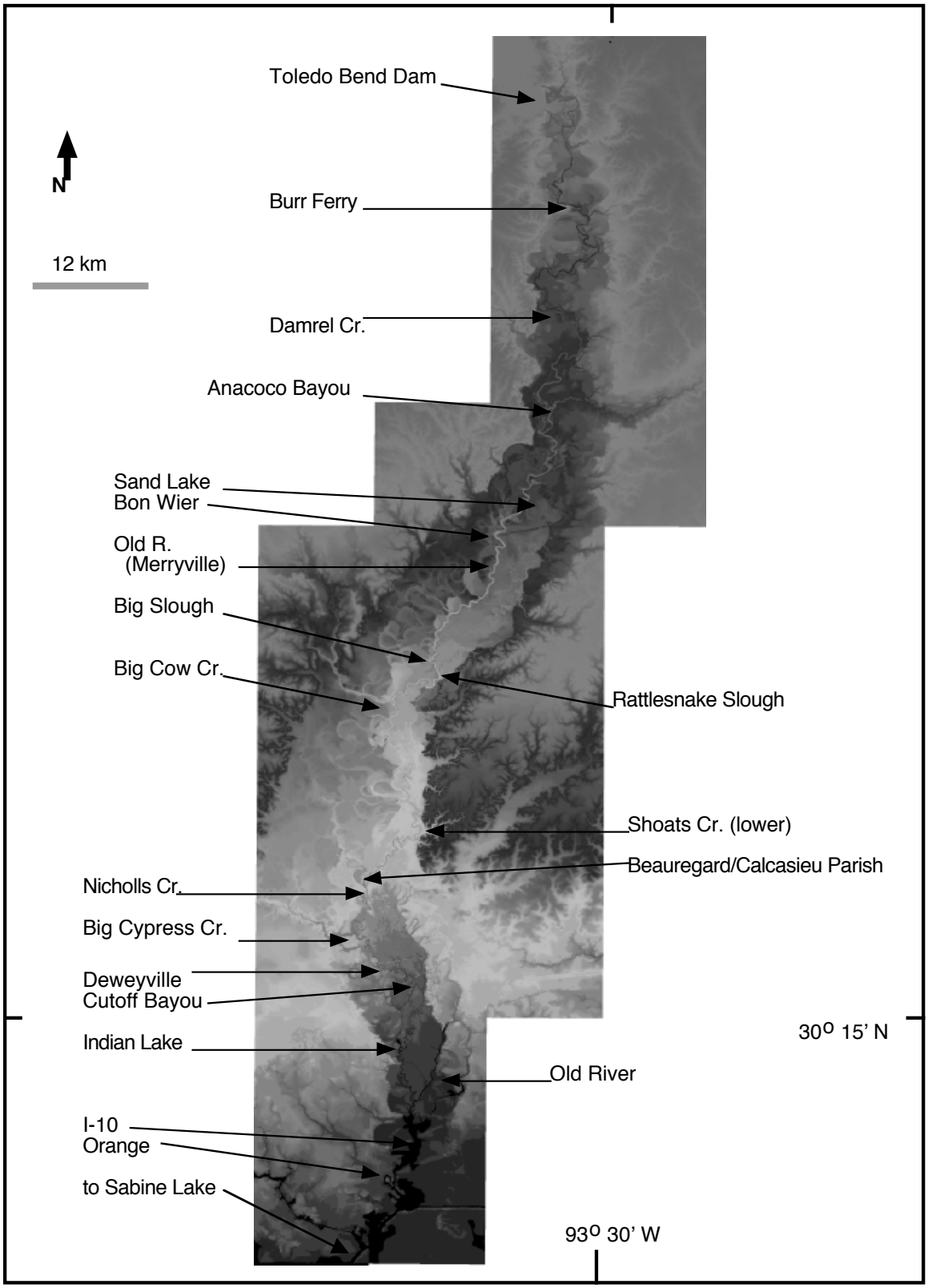

Figure 2. Study area, showing locations referred to in the text. Base map is is density plot derived from 30-m DEM data.

channel (Old River) but with several active subchannels. These systems are typically characterized by changes in the relative importance of subchannels, as the latter gain or lose flow in response to erosion or sedimentation during flood events. The avulsion regime of the Sabine and other rivers of southeast Texas is discussed in detail by Phillips (2008b).

In the vicinity of West Bluff (about 30 km upstream of Sabine Lake) the Old River and Sabine channels rejoin. From here, past Orange to Sabine Lake, the river is a low-gradient, meandering, tidally-influenced stream with an active channel.

Late Pleistocene and Holocene Context

The modern Sabine River valley is incised into the Pleistocene Beaumont formation (correlative with the Prairie Formation in Louisiana). Between the Beaumont surface which makes up the valley margins of much of the lower Sabine valley, and often merging into the modern floodplain, are a series of up to three alluvial terraces. These are usually referred to as Deweyville, though they are not now generally believed to be part of a single terrace system (Blum et al. 1995; Morton et al. 1996). In most locations two or three separate Deweyville surfaces are recognized. In Louisiana the Deweyville formations are divided into three alloformations--the Fredonia, Sandjack, and Merryville (youngest to oldest; Heinrich et al., 2002; Snead et al., 2002).

The lowermost Deweyville surfaces are only slightly higher than the modern floodplain, and in some cases are buried by the latter, with natural levees of the modern floodplain higher than backswamps of the lower Deweyville (Alford and Holmes 1985; Blum et al. 1995; Rodriguez et al. 2005). Aerial photographs show obvious paleomeanders in the Sabine Valley, expressed as swampy depressions or meander scrolls. These occur on the Deweyville surfaces, sometimes cut laterally into the Beaumont, with radii of curvature and amplitudes suggesting significantly larger paleodischarges than at present (Alford and Holmes 1985; Blum et al. 1995).

Alford and Holmes (1985) date the Deweyville terraces of the lower Sabine valley at 4 to 9 Ka. Otvos' (2005: 102) chronology indicates entrenchment of the Sabine from about 100 to 50 Ka, and aggradation, producing two terraces, from 40 to 20 Ka. These were followed by entrenchment from 20 to 18 Ka and aggradation from 18 to 2 Ka (Otvos 2005: 102). The Sabine, Neches, and Trinity River systems were connected during lower sea level stands on what is now the continental shelf, and Thomas et al. (1994) date the oldest incision of the Trinity-Sabine system at about 110 Ka. Other studies are consistent in placing the incision within a 75-115 ka time frame (Blum et al. 1995; Otvos, 2005). Multiple episodes of lateral channel migration, degradation, and aggradation occurred within those incised valleys during isotope stages 4, 3, and 2 glacials as channels graded to shorelines further out on the current continental shelf (Blum et al. 1995; Morton et al. 1996; Rodriguez et al., 2005).

Hydrology

Runoff and discharge in the lower Sabine River is influenced by the climate and hydrologic response of the drainage basin, releases from Toledo Bend Reservoir, water

withdrawals, and tidal and coastal backwater effects (e.g., temporary ponding or upstream flow). The hydrologic framework is described in more detail in an earlier report (Phillips and Slattery, 2007a), from which this section is condensed.

Toledo Bend Reservoir has a controlled storage capacity of 5.522 km^3 (4,477,000 acre-feet). The primary purposes are water supply, hydroelectric power generation, and recreation. The dam is not operated to perform flood control functions. The SRA of Texas estimates a dependable water yield of 7.07 million cubic meters per day (818 m^3 sec^{-1}). The design flow of the Toledo Bend spillway is 8,212 m^3 sec^{-1} (290,000 cfs). A minimum constant flow of about 5.7 m^3 sec^{-1} (200 cfs) is maintained via the spillway, but most of the flow is passed through the hydroelectric turbines. Maximum recorded release was 3,239.5 m^3 sec^{-1}, and a typical flow during turbine operation is 200 to 300 m^3 sec^{-1}.

The SRA of Texas operates an intake canal on one of the distributary channels of the lower Sabine between Deweyville and Orange. The Gulf Coast Canal system has a capacity of about 16 m^3 sec^{-1}. This maximum capacity represents about 12.5 percent of median and 6.7 percent of mean flow at the Deweyville gage.

Some diversions occur on the Louisiana side, but no data on these could be obtained. The Texas Water Development Board conducted inflow and water balance studies for the Sabine Lake (Sabine/Neches) estuary, which includes both the Sabine and Neches Rivers and some small coastal basins. The known or estimated total diversions relative to inflow (gaged river flows plus model estimates of ungaged areas) is shown in figure 3. The 1941-2005 trends in diversions as a percent of the mean, shown in Figure 4, show obvious seasonal patterns associated primarily with agricultural irrigation. Significant diversions between Toledo Bend and Sabine Lake occur only downstream of Cutoff Bayou on both the Texas and Louisiana sides. Hydrologic influences on the lower Sabine are summarized in Table 1.

Table 1. Influences on the hydrologic regime of the lower Sabine. See next section for definition of reaches/river styles.

Hydrologic Influence	River Style (reach)
Local runoff, precipitation, tributary inputs	1,2,3,4,5,6
Dam releases	1,2,3
Backwater effects	4,5,6
Tidal influence	5,6
Water diversions	6

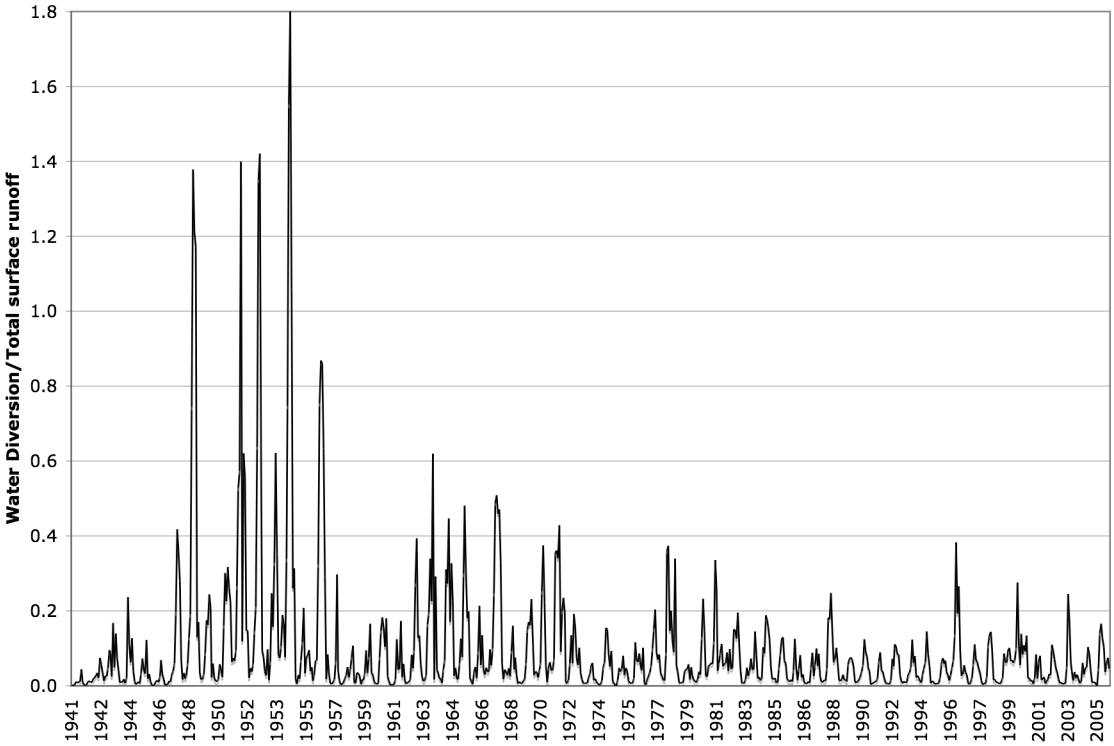

Figure 3. Water diversions for the Sabine/Neches estuary as a proportion of total surface runoff. Based on monthly model calculations of the Texas Water Development Board (http://hyper20.twdb.state.tx.us/data/bays_estuaries/hydrologypage.html)

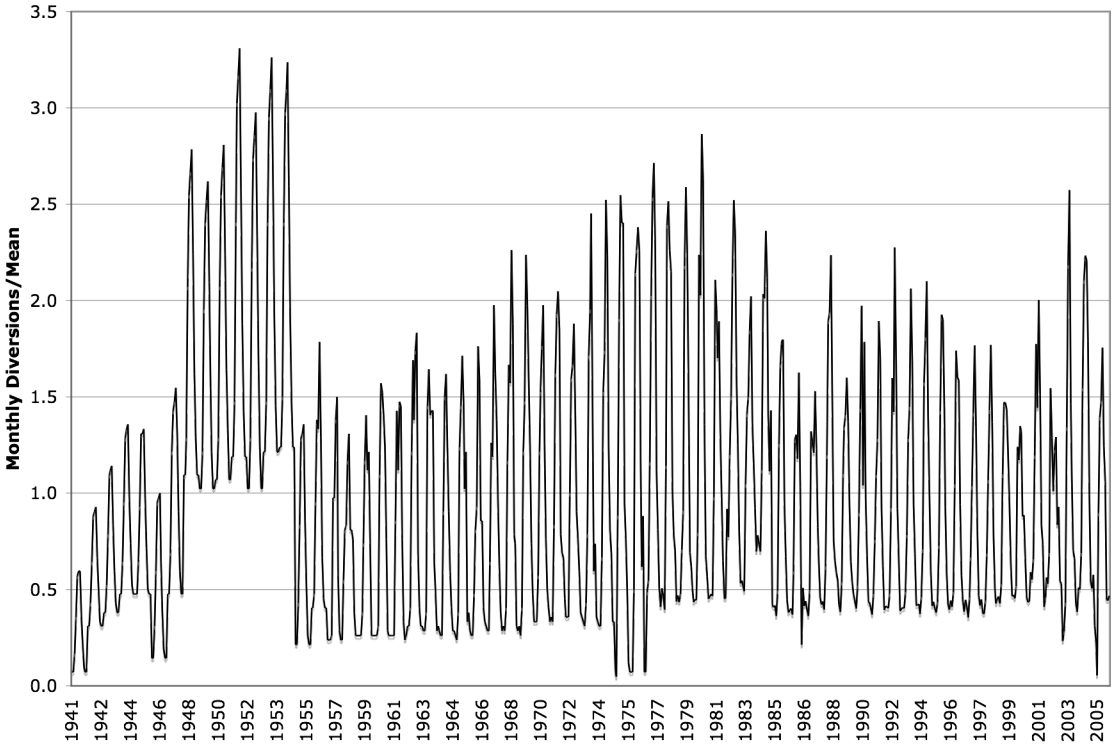

Figure 4. Water diversions for the Sabine/Neches estuary as a proportion of the mean monthly diversion. Seasonal patterns are readily apparent. Based on monthly model calculations of the Texas Water Development Board (http://hyper20.twdb.state.tx.us/data/bays_estuaries/hydrologypage.html).

The Sabine River supplies about 46 percent of the freshwater inflow to Sabine Lake (TCB, 2006). Calculations based on data presented by TCB (2006) show that mean flows at Beckville, upstream of Toledo Bend reservoir, account for about 30 percent of the total outflow of the river. Discharge at Toledo Bend dam represents about 64.5 percent of the flow, with the area beween Beckville and the dam contributing about 34.5 percent. The Sabine at Deweyville, about 47 km upstream of the mouth, discharges nearly 95 percent of the total flow, with the basin between Toledo Bend and Deweyville contributing about 30 percent of that. The area downstream of Deweyville contributes about 5 percent of the river outflow estimated by TCB (2006).

Mean and median flows and the one and ten percent probability flows increase as expected downstream from Burkeville to Bon Wier to Deweyville (see figure 2). The flood stage discharges, however, and thus the recurrence interval of overbank flow, decline. Flood stage at Burkeville is 1,880 m^3 sec^{-1}. The probability of mean daily flow exceeding that value is only about 0.1 percent, with a recurrence interval of 2.75 years. At Bon Wier, flood stage is less than half that, with mean daily flows exceeding flood stage about 3 percent of the time. Deweyville flood stage is lower still (510 m^3 sec^{-1}), with a 13 percent probability.

The hydrologic and geomorphic implications are that as one proceeds further downstream, overbank flow occurs more often, and channel-floodplain connectivity is greater. Further, cross-sectional stream power (the produce of discharge, slope, and specific weight of water) for a given discharge is lower at overbank flow levels, and this plus the floodplain inundation reduces sediment transport capacity and increases alluvial deposition opportunities. These trends are not unusual for the lower reaches of low-gradient coastal plain rivers (Phillips and Slattery, 2006; 2007b).

Previous studies have suggested that releases from Toledo Bend Dam have not significantly changed the discharge regime at Deweyville or inputs into Sabine Lake (Solis et al., 1994; Phillips, 2003; TCB, 2006), and that peak flows and mean flows have been minimally influenced. However, dam releases do clearly influence flows on hourly and daily time scales, and the seasonality of flow. Dam release effects on hydrology diminish downstream from Toledo Bend, and vary inversely with discharge.

Diurnal tidal ranges in the northern Gulf of Mexico are small—generally less than 0.6 m, and in the Sabine are further filtered by Sabine Lake. Nevertheless, the Sabine River channel is cut to below sea level upstream of Deweyville (where the gage datum is -1.8 masl), to at least Big Cypress and perhaps Nicholls Creek. The tidal signal in the discharge record at Deweyville is barely discernible as a subtle "sawtooth" pattern superimposed on the discharge and stage record.

GEOMORPHOLOGICAL ZONATION AND RIVER STYLES

In earlier work (Phillips and Slattery, 2007a; Phillips, 2008a) a geomorphological zonation was developed for the lower Sabine. Boundaries were delineated based on surficial geology, valley width, valley confinement, network characteristics (divergent vs. convergent), sinuousity, slope, paleomeanders, and point bars. The coincidence of multiple boundaries revealed five key transition zones separating six reaches of distinct hydrological and geomorphological characteristics. Geologic controls and gross valley morphology play a major role as geomorphic controls, as does an upstream-to-downstream gradient in the importance of pulsed dam releases, and a down- to upstream gradient in coastal backwater effects. Geomorphic history, both in the sense of the legacy of Quaternary sea level changes, and the effects of specific events such as avulsions and captures, are also critical. The transition zones delineate reaches with distinct hydrological characteristics in terms of the relative importance of dam releases and coastal backwater effects, single vs. multi-channel flow patterns, frequency of overbank flow, and channel-floodplain connectivity. The transitional areas also represent sensitive zones which can be expected to be bellwethers in terms of responses to future environmental changes.

A schematic diagram of the boundaries associated with geology, valley confinement, network geometry, slope, paleomeanders, and point bars is shown in Figure 5. Some obvious critical transition points are evident at 47 and 71 km where four different boundaries coincide. At 79 km three different boundaries coincide.

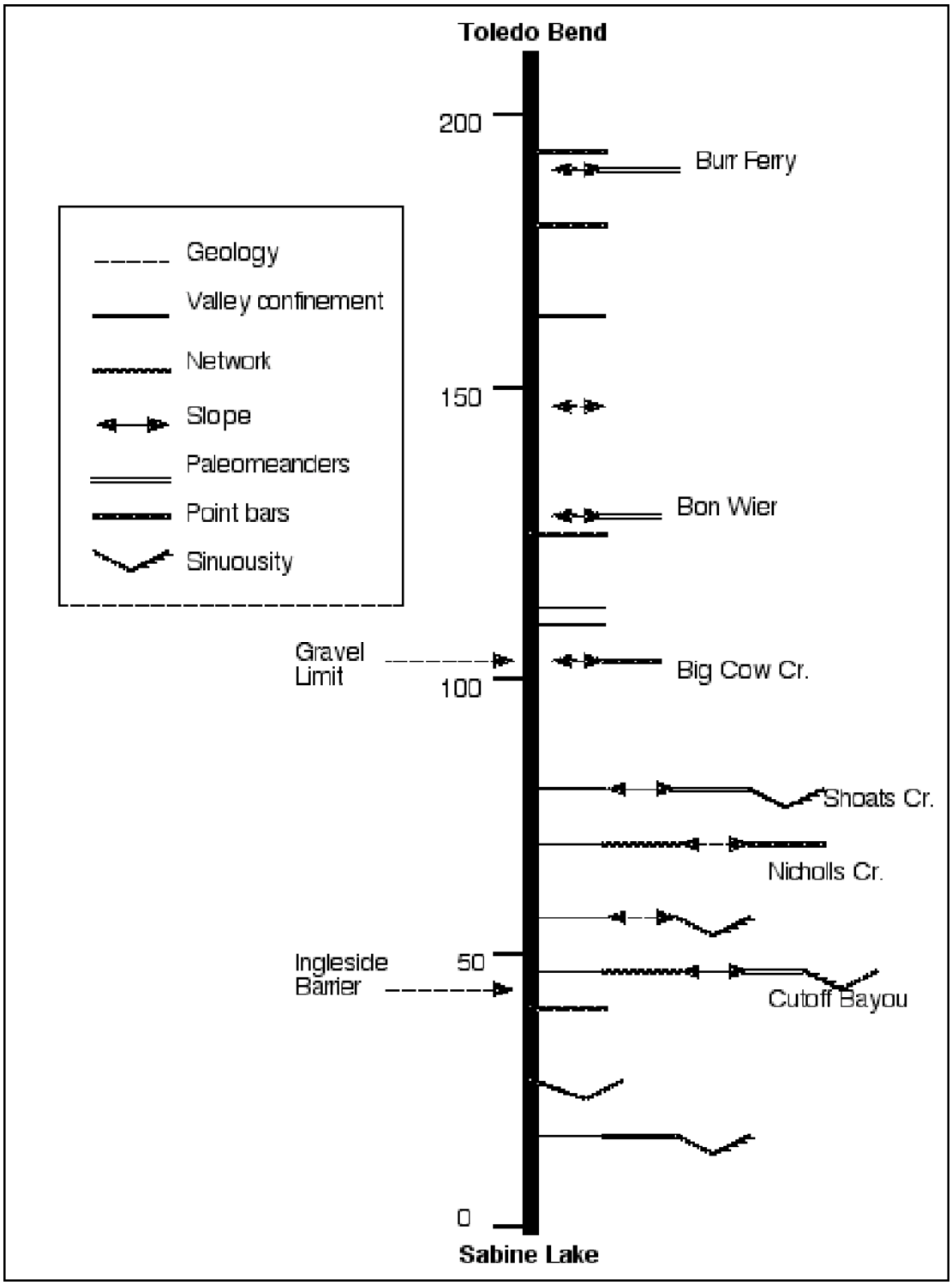

Figure 5. Schematic diagram of upstream/downstream river zonation based on various criteria. The locations of the downstream limit of Deweyville gravel deposits on point bars, and the intersection of the river channel and trend of the Pleistocene Ingleside barrer are also shown. Approximate distances (km) upstream of Sabine Lake are shown to the left. From Phillips and Slattery (2007a).

From Toledo Bend Dam to Burr Ferry (highway 63 crossing, and site of the Burkeville gaging station), the channel is characterized by a pronounced scour zone immediately downstream of the dam, and a generally incising regime throughout. Deweyville terrace deposits are being mobilized by lateral channel migration. The reach is relatively steep, with few point bars. Sediment loads are low due to trapping of sediment in Toledo Bend reservoir, and flows are highly pulsed due to dam releases. Bedrock control of the channel bed is evident in some locations, indicating limits on incision, and a valley constriction exists at the lower end. The primary controls on this reach are thus the geologic framework, and the operation of Toledo Bend Reservoir.

In the reach from Burr Ferry to the transition zone in the vicinity of Bon Wier, active lateral channel migration is dominant, characterized by large, active point bars and cut banks. The valley is generally wider than upstream, resulting in multiple generations of paleomeander scars being evident. An apparent avulsion near the lower end of the reach marks a transition in network geometry and floodplain-channel connectivity, with increased connectivity downstream of this reach.

From the Bon Wier vicinity to Big Cow Creek many aspects of the river are similar to those upstream, but with increased hydraulic connection between the Sabine River and former river channels now present as sloughs, yazoos, or oxbows. The number of paleomeander scars increases from two to three, and slope is less than that of the upstream and downstream reaches. Valley width and the avulsion site at the upstream end of the reach are important controls, along with neotectonics (a fault) at the lower end.

In the next major reach, from Big Cow to Shoat's Creek, slope increases, and the number and size of point bars declines. Gravels derived from Deweyville deposits disappear from point bars. The increased flow from Big Cow Creek is a significant control, as is apparent neotectonic activity on the upper end and coastal plain paleogeography at the lower end.

The reach from Shoats Creek Lower (and Devil's Pocket) to Cutoff Bayou marks a significant change in valley confinement associated with a geological boundary, which is in turn associated with coastal plain paleogeography (a Pleistocene shoreline). Sinuousity is significantly higher than upstream, and within this reach multiple high flow distributary channels become prominent. The increased sinuousity, apparent burial of one generation of paleomeander scars, increasing incidence of muddy rather than sandy point bars, and drowning of tributary creek mouths are all consistent with effects of Holocene sea level rise and the beginning of a fluvial/deltaic/coastal transition zone. In addition, the capture and diversion away from the Sabine of the Houston River by Pleistocene fault reactivation is an important control. This reach can be subdivided on the basis of slope, which first decreases relative to upstream sections, and then increases significantly in the lower portion of the reach.

The lowermost major reach, which could be subdivided according to increasing prevalence of coastal landforms and tidal influences in the lower portion, begins at Cutoff Bayou. This is the head of the delta, and the flow network is distributary at all flows. The current network geometry and flow patterns are influenced by the Houston

River capture (see Phillips, 2008a), and flow diversions between channels have been influenced by both natural and human activity.

The major zones (reaches or river styles) are shown in Table 2, and their associated hydrologic characteristics and controls in Table 3.

Table 2. Major reaches (river styles) of the lower Sabine River. Locations are in river distance upstream of Sabine Lake in kilometers (Sabine River Authority of Texas river mileages in *italics*).

Reach	*Location*	*Distinguishing Characteristics*	*Primary Geomorphic Controls*
1 Toledo Bend to Burr Ferry	213-192 *146-131*	Incision, steep slope, bedrock control, valley constriction, low sediment loads, pulsed flows	Geologic framework; Toledo Bend Dam releases
2 Burr Ferry to Bon Wier	192-131 *131-91*	Active lateral migration, ubiquitous large point bars, wider valley, larger sediment load	Valley width; avulsion
3 Bon Wier to Big Cow Creek	131-103 *91-70*	Active lateral migration, ubiquitous large point bars, wider valley, larger sediment load; high floodplain/channel connectivity; low slope	Valley width; avulsion; neotectonics
4 Big Cow Cr. to Shoats Creek lower	103-79 *70-54*	Active lateral migration, fewer point bars, high floodplain/channel connectivity, low slope	Neotectonics; valley width; coastal plain paleogeography
5 Shoats Cr. to Cutoff Bayou	79-47 *54-29*	Few and finer-grained point bars, high floodplain/channel connectivity with multiple high flow distributary channels, high sinuousity, embayed tributary mouths	Holocene sea level rise; geology & coastal plain paleogeography; Pleistocene stream capture
6 Cutoff Bayou to Sabine Lake	47-0 *29-0*	Rare point bars; distributary flow network; very high sinuousity; deltaic; tidal influence	Holocene sea level rise; tidal and coastal influences; Pleistocene stream capture

Table 3. Hydrologic regimes in major reaches of the lower Sabine River. Coastal effects refers to influence of tides and coastal backwater effects.

Reach	Dam pulses	Channels	Overbank flow	Connectivity	Coastal Effects
1 Toledo Bend to Burr Ferry	Flow dominated by dam releases	Single channel	Rare	Low channel-floodplain connectivity	None
2 Burr Ferry to Bon Wier	Flow strongly influenced by dam releases	Single channel	Occasional	Low channel-floodplain connectivity	None
3 Bon Wier to Big Cow Creek	Flow strongly influenced by dam releases	Multiple channels at high flows	Occasional	Moderate channel-floodplain connectivity	None
4 Big Cow Cr. to Shoats Creek lower	Strong influence of dam releases at low flow	Multiple channels at high flows	Occasional	High channel-floodplain connectivity	None
5 Shoats Cr. to Cutoff Bayou	Minor influence	Multiple channels	Common	Extensive connectivity	Minor
6 Cutoff Bayou to Sabine Lake	Minor influence at low flows	Multiple distributary channels	Common	Extensive connectivity	Significant

Geomorphic zones or river styles may be characterized by distinctive suites of geomorphic units. These are described and related to the zones above in the next chapter.

Chapter 2: Geomorphic Units

INTRODUCTION

This project is conducted in the context of the *river styles* approach to the assessment and management of rivers. A detailed exposition of the river styles framework is given by Brierly and Fryirs (2005), and an application to the Brazos River, Texas by Phillips (2006; 2007).

The river styles (RS) approach is hierarchical, with the catchment (watershed or drainage basin) as the broadest unit. Within watersheds are landscape units, which in the lower Sabine translates to physiographic units of middle and lower coastal plain and deltaic/coastal units. Within landscape units are the RS themselves, defined at the reach scale. The geomorphic zones described in the previous chapter are examples. *Geomorphic units* are specific landforms within reaches, e.g. point bars, natural levees, riffle-pool sequences. Hydraulic and microhabitat units are the most detailed level in the RS scheme, comprising specific hydrological and ecological elements such as large woody debris, bedforms, aquatic vegetation, and individual flow obstructions or roughness elements.

Geomorphic units are erosional, depositional, or transportational landforms, referred to by Brierly and Fryais (2005: 26) as "the building blocks of river systems." Each GU represents a distinct form-process association. GU's are generally capable of significant change on the scale of ~1 year, but may range from ephemeral to persistent due to the episodic, threshold-dependent nature of geomorphic change.

METHODS

The entire Sabine River and Old River channels from Burr Ferry to the Interstate 10 bridge was examined by boat at various times between 2005 and 2008; some reaches on multiple occasions. In addition, much of the reach from Toledo Bend Dam to Burr Ferry was also examined by small boat, canoe, or via land access in 2000-2001 and in 2006. Sections of the river between I-10 and Sabine Lake, and of various tributaries, distributaries, sloughs, and anabranches were also examined in the field via land access and canoe.

Over most of the sections traversed by boat, continuous digital photography was taken. Field investigations included detailed field mapping of specific cross sections, and general assessments of bed substrate and bank material, bank stability and vegetation, and the geometry and bedforms at tributary junctions. Measurements of bank height and channel width at selected cross-sections were made with a laser level, and of depth with a hand-held SONAR depth finder. The activity and stability of channel features was assessed on the basis of visible bedforms, vegetation cover, and evidence of downstream encroachment, lateral growth, or erosional diminution. Bank-attached and channel features were assessed on the basis of morphology, composition, and vegetation indicators of erosion-deposition processes and hydroperiod.

Hurricane Rita struck southeast Texas/Southwest Louisiana, making landfall in the Sabine Lake area, in September, 2005. Shortly thereafter the U.S. Army Corps of Engineers produced 0.3 m (1 ft) resolution vertical color aerial photography of much of the region, including the Sabine River from upstream of Bon Wier to Sabine Lake. This imagery was particularly useful in identifying floodplain and valley GUs difficult to observe in the field at such a broad scale.

In late October, 2007 low-flow and clear-water conditions allowed an opportunity for exceptional aerial observation of channel forms. A small-plane flight from Toledo Bend Dam to Deweyville was conducted, with continuous photography of the channel using a GPS-enabled digital camera. This oblique photography was obtained from a variable altitude of <200 m (~600 ft).

From these observations the variety of landforms was inventoried and either specifically mapped or assigned to the six geomorphological zones described in Chapter 1.

RESULTS

Geomorphic units were categorized as mid-channel, bank or bank-attached, and floodplain/valley. There is inevitably some fuzziness and overlap in these distinctions—point and lateral bars, for instance, connect mid-channels and banks, while crevasse-related features transcend banks and floodplains. These distinctions are, however, a convenient tool for organizing results.

In this section a general discussion and inventory of GUs is given, while separate appendices provide photographic examples of each GU.

Channel Units

Channels themselves are landforms, but specific features within them represent specific process-form associations and/or diagnostics of fluvial processes and evolution. The channel units can be roughly categorized as thalwegs, bedrock outcrops, bars, pool-related units, and large woody debris jams. The channel GUs are shown in Table 4.

Thalweg. The thalweg is the deepest portion of the channel, defined by connecting the lowest points at any cross-section, and is often thought of as a channel within the channel. All channels contain a thalweg, by definition.

Bedrock Outcrops. Resistant exposures or outcrops of pre-Quaternary bedrock locally limit the rate of bed and bank incision or erosion, and generally indicate recent erosional removal of Quaternary alluvium. These occur only in the reach from Toledo Bend to Burr Ferry, where scour following dam construction has exposed outcrops of Miocene material, mainly sandstones of the Fleming Group. These outcrops are particularly common immediately downstream of the dam. The bedrock GUs include mid-channel, channel margin, and cross-channel features.

Table 4. Mid-channel Geomorphic Units of the Lower Sabine River and their association with zones or river styles (see Table 2). Styles in italics indicate that the GU is significantly rarer than in the other listed styles. See Appendix A for examples.

Geomorphic Unit	River Style
Thalweg	1,2,3,4,5,6
Bedrock	
Mid-channel	1
Marginal	1
Cross-channel	1
Bars	
Marginal	
Point bar (normal and breached)	
Dominantly sand	1,2,3,4,*5,6*
Dominantly mud (fine-grained)	*5*,6
Lateral bar (normal and breached)	1,2,3,*4*
Tributary mouth (normal and breached)	1,2,3,4,5,6
Diagonal	1,2,3,*4*
Forced	1,2,3,4,*5,6*
Mid-channel	
Forced	1,2,3,*4,5*
Transverse (linguoid)	1,2,3
Compound	1,2,3
Longitudinal	1,2,3
Sand sheet	2
Connector	1,2,3,*4*
Pools	
Riffle-pool sequence	1,2,3,*4*
Circular meander pool	6
Forced pool	
Downstream	1,2,3
Backwater	*1,2,3,4,*5,6
Glide (run)	1,2,3,4,5,6
Large Woody Debris Jams	1,2,3,4,5,6

Bars. Bars are treated separately in Chapter 3, and are discussed briefly below for the sake of completeness. Bars in the lower Sabine river are dominantly sandy, though some mud (fine grained) point bars occur in the lowermost reaches, and bars in reaches 1, 2, and 3 may include small amounts of gravel derived from erosion of Deweyville terrace deposits. Bars may be marginal, mid-channel, or connector type.

Point bars occur on the inside of meander bends, and are a common feature of laterally migrating meandering rivers. Point bars are dominantly lateral accretion deposits, associated with erosion of the outside (cutbank) of the bend and deposition on the

inside. In general coarser materials tend to be deposited from traction bed load on the upstream end of the bar, and the finest from suspension on the distal end. Thus point bars may have gravel or coarse sand on the upstream end and mud drapes or alternating mud/sand layers are the downstream end. In the lowermost reaches (5, 6) finer-grained point bars occur. Point bars may occasionally be breached by flow along the upper edge of the bar, often by high river flows in combination with surface runoff or tributary inputs. Downstream movement of point bars is indicated by encroachment at the distal end on steep banks with tilted trees.

Lateral bars occur along banks in low-sinuousity reaches. Classic alternate-side lateral bars are rare in the Sabine, but lateral bars do occur in short relatively straight reaches between meanders. These may occasionally be breached, as with the point bars above. Lateral bars are most common in reaches 1, 2, and 3.

Tributary mouth bars are essentially deltaic features which may occur as deltas *per se* at the tributary mouth, or as spit-like bars aligned with the river channel and oriented downstream. These bars may be breached by tributary or river flow, and are associated with backwater effects on the tributary from the river.

Diagonal bars are usually bank-attached in the Sabine, but may also occur as cross-channel features. They are oriented diagonally to banks, with elongate, oval, or rhomboid planform shapes. Diagonal bars are formed where flow is oriented obliquely to the longitudinal axis of the bar, and may indicate reworking of riffles. While diagonal bars are usually associated with gravel or mixed-bed channels, those in the Sabine are predominantly sandy.

Forced bars are associated with sediment trapping behind obstructions, and may occur in mid-channel or attached to banks. All forced bars observed in the study area were associated with large woody debris.

The term transverse bar is used in a general way to refer to cross-channel bars, and in a more specific way in reference to mid-channel bars oriented perpendicular to flow and occupying most of the channel width. These are also referred to as linguoid bars. Linguoid bars are often lobate in shape and have a slip or avalanche face on the downstream end. They are often found at points of relatively abrupt flow expansion, and in the lower Sabine often occur just downstream (or at the downstream end of) flow constrictions associated with point or lateral bars. Linguoid bars are associated with diverging low with high availability of sand.

Longitudinal bars are mid-channel features oriented parallel to flow and more-or-less streamlined, often with a downstream-oriented teardrop shape. Longitudinal bars are deposited when transport capacity is exceeded by sediment supply in mid channel.

Changing flow and sediment transport conditions may lead to the formation of several generations of different types of bars in the same location. Further, downstream translation of midchannel bars may result in the welding together of various combindations of point, lateral, diagonal, linguoid, and longitudinal bars. In either case

the result may be compound bars, characterized by traits of two or more of the types described above.

Sand sheets are more or less uniform tabular sand sheets occupying the entire channel. They are associated with bedload deposition where sediment supply exceeds transport capacity, and may exhibit a variety of bedforms. At low water, they may resemble braided channels with multiple intertwining subchannels. Sand sheets are readily reworked, and may be translated downstream during floods. Several sand sheets were noted in tributaries throughout reaches 1-5, but in the main river they were restricted to reach 2.

All the bar types discussed above are generally recognized in the geomorphology literature (see, e.g., Brierly and Fryirs, 2005). In the lower Sabine an additional class of bar was indentified, termed connector bars. Connector bars extend from the downstream end of a point or lateral bar to the upstream end of a point or lateral bar downstream. They are distinct from the linguoid bars that sometimes occupy the gaps between marginal bars in that they lack obvious downstream slip faces, and are oriented parallel or diagonal to flows.

Pools. Pools are sections of channel with greater depths and lower velocities than adjacent sections. They are often associated with riffle-pool sequences, characterized by shallower, higher-velocity, higher-roughness patches (riffles) alternating with pools. In the study area riffles may be associated with linguoid or connector bars or sand sheets, while pools are often associated with outer portion of meander bends. Riffle-pool sequences are most typically associated with velocity reversal, whereby at lower flows the higher velocities in riffles keep them clear of finer materials, which may accumulate in pools. At higher flows, velocity increases faster in pools than riffles, and a relative velocity reversal occurs. Thus material entrained from riffles is transported through pools, maintaining the sequence. This phenomenon is described in more detail in any fluvial geomorphology text (e.g. Knighton, 1998; Brierly and Fryirs, 2005). A glide or run is a plane-bed section of channel which is neither pool nor riffle, associated with an approximate balance between transport capacity and sediment supply.

Forced pools are associated with flow obstructions—in the study area, often large woody debris. These units may be scour features downstream of resistant bedrock outcrops or large debris pieces, or backwater pools from ponding behind these obstructions. Backwater forced pools are also found immediately downstream of some point bars.

Circular meander pools were first recognized in the Houston River (Calcasieu Parish, LA), by Alford et al. (1982), who also found evidence for their occurrence in some other southeastern rivers. These pools are, in planform, approximately circular enlargements at the apices of tight meander bends. They are also characterized by unusually high depths, more so than normal meander pools—as much as three times the maximum depth of adjacent sections. Because the Houston River was apparently once a Sabine River tributary (Phillips 2008a), the possibility of these features in the study area was investigated. Though they had not specifically investigated these features, SRA-Texas field personnel indicated they encountered unusually deep holes at some meander apices in the tidal portion of the river. At least one circular meander pools is at Blue

Elbow bend, where maximum depths of nearly 20 m are thee times that of upstream sections. Aerial photography suggests other possible occurrences in reach 6.

Alford et al. (1982) found circular meander pools on very tight bends on low gradient rivers with large backswamp areas, and suggested that the pools are formed by counter-currents developed during high flow. Andrle's (1994) study of circular meander pools elsewhere also noted large countercurrents occupying about half the pool, on the outside of bends. He also noted an association with cohesive banks which slow channel migration and inhibit cutoffs.

Large woody debris (LWD; logs, trees, large limbs) is generally considered as hydraulic or microhabitat units rather than a geomorphic unit. However, significant LWD accumulations (jams), as opposed to individual pieces of wood, represent form/process interactions and are thus legitimate GUs. Beyond the importance of LWD for aquatic habitat and river ecology, LWD jams may play a role in avulsions (Phillips, 2008b), influence channel hydraulics, and are indicative of hydrodynamic conditions. The largest LWD jams occur in tributary mouths, where they may pond or deflect tributary inflow, and reflect backwater flooding and recirculating eddies at high flows, where floating wood is deposited as flows recede. The second largest class of LWD jams occurs along eroding river banks, where rapid recruitment of toppled trees, coupled with entanglement of floating debris, creates the jams. Mid-channel LWD jams are associated with entanglement of LWD with large trees embedded in the bed. These are both smaller and less frequent than the tributary mouth or bank jams.

Bank-Attached Units

Bank-attached geomorphic units (Table 5) include the channel banks themselves, and significant subunits along the banks. Geomorphic units that lie partly within the channel (such as marginal bars) are treated in the section on mid-channel units, while GUs connecting the banks and floodplain (such as natural levees and crevasses) are covered under floodplain/valley units.

Benches and Ledges. Benches and ledges are low-relief shelf-like features along channel banks and margins. These features are sometimes termed channel shelves, particularly when no inference about their origins are drawn.

Benches are depositional features related to infilling that may be associated with lateral channel migration where they occur on only one side of the channel, or with channel narrowing where they occur on both sides. They are composed of the same general type of sediments normally comprising the channel bed, bars, and banks, which is typically sand in the Sabine. Buried or partially buried vegetation or organic layers, sedimentary stratification, and other typical indicators of deposition are often present.

Ledges are morphologically similar, but are erosional features. Bank erosion may encounter resistant layers which retreat more slowly than less-resistant overlying layers. Ledges of this type are therefore often composed of bedrock or cohesive clays underlying sandier material. Ledges may also occur where an episode of incision cuts a narrower channel into the former channel bed. Remnants of the former bed appear as

ledges inset into the channel banks. Ledges of the latter type were not observed on the Sabine, but have been documented on tributaries of the Trinity and Angelina Rivers (Phillips, 2001; Phillips et al., 2005), and may exist on some lower Sabine tributaries, particularly in reaches 1 and 2.

Table 5. Bank-attached Geomorphic Units of the Lower Sabine River and their association with zones or river styles (see Table 2). Styles in italics indicate that the GU is significantly rarer than in the other listed styles. See Appendix A for examples.

Geomorphic Unit	River Style
Bench (depositional)	3,4,5,6
Ledge (erosional)	*1,*2
Bedrock bank	1
Concave bank	1,2,3,4,5,6
Convex bank	1,2,3,4,5,6
Straight bank	1,2,3,4,5,6
Convexo-concave	1,2,3,4,5,6
Concavo-convex	1,2,3,4,5,6
Buttressed (cypress)	3,4,5,6
Slump	1,2,3,4,5,6
Slump scar	1,2,3,4,5,6
Chute channel	4
Sand rampart	2

Unconsolidated Banks. Compositionally, geomorphic units associated with sandy and muddy material reflect the variety of soils and sediments in the Sabine valley. Banks reflect a vast number of combinations of material, morphology, and vegetation cover. The units were identified here primarily on the basis of profile (bank top to channel bed) shape. The profile shape reflects the cumulative impacts of the interactions among channel and riparian hydrology, bank materials, vegetation, and slope processes.

Concave banks indicate active or recent erosion, and are often found on cutbanks. Most commonly they indicate lateral channel migration, but if they occur on both sides of the channel indicate widening. Vegetation cover is typically minimal. Convex banks are usually well vegetated, and indicate stable or accreting banks. Where convex upper banks occur with concave lower banks (convexo-concave), this may indicate a transition from a stable or accreting to an erosional state, preferential erosion of the lower bank due to lower resistance (e.g., associated with vertical variations in shear strength), the removal of protective features from the lower bank (e.g., vegetation cover or LWD), or locally higher shear stress during lower flows, perhaps due to flow deflections or accelerations. Continuation of whatever processes create this bank morphology may result in conversion to concave banks as the upper convex section is undermined. A subclass of this GU—undercut banks, where a portion of the bank overhangs and shades the water—may be of particular interest for aquatic habitats. Concavo-convex banks,

with a concave upper and convex lower section, are indicative of recovering cutbanks, where active erosion and bank retreat have ceased.

Bald cypress (*Taxodium distichum*) is a common riparian and wetland tree in the lower Sabine, which can grow in saturated or flooded conditions and develops characteristic rampart-like subaerial roots called knees. The wide, buttressed cypress trunks and knees, where they occur along banks, provide a measure of erosion protection. Bald cypress is an obligate wetland plant (grows naturally only in wetlands), but cannot germinate in inundated conditions. Thus cypress growing in conditions of normally standing water indicates a local rise in water level subsequent to tree establishment, or distinct seasonal variations in water level.

Buttressed banks upstream of the delta (reaches 3,4,5) are most often associated with local channel aggradation. As the bed accretes, displacing flow upward, banks and benches with cypress become inundated, creating buttressed banks. In the delta area (reach 6) buttressed banks may be associated with seasonal water level changes (seedlings may become established during the low water period), or with gradual lateral migration of low-relief banks.

Rotational slumps may occur along eroding concave banks, where significant vertical variations in material properties due to soil strength and/or root mats results in rotational failures. Active slumps are typically characterized by one or more trees and associated understory vegetation with a root mat holding the slumped material together. Active slumps without root mats, composed of sandy material over clay failure planes, have been observed on the lower Trinity River, but were not documented on the lower Sabine during this study. Eventual removal or dispersal of the slumped material leaves a characteristic scallop-shaped slump scar.

Other Bank-Attached Units. Bedrock banks occur in reach 1, associated with the bedrock channel units, and are likewise associated with post-dam channel scour.

Chute channels are high-water channels across point bars, which may eventually lead to chute cutoffs.

Sand ramp is a termed coined in this study to describe sandy bank deposits observed in reach 2 which extend from channel to the natural levee. These are distinct from marginal bars in that the latter do not extent to the top of the banks, and from point bars in that the sand ramps are much narrower and do not occur on the inside of meander bends. Little is known of these features, but their position in the channel and the presence of organic layers within the sand suggest that they result from flow obstructions and temporary backwater effects during high flows.

Floodplain/Valley Units

Abandoned Channels. Channel shifts or relocations significantly longer than a single meander loop are called avulsions, and leave abandoned or paleochannels. In some cases both the new and old channel persist, resulting in development of an anabranch if the channels rejoin downstream, or a distributary otherwise. The latter include deltaic

distributaries which terminate within the delta, and alluvial distributaries which terminate in flood basins (floodplain depressions).

The distinction among other abandoned channels depends on their age, rate of infilling, and frequency of flow. Infilled abandoned channels have accreted to nearly the level of the surrounding floodplain surface, and do not convey flow, except perhaps as part of general down-valley flow during extreme floods. Semi-active channels convey flow during high flow events (but not necessarily overbank), but are dry during low and normal flows. Billabongs are channel remnants which are not fully infilled and usually hold ponded water, but have no hydraulic connection to the main channel except during floods. The term billabong rather than slough is employed because the latter term is used to refer to a variety of different features.

Evidence of avulsions occurs throughout the study area, with the exception of reach 1. More detailed discussion of avulsions in Texas Coastal Plain rivers and their geomorphic significance is provided by Aslan and Blum (1999) and Phillips (2008b).

Table 6. Floodplain and alluvial valley Geomorphic Units of the Lower Sabine River and their association with zones or river styles (see Table 2). Styles in italics indicate that the GU is significantly rarer than in the other listed styles. See Appendix A for examples.

Geomorphic Unit	River Style
Abandoned channel (infilled)	2,3,4,5,6
Abandoned channel (semi-active, high flow)	2,3,4,5,6
Anabranch	5,6
Delta distributary	5,6
Alluvial distributary	3,4
Billabong (slough)	2,3,4,5,6
Low-flow tributary/high-flow distributary or anabranch	3,4
Tie (batture) channel	2,3
Alluvial/colluvial fans or wedges (valley wall)	1,2,3,4,5,6
Backswamp, ridge-and-swale	1,2,3,4,5
Backswamp, flat	4,5,6
Pleistocene meander scars/depressions	1,2,3,4,5
Cutoff meander	3,4,5
Oxbow lakes or swamp	1,2,3,4,5,6
Infilled oxbow	1,2,3,4,5,6
Crevasse splay	1,2,3,4,5,6
Crevasse channel	2,3,4
Natural levee	1,2,3,4,5,6
Island	5,6
Tributary	1,2,3,4,5,6
Alluvial terrace	1,2,3,4,5,6

Cutoffs and Oxbows. Cutoff meanders as listed in Table 6 refers to recently cut off features which are still within a few channel widths of the (new) active channel. Older cutoffs (oxbows) occur in various states of infilling—oxbow lakes, swamps, and infilled oxbows. This depends partly on local sediment dynamics, but mainly reflects the age or time since the cutoff occurred. In some cases tie channels (or batture channels) connect oxbows or billabongs to the river. These channels may alternately drain or fill the floodplain features, depending on hydraulic conditions.

Meander cutoffs (as well as meander growth indicated by active point bars and cutbanks) are common and expected features in alluvial rivers such as the Sabine, and occur throughout the study area.

Levees and Crevasses. Natural levees are ridges just above the bank tops, at the outer edge of the floodplain. They form due to localized sediment deposition when flows go overbank. Natural levees are an expected feature along alluvial rivers, and occur throughout the study area.

Breaches of the levee from the river side are crevasses. Where flows diverge on the floodplain side of the levee, flow decelerates rapidly and sediment is deposited in fan-like deposits called crevasse splays. Splays are undoubtedly present in the lower Sabine, but none were documented in this study. Crevasse splays cannot be observed from aerial photography in forested environments, and the lower Sabine floodplain is almost entirely forested. Because of rapid vegetation establishment and litter coverage, splays are also difficult to observe in the field in forested settings unless they were recently deposited.

When crevasses lead to concentrated flow and channels are incised, crevasse channels result. Larger, persistent crevasse channels result in avulsions (see abandoned channels above). Because crevasse channels slope away from the natural levee, they are important for channel-floodplain hydrologic connectivity during floods. These channels may locally reduce the likelihood of levee breaches nearby, but may represent future potential avulsion sites if cross-valley slope advantages exist and aggradation is occurring within the river channel (see Jerolmack and Mohrig, 2007; Phillips, 2008b).

Floodplain Depressions. Alluvial floodplain evolution may result in depressional areas in the valley bottom other than oxbows, billabongs, and abandoned channels. Backswamp is a general term for lower areas behind the natural levee, but more specific backswamp features are associated with ridge-and-swale topography. The latter results from lateral channel migration, with former natural levees appearing as slightly higher ridges separated by intervening linear swales. These features create local variations in hydroperiod, water tables, and soil moisture which are important in vegetation and other ecological patterning on the floodplain. Backswamps in general occur throughout the study area. Reaches 1-3 are dominated by ridge-and-swale topography, and reach 6 by generally lower-elevation flat backswamps with few ridges. Reaches 4-5 are transitional, and include both general types of backswamp.

Rivers of the southeast Texas coastal plain experienced higher mean discharges during the Pleistocene, with larger channels and meanders with substantially larger amplitudes

and wavelengths than the contemporary rivers. In the Brazos and Colorado Rivers these have largely been buried by subsequent valley aggradation, but their legacy is sometimes evident in large scallops in the valley wall which represent former cutbanks of the paleochannel. In the Trinity-Neches-Sabine system these "Deweyville" paleomeander features are quite common. They occur as large depressions, evident from aerial and satellite images due to their distinctive topography, hydrology, soil, and vegetation patterns. These paleomeander depressions, beyond being significant landforms and habitats in their own right, exert important influences on local water flows, routing and distribution of flood waters, and contemporary geomorphic evolution of the fluvial system (Blum et al. 1995; Morton et al., 1996; Blum and Aslan, 2006; Sylvia and Galloway, 2006; Phillips and Slattery, 2007b, 2008; Phillips, 2008a, 2008b).

The paleomeander depressions occur throughout the study area, though in the delta (reach 6) they are evident only on the valley margins due to burial by Holocene sedimentation. Three separate generations of paleomeanders can be found within the lower Sabine valley, but not all are evident in every reach, as described by Phillips (2008a).

Other Valley Features. Remnants of previous floodplain levels—alluvial terraces—occur throughout the lower Sabine valley, except in the delta where these features are buried. These are generally referred to as "Deweyville" terraces, though at three separate generations or alloformations are recognized. One to three terrace surfaces are evident at various points along the valley, roughly coincident with the generations of paleomeander features exposed, as outlined by Phillips (2008a). The terraces are slightly higher and relatively drier components of the valley, except in the case of the youngest and lowest terraces, which may be only slightly higher than, or at the same elevation as, the modern floodplain.

Tributary channels occur throughout the study area. Valley-wall colluvial and alluvial sediment accumulations (fans or wedges) are also no doubt common, but difficult to identify in forested environments for the same reasons as crevasse splays.

Islands are semi-stable, vegetated land surfaces in anabranching reaches of the Sabine and its tributaries which are not inundated except during floods. These occur in the delta (reach 6), in conjunction with the multiple high flow channels in reach 5, and in some larger tributaries in reach 5.

RELATIONSHIPS WITH INSTREAM FLOWS

The geomorphic units of the lower Sabine River valley occur at various elevations from the lowest points of the river channel to the margins of the valley. Accordingly, the GUs are inundated at various flow levels, which in turn influences their hydrologic functions, habitat characteristics, and rates and frequency of geomorphic change.

Five fundamental instream flow levels can be identified from a hydrogeomorphic perspective. The lowest, *thalweg connectivity,* is the minimum amount of discharge required to maintain continuous downstream water movement. *Bed inundation* is the flow level at which the entire channel bed is underwater and all mid-channel features

are at least partially inundated. The *sub-bankfull* level is the higher range of flows which can occur before overbank flow begins to occur. *Channel-floodplain connectivity* flows are those which result in river-to-floodplain flow via crevasse and tie channels, high-flow distributaries and anabranches, and tributary backwater flooding. Depending on local channel and levee morphology, this may occur at sub-bankfull levels. *Flood* flows are defined in this sense as those which result in levee overtopping.

Table 7 below relates these flow levels to the geomorphic units which become inundated.

Table 7. Inundation of geomorphic units (see tables 4-6) at various instream flow levels.

Thalweg Connectivity	
	Thalweg
	Pools
Bed Inundation	
	All channel units except upper portions of marginal bars
Sub-Bankfull	
	All channel units
	All bank-attached units
Channel-Floodplain Connectivity	
	Semi-active abandoned channels
	Anabranches
	Distributaries
	Low-flow trib/high-flow distributaries/anabranches
	Tie channels
Flood	
	All units except terraces and valley-wall fans (minor to moderate flood)
	All units (major flood)

Chapter 3: Transverse Bars

BACKGROUND

Field research in the lower Sabine River prior to this project noted the presence of a number of cross-channel or transverse bars. These bars, in addition to being significant geomorphic and hydraulic units, are also likely to be significant as aquatic habitat. Even more than the geomorphic units described in Chapter 2 (except for perhaps some pools), bars are transitory features with respect to location, size, and their very existence. Bars and associated features such as pools and bedforms may appear, disappear, and undergo modifications in response to individual flow events, season flow patterns, and over longer time scales.

Mobile-bed streams, particularly sand-bed rivers such as the lower Sabine, may exhibit a hierarchy of bed forms, ranging from highly transient, centimeter-scale ripples to bars which occupy the majority of the channel, and which may be relatively persistent. In the Sabine and other sandy rivers it is not unusual to have three hierarchical levels of bed forms at a single site, with ripples superimposed on dunes or lobes which are in turn superimposed on bars.

The term "transverse" is used in a general sense to refer to bars which extend across, or nearly across, the entire channel width. The term is also sometimes used to refer to a specific type of transverse bar which is also called a linguoid bar. In this report the term "transverse bar," without modification, should be understood in the general sense.

Some observations from TWDB field work indicated that transverse bars occurred in association with, but downstream of, the apex of sandy point bars. This, combined with the morphology and apparent evolution of meander bends on the Sabine River, led to the hypothesis that the transverse bars are related to downstream migration of meander bends. If the rate of movement of point bars exceeds the overall rate of downstream migration of the meander bend, it was hypothesized, then the extensions of the point bar into the channel (i.e., the transverse bar) should occur downstream of the bend apex. The reasoning was that the sandy bars are mobilized at lower shear stresses than those required for bank erosion, and thus bar mobility occurs more often than cutbank erosion, which is required for migration of the meander as a whole. As indicated below, this hypothesis was abandoned early in the project, and this portion of the study was reoriented toward a general study of the occurrence and geomorphic interpretation of cross-channel bars.

Meander Translation Hypothesis

Field measurements of shear strength of sandy point bars and adjacent bank material were made in October, 2007. Vertical shear strength was measured with a hand-held penetrometer, and horizontal shear strength with a shear vane apparatus. Each sample site was 0.35 m^2 in area, and 10 readings were taken with each instrument and averaged. Bar measurements were taken on lower, wet sand areas.

As expected, shear strength of bank materials was significantly higher than that of bars, due to greater cohesion and plant root binding. Vertical shear strength for the bars was uniformly <1 kg cm^{-2}, with mean values for specific sites ranging from 0.51 to 0.68. Bank materials had vertical shear strength values significantly higher (182 to 286 percent greater), with mean values ranging from 1.24 kg cm^{-2} for sandy banks to 1.46 in finer, more cohesive material. Horizontal shear strength as indicated by shear vane tests showed the same general trends, ranging from 162 percent higher in sandy bank materials than on the bars, to 328 percent greater for cohesive banks.

However, both river-level (on foot and by boat) and aerial observations indicated that:

(1) A variety of cross-channel bars exist in the lower Sabine River.

(2) Most of the transverse bars have no apparent direct relationship to downstream meander translation.

(3) Few, if any of the transverse bars exhibited morphology and geometry associated with the hypothesis.

Therefore it was determined that even if the hypothesis that point bars move more rapidly than other portions of meander forms during downstream translation is true, this is not an adequate explanation of transverse bars in the lower Sabine River.

METHODS

Several reaches of the lower Sabine were traversed by boat or accessed via land in October, 2007 to examine transverse bars. A total of 34 bars were examined in the field, in the general vicinities of Burr Ferry, Harvey Creek, Red Bank Creek, Anacoco Bayou, Palmer Lake, Bon Wier, Deweyville, Cutoff Bayou, and Indian Bayou. The upstream terminus was mapped using a GPS receiver. The orientation of the bar, and of the channel, was determined by compass azimuth. An *ad hoc* classification or description was derived in the field, for later refinement.

On 31 October, 2007 low-flow and clear-water conditions allowed an opportunity for exceptional aerial observation of channel forms. A small-plane flight from Toledo Bend Dam to Deweyville was conducted, with continuous photography of the channel using two digital cameras, one of which was GPS-enabled. This oblique photography was obtained from a variable altitude of <200 m (~600 ft).

A classification of bar types was developed, based on Brierly and Fryirs (2005, p. 86-97), with some expansion for bar types observed in the Sabine which did not fit in the Brierley/Fryirs typology. The aerial photography was then used to classify the bars from Toledo Bend to Deweyville to determine the relative proportion of each type.

Geomorphic interpretations of the bar types were based on standard fluvial geomorphology principles (e.g., Brierely and Fryirs, 2005, p. 86-97), on the geomorphic context of the bars observed in the Sabine, and on field indicators of processes and history as described in earlier work (Phillips, 2003; 2008a).

BAR TYPES

Bank-Attached Bars

Marginal or bank-attached bar types in the lower Sabine include point and lateral bars, tributary mouth bars, diagonal bars, and forced bars (Figure 6). Examples of each type are shown in Appendix B.

Figure 6. Point and lateral bars in the Sabine River near Brushy Creek. Photographic examples of all major bar types in the study area are shown in Appendix B.

Point bars are arcuate-shaped bars developed on the convex inside banks of meander bends, generally following the alignment of the bend. They may be active, as indicated by minimal vegetation cover and smaller scale bed forms superimposed on the bar. Active bars may also exhibit encroachment on downstream banks. Stabilized point bars are characterized by vegetation cover, and sometimes by incised gullies across the bar. Point bars are dominantly sandy in river styles 1-4, while reaches 5-6 include both sandy and fine-grained point bars. Bars are mostly active in reaches 1-3, with reaches 4-5 featuring a combination of active and stabilized bars. Bars in reach 6 are dominantly stabilized.

Lateral bars, also called alternate or side bars, occur along banks in low-sinuousity reaches. In many cases the development of lateral bars on alternate sides of the channel is the first stage in the eventual development of meanders. Lateral bars are mainly confined to river styles 1-3, though they do occur infrequently in reaches 4 and 5.

Both point and lateral bars may be breached by channels incised during the rising stage of high flows. If such channels persist, and are cut to the level of the river bed, they may result in chute cutoffs of point bars, or the development of short-lived mid-channel bars from lateral bars. Otherwise, the breaches infill over time.

Tributary mouth bars are deltaic features which occur as tributary flow is impeded by backwater effects from the dominant channel. While the general presence of a tributary mouth bar is often consistent over time, the specific shape, size, and location (upstream vs. downstream relative to the river, inside or outside of the tributary mouth) are typically quite dynamic, depending on the relative flow dynamics of the river and tributary. These occur in all reaches of the study area.

Diagonal bars are oriented diagonally to the banks, and are considered mid-channel units by Brierly and Fryirs (2005, p. 88). They have been classified as bank-attached units in the Sabine because all observed diagonal bars in the study area are bank attached, and some are confined to channel margin areas. Diagonal bars generally form due to dissection and reworking of riffles or lateral bars. They were observed in reaches 1-3.

Bank-attached forced bars occur sporadically throughout the lower Sabine. These are local deposition associated with obstacles to flow, most often toppled trees oriented more-or-less perpendicular to the banks.

The geomorphic interpretation of bank-attached bars is summarized in Table 8. None of the bank-attached bars except some diagonal bars are cross-channel features, but point and lateral bars are often associated with transverse bars.

Table 8. Geomorphic interpretation of marginal (bank attached) bars.[a]

Gemorphic Unit (bar type)	*Process Interpretation*	*Geomorphic History/Development*
Point Bar (active)	Meander growth & migration; deposition at bend apex coupled with cutbank erosion	Meandering, lateral channel migration
Point Bar (stabilized)	Sedimentation dominated by vertical accretion; limited lateral migration; vegetation establishment	Meander stabilization
Lateral Bar	Lateral accretion associated with meandering of thalweg within banks	Possible precursor to meander formation & growth
Breached Point or Lateral Bar	Erosional dissection of bar during rising stage of high flow	Possible precursor to chute cutoff
Tributary Mouth	Deposition associated with reduced stream power at junction; short-term changes reflect relative dominance of river and tributary flows	Lags in watershed sediment transport; adjustment of junction angles
Diagonal	Oblique flow relative to bank	May be associated with high sediment loads relative to transport capacity, or reworking of riffles
Forced	Deposition due to reduced stream power upstream of an bank-attached obstacle	NA1

[a] [a]NA1: not applicable due to a large number of possibilities or complex relationships between forms, processes, and history. NA2: not applicable due to insufficient knowledge or information.

Mid-Channel Bars

Mid-channel bars found in the lower Sabine River include forced, linguoid, longitudinal, and compound bars, and sand sheets (Figure 7). Examples of each type are shown in Appendix B.

Forced bars are sediment accumulations behind flow obstructions; typically large woody debris. These occur throughout the study area, but are less common in reaches 1 and 6.

Figure 7. Mid-channel bars in a straight reach of the lower Sabine River. Photographic examples of all major bar types are given in Appendix B.

Linguoid transverse bars are oriented perpendicular to flow, usually with a lobate but occasionally with a sinuous form. Linguoid bars have a slip face on the downstream end, and generally occur at points of abrupt flow expansion. In the study area, they typically occur in the vicinity of point or lateral bars, downstream of the widest point of the latter. Linguoid bars are associated with flow divergence in situations of high sediment load relative to transport capacity.

Longitudinal bars are droplet-shaped, with the lobate end upstream and the pointed end downstream. Coarser sand or gravel is typically found at the upstream end. This type of bar is associated with mid-channel deposition where either the size or amount of sediment exceeds transport capacity. As heavier material is deposited mid-channel, some finer particles are trapped in the wake.

Compound mid-channel bars are combinations of two or more of linguoid, longitudinal, forced, or breached marginal bars. They may be formed by welding of bars due to differential rates of downstream migration, or as a result of dissection of sand sheets. The latter are general bank-to-bank sand accumulations. Sand sheets are relatively uniform and tabular, but typically have a variety of superimposed smaller bedforms, and braided subchannels. Sand sheets reflect sediment supply greatly in excess of transport capacity.

The geomorphic interpretations of mid-channel bars is summarized in Table 9. Linguoid bars, sand sheets, and some compound bars are cross-channel, while longitudinal and forced bars are not transverse.

Table 9. Geomorphic interpretation of mid-channel bars.[a]

Gemorphic Unit (bar type)	*Process Interpretation*	*Geomorphic History/Development*
Forced bar	Deposition due to reduced streampower upstream of an obstacle	NA1
Linguoid (transverse) bar	Flow divergence in conditions of high sand bed load supply; abrupt flow expansion	High sand sediment supply; downstream bar migration
Longitudinal bar	Sediment supply exceeding transport capacity; flow divergence following deposition of coarser sediment the flow is not competent to transport	High sand and/or gravel sediment supply
Compound Bar	Recent variation in flow & sediment transport regime; welding of different bar types due to differential downstream migration	NA1; NA2
Sand Sheet	Local increase in sand supply or decrease in flow competence	Channel aggradation or pulsed bedload transport

[a]NA1: not applicable due to a large number of possibilities or complex relationships between forms, processes, and history. NA2: not applicable due to insufficient knowledge or information.

Connector Bars

Connector bars are not recognized in the Brierly and Fryirs (2005) typology, though some individual connector bars could be classified as riffles, linguoid, longitudinal, or compound bars. Connector bars are treated separately here because some of those observed in the study area do not conform to the typical morphology of other bar types, and because they have a unique geomorphic interpretation. Several additional examples are shown in Appendix B.

Connector bars (Figure 8) connect point and/or lateral bars to each other. They may be lobate, elongated, or amorphous, but extend from the downstream end of one bar to the upstream end of the next. Connector bars may be distinguished from linguoid bars or riffles, which are oriented perpendicular or parallel to the axis of the channel (figure 9). Connector bars are oriented diagonally to the channel axis, and appear to be associated with bar-to-bar sand transfer.

A sub-type is an extender bar, which extends from the downstream end of a point or lateral bar toward a downstream marginal bar, but does not cross the channel.

Figure 8. Connector bar, indicated by box.

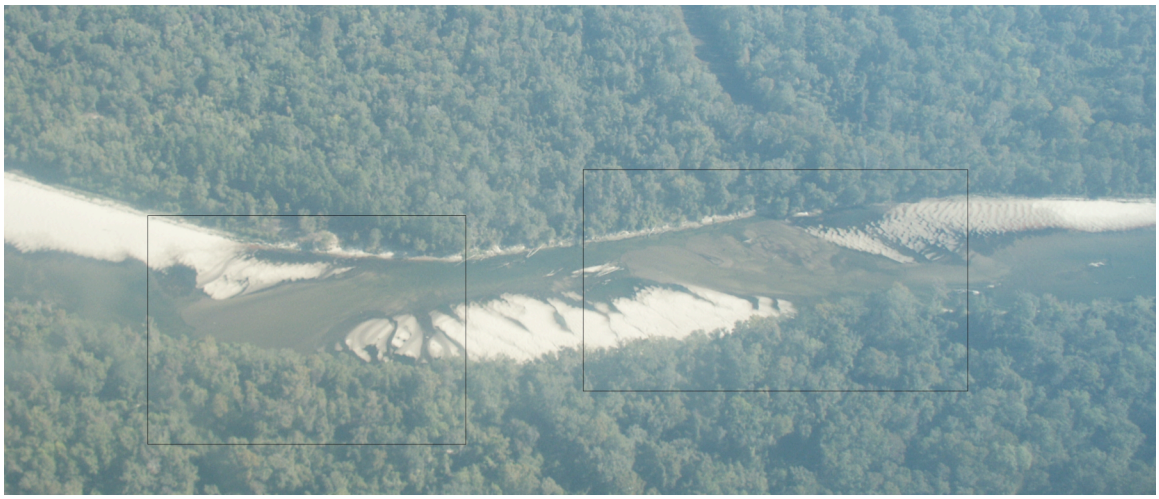

Figure 9. Linguoid bar (left box) and riffle bar (right box) connecting lateral bars. Contrast with the connector bar in figure 8.

The compass azimuths of the general flow/channel direction, and of the bar orientation (along the axis from the connected point and/or lateral bars) was measured in the field for 16 connector bars (some of these were downstream of Deweyville and thus not included in the inventory described in the next section). The angular differences ranged from a minimal 2°, with bar orientation almost parallel to the axis of the channel, to 90°, indicating bar orientation at a right angle to the axis of flow. The mean difference was 44° (median 45.5^{o}), with bar orientations both left and right of the channel axis, with no apparent dominant trend.

Many connector bars appear streamlined (Figure 8) or are composed of a series of cuspate bedforms (Figure 10). Others, particularly when observed at ground/river level, appear to have originally had such forms, with subsequent modifications by cross-bar flows and reworking (Figure 11).

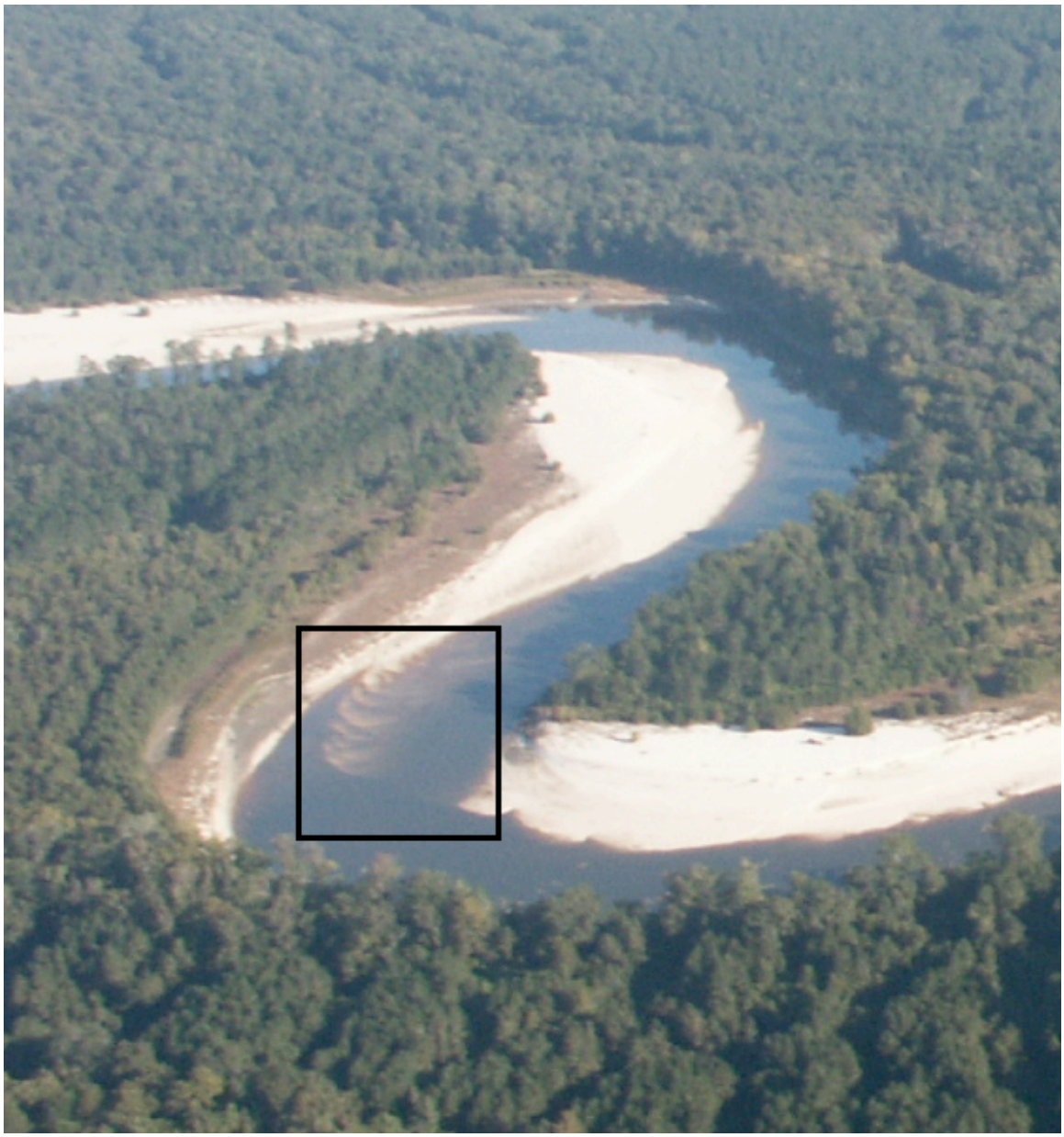

Figure 10. Cuspate bedforms on an extender type of connector bar.

Figure 11. Connector Bar showing evidence of cross-bar flow and reworking.

RELATIVE ABUNDANCE

The 155 km of river channel for which the low-altitude aerial photographs were inventoried contained 266 visible large bars (defined as bars which, at their widest or longest point, occupied at least half the channel width). Due to the low, clear, water conditions it is likely that few, if any large bars bars were missed.

Bank attached bars were by far the most common, with 166 point bars (62 percent of total bars) and 53 lateral (20 percent) counted. In addition, several breached point bars were noted. The relative abundance of bar types is shown in table 10.

Table 10. Bar types in the Sabine River, Toledo Bend to Big Cypress Creek. Cross-channel bars are shown in *italics.* Note that only large bars, as defined in the text, were included.

Type of Bar	Number
Active Point Bar	166
Breached Point Bar	7
Lateral Bar	53
Diagonal Bar	5
Tributary Mouth	3
Compound Mid-channel Bar	14
Mid-channel Forced Bar[a]	13
Sand Sheet	*12*
Longitudinal Bar	3
Linguoid	*30*
Point Bar Connector	*7*
Lateral Bar Connector	*2*
Total	266
Total transverse	*51*

[a]Bank-attached forced bars were observed in the field, but were too small to be included in the aerial photograph inventory

The sand sheets identified in Table 10 may be mobilized during higher flows, but are likely to be a common feature at low flows, given the transport-limited nature of the lower Sabine River in all river styles except reach 1 (Phillips, 2003; 2008a). Of the 30 linguoid transverse bars identified, all but one occurred in the riffle zone between point and/or lateral bars.

The study reach contained 51 transverse bars, a mean of about one for each 3 km of river channel. Note that while point and lateral bars are not transverse, connector and linguoid bars generally link the larger marginal bars, making the latter key in transverse bar development.

DISCUSSION

Transverse Bars

Transverse bars are common features in the lower Sabine River, particularly in reaches 1-3 where there is about one cross-channel bar for every 3 km of river channel. Transverse bars were also observed in reaches 4 and 5.

The transverse bars are dominantly linguoid bars essentially connecting closely-spaced point bars. Flow constriction occurs where the upstream end of one marginal bar is close to the downstream end of another. Bed load transported through the constriction is deposited as a linguoid bar as flow diverges and decelerates at the downstream end of the local constriction (Figure 12). All but one of the linguoid bars observed in the October 2007 aerial photographs were formed in this way. Another seven transverse bars are connector-type bars, chiefly connecting point bars. Thus, while the original hypothesis regarding transverse bars was not supported, clearly point (and to a lesser extent, lateral) bars play a critical role in developing transverse bars—based on the sample above, nearly 75 percent of the cross-channel bars connect marginal bars. The others—sand sheets and one of the observed linguoid bars—are likely to be more temporally ephemeral and spatially mobile. Therefore, relatively persistent or recurring transvserse bars are directly related to point and other marginal bars, and are likely to be present in rough proportion to the number of point and lateral bars.

Figure 12. Linguoid bar formed due to constriction between two closely-spaced alternate side marginal bars.

Connector Bars

The connector bars identified in this study have not been discussed in the literature, though they are likely present in other meandering sand-bed rivers. Based on their form and orientation relative to the bars and the river channel, a reasonable hypothesis is that they result from flow/bedform interactions. At high discharges, flow in the vicinity of the downstream edge of a point bar is deflected by the bar itself, resulting in sand transport in a direction determined by the orientation of the distal end of the marginal bar. As discharge and stream power declines on the falling stage, the flow is no longer competent to transport this bedload, resulting in deposition of the connector (or extender) bar. At this point flow deflection by the marginal bar is no longer significant, and lower-discharge dissection or reworking of the connector bar may occur.

The sequence described above is purely speculative at this point, and could be tested by a combination of sequential observations of bar development and process measurements during high and low flows.

Further study is also needed to determine the circumstances under which linguoid vs. connector bars form between marginal bars. An initial hypothesis is that the linguoid bars are associated with a closer spacing between alternate-side marginal bars.

Geomorphic Interpretations

The point bars are expected features in a meandering river such as the lower Sabine, as are the alternate side lateral bars in relatively straight reaches. The trend toward fewer, finer-grained, and more stable bars in reaches 4-6 is also expected, and occurs in similar situations on other rivers such as the Neches and Trinity (Morton et al., 1996; Phillips and Slattery, 2008).

With the exception of the connector bars discussed above, the types of bars found in the lower Sabine are common types recognized in sand-bed streams. The mid-channel bars are associated with conditions where flows are not competent to transport some of the bedload, and/or where sediment supply significantly exceeds transport capacity. The latter is far more likely in the Sabine, where the gravel content of bedload is small and highly localized. This is consistent with previous work on the lower Sabine (with the exception of the scour zone in reach 1) showing it to be a transport-limited fluvial system (Phillips, 2003; 2008a).

While the presence, prevalence, and nature of the bars in the study area reflect a transport-limited situation, the bars are mobile, and feature smaller superimposed bedforms which indicate sediment movement. This suggests that a significant portion of the Sabine River sediment transport is moved as bed load, and that measurements of suspended load may significantly underestimate sediment transport in the Sabine River. The limited available measurements are not sufficient to confirm or refute this, however.

CONCLUSIONS

The major findings and conclusions of this chapter are as follows:

•The lower Sabine River includes several different types of marginal or bank-attached bars, especially point and lateral bars. Almost all of these in reaches 1-3 are active, as are many in reaches 4 and 5. Other bank-attached bar types include diagonal and forced bars.

•None of the bank-attached bars are cross-channel or transverse, but marginal bars, particularly point bars, play a key role in the development of transverse bar forms.

•The study area includes several different types of mid-channel bars, including longitudinal, linguoid, compound, and forced bars. The linguoid bars are transverse, and the overwhelming majority in the lower Sabine are directly associated with marginal bars.

•The mid-channel bars are mainly associated with conditions where sediment supply exceeds transport capacity, consistent with the characterization of most of the lower Sabine as a transport-limited fluvial system. These bars and their superimposed bedforms also suggest that a significant portion of sediment transport is in the form of sandy bed load.

•An apparently previously unrecognized bar type is relatively common in the study area; connector bars which link marginal bars. The formation of these needs further study, but they are apparently involved in bar-to-bar sediment transfer, and may be related to flow-bedform interactions at the downstream end of marginal bars.

•Most of the transverse bars—particularly the ones likely to be most persistent or recurrent—are linguoid or connector bars linking marginal bars. This affirms the important role of active point bars in the development of transverse bars, and suggests that transverse bars will occur roughly in proportion to the spatial density of active point bars.

Chapter 4
Geomorphic Interpretations

INTRODUCTION

Short of continuous direct monitoring or observation, fluvial and alluvial landforms are the single best indicator of hydrological and ecological processes and regimes in river systems. Additionally, relationships between forms and processes allow for assessment of the geomorphic condition of a river reach or cross-section, and for assessing trajectories of geomorphic change. This is the basis for the broad-scale geomorphic characterization of the lower Sabine (Phillips and Slattery, 2007a; Phillips, 2008a). This section focuses on the interpretation of geomorphic units at more detailed scales.

As a caveat, note that while there exist systematic relationships between landforms and geomorphic processes, these are *not* uniformly one-to-one. That is, sometimes multiple processes or causes (or combinations thereof) can result in the formation of a particular feature. Thus, for example, concave banks usually represent bank erosion due to hydraulic stress from river flows, but may also reflect groundwater and slope processes resulting in bank failure. Thus, whenever possible, multiple features or lines of evidence should be used in making geomorphic inferences.

Most of the form-process relationships described below are based on standard principles of fluvial geomorphology (see, e.g., Knighton, 1998; Brierly and Fryirs, 2005, Schumm, 2005), and/or previous work in southeast Texas.

In addition, many of the environmental indicators used to delineate wetlands may be applied to make inferences about hydrologic regimes. These are discussed in detail by Brinson (1993) and Johnson (2005).

GEOMORPHIC UNITS

The geomorphic implications of bars are discussed in Chapter 3. Tables 11-13 below summarize the interpretations of the GU's in Chapter 2. Note that these are based on the presence the specific features. The size, morphology, and context of individual GU's, as well as presence/absence and characteristics of smaller scale features (hydraulic and habitat units) can clarify or modify inferences and deductions. The specifics of riparian vegetation as geomorphic indicators are reviewed by Hupp and Osterkamp (1996).

The contemporary processes column indicates what recent or ongoing processes are reflected by the unit, and the geomorphic history column shows what the feature may indicate with respect to recent landform change and landscape evolution. The possible transformations column indicates potential near-future transformations.

In some cases a number of different processes or historical pathways, separately, or in combination, can result in the formation of a given unit. Thus the presence of a thalweg, for example, does not reveal anything about contemporary processes or geomorphic

history. In a few cases (e.g. islands) there is simply not enough known to make confident geomorphic interpretations.

Table 11. Geomorphic interpretation of mid-channel geomorphic units.[a] Bars are treated separately in Chapter 3.

Geomorphic Unit(s)	*Contemporary Processes*	*Geomorphic History*	*Possible Transformations Or Changes*
Thalweg	NA1	NA1	Lateral migration; sinuousity
Bedrock outcrops	Minimal channel incision	Channel incision	Expansion or burial
Riffle-pool	Selective bedload transport	NA1	NA1
Glide (run)	Steady-state sediment transport	NA2	Development of bars, riffle-pool sequences
Circular meander pool	High-flow countercurrents	Slow lateral migration; inhibition of cutoffs	NA2
Downstream forced pool	Scour downstream of obstacle	NA1	Infilling, smoothing
Forced backwater pool	Flow obstruction and ponding	NA1	Infilling, smoothing
LWD jams	Bank erosion, LWD transport, logging waste	NA1	Removal by transport; local bank or bed scour; local backwater effects; avulsion due to flow deflection

[a]NA1: not applicable due to a large number of possibilities or complex relationships between forms, processes, and history. NA2: not applicable due to insufficient knowledge or information.

Table 12. Geomorphic interpretation of bank-attached geomorphic units.[a] Bars are treated separately in Chapter 3. ([a]NA1: not applicable due to a large number of possibilities or complex relationships between forms, processes, and history. NA2: not applicable due to insufficient knowledge or information).

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Geomorphic Unit(s)	*Contemporary Processes*	*Geomorphic History*	*Possible Transformations Or Changes*
Bench	Infilling	NA1	NA1
Ledge	Bank or bed erosion	Incision into former channel bed	NA1
Bedrock bank	Minimal bank erosion	Channel widening and/or downcutting	NA1
Concave bank	Erosion and bank retreat	Lateral channel migration or widening	Stabilization and recovery to concavo-convex
Convex bank (vegetated)	Bank stability or slow accretion	NA1	Conversion to concave, straight, or complex erosional forms
Convex bank (unvegetated)	Recent or chronic accretion; marginal bar development	NA1	Stabilization to vegetated convex bank
Straight bank (vegetated)	Stable or slowly eroding banks in cohesive materials	NA1	Conversion to concave, straight, or complex erosional forms; conversion to stable convex form
Straight bank (unvegetated)	Bank erosion, lateral channel migration	NA1	Conversion to concave, or complex erosional forms; stabilization to vegetated straight bank
Convexo-concave bank	Erosion of banks of variable resistance; removal of lower bank vegetation or LWD; local low-flow acceleration or deflection	Transition from stable or accreting to eroding bank	Conversion to concave erosional bank
Concavo-convex bank	Recent cessation or deceleration of bank erosion	Recovering cutbank	Conversion to stable convex or concave erosional bank
Cypress buttress	Recent channel aggradation; or seasonal water level variation	Channel aggradation	Erosion, drowning of cypress
Slumps & slump scars	Rotational bank slope failures	Channel incision and/or lower bank erosion	Conversion to or incorporation into concave erosional bank
Chute channel	Concentrated high flow across point bar	Meander development and migration	Chute cutoff or point bar breaching
Sand rampart	Localized marginal deposition	NA2	Removal

.

Table 13. Geomorphic interpretation of floodplain and valley geomorphic units.[a]

Geomorphic Unit(s)	*Contemporary Processes*	*Geomorphic History*	*Possible Transformations Or Changes*
Infilled abandoned channel	Vertical accretion	Avulsion and channel abandonment	Reoccupation by future avulsions (sand filled); inhibition of future avulsions (clay plugs)
Semi-active abandoned channel	High-water flow	Avulsion and channel abandonment	Infilling, or reoccupation by future avulsions or by tributaries
Anabranch	NA1	Valley aggradation & avulsion	Abandonment
Delta distributary	Deltaic sedimentation and divergent flow	Delta development	Abandonment; growth by flow capture
Alluvial distributary	Sediment and water dispersion to floodplain	Flood basin development plus avulsion	Abandonment; growth by flow capture
Billabong	Water storage	Avulsion	Infilling; reactivation by future avulsion or tributary occupation
Low-flow trib/ high-flow distributary	Influx to river at low flows; divergent fluxes from river at high flows	Tributary occupation of abandoned channels following avulsion	Infilling; coversion to tributary or distributary
Tie channel (batture)	Oxbow to river flux at low flows; opposite at high flows	Recent cutoff; crevasse channel cut to oxbow	Infilling; avulsion
Ridge-and-swale backswamp	Vertical accretion	Lateral channel migration	Burial by vertical accretion
Flat backswamp	Vertical accretion	Burial of ridge-and-swale; infilling of floodplain depressions	Alluvial terrace
Pleistocene meander scars/depressions	Infilling	Incision of pre-Holocene valleys formed during higher discharges	Infilling
Cutoffs, oxbows	Infilling, water storage	Meander cutoff	Lakes to swamps to infilled
Continued on	Following Page		

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Natural levee	Ongoing or recent deposition	Overbank deposition	NA1
Crevasse splay	NA1	Levee breaching with decelerating sheet flow	NA1
Crevasse channel	High-water river to floodplain flow	Levee breaching with concentrated flow	Infilling; avulsion
Tributary channels	Water, sediment flux to river	NA1	NA1
Islands	NA2	Valley aggradation and anabranching; inheritance from Pleistocene anabranching	NA2
Alluvial terraces	NA1	Quaternary aggradation-degradation sequences	Burial of lower terraces; erosional dissection of higher terraces

[a]NA1: not applicable due to a large number of possibilities or complex relationships between forms, processes, and history. NA2: not applicable due to insufficient knowledge or information.

BANK GEOMORPHIC INDICATORS

Mid-channel geomorphic units may be difficult to observe except at low flows, and floodplain/valley features may be both difficult to observe or access, and of less direct relevance to instream flows. Bank conditions are the most readily assessed at bed inundation to sub-bankfull flow levels. The following keys are thus offered as an aid to the geomorphic assessment of bank conditions.

Table 14 is a key for interpreting morphology of banks at individual cross-sections and reaches. Table 15 then indicates what comparisons of left and right banks infer about channel behavior.

Table 14. Key for interpreting bank profile morphology.

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1. Bank profile morphology
    - Simple (entire bank convex, concave, straight): 2
    - Complex: 5

2. Concave?
    - Yes: *eroding cutbank*
    - No: 3

3. Convex?
    - Yes: s*table or accreting bank*: 3.1
        - 3.1. Vegetated?
            - Yes: *stable bank or stabilized bar*
            - No, or minimal vegetation cover: *accreting bar or infilling bank*
    - No: 4

4. Straight?
    - Yes: 4.1
        - 4.1. Vegetated, or with coating of algae, lichens, or biofilm?
            - Yes: *stable bank*
            - No: *eroding bank*
    - No: 5

5. Upper bank/lower bank
    - Convex/concave: 6
    - Concave/convex: *Recovering cutbank*
    - Other: 7

6. Convex upper bank, concave lower bank: possible causes; requires detailed investigation
    - *Transition, stable or accreting to eroding bank*
    - *Resistance variations, upper vs. lower bank*
    - *Removal of lower bank protection*
    - *Locally higher shear stress*
        - *Low-flow acceleration*
        - *Flow deflection*

7. Channel shelf?
    - Yes: 8
    - No: requires detailed investigation

8. Bench (depositional): *Infilling bank*
   Ledge (erosional): 9

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9. Ledge composition
    Similar to bed, banks: *incision into former channel bed*
    Resistant material: *bank erosion*

Table 15. Key for inferring channel behavior based on left:right bank comparison.

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1. Both banks in same state
    Yes: 3
    No: 2

2. One eroding, one stable: *channel widening*
   One eroding, one accreting: 2.1
    2.1 Erosion > accretion: *channel widening & lateral migration*
    Erosion < accretion: *channel narrowing & lateral migration*
    Erosion ≈ accretion: *lateral migration*
   One stable, one accreting: *channel narrowing*

3. Both stable: *stable channel*
   Both accreting: *channel narrowing*
   Both eroding: *channel widening*

INCISION AND AGGRADATION

Channel incision is caused by vertical erosion into the channel bed and is also known as downcutting or degradation. Any channel—particularly alluvial channels such as the lower Sabine—can experience short-term, local erosion (and deposition) in the channel bed. The indicators in Table 16 are suggestive of general, net incision independent of more localized changes.

Table 16. Field indicators of channel incision. None of the following is caused exclusively by general channel incision; two or more indicators should be present for confident interpretations. Potential alternate causes for the indicators are given in [brackets].

•*Exposure or undercutting of cultural features* such as bridge pilings, boat ramps, docks, pilings, etc. [localized flow or slope increases or flow deflections]

•*Exposure of bedrock* or pre-Quaternary material in bed [lithological variations]

•*Knickpoints* [lithological or structural variations; antecedent morphology; local sediment inputs]

•*Channel ledges or paleobanks* [lateral infilling]

•*Obligate hydrophytes* well above normal water levels [perched ground water]

•*Back-tilted riparian trees* (tilted away from river) [wind throw]

•*Evidence of reduced overbank flow*, e.g., reduced sedimentation, soil formation, soil redox features, vegetation changes [vertical floodplain accretion]

•*Channel narrowing* without evidence of significant changes in discharge, stream power, or sediment supply. [local slope failures]

•*Tributary downcutting* (indicators above observed in tributaries)

Table 17 lists field indicators of channel aggradation, characterized by persistent net deposition or infilling of the channel. While all are linked to deposition or aggradation, multiple locations should be assessed to distinguish between general reach-scale aggradation and temporary local deposition.

With respect to floodplains, stability or slow accretion is indicated by soil development and minimal presence of the aggradation indicators in Table 18. Floodplain erosion or stripping is indicated by exposed tree roots, truncated soil profiles, and rills, gullies, or erosion pavements on the floodplain surface. Recent accretion or aggradation is signified by the indicators in Table 18.

Table 17. Field indicators of recent channel aggradation. While all the following are associated with aggradation, they may be related to localized deposits rather than general aggradation. Therefore multiple locations should be assessed.

•*Burial or partial burial of channel and lower-bank vegetation.*

•*Burial of LWD.*

•*Island formation* (relatively young islands as indicated by vegetation and soil characteristics)

•*Sand sheets.*

•*Cypress buttressed-banks* in non-deltaic or fluvial/estuarine transition zones.

•*Crevasses and avulsions* [local levee damages or flow diversions]

•*Evidence of increased frequency of overbank flow*, e.g., increased floodplain sedimentation, soil redox features, vegetation changes, floodplain flow and hydrologic indicators [erosional floodplain stripping; increased discharge]

•*Tributary aggradation* (indicators above observed in tributaries)

•*Increased tributary backflooding* (indicators of floodplain or channel aggradation along lower tributary reaches; organic deposits near tributary mouths)

Table 18. Field indicators of recent floodplain aggradation. While all the following are associated with aggradation, they may be related to localized deposits rather than general aggradation. Therefore multiple locations should be assessed.

•*Burial of understory vegetation.*

•*Burial of tree root crowns and basal flares*

•*Burial of leaf and litter layers*

•*Fresh sediment deposits*

•*Stratified or massive surficial sediments* with minimal pedogenic development.

•*Burial or partial burial of cultural features,* e.g. buildings, pilings, fences, etc.

•*Recent cultural materials in sediment deposits*, with stratification preserved; e.g., plastic and synthetic materials, recent glass, electronic components, appliances

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OTHER INDICATORS

Several features are found in the lower Sabine River valley which do not meet the definition of geomorphic units, but which are useful diagnostics or indicators of geomorphic and hydrologic processes.

One of these is the presence of identifiable buried soils or paleosols in the floodplain. This indicates that the floodplain experienced a period of relative stability (limited or slow accretion or erosion) which allowed a soil profile to form. Subsequent deposition—either from one or more large events, or a general increased deposition rate—resulted in the burial of the profile (Figures 13-14). Buried soils or analogous stratigraphic unconformities may also be associated with deposition of dredge spoil.

Such buried soils do occur in the lower Sabine valley, but they have not been extensively studied or inventoried and their distribution is unknown.

Figure 13. The dark layer is the organic-rich A-horizon of a soil profile buried by subsequent floodplain deposition.

Figure 14. A paleosol in the Sabine delta. A horizontal line has been drawn at the approximate top of the buried soil. In some cases detailed examination and significant pedological expertise is needed to recognize buried soils.

Fluvially-transported organic matter generally floats, and even when waterlogged has a very low settling velocity. The deposition of fine macroscopic organic matter (twigs, leaves, small wood fragments, etc.) in layers more than about a cm thick generally represents either sites of ponded water, or situations where water levels decline rapidly, leaving organic matter accumulations in a manner roughly analogous to a bathtub ring. Thick organic accumulations (>15 cm) are usually associated with backwater conditions or recirculating eddies, where organic matter accumulates in the flow before being deposited as water levels fall.

Several examples of such deposits were found during fieldwork in the lower Sabine; some are shown in Figures 15-17.

Figure 15. The thick organic layers in this sand ramp downstream of Burr Ferry indicate relatively rapid water level changes.

Figure 16. The thick, minimally decomposed organic layer in the Sabine delta, overlain by sand, suggests recent changes in the hydrogeomorphic dynamics at this site, from a backwater to a more energetic flow regime.

Figure 17. Thick organic layers just inside Cutoff Bayou at its confluence with the Sabine suggest that recirculating eddies may form during high flows.

Some bars and bedforms exposed in the lower Sabine during low flow conditions have extensive algal mats. Such mats cannot form in high-energy environments or on highly mobile sediments. Thus these algal mats—some of which oxidize to orange, brown, or red colors when exposed to the air—may indicate at least temporary stabilization of bedforms (figures 18-19).

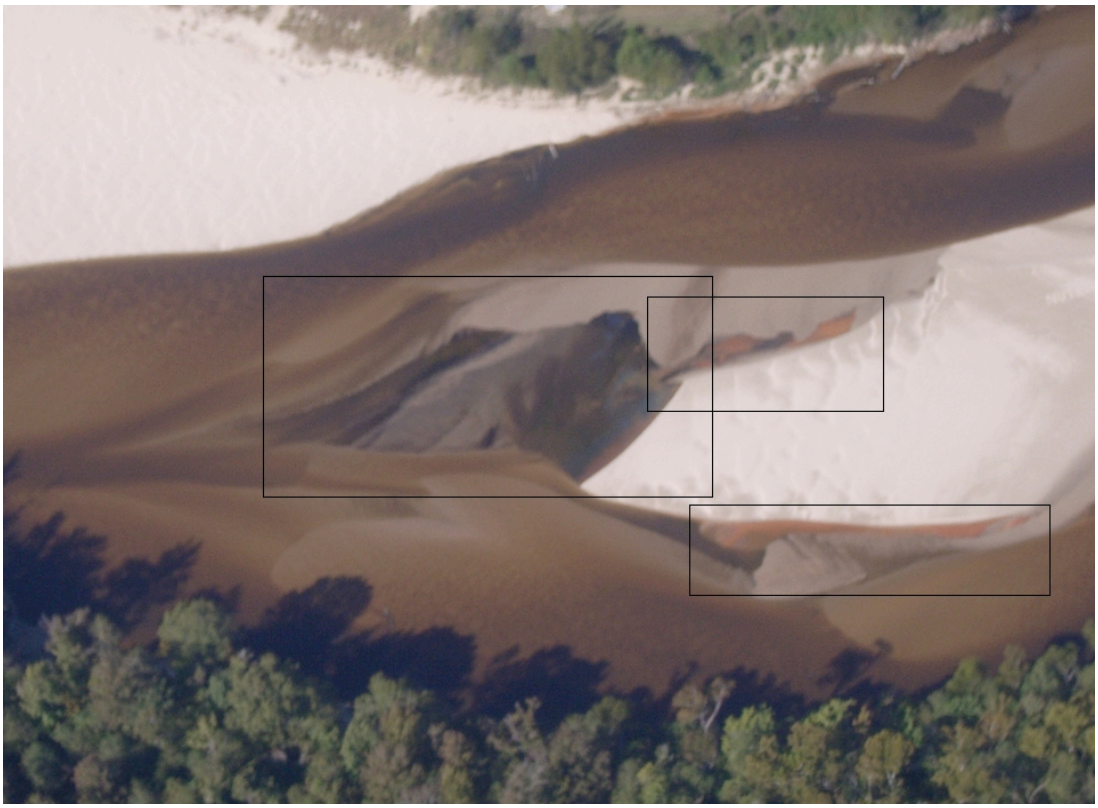

Figure 18. Algal mats (boxes) on mid-channel bars.

Figure 19. Algal mats (orange colors) on an exposed portion of the upstream end of a marginal bar.

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Scope of Work

SCOPE OF WORK PLAN

Geomorphic Units of the Lower Sabine River

Jonathan D. Phillips

August 2007

Overview

This work plan addresses a cooperative research study of the subreach-scale landforms of the lower Sabine River, Texas/Louisiana from Toledo Bend Dam to Sabine Lake. Building on previous work delineating geomorphic zones or reaches (river styles) and associated environmental controls and hydrologic and geomorphic processes, this study addresses the characteristic landforms within those zones. The dominant (in terms of size, frequency of occurrence, and influence on hydrologic and ecological conditions) geomorphic units will be identified, described, and related to hydrologic and geomorphic processes and controls and the river styles zonation. Particular emphasis will be placed on transverse bars. These (more-or-less cross-channel) sand bars are important bedforms and aquatic habitat elements in rivers. In meandering coastal plain streams such as the lower Sabine River, transverse bars are usually associated with point bars on the inside of bends, and typically occur at or near the apex of the bend. In the lower Sabine, however, transverse bars have been found downstream of the meander inflection points. The goal of this study is to predict the location and future migration of transverse bars in the lower Sabine, and to test a hypothesis regarding the bars' occurrence downstream of the bend apex.

The specific objectives are to:

(1) Identify and describe major geomorphic units associated with the geomorphic zones identified in previous work (Phillips 2007; Phillips and Slattery 2007).

(2) Describe geomorphic units with respect to size, form, origin, longevity (e.g., typical time scales or persistence) and relationships to particular fluvial or ecological processes.

(3) Assess the geography of geomorphic units with respect to environmental settings, longitudinal (up-downstream) distribution, and association with geomorphic zones.

(4) Test the hypothesis below regarding transverse bars.

Transverse Bars

Some point bars in the Sabine show evidence of downstream translation. If the rate of such movements exceeds the rate of overall meander bend migration, then the extensions of the point bar into the channel (i.e., the transverse bar) should occur downstream of the bend apex. I hypothesize that the sandy bars are mobilized at lower

shear stresses than those required for bank erosion, and thus bar mobility occurs more often than cutbank erosion, which is required for migration of the meander as a whole.

Results will provide an assessment of the current state of point and transverse bars in the study area, predictions of trajectories of change, and guidelines for field and GIS-based assessment of bars to facilitate samplng and resource assessments.

Methods

Geomorphic unit inventories and characterizations will be based on the following data sources:

•Map, aerial photography, digital elevation model, hydrologic, soil, and geologic data collected in connection with previous projects (Phillips 2003; 2007; Phillips and Musselman 2003; Phillips and Slattery 2007).

•Field measurements, observations, and photographs collected in connection with previous projects (Phillips 2003; 2007; Phillips and Musselman 2003; Phillips and Slattery 2007).

•0.3 m (1 foot) resolution aerial photography flown in September, 2005 (post Hurricane Rita).

•Field measurements and observations, with sampling stratified by identified geomorphic zones.

The transverse bars will be approached thus: The size and geometry of all point bars between Burr Ferry (SH 63 crossing near Burkeville, TX) and Big Cow Creek will be examined via digital orthophotoquads (2004 images) to determine the correspondence between bend apices and transverse bars. A sample of 20 bars will be examined in the field. Geomorphic and vegetation evidence of downstream translation will be examined, and point bar and cutbank sediments will be sampled. Shear strength tests of cutbanks will be performed using a shear vane and penetrometer, and cross-sections will be surveyed. Cross-sectional data and flow data from gaging stations at Burr Ferry and Bon Wier will be used to relate the critical shear stresses for sand mobility and bank erosion to flow frequencies.

Personnel and Responsibilities

TWDB will oversee the activities of the project and serve as contract manager. Dr. Jonathan Phillips/Copperhead Road Geosciences (University of Kentucky, but functioning as an independent contractor) will be principal investigator, with research assistants.

Tasks

(1) Synthesis and assessment of existing data.
(2) Acquisition and processing of 2005 high-resolution aerial photography.
(3) Field data collection.

(4) Data analysis and interpretation.
(5) Produce report.

Timeline

The timeline is based on a September 1, 2007 start date and should be adjusted proportionally for any later start.

Task	Time Frame
(1)	September-November, 2007
(2)	September-December, 2007
(3)	October, 2007-May, 2008*
(4)	May-July, 2008
(5)	July-August, 2008

*Dates contingent on travel schedules, weather, and coordination with Sabine River Authority of Texas.

Salinity Suitability Analyses of *Rangia cuneata* and Other Characteristic Species and Communities of the Sabine-Neches Estuary in Order to Develop a Freshwater Inflow Regime

October 31, 2009

Salinity Suitability Analyses of *Rangia cuneata* and Other Characteristic Species and Communities of the Sabine-Neches Estuary in Order to Develop a Freshwater Inflow Regime

Submitted to: Sabine and Neches Bay and Basin Expert Science Team

10/25/09

Submitted by:

National Wildlife Federation, Austin, Texas

Analyses performed by:

Norman D. Johns, Ph.D. of the National Wildlife Federation

This project made possible with financial support from the Cynthia and George Mitchell Foundation.

Acknowledgements: *Rangia cuneata* fieldwork undertaken by BIO-WEST, Inc. pursuant to contract with National Wildlife Federation.

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Introduction

The Sabine-Neches Bay and Basin Expert Science Team (BBEST) was created under the auspices of Senate Bill 3 of the 2007 Texas Legislature. The BBEST is tasked with developing an environmental flow regime to support a "sound ecological environment" for Sabine Lake as well as the Neches and Sabine River basins.

The recent SB 3 Science Advisory Committee report (SAC, 2009a) on methods for establishing an estuarine inflow regime recognizes a variety of potential approaches. The goal of these approaches is to link freshwater inflows, and its various attributes such as timing and volume, to the biologic response of the estuary. One of the principal methods for characterizing the biota of the estuary is recognized by the SAC as the "Key Species" method.

"[The] basis for selection of a key species is either (1) that the species enjoys some prominence, typically as a favored recreational target, as a commercial fishery hence having economic significance, or as a charismatic species commanding widespread public interest, or (2) that the species typifies in some way a key element of the ecosystem."

For the purposes of establishing an estuarine inflow regime, the SAC goes on to state that:

"The utility of key species is enhanced if they exhibit sensitivity to inflow-controlled parameters such as salinity or nutrient concentrations."

Approaches focused on key species with specified salinity tolerance ranges (salinity suitability relationships) are in widespread use with a variety of methods for coupling the species' biologic response to the inflow-salinity patterns. Recent examples would include the efforts of the LCRA-SAWS project studies (LCRA-SAWS 2008) which utilized a suite of characteristic species in Matagorda Bay and their respective salinity preferences to design a tiered inflow regime. The work of Doering, et al. (2002) focused on rooted plants with established salinity preferences to design a freshwater inflow range for a major southern Florida estuary.

The analyses presented herein were designed to support the efforts of the Sabine-Neches BBEST to develop an estuarine inflow regime for the Sabine-Neches Estuary (Sabine Lake). We have focused on a suite of four specific species and two marshland communities, all with well-established and published salinity tolerance (a.k.a. salinity suitability) information. These key species and communities are:

Rangia cuneata larvae
blue crab (*Callinectes sapidus*) juveniles
oysters (*Crassostrea virginica*) adults
Olney bulrush (*Schoenoplectus americanus*) adults & seedlings
intermediate marsh
brackish marsh

The species *Rangia cuneata* (or just *Rangia* herein), blue crabs, oysters, and the Olney bulrush were recommended "focal species" in a previous report to the BBEST (Bio-West 2009). The spatial extent and abundance of oyster and blue crabs are well known in Sabine Lake based on the Texas Parks and Wildlife Department's long-term sampling program. The Olney bulrush is recommended by Bio-West (2009) due to its likely occurrence in the marsh types surrounding

Sabine Lake. The spatial extent and abundance of *Rangia* was not well established for Sabine Lake and thus an important preliminary portion of this work was a field investigation with sonar imaging and field sampling. Appendix A details this work. In summary, *Rangia* are widespread in the majority of Sabine Lake, approximately the upper three-fourths of the estuary. Based on these results we are confident that *Rangia* are a very good key species for this estuary evaluation not only because of the well-defined salinity tolerance limits of the larvae (more below), but also due to the fact that they comprise a substantial benthic biomass in much of the estuary. The two marshland communities are widespread around the margins of Sabine Lake as indicated by TPWD & TWDB (2005).

For the four individual species, there are well-established salinity suitability relationships (see Methods). These are quite specific (e.g. 10-20 ppt is optimal for oysters) and often focused on a particular life stage (*e.g*. for *Rangia*). For the marshland communities, the salinity suitability relationships are broad levels thought to support that particular community over a long-term.

The availability of a set of existing salinity-inflow regression equations at several points in the estuary greatly facilitates the examination of how these species and communities are likely to respond to freshwater inflows and associated salinity patterns. The primary focus of these assessments is on evaluating the potential freshwater inflows that would result from river-based environmental flow regimes that the BBEST is considering. However, this method can be used in a more direct manner to "design" the levels of freshwater inflow that may be necessary to support these species and communities and thus protect a "sound ecological environment."

Methodology

As mentioned above, the primary focus of the assessments herein is to evaluate the impacts of instream flow regime components that the BBEST is considering. The resulting inflows have not been derived specifically for Sabine Lake, but are the product of the BBEST's efforts to develop environmental flow regimes at several points in the lowermost portions of the Sabine and Neches River basins. These points are specifically the Sabine River at Ruliff (USGS gauge #08030500), the Neches River at Evadale (8041000) and Village Creek near Kountze (8041500). The draft environmental flow regimes for these points were developed primarily with the Hydrology-Based Environmental Flow Regime (HEFR) methodology as described in SAC (2009b). In the terminology of the SAC, the work here amounts to an "overlay analysis" of the instream environmental flow regimes to examine their suitability from the perspective of freshwater inflows.

Creating an Inflow Record with HEFR-Derived Instream Flows

The BBEST and their consultant applied the HEFR method at many sites within the Sabine and Neches River basins. Figure 1 shows the location of the sites Sabine River at Ruliff, the Neches River at Evadale, and Village Creek relative to the Sabine-Neches Estuary.

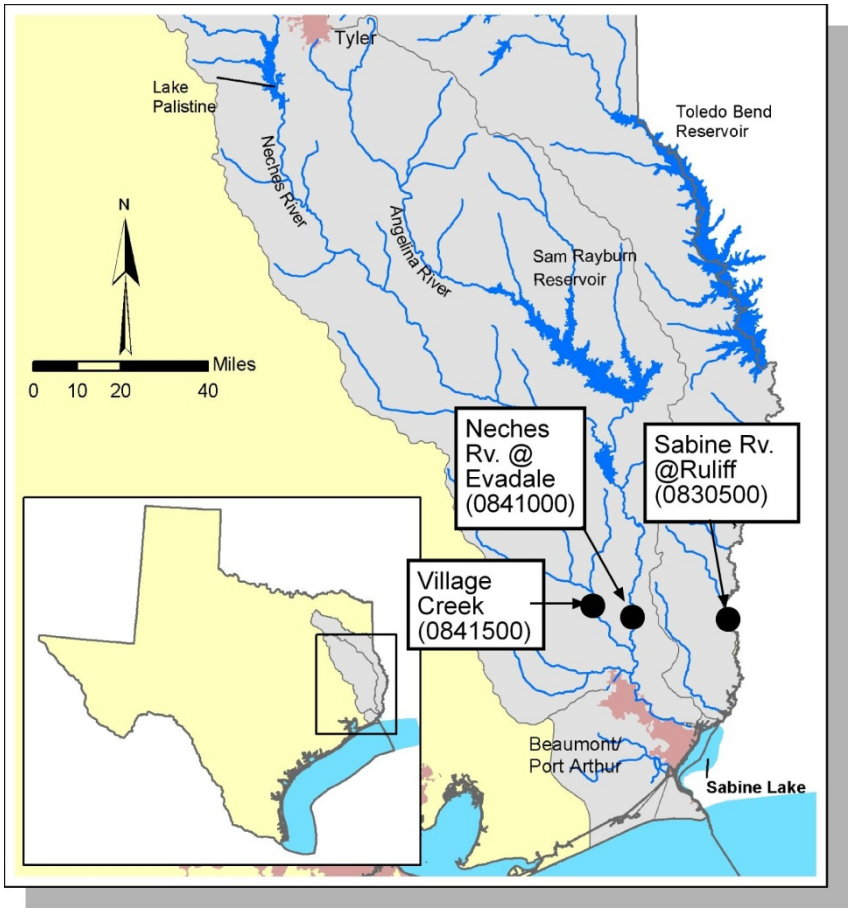


Figure 1 – The BBEST Sites at Ruliff, Evadale, and Village Creek relative to Sabine Lake.

As is evident in Figure 1, the flows at these three points do not comprise all of the potential inflow to Sabine Lake. There are also contributions from other gauged watersheds (Pine Island Bayou and Cow Bayou) as well as ungauged areas below these gauges or other wholly ungauged drainages. For these areas the Texas Water Development Board (TWDB) has estimates of inflows dating back to 1941 on a monthly basis. The TWDB also has records, or estimates, of diversions, return flows, direct precipitation onto Sabine Lake, and evaporation that must also be taken into account. Although these later components are generally minor compared to the mainstem river contributions they can be important for very low portions of the environmental flow regimes as will be seen.

Figure 2 illustrates the HEFR-derived flow regimes for the Sabine River at Ruliff, the Neches River at Evadale, and Village Creek sites. As shown, there are several flow components, such as “base flows,” each of which have fairly well established roles at maintaining a sound ecological environment for a river or stream setting (TIFP 2008). In the analyses discussed here, we have focused on two of these components in particular because of their likely importance in the overall flow regimes and potential role in influencing the ecology of Sabine Lake. Although a more complete evaluation of the full spectrum of flow components would be preferable, time limitations have prevented that, at least for the time-being. First, we focused on the “base average” condition flows because they may be in effect for a substantial portion of the time as these environmental flow regimes are implemented. However, because, to our knowledge, no attainment frequency for this component has been explicitly specified as of

the time of this analysis, the precise percentage of time those conditions might be expected to pertain is unclear. Our second primary area of focus is on the so-called “subsistence” level of flows. Flows of this low magnitude should be rare events, occurring only during very dry, near drought-of-record, periods (TIFP 2008). We focus on this flow level in order to assess the implications of these very low flows on Sabine Lake. Another reason for analyzing these particular portions of the flow regime is that the higher flow, or wet period, portions of the flow regime, are less likely to be substantially affected by new water projects, particularly in the near-term.

USGS 08030500 Sabine Rv nr Ruliff, TX
Full Period

Overbank Flows	Qp: 41,300 cfs with Frequency 1 per 2 years Volume is 2,581,061 Duration is 82			
High Flow Pulses	Qp: 9,880 cfs with Frequency 1 per season Volume is 261,464 Duration is 22	Qp: 9,880 cfs with Frequency 1 per season Volume is 253,851 Duration is 21	Qp: 6,600 cfs with Frequency 1 per season Volume is 157,936 Duration is 19	Qp: 6,030 cfs with Frequency 1 per season Volume is 110,471 Duration is 15
	Qp: 1,600 cfs with Frequency 2 per season Volume is 10,202 Duration is 3	Qp: 3,250 cfs with Frequency 2 per season Volume is 42,883 Duration is 8	Qp: 3,380 cfs with Frequency 2 per season Volume is 54,321 Duration is 11	Qp: 2,020 cfs with Frequency 2 per season Volume is 17,662 Duration is 5
Base Flows (cfs)	5063	3035	1430	1400
	2565	1795	870	970
	1520	1208	670	735
Subsistence Flows (cfs)	396	396	396	396
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

USGS 08041000 Neches Rv at Evadale, TX
Full Period

Overbank Flows	Qp: 26,800 cfs with Frequency 1 per 2 years Volume is 1,762,388 Duration is 46			
High Flow Pulses				
	Qp: 8,700 cfs with Frequency 1 per season Volume is 255,138 Duration is 22	Qp: 8,700 cfs with Frequency 1 per season Volume is 250,330 Duration is 23	Qp: 3,390 cfs with Frequency 1 per season Volume is 64,197 Duration is 13	Qp: 3,820 cfs with Frequency 1 per season Volume is 68,248 Duration is 13
	Qp: 2,000 cfs with Frequency 2 per season Volume is 21,702 Duration is 6	Qp: 3,440 cfs with Frequency 2 per season Volume is 64,381 Duration is 12	Qp: 1,190 cfs with Frequency 2 per season Volume is 15,630 Duration is 8	Qp: 1,150 cfs with Frequency 2 per season Volume is 12,160 Duration is 6
Base Flows (cfs)	4980	3868	3210	2630
	2590	3070	2140	1280
	1760	1553	471	438
Subsistence Flows (cfs)	228	228	228	228
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

USGS 08041500 Village Crk nr Kountze, TX
Full Period

Overbank Flows	Qp: 12,400 cfs with Frequency 1 per 2 years Volume is 170,313 Duration is 29			
High Flow Pulses				
	Qp: 2,070 cfs with Frequency 1 per season Volume is 38,134 Duration is 13	Qp: 2,070 cfs with Frequency 1 per season Volume is 31,650 Duration is 15	Qp: 814 cfs with Frequency 1 per season Volume is 11,418 Duration is 13	Qp: 2,070 cfs with Frequency 1 per season Volume is 31,143 Duration is 13
	Qp: 2,010 cfs with Frequency 2 per season Volume is 36,927 Duration is 13	Qp: 1,380 cfs with Frequency 2 per season Volume is 23,093 Duration is 13	Qp: 341 cfs with Frequency 2 per season Volume is 6,159 Duration is 8	Qp: 712 cfs with Frequency 2 per season Volume is 11,426 Duration is 9
Base Flows (cfs)	672	335	135	236
	424	189	91	138
	240	106	70	89
Subsistence Flows (cfs)	41	41	41	41
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

Figure 2 – The HEFR-based environmental flow regimes derived for the sites Sabine River at Ruliff, Neches River at Evadale, and Village Creek near Kountze (as of Oct. 15, 2009).

In order to assess the implications of adopting and implementing the proposed HEFR-derived flows, we followed a procedure quite similar to that employed by the TWDB and TPWD in earlier salinity modeling of Sabine Lake (TPWD & TWDB 2005). Essentially, in that methodology, a short-term (one-year) synthetic inflow sequence is developed by substituting in

the derived flows at select points for the actual historic values, while other inflow contributions from the historic record for that year are held constant. Although those efforts, by TWDB and TPWD, were focused on a very different type of recommended flow pattern, the same basic methodology of constructing a synthetic inflow record can be applied here. In the case of the work here, the HEFR-derived flow values are substituted for the actual historic values at the three BBEST sites Sabine River at Ruliff, Neches River at Evadale, and Village Creek near Kountze. Other historic inflow contributions as reflected in TWDB records, including from other gauged watersheds (Pine Island Bayou and Cow Bayou) as well as ungauged areas below these gauges and other wholly ungauged drainages, remain unchanged.

For the creation of the synthetic flows, several steps and a few assumptions were necessary:
1) for any flow component being evaluated, we assumed that that flow level (e.g. base avg & high-tier seasonal pulse) was occurring at all three sites (Ruliff, Evadale, and Village Creek) simultaneously;
2) HEFR components that are depicted as flow rates in cubic feet per second (cfs) were converted to a volumetric value considering the number of applicable days in the month;
3) high flow pulses, expressed as a volume, are added to the converted base flows. However, due to the mechanics of the HEFR program, to avoid double counting volume, the duration of the pulse (days) must be deducted from the applicable days of base flow (this is consistent with the exercise performed by TWDB and TPWD for the SAC in evaluating a Guadalupe Estuary example). For example if adding a low-tier seasonal pulse volume of 10,202 ac-ft at Ruliff to the base flows for the month, the 3 days that the pulse occur are not counted as base flow days in that month;
4) for the "low-tier pulses" that occur twice per season we assumed these to occur in the first and second month of the season;
5) the higher tier pulses, occurring once per season, were assumed to occur in the middle month of the season; and
6) when assembling the synthetic subsistence inflow record we assumed that the subsistence level of flows were imposed for the period of March-June, a duration of approximately 120 days, and this flow level was occurring at all three HEFR sites. For the remainder of the year, historic inflows occurred.

We selected representative years for the creation of the synthetic inflow sequences in the following manner. For our efforts to analyze "average" conditions and the presumed occurrence of "base average" flows at the HEFR sites, we used all years in the 1941-2005 period in which the historic total inflows were between the 40th and 60th percentiles on an annual basis. To analyze "subsistence" conditions we chose all years in which the historic total inflows were less than or equal to the 5th percentile on an annual basis. The results of this selection process are shown in Table 1.

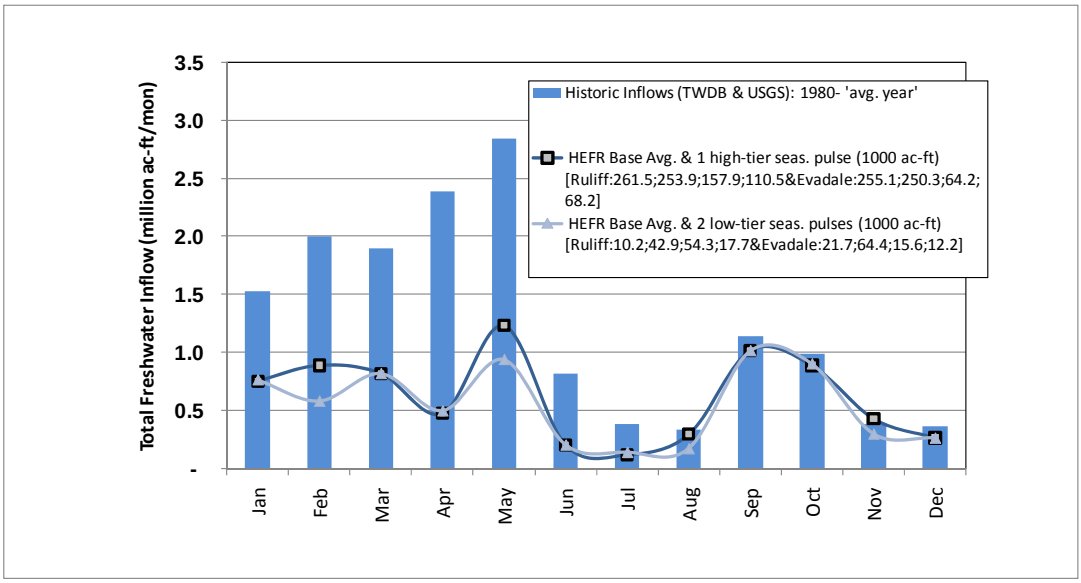
Year	Inflow (million ac-ft/yr)	Inflow Percentile	Representative Average year	Representative Very dry year
1942	15.25	53.1	yes	
1947	15.17	51.5	yes	
1954	4.71	3.1		yes
1958	14.33	46.8	yes	
1960	12.11	43.7	yes	
1967	3.27	0.0		yes
1968	12.09	42.1	yes	
1971	4.13	1.5		yes

1980	15.04	50.0	yes	
1984	12.07	40.6	yes	
1985	12.43	45.3	yes	
1986	15.46	59.3	yes	
1987	15.26	54.6	yes	
1990	15.34	57.8	yes	
1996	4.79	4.6		yes
1999	14.34	48.4	yes	
2003	15.33	56.2	yes	
total			13	4

Table 1 – Selection of representative years for the creation of synthetic inflow records to examine "base average" and "subsistence" inflow conditions.

The results of these efforts to create synthetic inflow records are illustrated in Figure 3 for two of the selected "average" years: 1980 and 1999. For each of these, we depict the resulting total inflow after performing the flow substitution, as described above, at the Ruliff, Evadale, and Village Creek sites. We have shown two HEFR-derived levels that could comprise more or less "average" conditions, namely, "base average and low-tier seasonal pulses" and "base average and high-tier seasonal pulse." The HEFR-derived values used for these base flows and pulses are those available to us as of mid-October 2009 and are shown in Figure 2

We should point out that the HEFR-derived flows for "base average" conditions are the same in each representative year, (e.g, the values substituted in at the Ruliff gauge for the historical gauged flows at that location are the same for 1980 and 1999), and thus the assumed contribution of freshwater inflow to the estuary from upstream of the three gauges is the same in all years evaluated. However, by retaining the other aspects of the historic record in these analyses for the respective years, we are able to preserve, and evaluate, the variability caused by other inflow components, namely flows from Pine Island Bayou and Cow Bayou gauges and from ungauged areas. This variability is illustrated in Figure 3a and 3b for two of the selected "average" years 1980 and 1999. For instance the very large difference in inflows for the Sept.-Oct. period between these two years is due primarily to an ungauged area inflow of 1.38 Million ac-ft (maf) in 1980 while this same area contributed only 0.12 maf in Sept.-Oct. 1999.



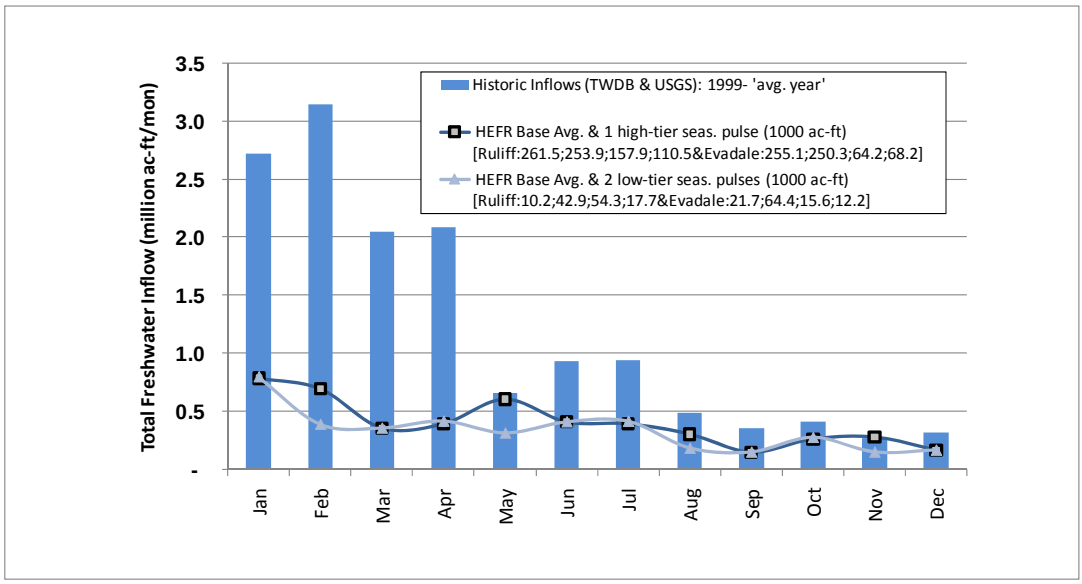
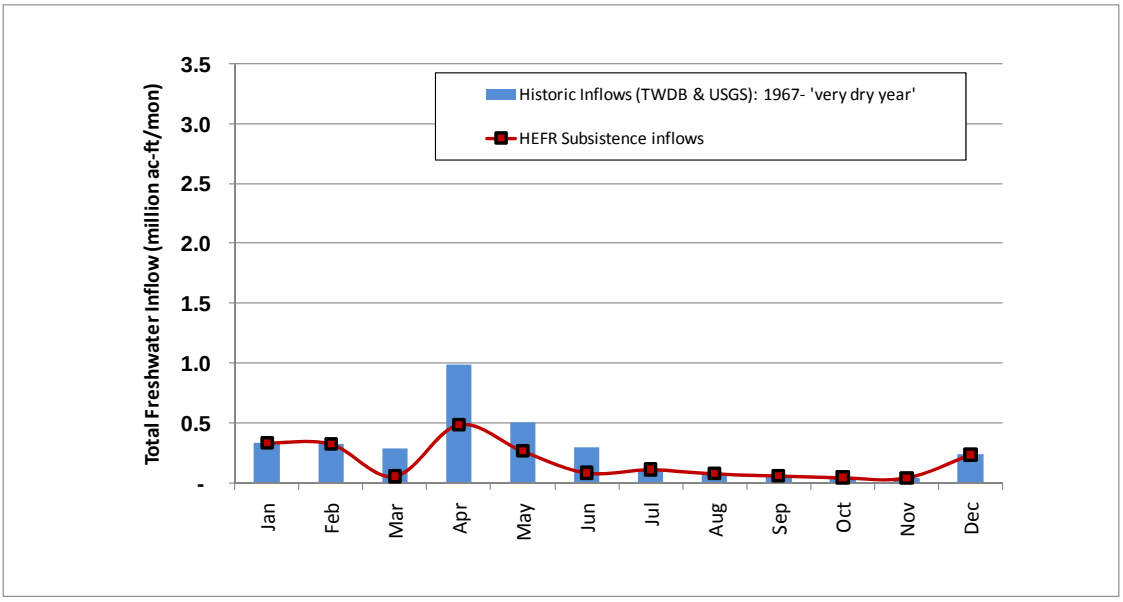


Figure 3 Illustration of the results, in terms of total inflow, of substituting in the HEFR-derived "base average" flow values with both "low-tier" and "high-tier" seasonal pulses. Flows substituted for Sabine River at Ruliff, Neches River at Evadale, and Village Creek near Kountze using 1980 and 1999 as representative "average" years (50th and 48th percentiles of historic record, respectively).

Similarly, Figure 4 shows the two very dry years 1967 and 1996 with subsistence flows substituted in for the historic flows at the three HEFR sites for the March-June period in each. Although the maximum acceptable duration of subsistence flow levels has not been specified, to our knowledge, by the BBEST, because the subsistence flow values are set at such a low level, we did not consider it appropriate to assume that those levels would be in effect for any extended period.



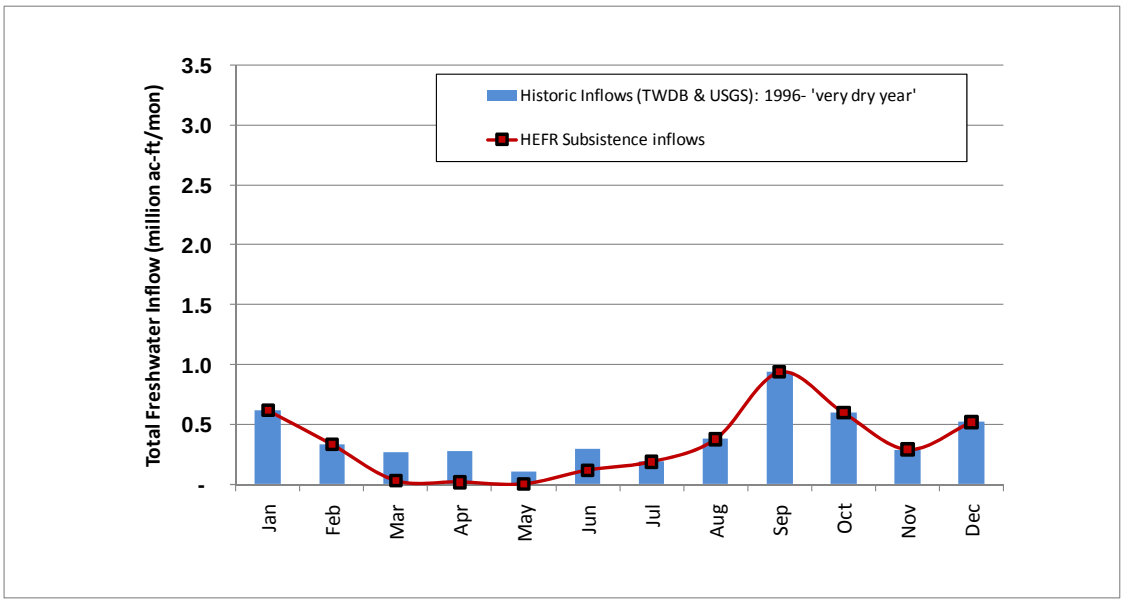


Figure 4. Illustration of the results, in terms of total inflow, of substituting in the HEFR derived "subsistence" flow values for the March-June period in very dry years 1967 and 1996. Flows substituted for Sabine River at Ruliff, Neches River at Evadale, and Village Creek near Kountze. [Note: subsistence level flows are as of Oct. 15, 2009 as shown in Figure 2]

Predicting the Salinity Response in Sabine Lake

After the synthetic inflow record is created with the HEFR-derived inflows, it is next necessary to predict the salinity response in the estuary. For this step we relied upon previously developed inflow – salinity regression equations as presented in TPWD and TWDB (2005). These equations were derived for three areas of Sabine Lake as shown in Figure 5.

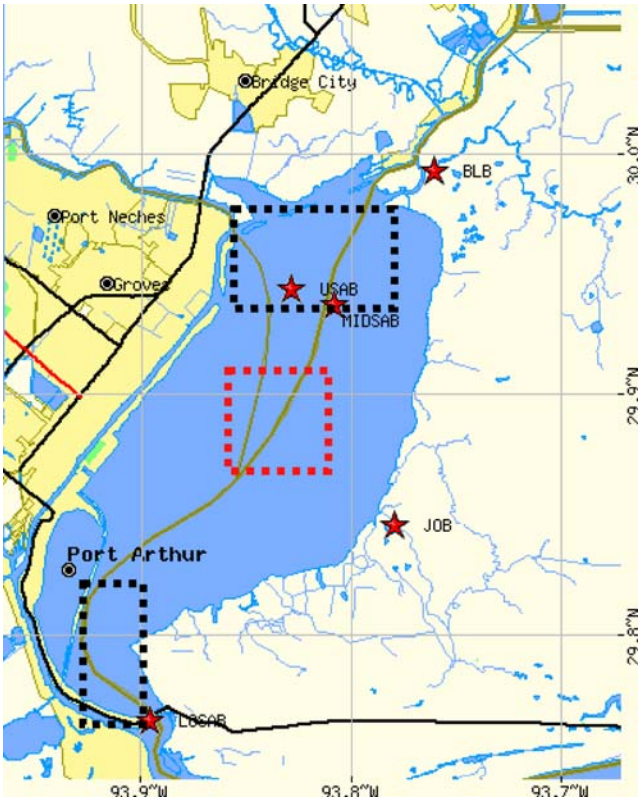


Figure 5 – Areas of Sabine Lake for which salinity inflow regressions were previously developed as in TPWD and TWDB (2005).

The regression equations and statistical r-squared values are:

Upper: Sal= 41.7760 – 4.3824*ln(Q1) – 0.9153*ln(Q2) [r^2=0.73]
Middle: Sal = 42.1146 – 4.6393*ln(Q1) – 0.7225*ln(Q2) [r^2=0.71]
Lower: Sal = 61.2663 – 7.1793*ln(Q1) – 0.0521*ln(Q2) [r^2=0.75]

Where Sal is predicted salinity, ppt;
Q1 = cumulative inflow volume over previous 30 days, 1000 ac-ft;
Q2 = cumulative inflow volume for previous 31-60 days, 1000 ac-ft

These equations are based on inflows and salinity data for the 1977-97 period (TPWD and TWDB 2005).

Figure 6 illustrates the salinity response at the mid-estuary site for a representative recent "average" year: 1999. For 1999 the salinities shown are those predicted with the salinity-inflow regression for both the historic inflows and the synthetic inflow record constructed with the HEFR-derived values at the "base average and high-tier seasonal pulse" levels at the Ruliff, Evadale, and Village Creek sites (see Figure 3). Similarly, Figure 7 illustrates the salinity response for a very dry year: 1967. The regression-predicted salinity responses are shown for both the historic values and the synthetic inflow record, but here HEFR subsistence flows at the three sites are substituted in for the March-June period.

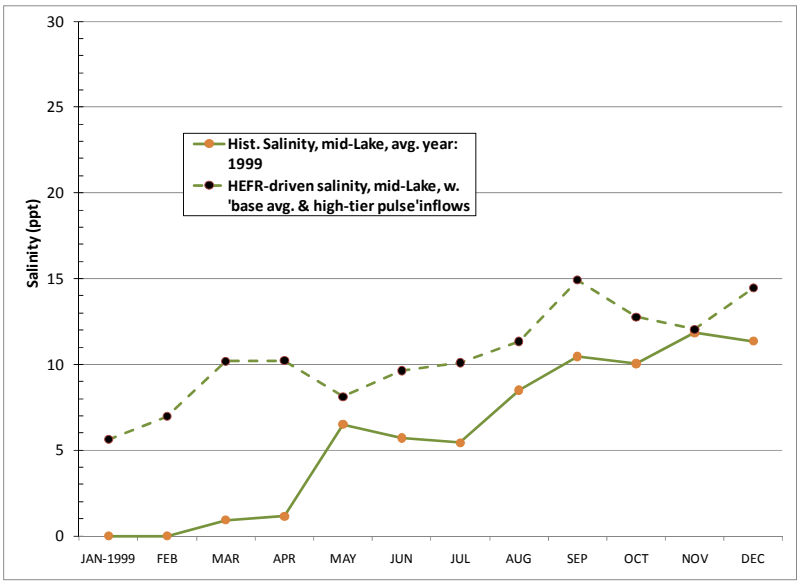


Figure 6 – Illustration of the predicted salinity in Sabine Lake under the original historic inflows for 1999 and with the synthetic inflow record of HEFR-derived values corresponding to “base average and high-tier seasonal pulse” for the sites at Ruliff, Evadale, and Village Creek.

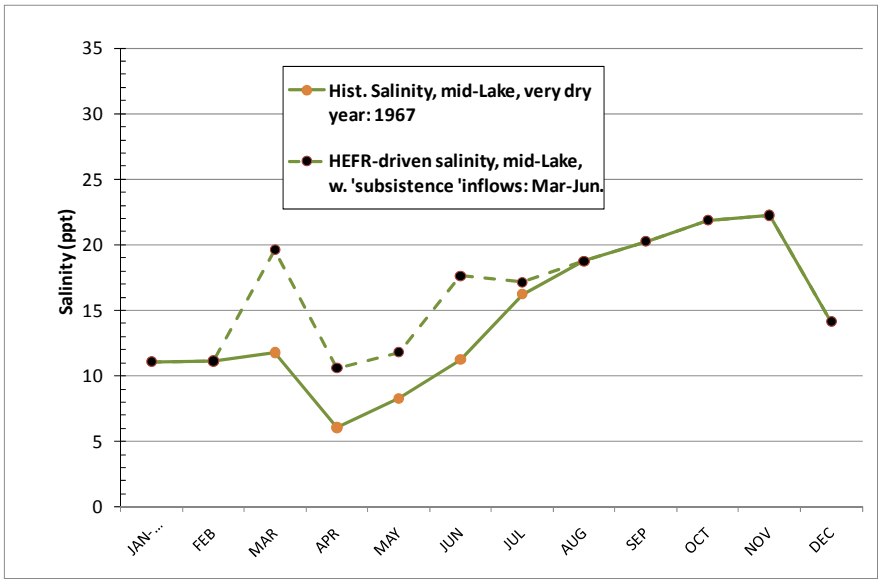


Figure 7 – Illustration of the predicted salinity in Sabine Lake under the original historic inflows for 1967 and with the synthetic inflow record of HEFR-derived values corresponding to “subsistence” levels for the March – June period at the sites at Ruliff, Evadale, and Village Creek.

There is one additional consideration of importance regarding salinity prediction in these analyses. In the case of salinity tolerances of floral species, the salinity of concern is the soil salinity in the marshlands themselves. For the work here we are assuming that changes in salinity in the open body of Sabine Lake are related to the salinity in the surrounding marshlands to some spatial extent. However, we acknowledge the considerable uncertainty

regarding the relationship of these two components; there are certainly complex transport processes and potential time lags in the response times of the marshes to open water salinity changes. Thus, while a prediction of salinity in Sabine Lake itself may not translate directly into a salinity in the marshlands in an absolute sense, we do believe that relative salinity changes may be related, especially over considerable time frames (multi-month). We believe this should be a priority area of continued investigation if the BBEST believes that the surrounding marshlands of Sabine Lake are ecologically important.

Salinity Suitability of Key Species and Communities

Another essential element of these analyses is the published salinity suitability information for the four key species (*Rangia cuneatea*, oysters, blue crab, and Olney bulrush) and two key marshland community types (intermediate and brackish). This information provides the critical link between freshwater inflows, the associated salinity patterns, and the ecological health of the biota in the estuary. With a salinity suitability relationship, as shown in Figure 8 for blue crabs, we are able to ascribe a relative level of significance for any given salinity for that species or community. With a suite of such relationships we may gain a broad perspective on the potential effects of salinity changes tied to freshwater inflow alterations.

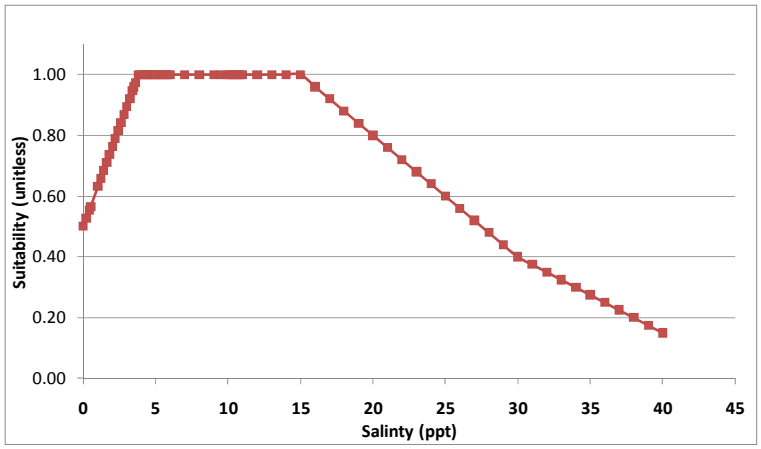


Figure 8. The salinity suitability relationship for blue crabs (based on the synthesis of literature from LCRA-SAWS (2007)).

In Appendix B, we present a salinity suitability relationship or "curve" for each of the key species and communities of interest. For blue crabs and oysters we are using existing salinity suitability curves directly. For the other species and marshland types we have synthesized literature information into the curve format. In those instances, in Appendix B we also present the sources of specific information that allowed us to construct these curves.

For each of the key species and communities there are also important seasonal considerations. These are essentially the portion of the year in which the relationship of salinity to biologic health is thought to be most important. For example, existing literature indicates that *Rangia* spawning peaks from March through November (LaSalle and de la Cruz 1985). Blue crab juveniles are at their peak abundance in Sabine Lake from February through July (TPWD & TWDB 2005). As a result, in our analyses, we limited the time period during which the salinity suitability curves were applied accordingly. Table 2 presents the time of year that the salinity suitability relationships are applied for each species and community evaluated.

Species or community	Period	Considerations (source)
Rangia cuneata larvae	Mar.-Nov.	Spawning (LaSalle and de la Cruz 1985)
blue crab juveniles	Feb.-July	Peak juvenile abundance (TPWD & TWDB 2005)
oysters (adults)	Apr.-Oct.	Spawning at temp. >20°C (Bio-West 2009)
olney Bulrush (adults & seedlings)	Apr.-Sept.	Growth of established plants begins Apr. and seed maturation in Sep. (Bio-West 2009)
intermediate Marsh	Apr.-Oct.	Warm months growing season
brackish Marsh	Apr.-Oct.	Warm months growing season

Table 2. The time of year constraints for each key species or marsh community type.

Figure 9 illustrates how the predicted salinities, salinity suitability curve, and the seasonal constraints (blue crabs as an example) are utilized in this analysis. Here we use 1999, an "average" year as an example. On the bottom half of the figure we illustrate the previously presented (Figure 6) salinity responses for both the historic inflows and the HEFR-derived "base average and high-tier seasonal pulse" inflows at the Ruliff, Evadale, and Village Creek sites. In the top half of the graph we present the computed salinity suitability for both of the salinity traces. However, in the upper panel, only salinities for the period Feb.-July are utilized. For the remainder of the months, a default value of 0.0 is shown.

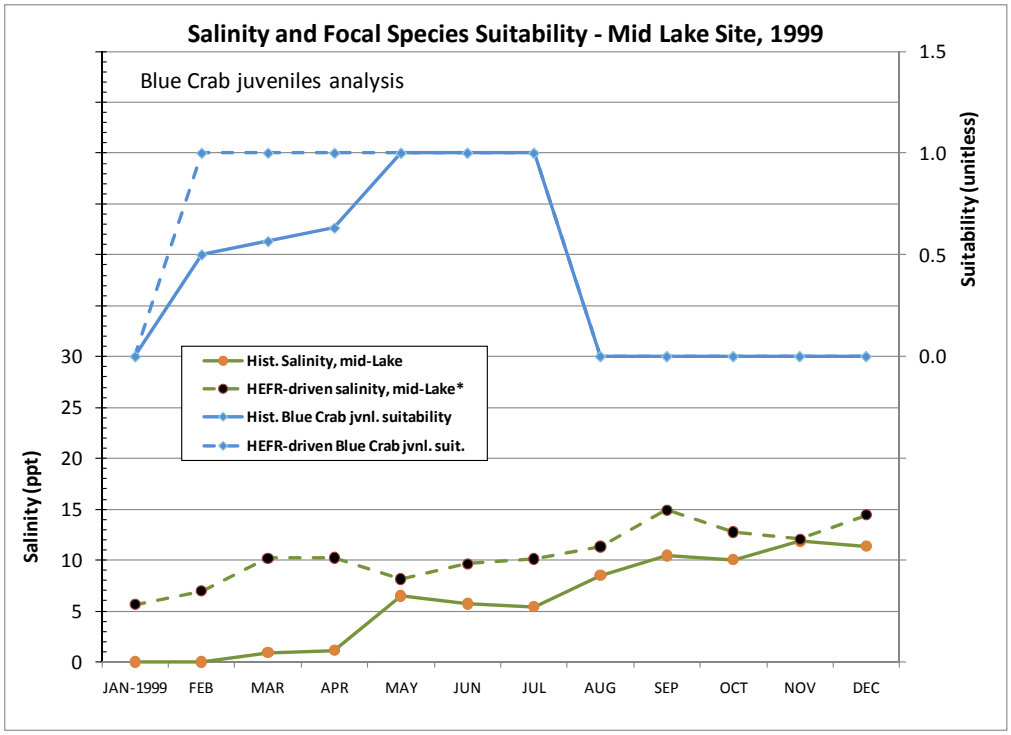


Figure 9. An illustration of how the salinity suitability relationship for blue crabs is combined with the predicted salinity values from the historic record and for HEFR-derived values. Salinities on the lower portion are for historic and HEFR-based "base average and high-tier seasonal pulse" inflows. Corresponding suitabilities for each month in the Feb-July period are in top panel. A default value of 0.0 is shown for the other months but is not used in our analyses.

Assembly of Annual Summaries of Salinity Impacts

Because of the high number of computations that this analysis entails (3 sites in Sabine Lake x 6 key species and communities x 13 average years [and 4 subsistence years]) it becomes important to be able to characterize the results in a summary fashion. Thus we also calculate the average suitability for each key species or community within a year (more specifically, within that portion of the year for which the particular suitability curve applies) and across years. For example in Figure 9, the average suitability for the line “Hist. Blue Crab jvnl. suitability” is 0.78 at that site for 1999 while for the corresponding “HEFR –driven” line, it is 1.0, indicating that on average the predicted suitability for blue crabs would improve with the HEFR-derived inflows for that year.

Results

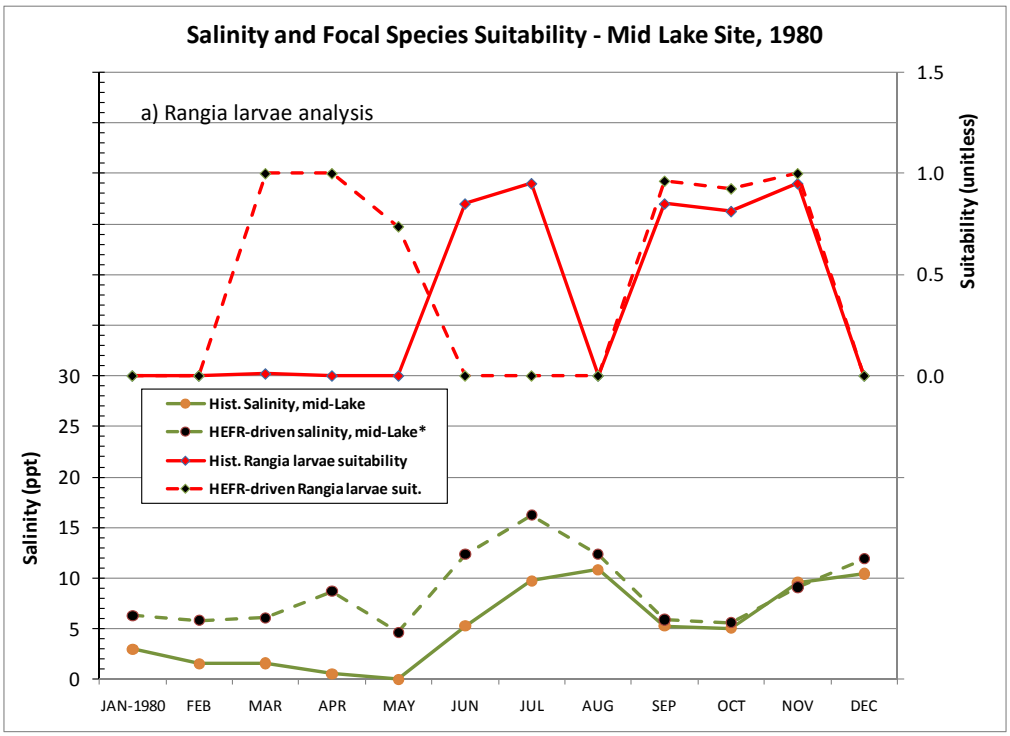
Appendix A. details the supporting work to establish the spatial extent and abundance characteristics of *Rangia cuneata*. In summary, this work established that *R. cuneata* are widespread in the majority of Sabine Lake, approximately the upper three-fourths of the estuary. Based on these results we are confident that *Rangia* is a very good key species for this estuary evaluation not only because of the well-defined salinity tolerance limits of the larvae but also due to the fact that they comprise a substantial benthic biomass in much of the estuary.

Below we present the results in graphical form for the key species and communities. As mentioned above because of the high number of computations and potential graphs that this analysis entails we do not present all possible combinations of species-location-year. First we present just some results of representative years within the "base average and high-tier seasonal pulse" and "subsistence" analyses. A second consideration for selecting the graphs for presentation is the geographic area of the species or community. For instance since our field work found no *Rangia* at the lower end of Sabine Lake and essentially no oysters at the upper end, we do not present the salinity suitability response of these organisms at these locations. Summary tables are presented at the end for all other possible combinations however.

Salinty Suitability Analysis of HEFR-derived Inflows

Inflows at the "base average and high-tier seasonal pulse" level

Figure 10, in multiple panels, illustrates the results of inflows to Sabine Lake when the three BBEST sites Sabine River at Ruliff, Neches River at Evadale,and Village Creek near Kountze have flows at the "base average and high-tier seasonal pulse" level for the whole year. We use 1980 as an example year since historic total inflows were at the 50th percentile of the historic record for 1941-2005. All other inflow contributions to Sabine Lake are maintained at their historic level during the year. Each figure shows both the predicted salinity response and predicted salinity suitability for individual key species and communities for the year.


Salinity and Focal Species Suitability - Mid Lake Site, 1980
a) Rangia larvae analysis
Salinity (ppt)
Suitability (unitless)
Hist. Salinity, mid-Lake
HEFR-driven salinity, mid-Lake*
Hist. Rangia larvae suitability
HEFR-driven Rangia larvae suit.
JAN-1980
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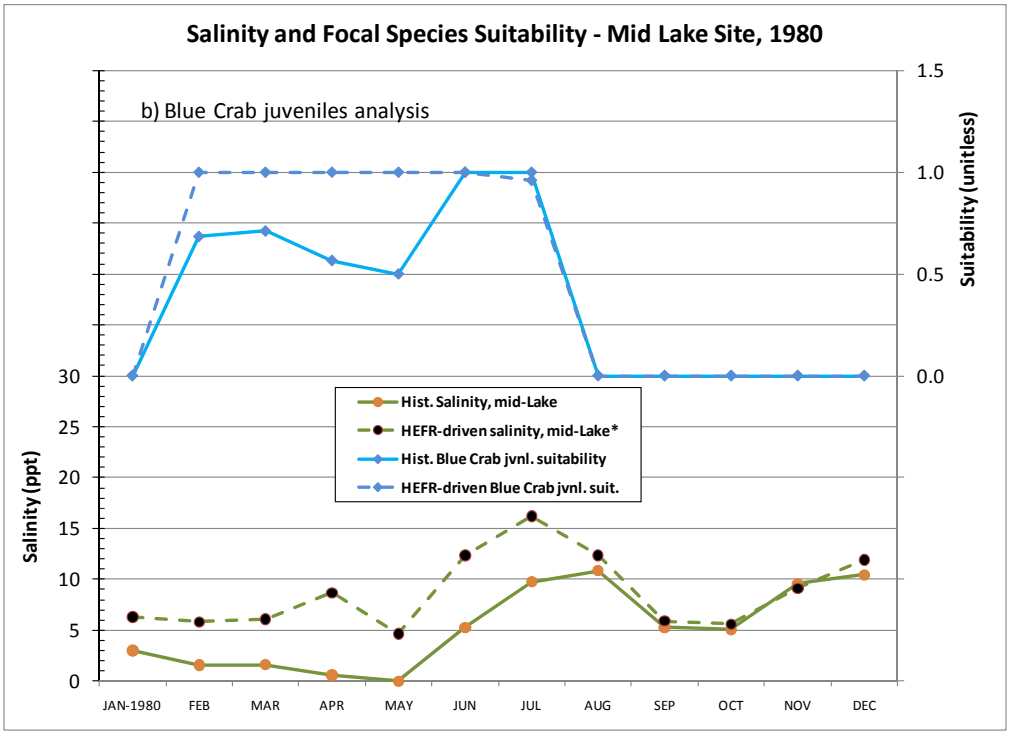
JUL
AUG
SEP
OCT
NOV
DEC


Salinity and Focal Species Suitability - Mid Lake Site, 1980
b) Blue Crab juveniles analysis
Salinity (ppt)
Suitability (unitless)
Hist. Salinity, mid-Lake
HEFR-driven salinity, mid-Lake*
Hist. Blue Crab jvnl. suitability
HEFR-driven Blue Crab jvnl. suit.
JAN-1980
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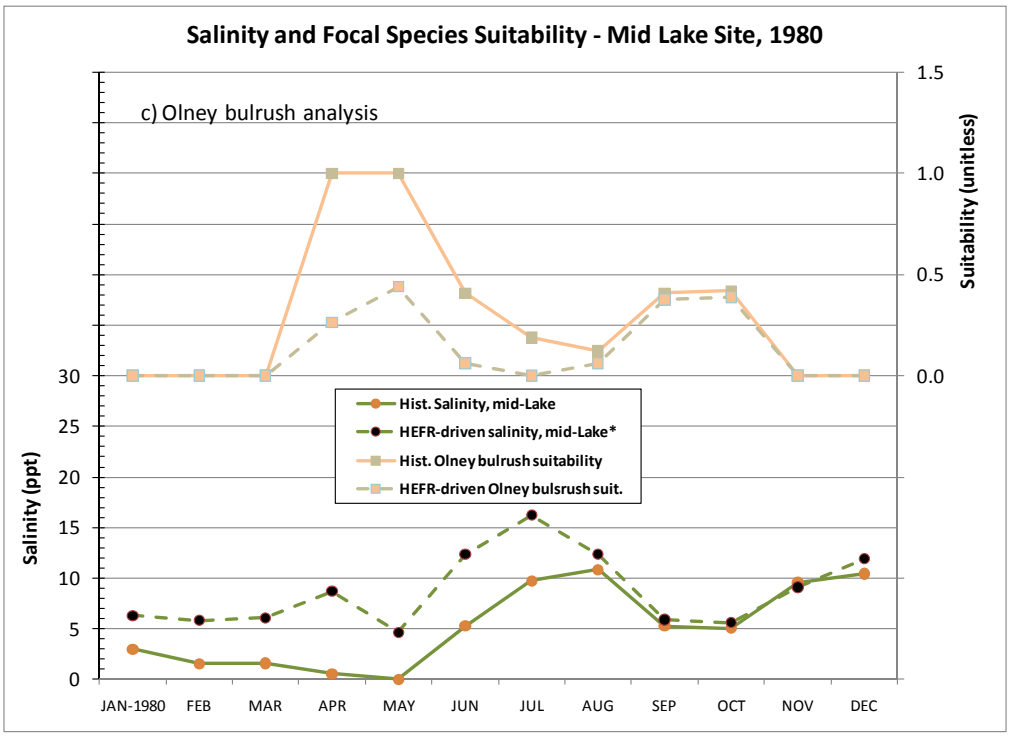
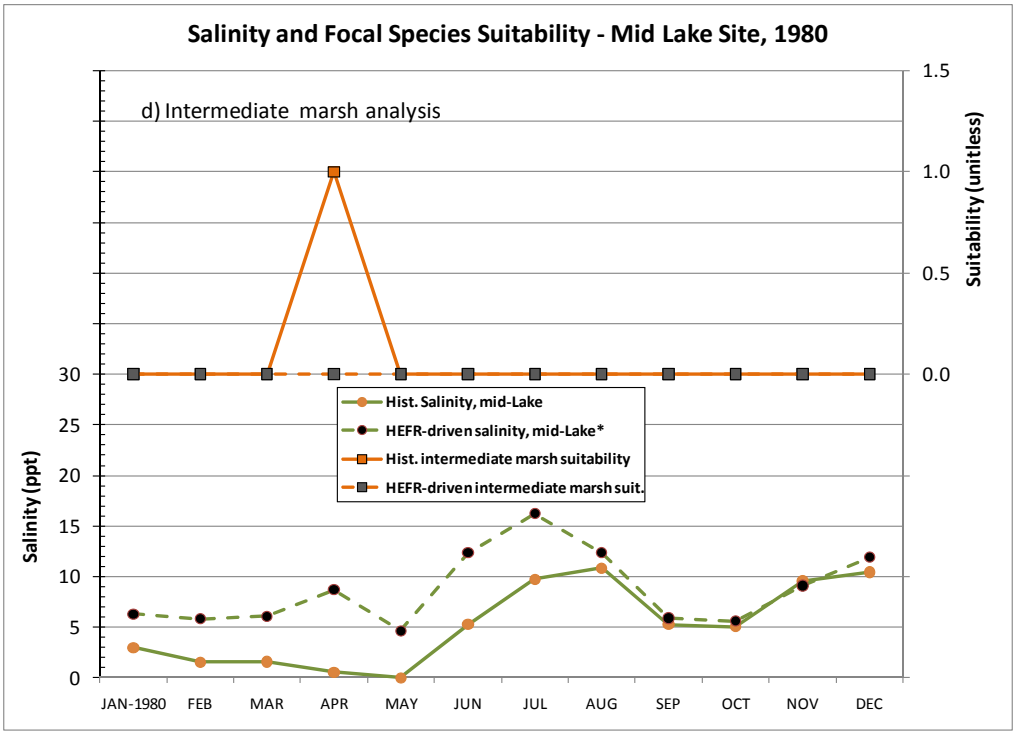
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC


Salinity and Focal Species Suitability - Mid Lake Site, 1980
c) Olney bulrush analysis
Salinity (ppt)
Suitability (unitless)
0
5
10
15
20
25
30
0.0
0.5
1.0
1.5
JAN-1980
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
Hist. Salinity, mid-Lake
HEFR-driven salinity, mid-Lake*
Hist. Olney bulrush suitability
HEFR-driven Olney bulsrush suit.


Salinity and Focal Species Suitability - Mid Lake Site, 1980
d) Intermediate marsh analysis
Salinity (ppt)
Suitability (unitless)
0
5
10
15
20
25
30
0.0
0.5
1.0
1.5
JAN-1980
FEB
MAR
APR
MAY
JUN
JUL
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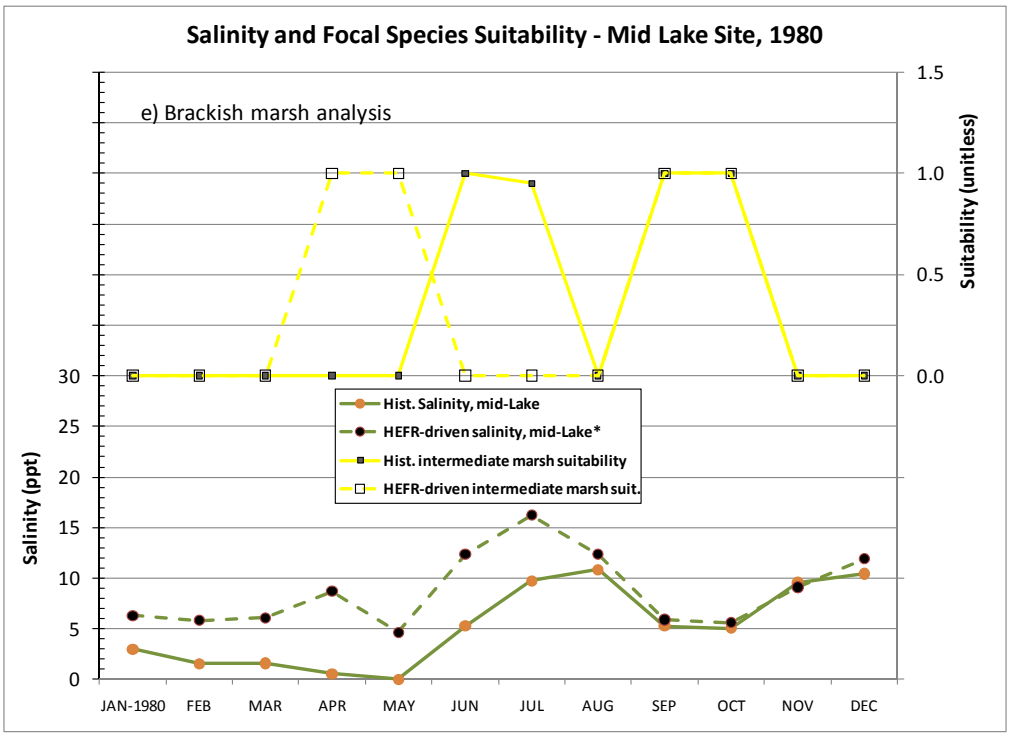
NOV
DEC
Hist. Salinity, mid-Lake
HEFR-driven salinity, mid-Lake*
Hist. intermediate marsh suitability
HEFR-driven intermediate marsh suit.



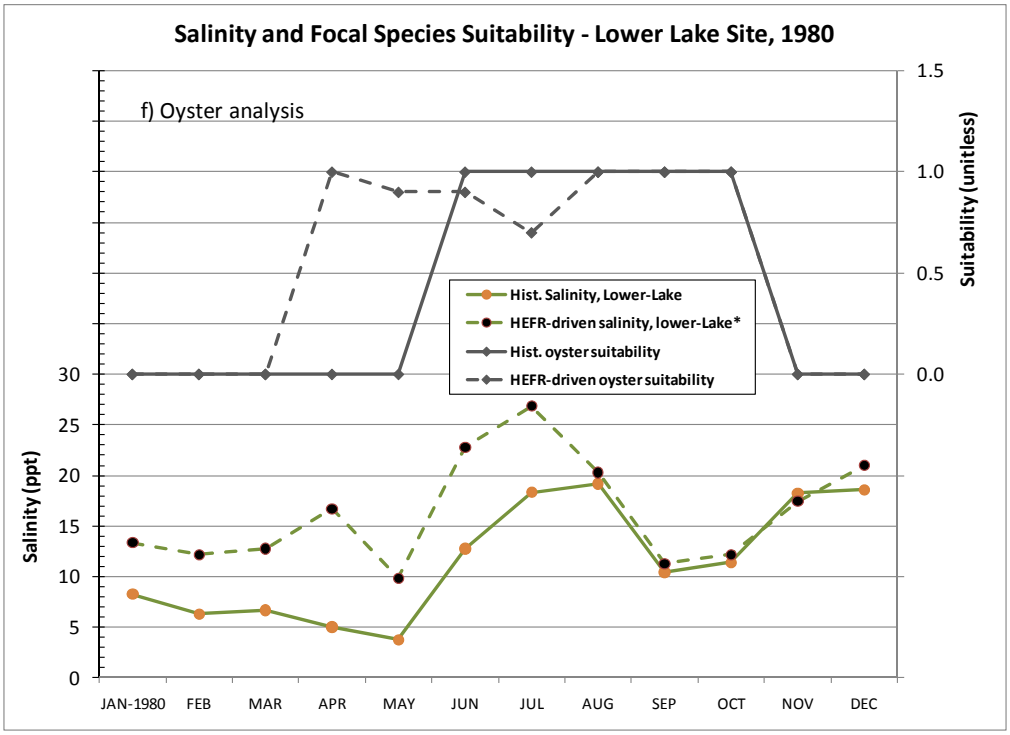


Figure 10 (panels a-f.) The predicted salinity and salinity suitability results of several key species and communities after substitution of the HEFR-derived instream flow "base average and high-tier seasonal pulse" values for the three BBEST sites (Sabine River at Ruliff, Neches River at Evadale,and Village Creek near Kountze) for 1980. The instream flow base average values and pulse volumes used are given above in Figure 2.

Table 3a, 3b, and 3c summarize the salinity suitability results for all thirteen of the “average” years. As before, in each year, the HEFR-derived “base average and high-tier seasonal pulse” values for the three BBEST sites Sabine River at Ruliff, Neches River at Evadale, and Village Creek near Kountze are substituted in for the historic values at those sites. All other inflow contributions, such as those from ungauged areas, are at the historic level.

Table 3A) Upper-Lake: Substitute HEFR Base Average & High-tier seasonal pulses into all "avg." years.

	Rangia larvae average suitability		Blue Crab average suitability		Olney Bulrush average suitability		Intermediate Marsh average suitability		Brackish Marsh average suitability	
Year	Hist.	HEFR	Hist.	HEFR	Hist.	HEFR	Hist.	HEFR	Hist.	HEFR
1942	0.271	0.740	0.743	1.000	0.697	0.308	0.429	0.000	0.286	0.857
1947	0.211	0.417	0.807	1.000	0.370	0.131	0.286	0.000	0.229	0.371
1958	0.564	0.514	0.895	1.000	0.592	0.195	0.429	0.000	0.443	0.521
1960	0.557	0.539	0.899	1.000	0.175	0.154	0.000	0.000	0.564	0.429
1968	0.730	0.517	0.904	1.000	0.531	0.233	0.414	0.000	0.707	0.571
1980	0.501	0.633	0.748	0.993	0.505	0.232	0.143	0.000	0.564	0.571
1984	0.635	0.444	0.884	1.000	0.275	0.147	0.000	0.000	0.729	0.286
1985	0.810	0.663	0.910	1.000	0.318	0.181	0.000	0.000	1.000	0.564
1986	0.719	0.499	0.890	1.000	0.478	0.206	0.143	0.000	0.700	0.421
1987	0.624	0.632	0.875	1.000	0.421	0.210	0.143	0.029	0.714	0.579
1990	0.448	0.515	0.686	1.000	0.573	0.189	0.300	0.000	0.443	0.429
1999	0.551	0.500	0.787	1.000	0.388	0.135	0.143	0.000	0.714	0.493
2003	0.659	0.924	0.873	1.000	0.445	0.383	0.171	0.143	0.800	0.850
avg.	0.560	0.580	0.839	0.999	0.444	0.208	0.200	0.013	0.607	0.534

Table 3B) Mid-Lake: Substitute HEFR Base Average & High-tier seasonal pulses into all "avg." years.

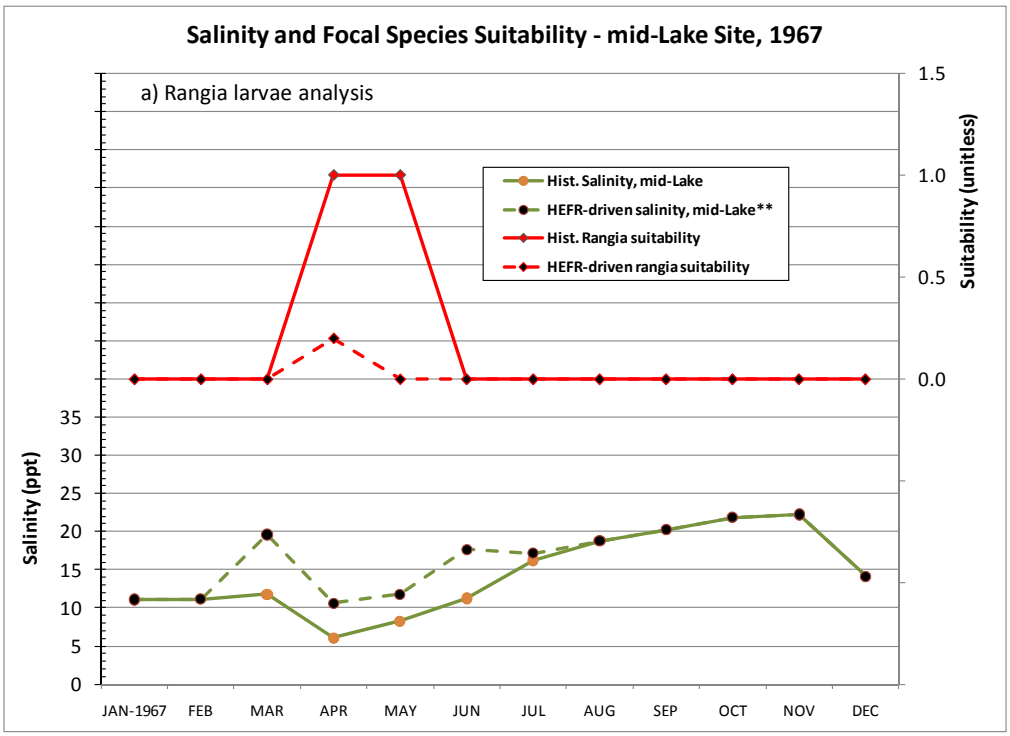
	Rangia larvae average suitability		Blue Crab average suitability		Olney Bulrush average suitability		Intermediate Marsh average suitability		Brackish Marsh average suitability	
Year	Hist.	HEFR	Hist.	HEFR	Hist.	HEFR	Hist.	HEFR	Hist.	HEFR
1942	0.263	0.732	0.739	1.000	0.698	0.309	0.429	0.000	0.286	0.857
1947	0.150	0.417	0.803	1.000	0.369	0.133	0.286	0.000	0.157	0.371
1958	0.533	0.510	0.886	1.000	0.592	0.189	0.429	0.000	0.443	0.521
1960	0.562	0.533	0.890	1.000	0.171	0.154	0.000	0.000	0.571	0.429
1968	0.715	0.513	0.882	1.000	0.610	0.227	0.300	0.000	0.564	0.571
1980	0.491	0.625	0.743	0.993	0.507	0.227	0.143	0.000	0.564	0.571
1984	0.631	0.436	0.879	1.000	0.277	0.150	0.000	0.000	0.729	0.286
1985	0.806	0.663	0.906	1.000	0.319	0.195	0.000	0.000	1.000	0.564
1986	0.689	0.481	0.890	1.000	0.480	0.204	0.143	0.029	0.700	0.414
1987	0.615	0.628	0.860	0.996	0.421	0.219	0.143	0.107	0.714	0.579
1990	0.458	0.528	0.678	1.000	0.571	0.191	0.300	0.000	0.443	0.429
1999	0.546	0.500	0.783	1.000	0.389	0.135	0.143	0.000	0.714	0.493
2003	0.590	0.910	0.873	1.000	0.445	0.380	0.171	0.143	0.729	0.843
avg.	0.542	0.575	0.832	0.999	0.450	0.209	0.191	0.021	0.586	0.533

Table 3C) Lower-Lake: Substitute HEFR Base Average & High-tier seasonal pulses into all "avg." years.

	Oysters average suitability		Blue Crab average suitability		Olney Bulrush average suitability		Intermediate Marsh average suitability		Brackish Marsh average suitability	
Year	Hist.	HEFR	Hist.	HEFR	Hist.	HEFR	Hist.	HEFR	Hist.	HEFR
1942	0.579	0.971	0.991	1.000	0.232	0.041	0.136	0.000	0.557	0.129
1947	0.693	0.936	0.973	0.920	0.099	0.009	0.000	0.000	0.286	0.000
1958	0.714	0.957	0.987	0.907	0.168	0.027	0.000	0.000	0.429	0.136
1960	0.979	0.979	0.940	0.893	0.000	0.000	0.000	0.000	0.000	0.000
1968	0.714	0.964	0.960	0.940	0.166	0.036	0.000	0.000	0.429	0.007
1980	0.714	0.929	0.976	0.873	0.175	0.052	0.107	0.000	0.300	0.136
1984	1.000	0.950	0.973	0.847	0.041	0.020	0.000	0.000	0.129	0.007
1985	1.000	0.993	0.993	0.907	0.033	0.001	0.000	0.000	0.000	0.000
1986	0.800	0.964	0.958	0.920	0.200	0.039	0.143	0.000	0.143	0.143
1987	0.886	0.900	1.000	0.960	0.089	0.039	0.000	0.000	0.150	0.143
1990	0.606	0.986	1.000	0.953	0.175	0.017	0.000	0.000	0.429	0.000
1999	0.880	0.957	0.982	0.927	0.086	0.000	0.000	0.000	0.143	0.000
2003	0.880	0.914	0.969	0.967	0.114	0.061	0.000	0.000	0.279	0.143
avg.	0.803	0.954	0.977	0.924	0.121	0.026	0.030	0.000	0.252	0.065

Inflows at the "subsistence" level

Figure 11, in multiple panels, illustrates the results of our evaluation of inflows to Sabine Lake when the three BBEST sites Sabine River at Ruliff, Neches River at Evadale, and Village Creek near Kountze have flows at the "subsistence" level for the March-June period. We use 1967 as an example year since historic total inflows were at their lowest in the historic record for 1941-2005. During March-June, and for the remainder of the year, all other inflow contributions are maintained at their historic level. Each figure shows both the salinity response and individual key species and community salinity suitability for the year.


Salinity and Focal Species Suitability - mid-Lake Site, 1967
a) Rangia larvae analysis
Hist. Salinity, mid-Lake
HEFR-driven salinity, mid-Lake**
Hist. Rangia suitability
HEFR-driven rangia suitability
Salinity (ppt)
Suitability (unitless)
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JAN-1967
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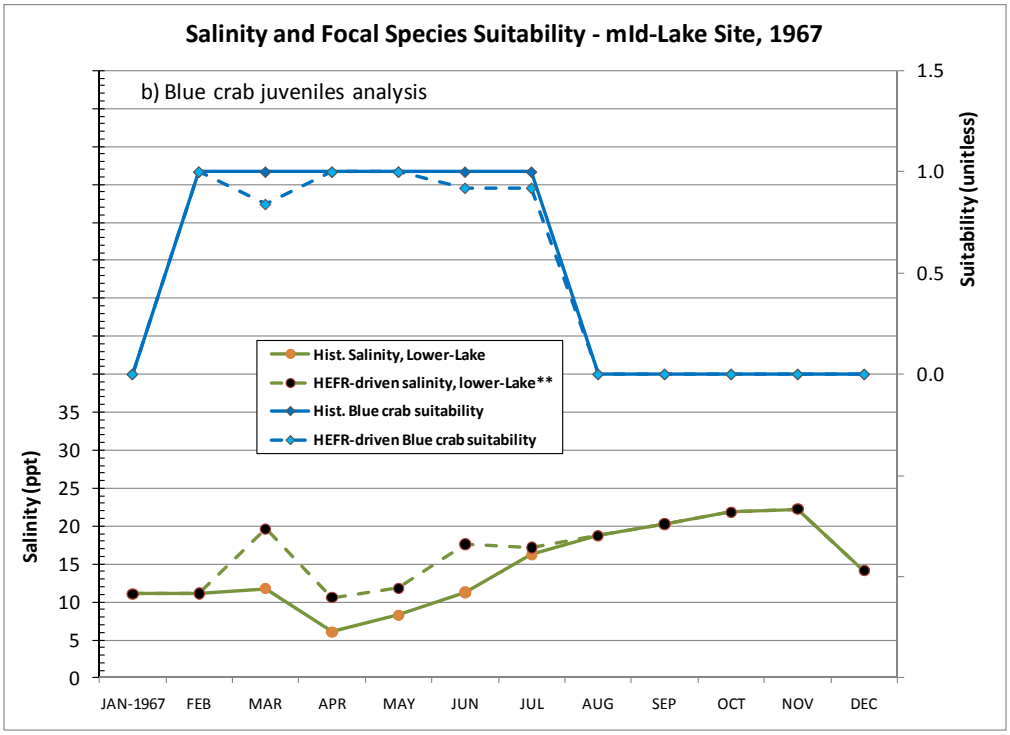
Salinity and Focal Species Suitability - mId-Lake Site, 1967
b) Blue crab juveniles analysis
Hist. Salinity, Lower-Lake
HEFR-driven salinity, lower-Lake**
Hist. Blue crab suitability
HEFR-driven Blue crab suitability
Salinity (ppt)
Suitability (unitless)
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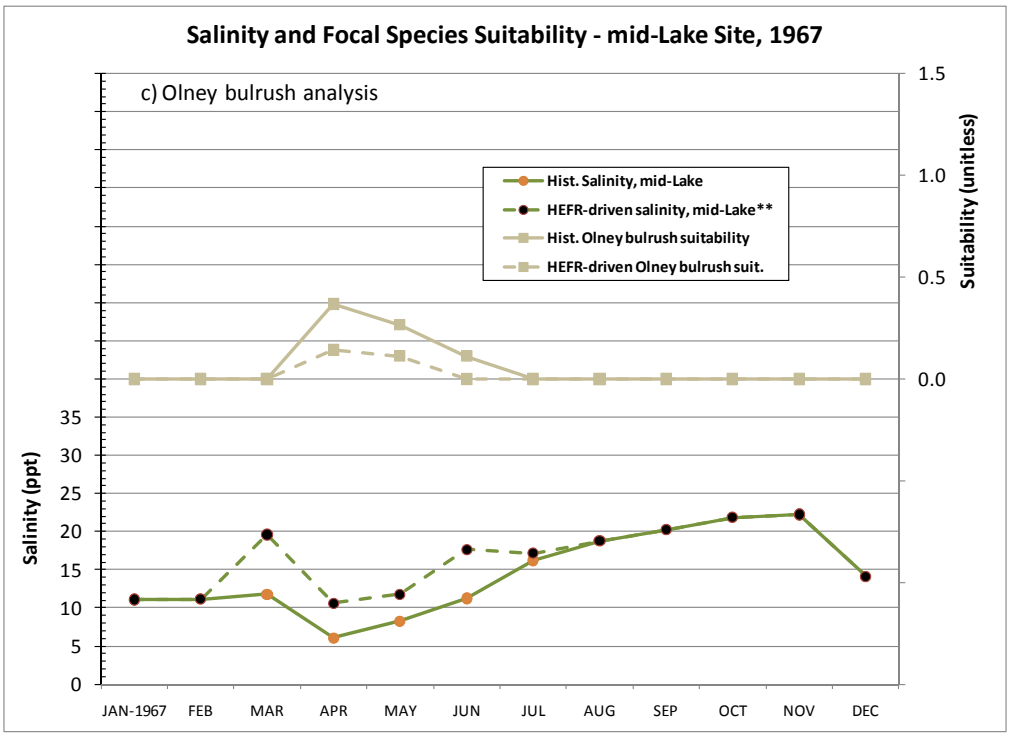
Salinity and Focal Species Suitability - mid-Lake Site, 1967
c) Olney bulrush analysis
Hist. Salinity, mid-Lake
HEFR-driven salinity, mid-Lake**
Hist. Olney bulrush suitability
HEFR-driven Olney bulrush suit.
Salinity (ppt)
Suitability (unitless)
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0.0
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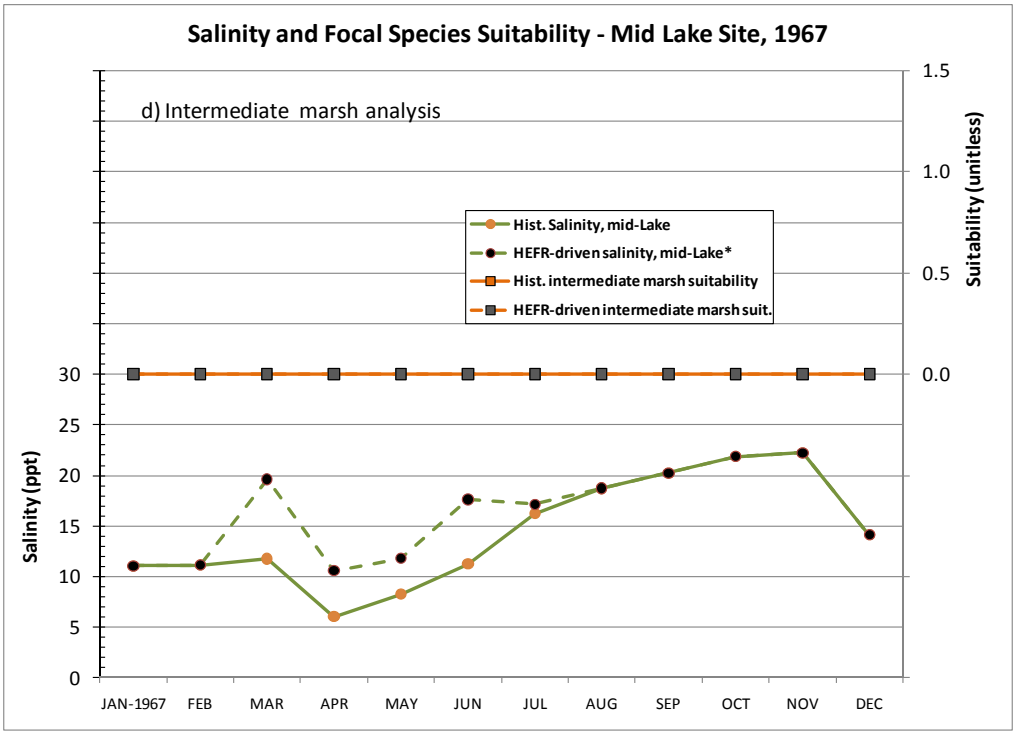
Salinity and Focal Species Suitability - Mid Lake Site, 1967
d) Intermediate marsh analysis
Hist. Salinity, mid-Lake
HEFR-driven salinity, mid-Lake*
Hist. intermediate marsh suitability
HEFR-driven intermediate marsh suit.
Salinity (ppt)
Suitability (unitless)
0
5
10
15
20
25
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0.0
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JAN-1967
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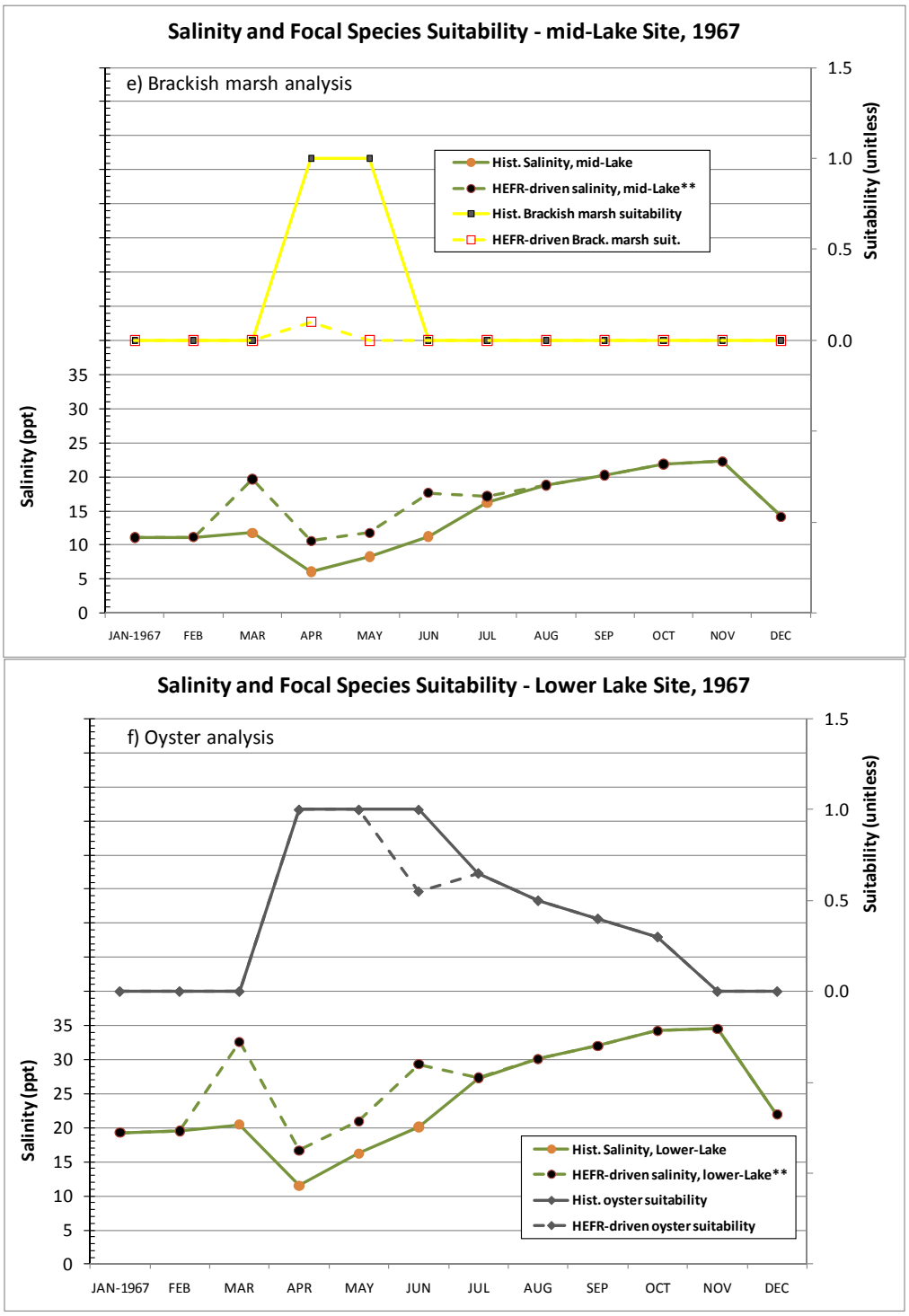

Figure 11 (panels a-f) The predicted salinity and salinity suitability results of several key species and communities after substitution of the HEFR-derived instream flow "subsistence" values for the three BBEST sites Sabine River at Ruliff, Neches River at Evadale,and Village Creek near Kountze for 1980. The instream flow subsistence flows used are given above in Figure 2.

Table 4a, 4b, and 4c summarize the salinity suitability results for all four of the “very dry” years. In each year, the HEFR-derived “subsistence” values for the three BBEST sites Sabine River at Ruliff, Neches River at Evadale, and Village Creek near Kountze are substituted in for the historic values for March-June at those sites. For the remainder of the year at those sites, historic flows are again utilized. In all cases, all other inflow contributions from ungauged areas, etc. are at the historic level.

Table 4A) Upper-Lake: Substitute HEFR Subsistence values for Mar.-Jun. into all "very dry" years.

	Rangia larvae average suitability		Blue Crab average suitability		Olney Bulrush average suitability		Intermediate Marsh average suitability		Brackish Marsh average suitability	
Year	Hist.	HEFR	Hist.	HEFR	Hist.	HEFR	Hist.	HEFR	Hist.	HEFR
1954	0.298	0.000	0.993	0.759	0.136	0.000	0.129	0.000	0.421	0.000
1967	0.222	0.000	1.000	0.947	0.106	0.032	0.000	0.000	0.286	0.000
1971	0.106	0.000	1.000	0.813	0.017	0.016	0.000	0.000	0.000	0.000
1996	0.222	0.222	0.993	0.686	0.133	0.114	0.000	0.000	0.286	0.286
avg.	0.212	0.056	0.997	0.801	0.098	0.040	0.032	0.000	0.248	0.071

Table 4B) Mid-Lake: Substitute HEFR Subsistence values for Mar.-Jun. into all "very dry" years.

	Rangia larvae average suitability		Blue Crab average suitability		Olney Bulrush average suitability		Intermediate Marsh average suitability		Brackish Marsh average suitability	
Year	Hist.	HEFR	Hist.	HEFR	Hist.	HEFR	Hist.	HEFR	Hist.	HEFR
1954	0.281	0.000	0.987	0.766	0.208	0.000	0.143	0.000	0.293	0.000
1967	0.222	0.022	0.993	0.947	0.106	0.036	0.000	0.000	0.286	0.014
1971	0.111	0.000	1.000	0.813	0.017	0.016	0.000	0.000	0.000	0.000
1996	0.222	0.222	0.993	0.693	0.134	0.115	0.000	0.000	0.286	0.286
avg.	0.209	0.061	0.993	0.805	0.116	0.042	0.036	0.000	0.216	0.075

Table 4C) Lower-Lake: Substitute HEFR Subsistence values for Mar.-Jun. into all "very dry" years.

	Oysters average suitability		Blue Crab average suitability		Olney Bulrush average suitability		Intermediate Marsh average suitability		Brackish Marsh average suitability	
Year	Hist.	HEFR	Hist.	HEFR	Hist.	HEFR	Hist.	HEFR	Hist.	HEFR
1954	0.579	0.457	0.867	0.544	0.045	0.000	0.000	0.000	0.143	0.000
1967	0.693	0.629	0.820	0.652	0.016	0.000	0.000	0.000	0.000	0.000
1971	0.800	0.557	0.727	0.448	0.000	0.000	0.000	0.000	0.000	0.000
1996	0.929	0.714	0.740	0.478	0.016	0.016	0.000	0.000	0.000	0.000
avg.	0.750	0.589	0.788	0.530	0.019	0.004	0.000	0.000	0.036	0.000

Discussion

The analyses summarized above focus on the possible salinity response of Sabine Lake if various components of the HEFR-derived instream flow regime (values in Figure 2 as of mid-October, 2009) are implemented for the three BBEST sites Sabine River at Ruliff, Neches River at Evadale, and Village Creek near Kountze. We have analyzed inflows and associated salinity and salinity suitability for a suite of six key species and communities for both the “base average and high-tier seasonal pulse” and “subsistence” level of inflows.

Generally, the base average conditions, represented here by the “base average and high-tier seasonal pulse” analyses, appear to be reasonable in terms of the average salinity suitability

for *Rangia*, blue crabs, oysters, and brackish marsh. This is in spite of the predicted rise in salinity on the order of 4-8 ppt for typical months in an "average" year (as in Figure 6 or 10). As can be seen in Tables 3a-c, the avg. salinity suitability for these four key species and communities vary among years but the overall average for the thirteen years are not greatly different when comparing the historical conditions to the HEFR-based conditions. In fact, conditions for blue crabs and oysters would improve based on these analyses.

The most significant area of concern for the base average conditions is with the marshland species and community that are less salinity tolerant: the Olney bulrush and intermediate marsh. Both the upper- and mid-Sabine Lake areas show significant reductions in salinity suitability on average for this species and the intermediate marsh community. The potential for adverse impacts on these components of the ecosystem is troubling, particularly given the frequency with which these components of the flow regime likely would be controlling. In our opinion, this merits careful consideration. We do recognize that the degree to which inflows actually would be reduced to these levels during average rainfall years is dependent on the amount of water supply infrastructure built in the watersheds. However, it seems appropriate to acknowledge that this component of the flow regime, as currently specified, may not be sufficient to avoid substantial adverse impacts in Sabine Lake. Similarly, it seems appropriate to identify this issue as one meriting special consideration during development of a work plan.

With HEFR-derived subsistence flows (as of mid-October 2009) for a four-month period, we believe there would be much more potential for widespread deleterious impacts, although presumably on a less frequent basis. Since we are assuming these very low inflows would occur in what is already a very dry year (e.g. one similar to 1967), essentially the HEFR-derived inflows amplify an already bad situation for most of the key species and communities. For instance *Rangia* suitability moves from an already poor value of about 0.2 to just 0.06 on average at the upper lake site for the 4 very dry years (Table 4a). In fact, for even these four driest years of the historic record, there was some portion of the year in which *Rangia* reproduction (larval survival) was possible at the upper lake site. However, under the "subsistence" inflow scenario, three of the four years would lose even this limited suitability. A somewhat lesser, but still substantial, decline in *Rangia* suitability is evident at the mid-Sabine Lake site (Table 4b).

Unlike the analysis at "base average" conditions, "subsistence" inflows would be expected to result in a significant deleterious impact on the brackish marsh communities. Conditions for the less salinity tolerant Olney bulrush and intermediate marsh are already so poor, even under historic conditions in these very dry years, that the incremental effects of the "subsistence" inflows are small.

Finally, under the "subsistence" inflow conditions, there are even pronounced declines in salinity suitability conditions for blue crabs and oysters (Table 4b and 4c).

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Note – some of the citations to these are in appendices.

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Appendix A – Sonar Imaging and Field Sampling Effort to Establish Spatial Extent and Abundance Characteristics of *Rangia cuneat*a in Sabine Lake.

Kane (1961) indicated that Rangia cuneata were in the upper portion of Sabine Lake as of the early 1960s. Additionally, the routine field sampling program of the Texas Parks and Wildlife Department has found *Rangia cuneata* in Sabine Lake. However, the sampling equipment utilized by TPWD are not designed to sample for this burrowing species. Harrel (1993) states how the clam prefers soft sediments and is dispersed rather than forming concentrated reef-like masses. Thus, the modern spatial extent and abundance characteristics of the species were not well established. In support of the work of this project to potentially utilize *Rangia cuneata* as a key species, we worked with Bio-West, Inc. to design and execute a field program to fill in this information gap.

In mid August 2009, personnel from Bio-West utilized a side scanning sonar to make ten lengthwise transects of the bottom substrates of Sabine Lake as shown on Figure A-1. This work revealed abundant hard bottom substrates along many sections of these transects as shown in Figure A-2. The color coding on Figure A-2, indicating likely areas of *Rangia cuneata* versus oysters was facilitated in the sonar phase of the field work. The westernmost transect purposefully included known oyster abundant areas at the lower end of the estuary for comparative purposes. A comparison of the typical patterns of these two substrates is shown in Figure A-3.

After the sonar-based phase of this work a field sampling program was executed in early September, 2009 to 'ground truth' the sonar results. Figure A-4 summarizes the findings at the 40 sample sites. The details of the samples by site are shown Table A-1.

In summary this sonar and field sampling project established that *Rangia cuneata* is widespread and abundant in the majority of Sabine Lake, approximately the upper three-fourths of the estuary. Based on these results we are confident that *Rangia* are a very good key species for this estuary

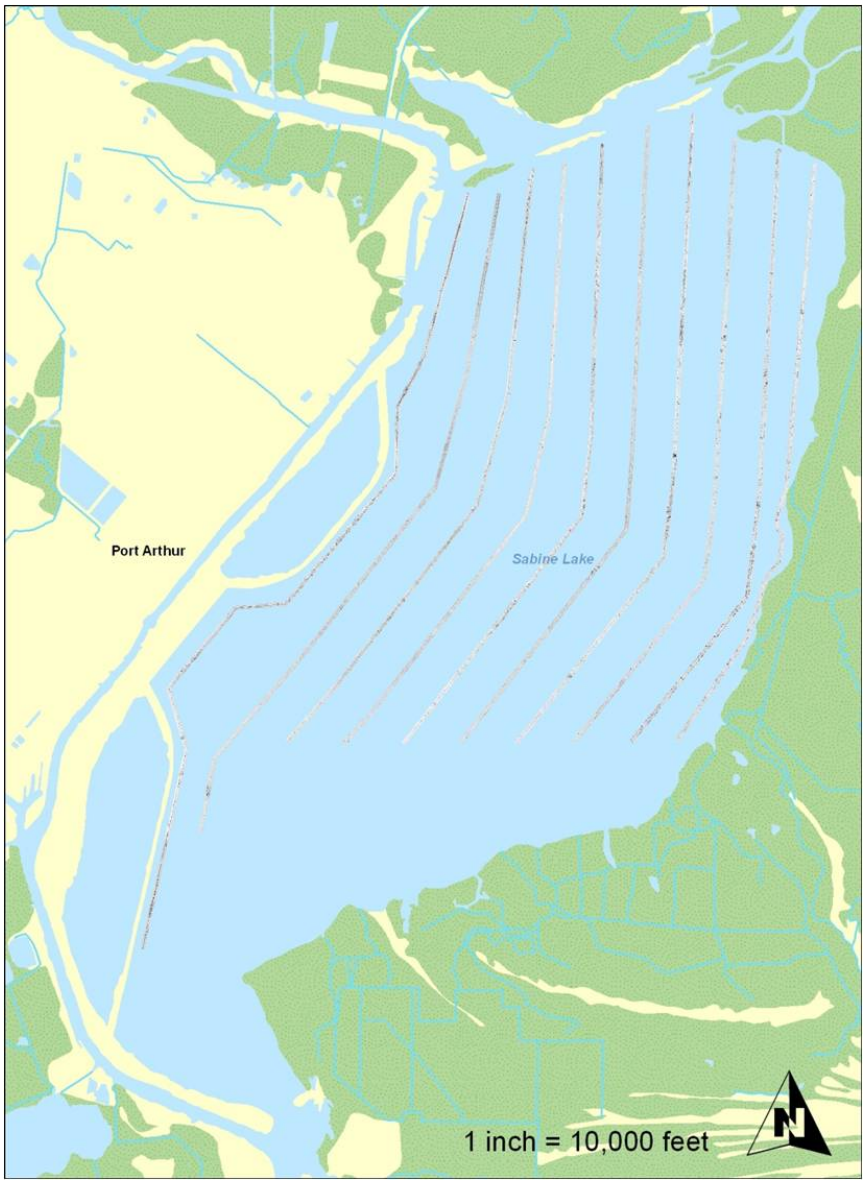


Figure A-1. The transects along Sabine Lake on which side-scan sonar equipment was deployed to scan the bottom for hard substrates (image courtesy of Bio-West, Inc.). The area along southeastern portion of Sabine Lake was covered in a previous survey which indicated probable occurrence of *Rangia cuneata*.

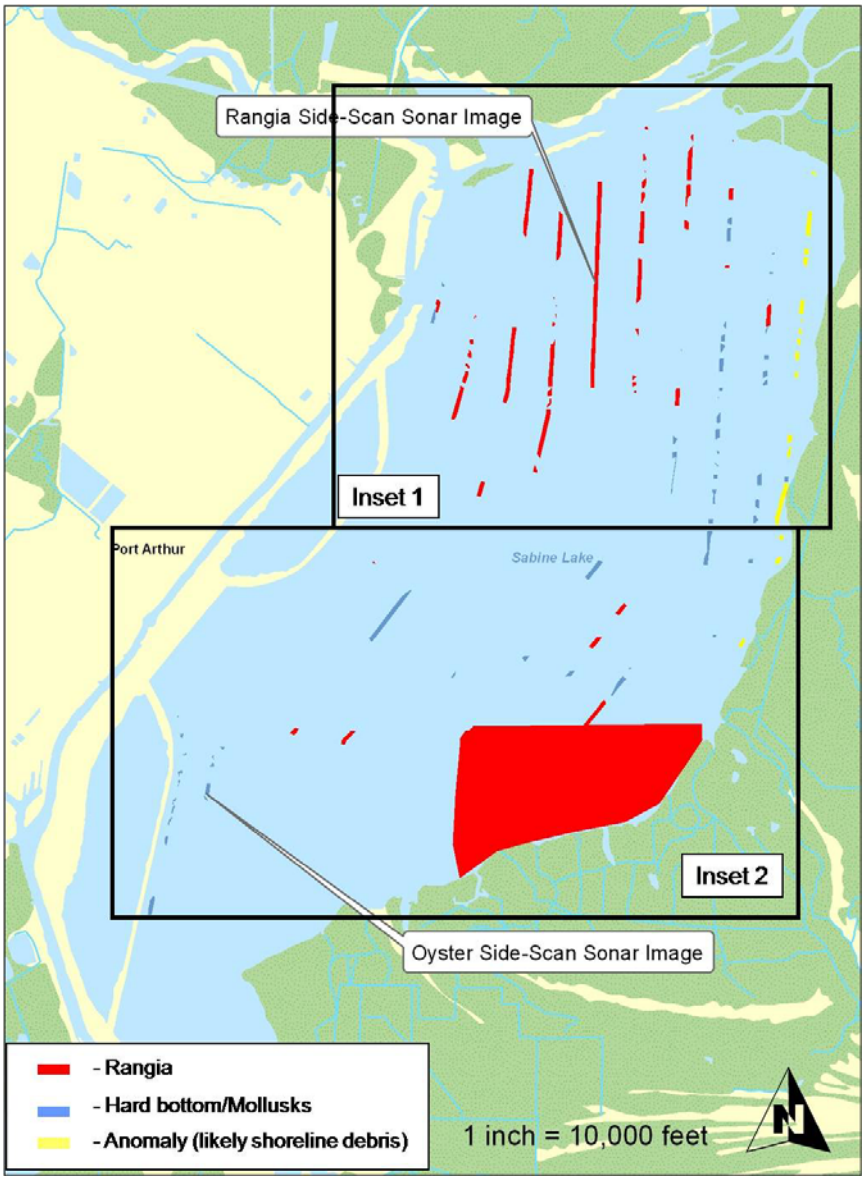


Figure A-2. Portions of the transects along Sabine Lake in which the side-scan sonar survey indicates the presence of a high proportion of hard bottom substrates (image courtesy of Bio-West, Inc.).

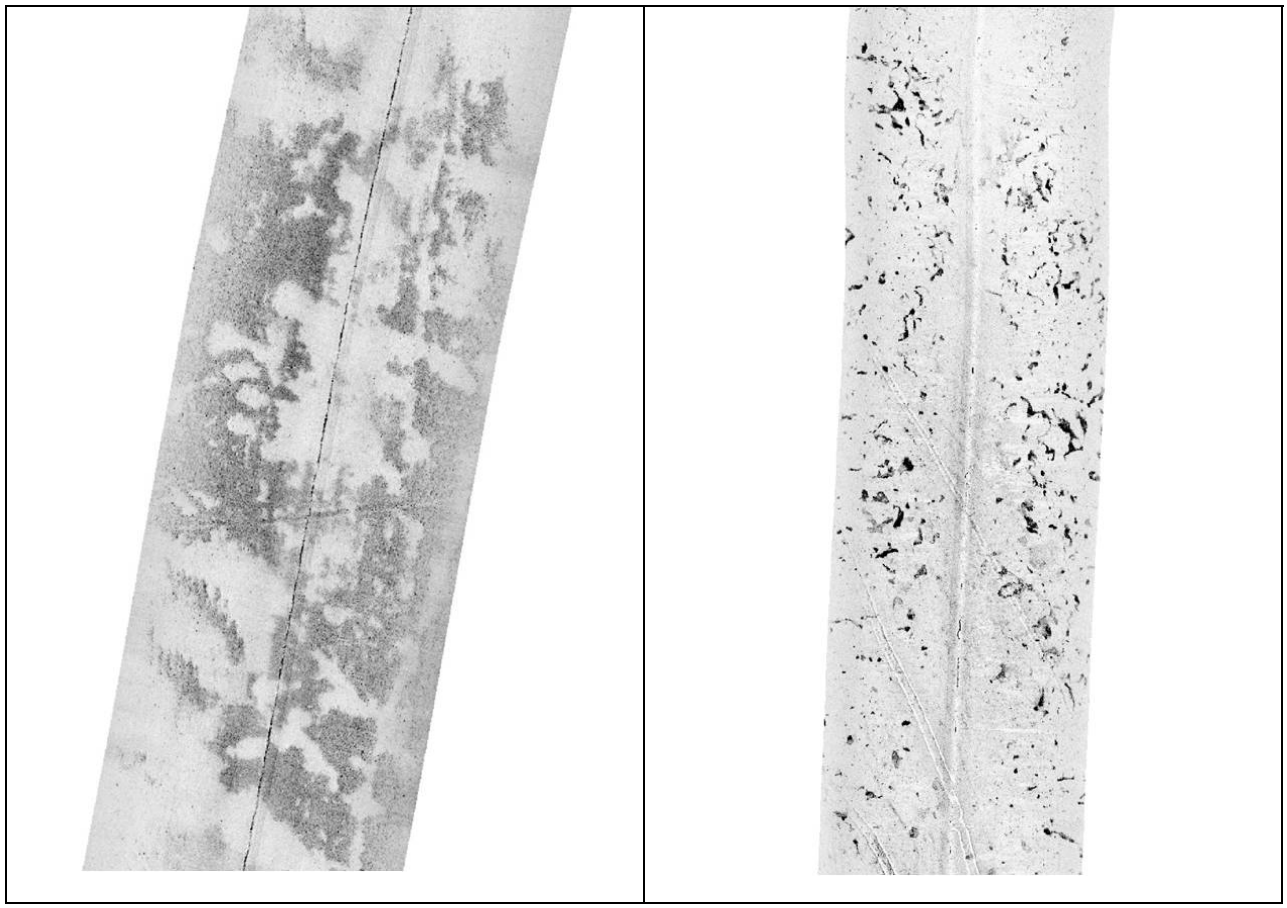


Figure A-3. Excerpt of two portions of the transects illustrating the difference in the sonar "signature" of oysters and what was confirmed to be areas of abundant Rangia cuneata (image courtesy of Bio-West, Inc.).

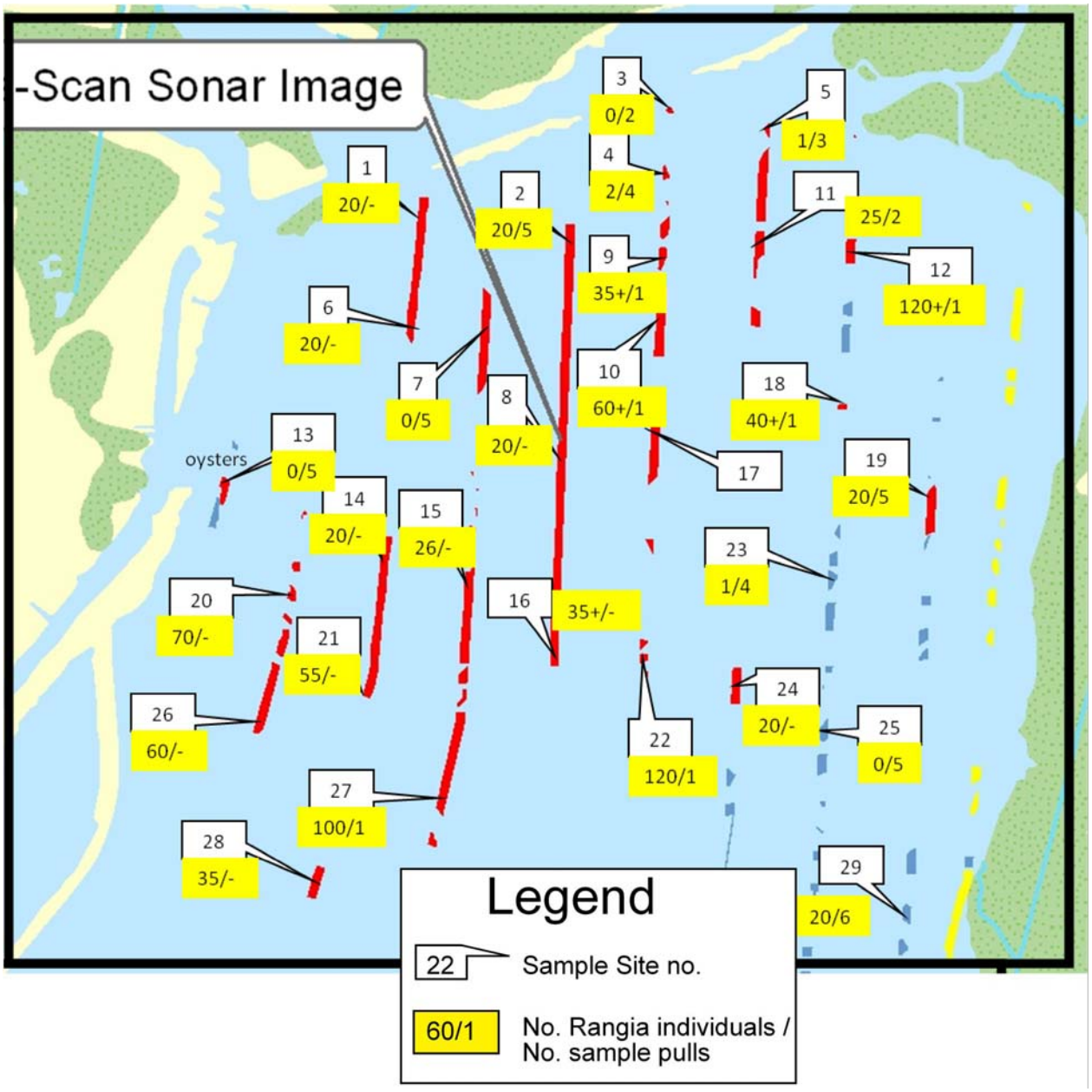


Figure A-4. Results of the field sampling for *Rangia cuneata* at sites along the sonar transects in upper portion of Sabine Lake.

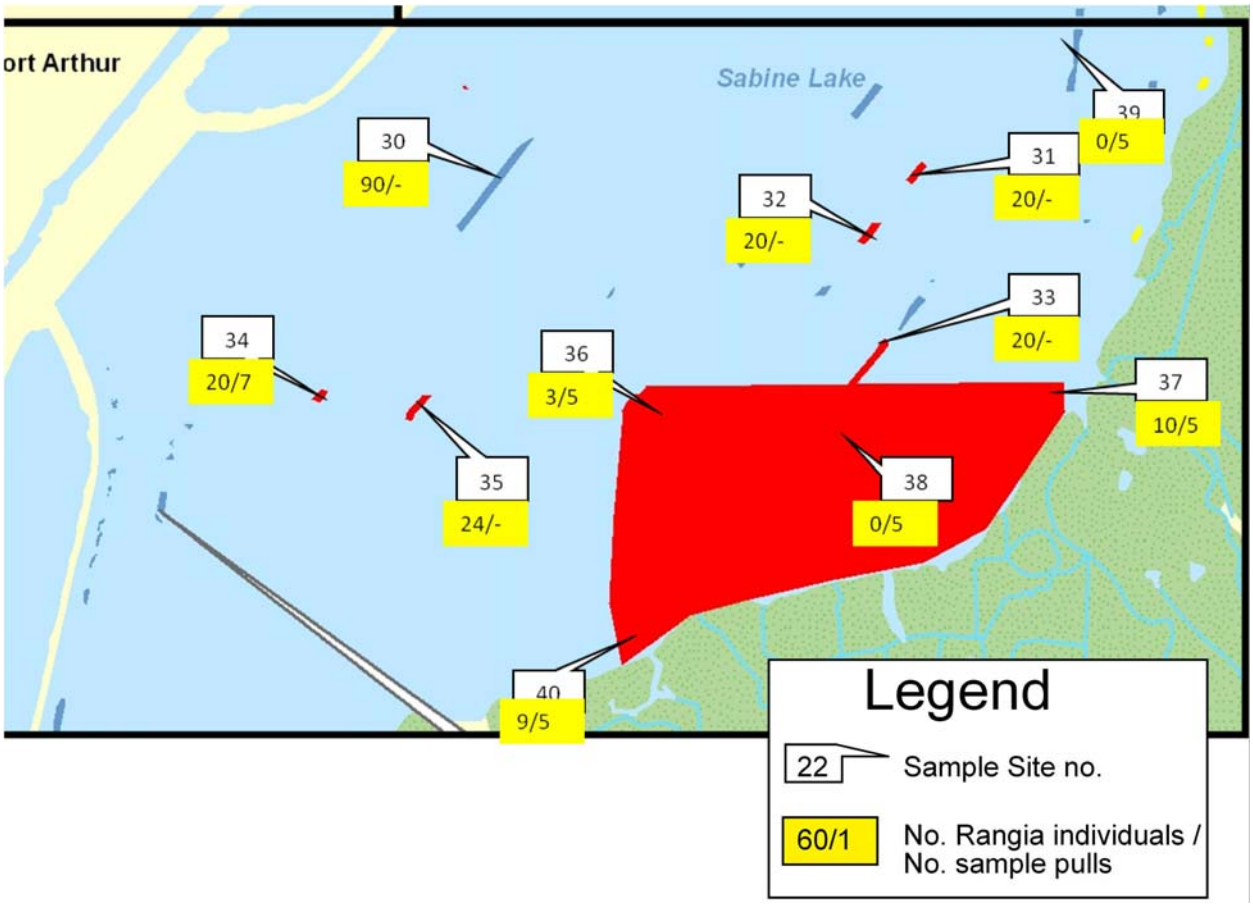


Figure A-5. Results of the field sampling for *Rangia cuneata* at sites along the sonar transects in lower portion of Sabine Lake.

Size class	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
0-4mm																				
5-9mm																				
10-14mm																				
15-19mm																				
20-24mm																			2	
25-29mm								1											5	
30-34mm		2						1							1		1			1
35-39mm	1	14				3		4	7	8		4		4	5	3	17	4		4
40-44mm	7	4				8		13	9	12	4	13	3	10	13	15	2	13		9
45-49mm	10			1		9		1	4		11	3	8	6	1	2		3	4	5
50-54mm	2			1							5		4						8	1
55-59mm																			1	
60-64mm					1															
65-69mm																				
70-74mm																				
>74mm																				
TOTAL	20	20	0	2	1	20	0	20	20	20	20	20	15	20	20	20	20	20	20	20
tows		5	2	4	3					1	2	1	5				2		5	
estimated total									+15	+40	+5	+100		20	+6	+15	50	+20		50

Size class	21	21	22	23	24	25	26	27	27	28	29	30	31	32	33	34	35	36	37	38	39	40
0-4mm																						
5-9mm																						
10-14mm																						
15-19mm																						
20-24mm																						
25-29mm																						
30-34mm			1		1																	
35-39mm	6	6	6		1		4	1	1	3			1				1					
40-44mm	9	9	11		3		11	10	10	10	1	4	9	7	10							1
45-49mm	4	4	2	1	7		4	7	7	5	1	12	9	11	8	1	2		2			1
50-54mm	1	1			7		1	2	2	2	18	4	1	2	2	5	6	2	4			2
55-59mm					1											12	14		4			5
60-64mm																2	1	1				
65-69mm																						
70-74mm																						
>74mm																						
TOTAL	20	20	20	1	20	0	20	20	20	20	20	20	20	20	20	20	24	3	10	0	0	9
tows				4							6					7			5	5		5
estimated total	35	35	+100				40	80	80	35		90										

Table A-1. Results of field sampling at forty sites indicated in Figures A-4 and A-5. For each site 20 randomly chosen individuals were measured. Number of additional individual clams estimated. Also shown for many sites are the number of “tows”, each of approximately the same duration / length.

Appendix B – Salinity Suitability Information for Key Species and Communities in and around Sabine Lake.

For each of the key species and communities utilized in this analysis we utilized a salinity suitability relationship of curve. For blue crabs and oysters we are using existing salinity suitability curves directly from the recent work on Matagorda Bay (LCRA & SAWS 2007). For the other species and marshland types we have synthesized literature information into a curve format. In those instances, we also present the sources of specific information that allowed us to construct these curves.

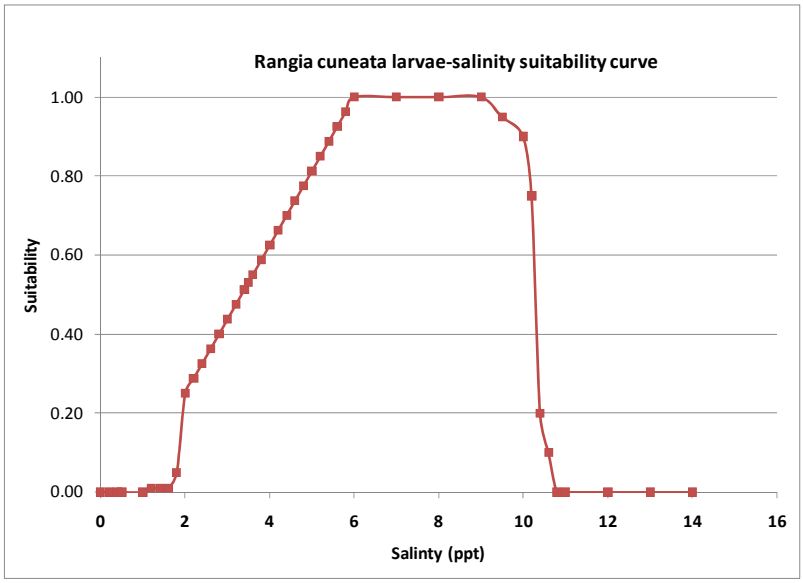
Rangia cuneata larvae

□ Specific salinity tolerance consideration and source(s):

▪ *R. cuneata* are concentrated in areas where salinity seldom exceeds 18 ppt (LaSalle and de la Cruz 1985).

▪ Studies indicate optimum conditions for embryo development are water temperatures of 18 to 29 °C and salinities of 6 to 10 ppt. Embryos did not develop at 0 ppt salinity (Cain 1973, 1974).

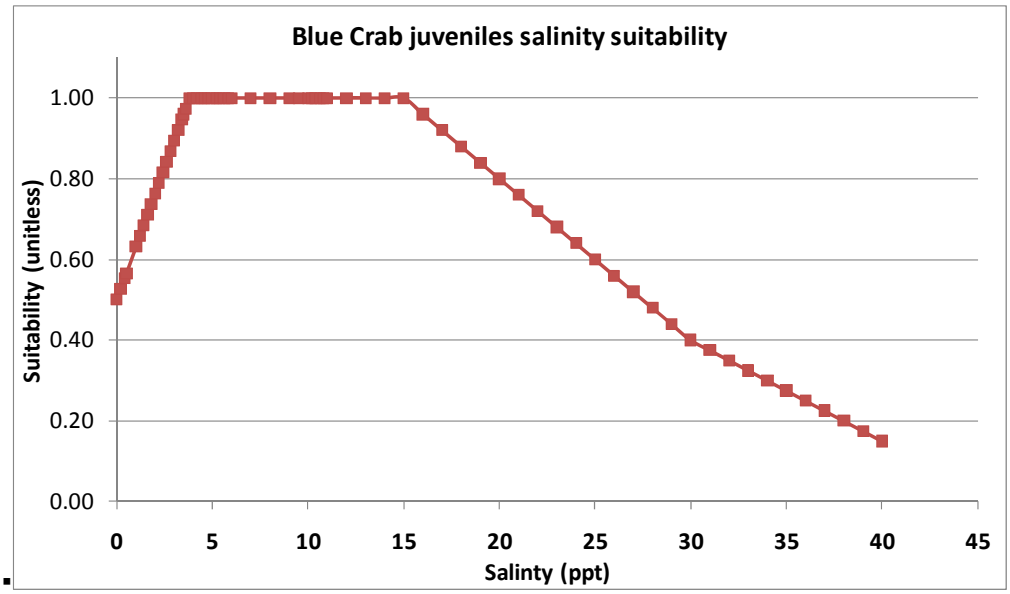
▪ Larvae of *Rangia cuneata* ... require salinity within a narrow range: 2 – 10 ppt for early larvae, 2 to 20 ppt for later larvae." (Hopkins et al, 1973)



Blue crabs juveniles

□ Specific salinity tolerance consideration and source(s):

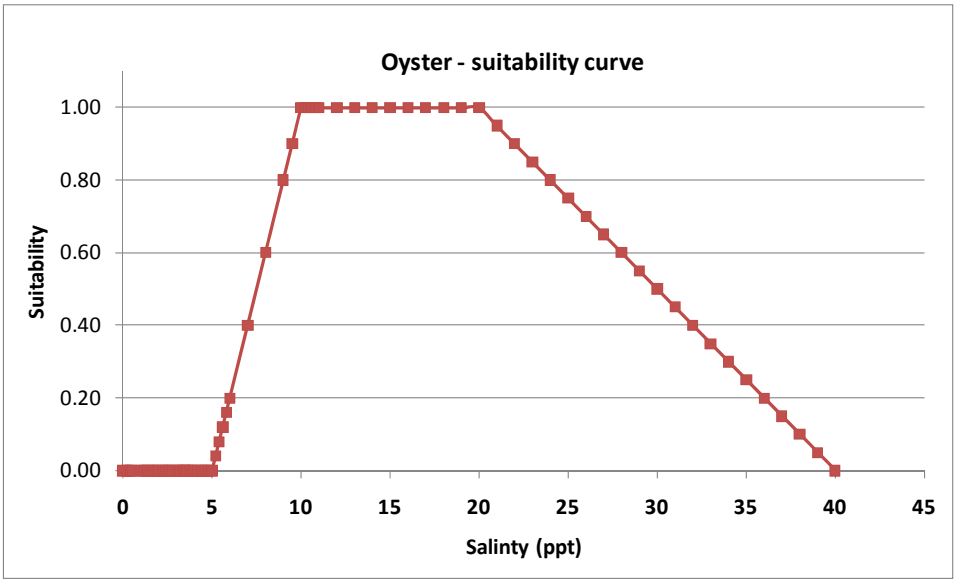
The salinity suitability curve here for juveniles is directly from LCRA& SAWS (2007).



Oysters, adults

□ Specific salinity tolerance consideration and source(s):

The salinity suitability curve here is directly from Cake (1983).



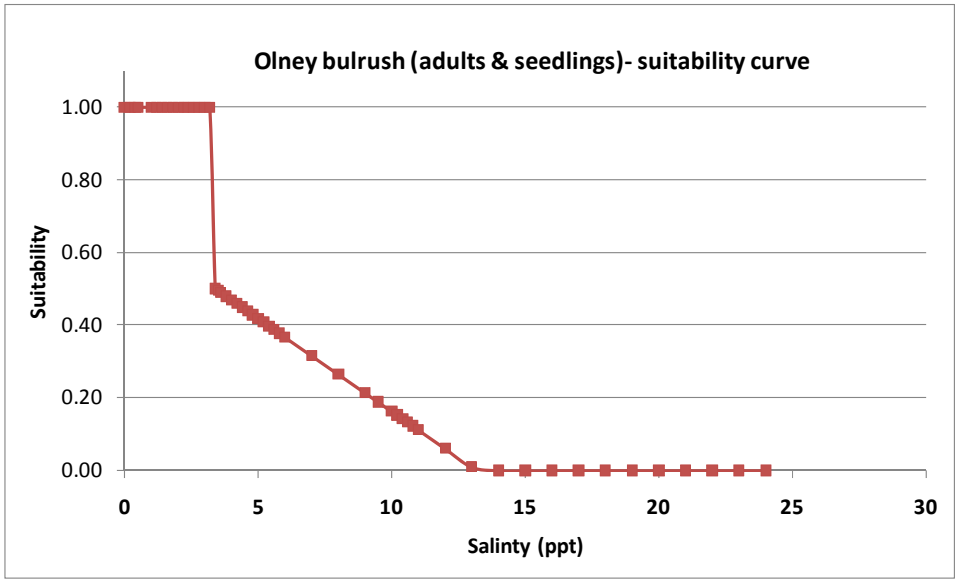
Olney bulrush (Schoenoplectus americanus)

□ Specific salinity tolerance consideration and source(s):

▪ *S. americanus* can occur in fresh, intermediate and brackish marshes, surviving in salinities from 0 to 12 ppt (Howard & Mendelssohn 1999). However, *S. americanus* reaches its maximum

productivity in intermediate marshes where salinities are generally below 3.5 ppt (Stutzenbaker 1999) [as cited in Bio-West, 2009]

▪ At a salinity of 4 ppt, germination is reduced by 50 percent, and above 13 ppt no germination occurs (Palmisano and Newsom 1968). [as cited in Bio-West, 2009]

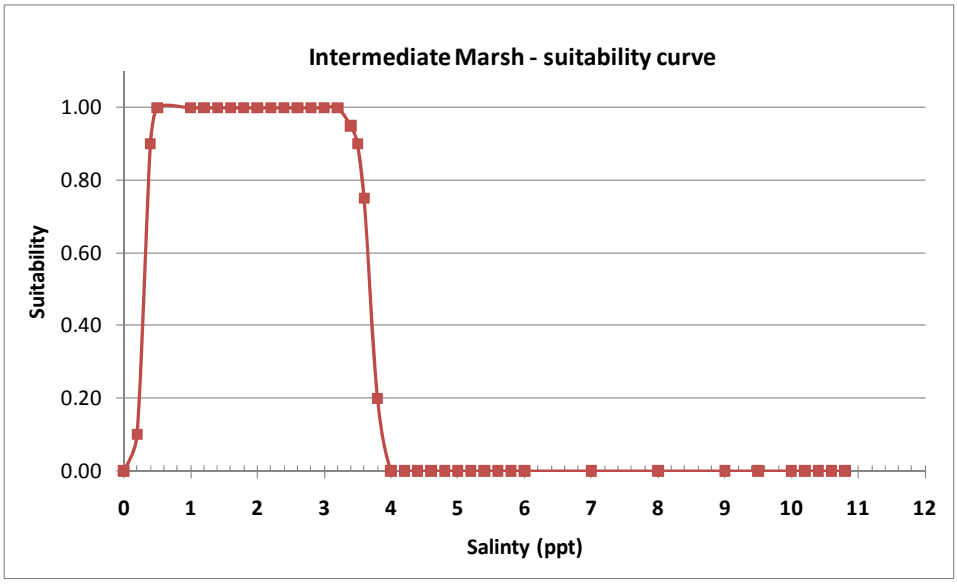


Intermediate marsh community

□ Specific salinity tolerance consideration and source(s):

▪ The majority of Sabine Lake is surrounded by intermediate to brackish wetlands. (TPWD & TWDB 2005)

▪ intermediate marsh .. tolerates a range of soil salinities between 0.5 – 3.5 ppt. (Stuzenbaker 1999) [as cited in TPWD & TWDB (2005)]

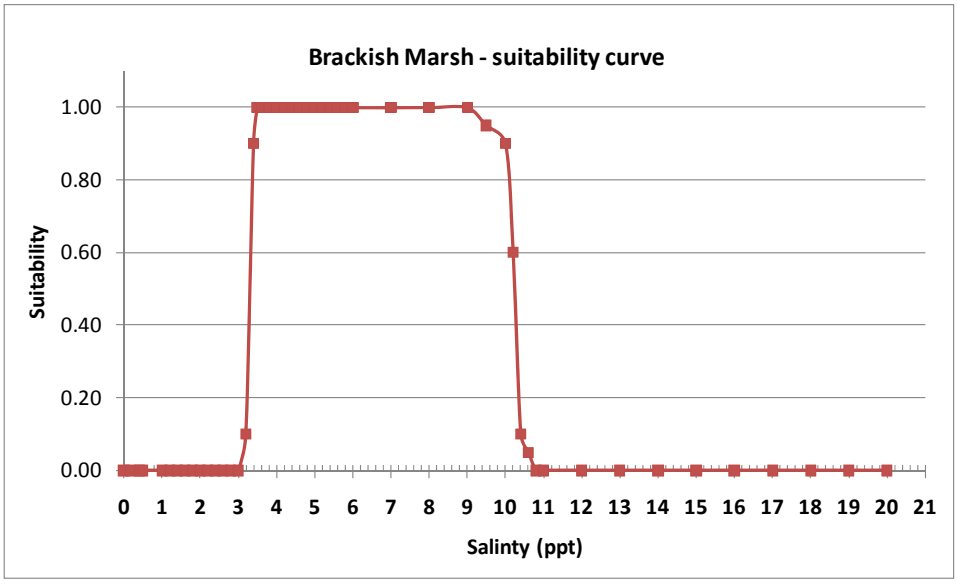


Brackish marsh community

□ Specific salinity tolerance consideration and source(s):

▪ The majority of Sabine Lake is surrounded by intermediate to brackish wetlands. (TPWD & TWDB 2005)

▪ brackish marsh .. tolerates a range of soil salinities between 3.5 – 10 ppt. (Stuzenbaker 1999) [as cited in TPWD & TWDB (2005)]



Analyses of Satellite Imagery in the Sabine and Neches River Basins in Support of Developing Overbank Instream Flow Recommendations for the Maintenance of Bottomland Hardwood Forests

October 23, 2009

Interim Report

Greater Edwards Aquifer Alliance

Analyses of Satellite Imagery for Overbank Events in the Sabine and Neches River Basins in Support of Developing Instream Flow Recommendations for the Maintenance of Bottomland Hardwood Forests

Submitted to: Sabine and Neches Bay and Basin Expert Science Team

10/23/09

Submitted by:

National Wildlife Federation, Austin, Texas

Greater Edwards Aquifer Alliance, Austin, Texas

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Acknowledgements: Duane German, Texas Parks and Wildlife Department.

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Appendix A - Analyses of Satellite Imagery for Inundated Area for Selected Overbank Events

Appendix B - Results of Analyses for Inundated Area for Selected Overbank Events Compiled by Site

Appendix C - Bottomland Hardwood Forest, Species Composition, Part 1

Appendix D - Bottomland Hardwood Forest, Species Composition, Part 2

Introduction

The Sabine-Neches Bay and Basin Expert Science Team (BBEST) was created under the auspices of Senate Bill 3 of the 2007 Texas Legislature. The BBEST is tasked with developing an environmental flow regime to support a "sound ecological environment". The Texas Instream Flow Program (TIFP) explicitly recognizes that occasional "overbank flows" are an important component of a flow regime. As stated in the TIFP technical overview document (TCEQ, TPWD, & TWDB, 2008),

> ".. overbank flows play a critical role in developing and maintaining riparian areas and floodplain habitats. The duration, rate of increase and decrease, and sequence of flow events also influence physical processes and may have important biological consequences."

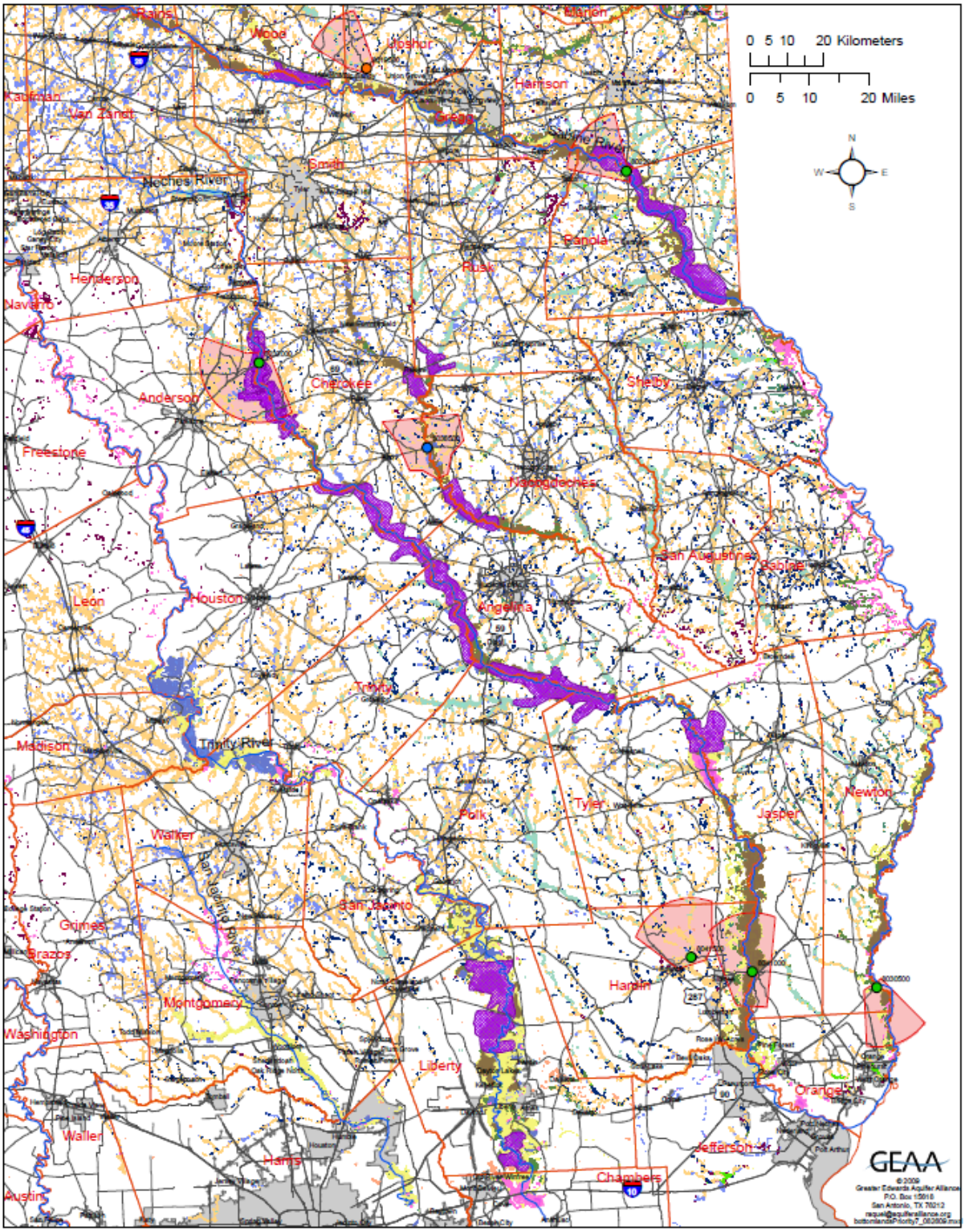
The recent SB 3 Science Advisory Committee report (SAC, 2009)on establishing instream flow regimes is even more explicit.

> "… overbank flows transport sediments and nutrients to riparian areas, recharge floodplain aquifers, and provide suitable conditions for seedlings. Overbank flows also provide lateral connectivity between the river channel and the active floodplain, supporting populations of fish or other biota utilizing floodplain habitat during and after flood events. Other objectives for overbank flows include the movement of organic debris to the main channel, providing life cycle cues for various species, and maintaining the balance of species in aquatic and riparian communities."

The analyses presented herein were designed to support the efforts of the BBEST to specify the attributes of necessary overbank events at the BBEST-selected points within the river basins of interest (corresponding in all cases to USGS streamflow gauges). For many of the BBEST's selected gauge sites, we have analyzed available NASA Landsat satellite imagery (Thematic Mapper imagery) for dates that correspond to times in which flows thought to be sufficient to reach the floodplain were occurring. Date selection was constrained by the need to find times that leaf cover was minimized in order to allow for identification of flooded areas. For each of these "overbank events" we analyzed the area inundated along a ten mile segment of the stream or river encompassing a BBEST-selected site. For each segment along the watercourse a variety of east Texas bottomland hardwood types (e.g. Pineywoods: Seasonally Flooded Bottomland Hardwood Forest) were encountered. We have also tabulated the flow magnitude and other characteristics on the date of the satellite imagery and for a preceding period in order to aid in the specification of attributes such as the peak magnitude, volumes, durations, etc. of an overbank component of the flow regime.

Figure 1 below shows a broad swath of east Texas, including the Sabine and Neches River basins, with forest cover classifications (legend on following page). Figure 2 shows the seven sites within the basins for which there was available satellite imagery corresponding to overbank events (selection process is described in the Methodology section below).

Figure 1: Overall East Texas Project Area with Texas Parks and Wildlife Bottomland Hardwood (BH) Layer (2009) and US Fish and Wildlife Service Priority-One Bottomland Hardwood Sites (legend follows).



Legend

Proposed Primary Sites:

- Priority 1
- Priority 2
- Priority 3
- Priority 4
- Priority 5
- Rivers
- Highways
- Study Area for Proposed Primary Site
- Cities and Towns
- County boundaries
- USFWS bottomlands*

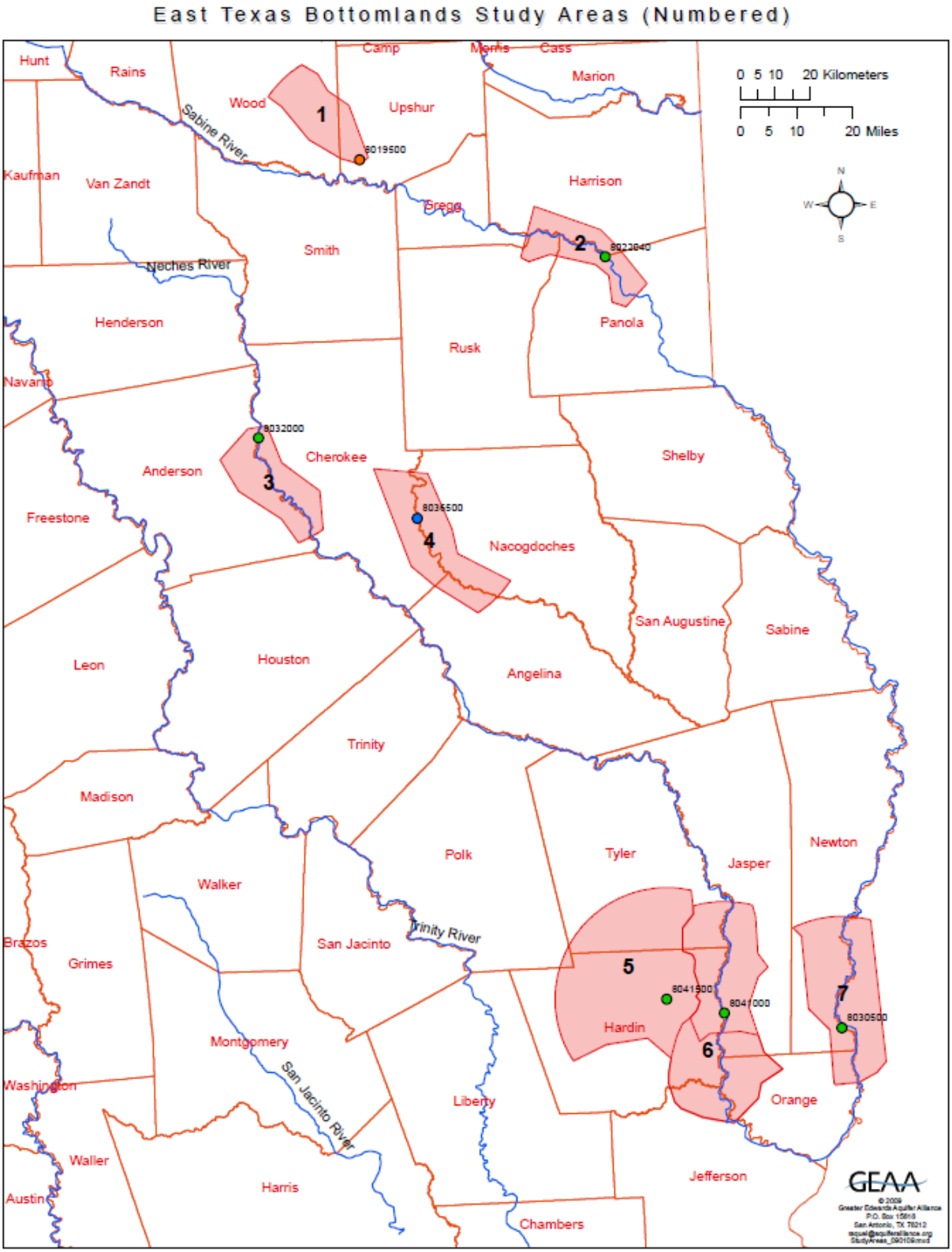
TPWD bottomlands:**

- Pineywoods: Baldcypress Swamp
- Pineywoods: Bottomland Herbaceous Wetland
- Pineywoods: Bottomland Wet Prairie
- Pineywoods: Deciduous Successional Bottomland Shrubland
- Pineywoods: Seasonally Flooded Bottomland Hardwood Forest
- Pineywoods: Small Stream and Riparian Baldcypress Swamp
- Pineywoods: Small Stream and Riparian Deciduous Successional Shrubland
- Pineywoods: Small Stream and Riparian Herbaceous Wetland
- Pineywoods: Small Stream and Riparian Live Oak Temporarily Flooded Forest
- Pineywoods: Small Stream and Riparian Seasonally Flooded Hardwood Forest
- Pineywoods: Small Stream and Riparian Temporarily Flooded Hardwood Forest
- Pineywoods: Small Stream and Riparian Temporarily Flooded Mixed Forest
- Pineywoods: Small Stream and Riparian Wet Prairie
- Pineywoods: Temporarily Flooded Live Oak Bottomland Hardwood Forest
- Pineywoods: Temporarily Flooded Mixed Pine / Hardwood Bottomland Forest
- Pineywoods:Temporarily Flooded Bottomland Hardwood Forest
- Swamp

* U.S. Fish and Wildlife Service. Texas Bottomland Hardwood Preservation Program Department of the Interior Final Concept Plan. May 1985. Albequerque, New Mexico.

** Texas Parks and Wildlife Department and Texas Natural Resources Information System. Draft of Texas Vegetation Classification Project, Phase II. 2008.

Figure 2: The Sabine and Neches River Basins with the seven bottomland hardwood study areas and gauge locations used in this analysis.



The specific sites shown on Figure 2 and summary information regarding the site's relation to nearby bottomland hardwood forest is given in Table 1.

Site No.	Station Name	USGS Gauge #	Assessed segment relative to guage	Working Overbank Threshold (cfs)	Bottom-land Hardwoods (BH) present?	USFWS Priority Bottomland Hardwoods	Notes
1	Big Sandy Ck near Big Sandy, TX	8019500	upstream	1,900	Y	2	
2	Sabine River near Beckville, TX	8022040	centered	12,600	Y	1	
3	Neches River near Neches, TX	8032000	downstream	4,700	Y	1	
4	Angelina River near Alto, TX	8036500	downstream	11,200	Y	(1)	just below & up from FWS 1
5	Village Creek near Kountze, TX	8041500	centered	8,150	Y	(5)	just below FWS 5
6	Neches River at Evadale, TX	8041000	centered	14,200	Y	N	extensive BH both up & down from site
7	Sabine River near Ruliff, TX	8030500	downstream	13,300	Y	2	

Table 1. Specific sites used in the analysis of bottomland hardwood inundation with satellite imagery.

Methodology

The efforts of these analyses can be broken into two principal steps and several substeps as summarized below.

I) Find candidate overbank events that may have corresponding satellite imagery.

1) Utilize the HEFR program output to compile the list of overbank events that occurred in or after 1987, the period during which Landsat images are available. An overbank event includes a sequence of days in which at least one day has an average daily discharge above the predefined 'overbank threshold' for that site. The HEFR program segregates portions of the streamflow time series at a site in which an overbank event occurs.

2) From the post-1987 list of overbank events, cull out all of those that are not likely to be in a "leaf-free" period of year. As a working timeframe, we utilized late November through mid-March for the "leaf-free" period with subsequent checks on images that were near the margins of this timeframe.

II) After finding the applicable overbank events, the next step is to classify the satellite imagery into the area of bottomland forest inundation.

1) Acquire LandSat Thematic Mapper (TM) imagery within the date ranges from Step 1. Import to image (.img) format for band 1-5 and 7.

2) Mask the area of interest using data provided by Greater Edwards Aquifer Alliance. Masking accomplished using Erdas Imagine Mask command. Mask image created from shapefile using ESRI ArcGIS Spatial Analyst Feature to Raster command. Resulting continuous image converted to thematic image during sub-setting process, using Erdas Imagine Subset command.

3) Site study area Landsat TM images were classified into 15 class thematic layer using the Erdas Imagine unsupervised classification (Isodata) process. Up to 10 iterations were allowed, to meet the 0.95 convergence threshold.

4) Thematic classes were then assigned to either inundated class or not-inundated class by visual interpretation using the raw image in either bands 4,5,3 or 4,3,2.

5) If one of the original 15 classes was not clearly separable into inundated / non-inundated class it(they) were used as a mask to subset the original raw imagery and steps 3 and 4 were repeated. This process continued until all thematic classes were separated into either inundated or non-inundated classes.

6) The resulting 2 class image was re-coded using either the Erdas Recode command or a custom model written with Erdas model builder into a new image with only 2 thematic classes.

7) The Erdas Imaging Clump command was then run on the 2 class image.

8) The clumped image was then used by the Erdas Eliminate command to remove all groups of pixels less than 1 hectare in area, those areas smaller than 1 ha. are assigned the value of nearby larger clumps.

Results

Table 2 summarizes the number of useable Landsat images located for each of the BBEST sites.

Station Name	USGS Gauge #	No. of suitable Landsat images for analysis*
Sabine River near Beckville, TX	8022040	3
Sabine River near Ruliff, TX	8030500	8
Neches River near Neches, TX	8032000	4
Neches River at Evadale, TX	8041000	3
Angelina River near Alto, TX	8036500	1
Big Sandy Ck near Big Sandy, TX	8019500	3
Village Creek near Kountze, TX	8041500	1

note:* for some sites a few images at flows below apparent overbank threshold were used as an aid to cross check suitability of that value (see Appendix B tables).

Table 2. Summary of BBEST gauge sites with available Landsat satellite imagery.

The resulting classified images are found in Appendix A. Appendix B details, in table format, the inundation results of all images classified for each overbank event and each site.

References

Science Advisory Committee (SAC). 2009. Use of Hydrologic Data in the Development of Instream Flow Recommendations for the Environmental Flows Allocation Process and the Hydrology-Based Environmental Flow Regime (HEFR) Methodology. Report # SAC-2009-01-Rev1. April 20, 2009.

Texas Commission on Environmental Quality (TCEQ), Texas Parks and Wildlife Department (TPWD), and Texas Water Development Board (TWDB), 2008: Texas instream flow studies: technical overview. Report 369, Texas Water Development Board, Austin.

[Additional references to be added in final version.]

Appendix A

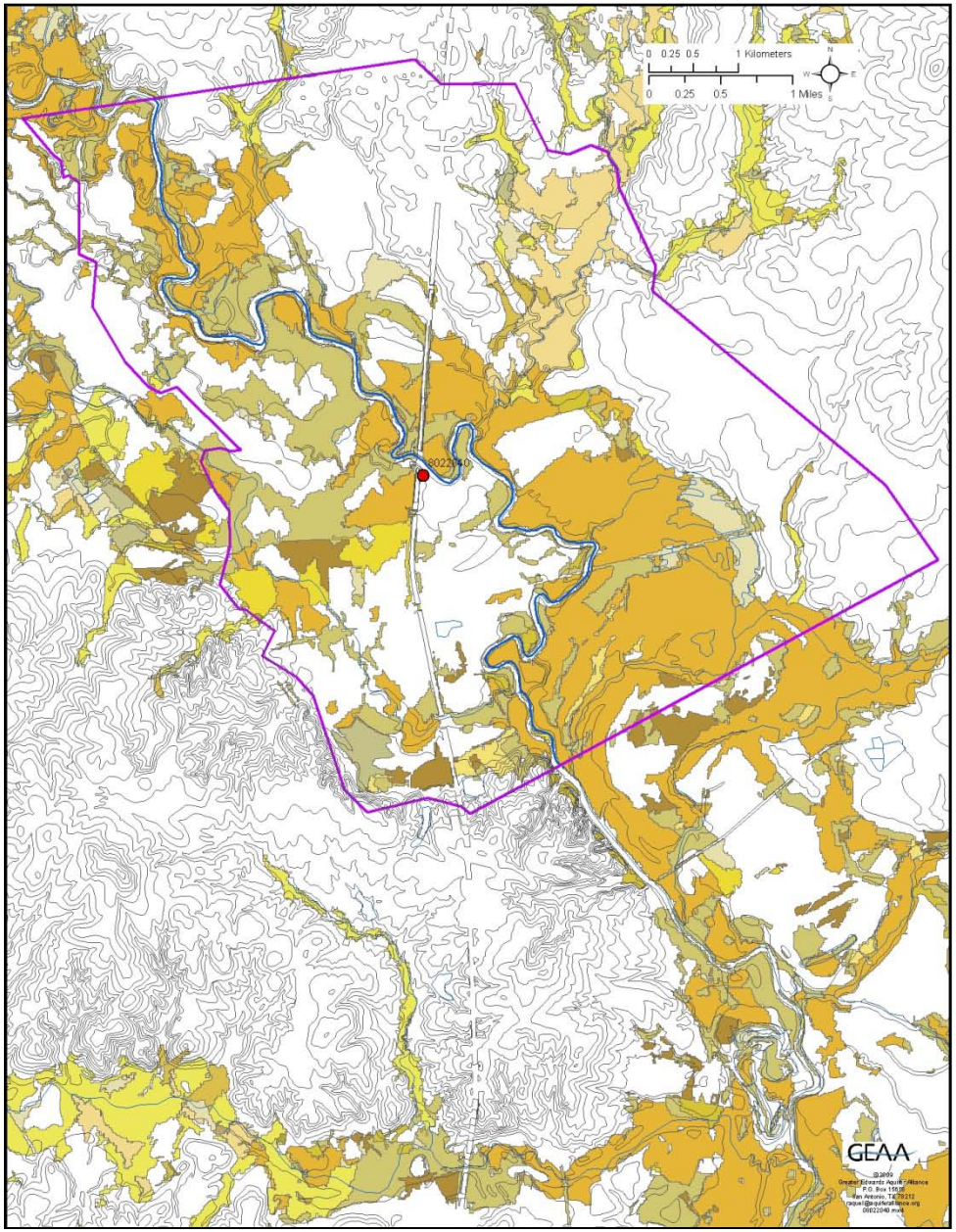
Analyses of Satellite Imagery for Inundated Area for Selected Overbank Events

Location	USGS Gauge no.	pages
Sabine River near Beckville, TX	8022040	A-1 to A-4
Sabine River near Ruliff, TX	8030500	A-5 to A-13
Neches River near Neches, TX	8032000	A-14 to A-18
Neches River at Evadale, TX	8041000	A-19 to A-22
Angelina River near Alto, TX	8036500	A-23 to A-24
Big Sandy Creek near Big Sandy, TX	8019500	A-25 to A-28
Village Ck near Kountze, TX	8041500	A-29 to A-31

Notes on terminology in figures:
BH – Bottomland Hardwood or “floodplain” forest.
OB – Overbank or Out-of-Bank.
Out-of-Bank Threshold – the assumed level at which inundation of the Bottomland Hardwood forest should begin. Based on information within Sept. 08, 2009 Freese & Nichols memo report to the Sabine and Neches Rivers and Sabine Lake Bay Basin and Bay Expert Science Team titled “Analysis of BBEST Stream Gages”.
TM – Thematic Mapper imagery from NASA’s Landsat satellite program.
TM date – date of the available Thematic Mapper imagery during the overbank event.
Mean Discharge – daily mean discharge in cubic feet per second, on the day of the Thematic Mapper imagery.
Pre-TM 10d – cumulative flow discharge volume, in million acre-feet, for 10 day period ending on the TM date.

Sabine River at Beckville
USGS Gage # 08022040

Bottomland Hardwoods
Environmental Inflows
Study Area



Legend

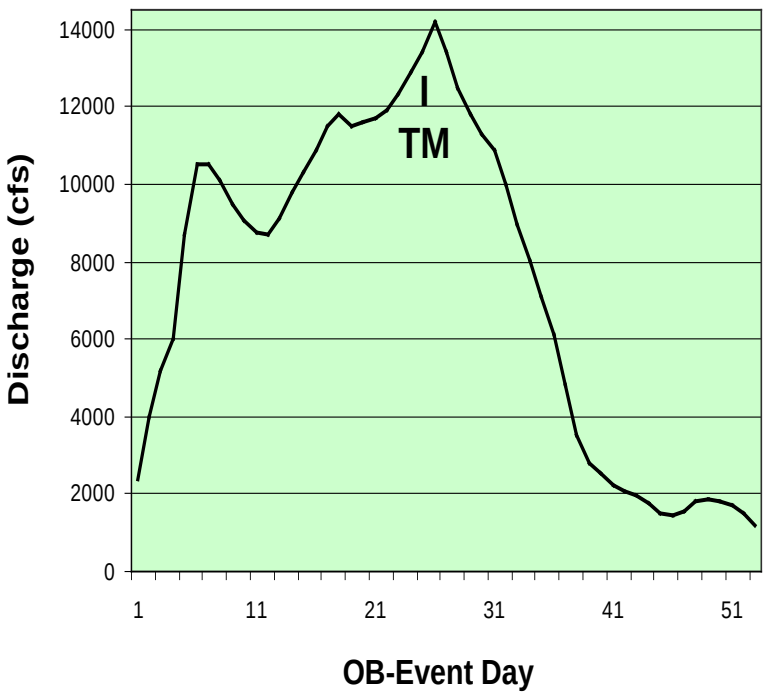
- Site 08022040
- Study Area: Bottomlands Contiguous to Main River Stem
- Rivers and Streams
- Elevation Contours in 5-foot Intervals

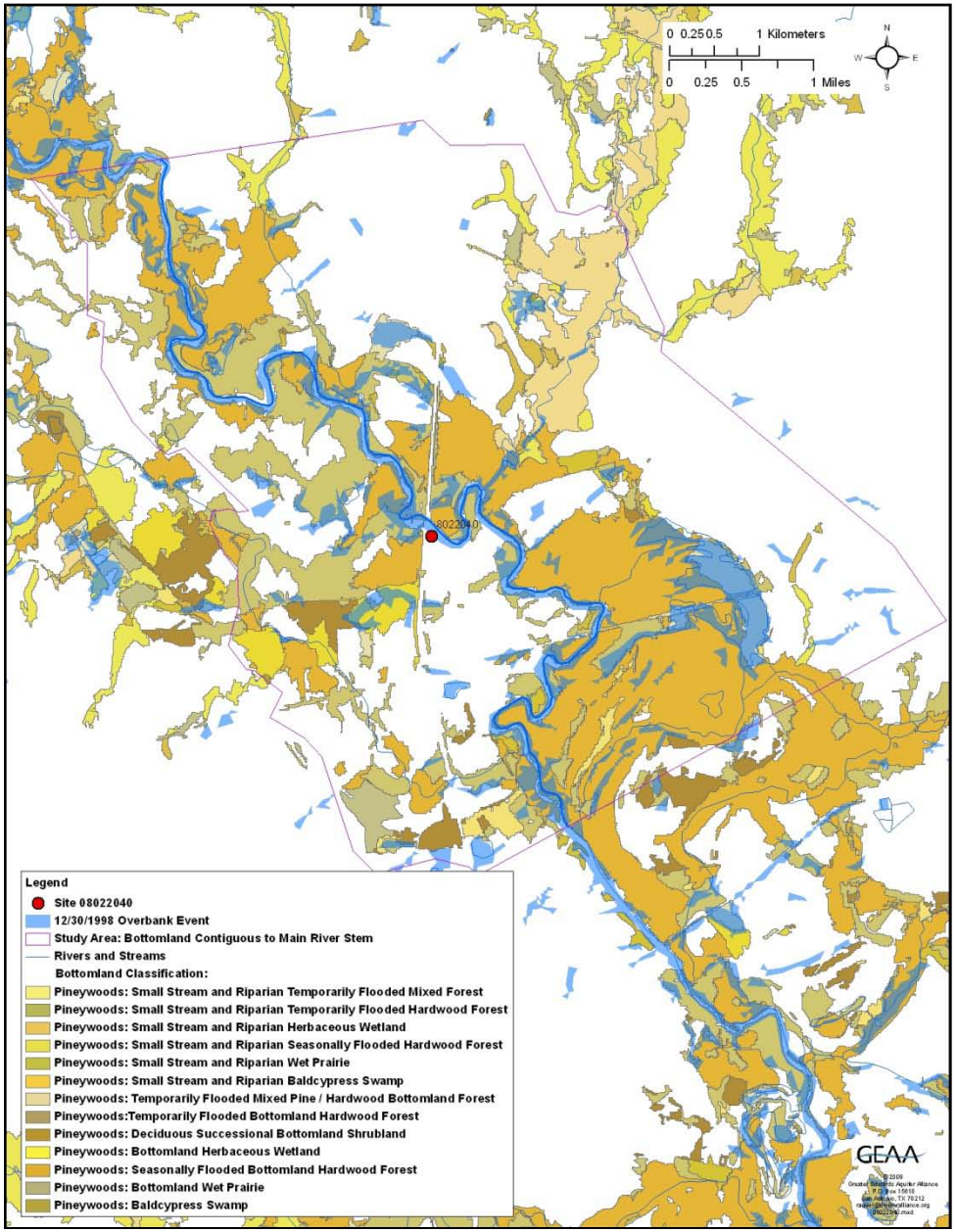
Bottomland Classification:

- Pineywoods: Small Stream and Riparian Temporarily Flooded Mixed Forest
- Pineywoods: Small Stream and Riparian Temporarily Flooded Hardwood Forest
- Pineywoods: Small Stream and Riparian Herbaceous Wetland
- Pineywoods: Small Stream and Riparian Seasonally Flooded Hardwood Forest
- Pineywoods: Small Stream and Riparian Wet Prairie
- Pineywoods: Small Stream and Riparian Baldcypress Swamp
- Pineywoods: Temporarily Flooded Mixed Pine / Hardwood Bottomland Forest
- Pineywoods:Temporarily Flooded Bottomland Hardwood Forest
- Pineywoods: Deciduous Successional Bottomland Shrubland
- Pineywoods: Bottomland Herbaceous Wetland
- Pineywoods: Seasonally Flooded Bottomland Hardwood Forest
- Pineywoods: Bottomland Wet Prairie
- Pineywoods: Baldcypress Swamp

Sabine River at Beckville-USGS Gage # 08022040
Overbank Event: 12/7/98-1/28/99

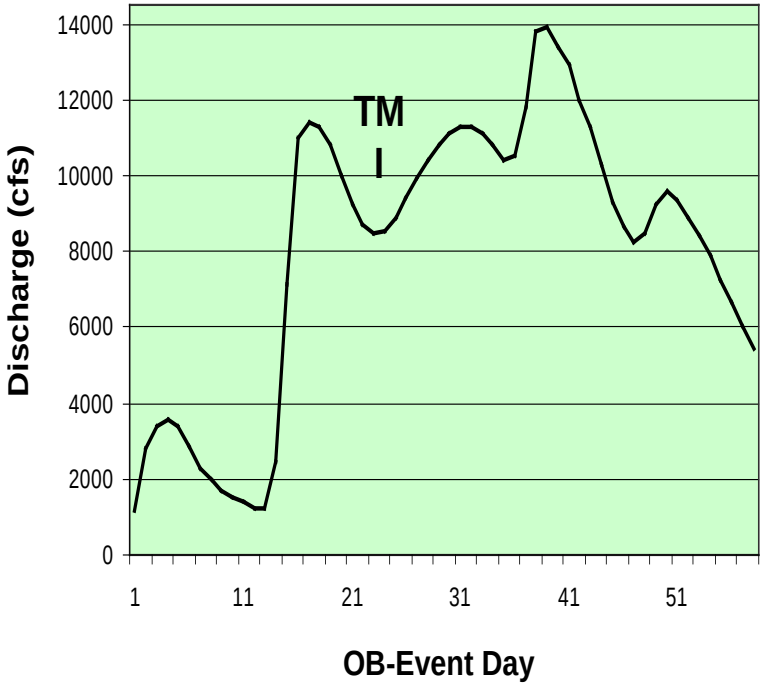
Out-of-Bank Threshold = 12,600 cfs								
TM Date	Mean Discharge (cfs)	Nearest Pre-TM Date Above Threshold	% BH Inudated	OB Event: Cumulative Discharge Volume (10^6 ac-ft)				
				Pre-TM 10d	Pre-TM 15d	Pre-TM 20d	Pre-TM 30d	Above-Threshold Days Prior to TM Date
12/30/98	**12,900**	12/30/98	**15.26%**	0.23	0.32	0.42	0.47	0.03

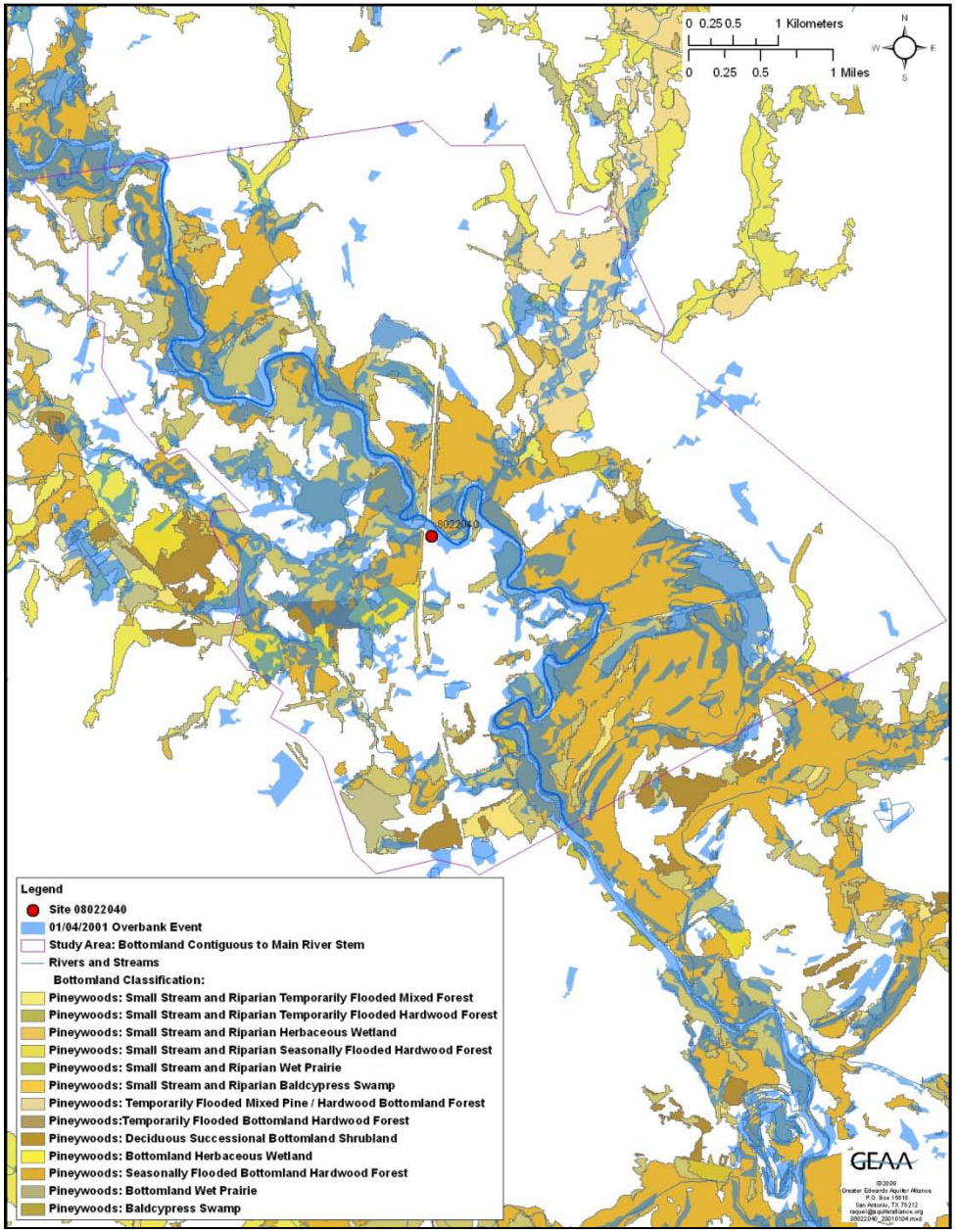




Sabine River at Beckville-USGS Gage # 08022040
Overbank Event: 12/13/00-2/8/01

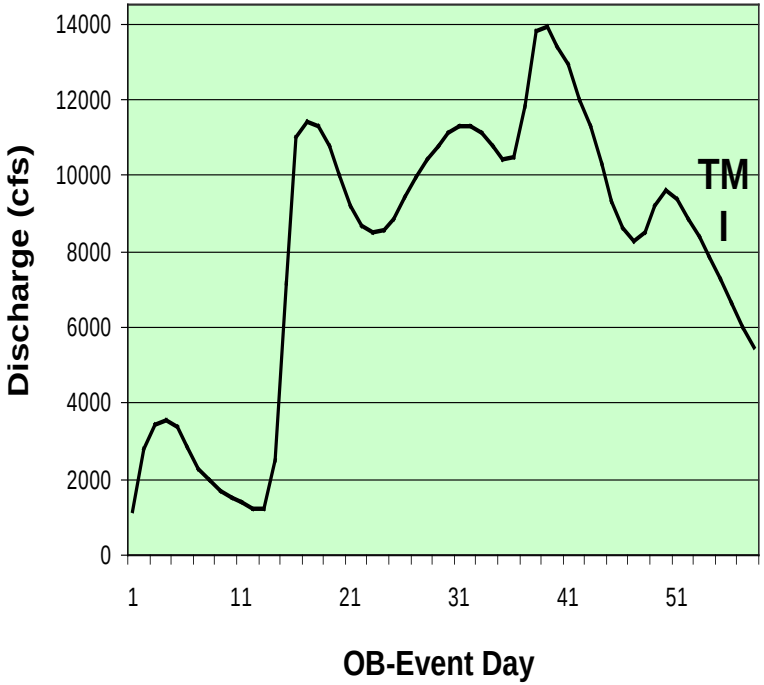
Out-of-Bank Threshold = 12,600 cfs								
TM Date	Mean Discharge (cfs)	Nearest Pre-TM Date Above Threshold	% BH Inudated	OB Event: Cumulative Discharge Volume (10^6 ac-ft)				
				Pre-TM 10d	Pre-TM 15d	Pre-TM 20d	Pre-TM 30d	Above-Threshold Days Prior to TM Date
1/4/01	8,500	2/3/99	33.30%	0.18	0.19	0.22	0.25	0.00

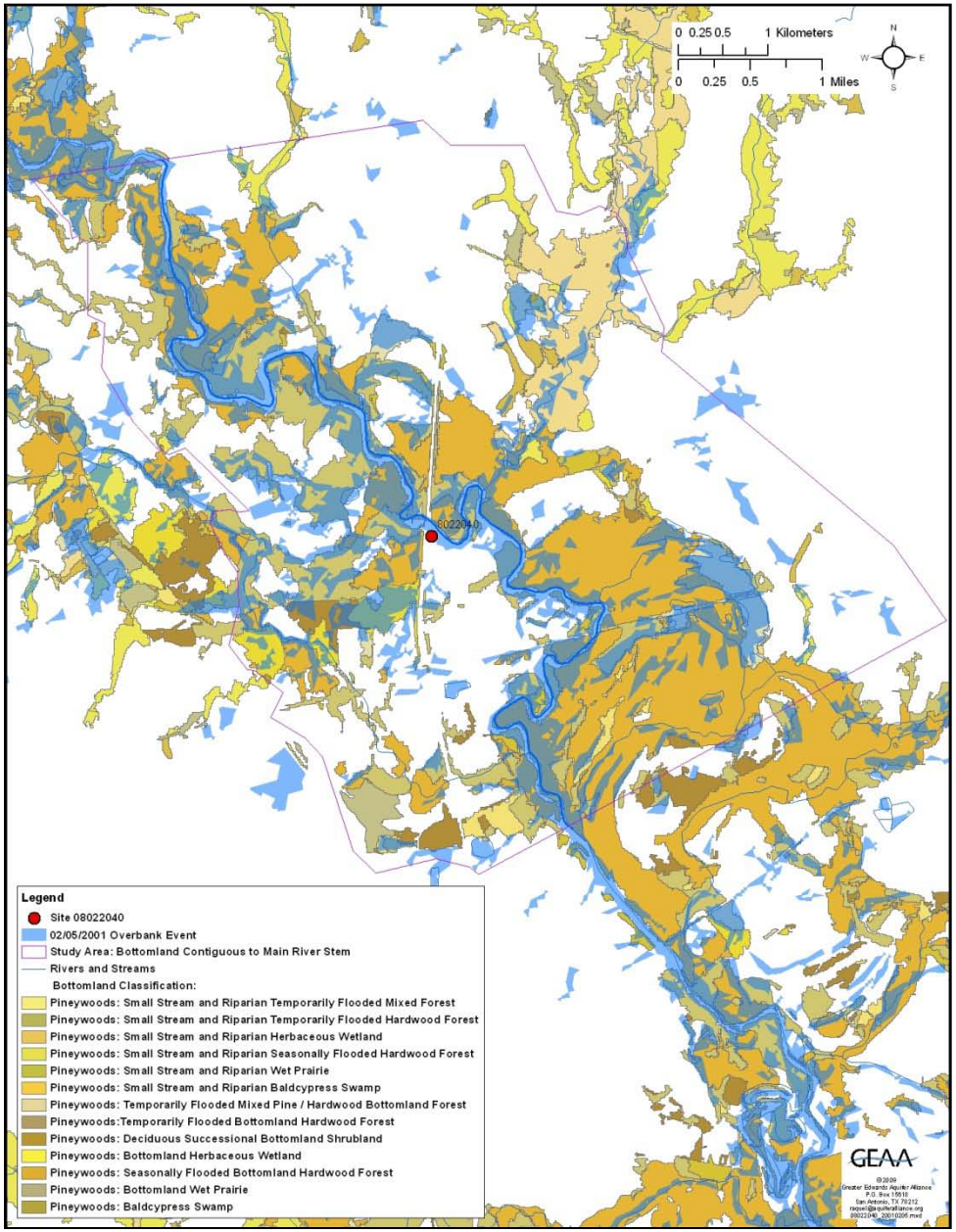




Sabine River at Beckville-USGS Gage # 08022040
Overbank Event: 12/13/00-2/8/01

Out-of-Bank Threshold = 12,600 cfs								
TM Date	Mean Discharge (cfs)	Nearest Pre-TM Date Above Threshold	% BH Inudated	OB Event: Cumulative Discharge Volume (10^6 ac-ft)				
				Pre-TM 10d	Pre-TM 15d	Pre-TM 20d	Pre-TM 30d	Above-Threshold Days Prior to TM Date
2/5/01	**7,270**	1/22/01	**33.20%**	0.17	0.28	0.41	0.62	0.11



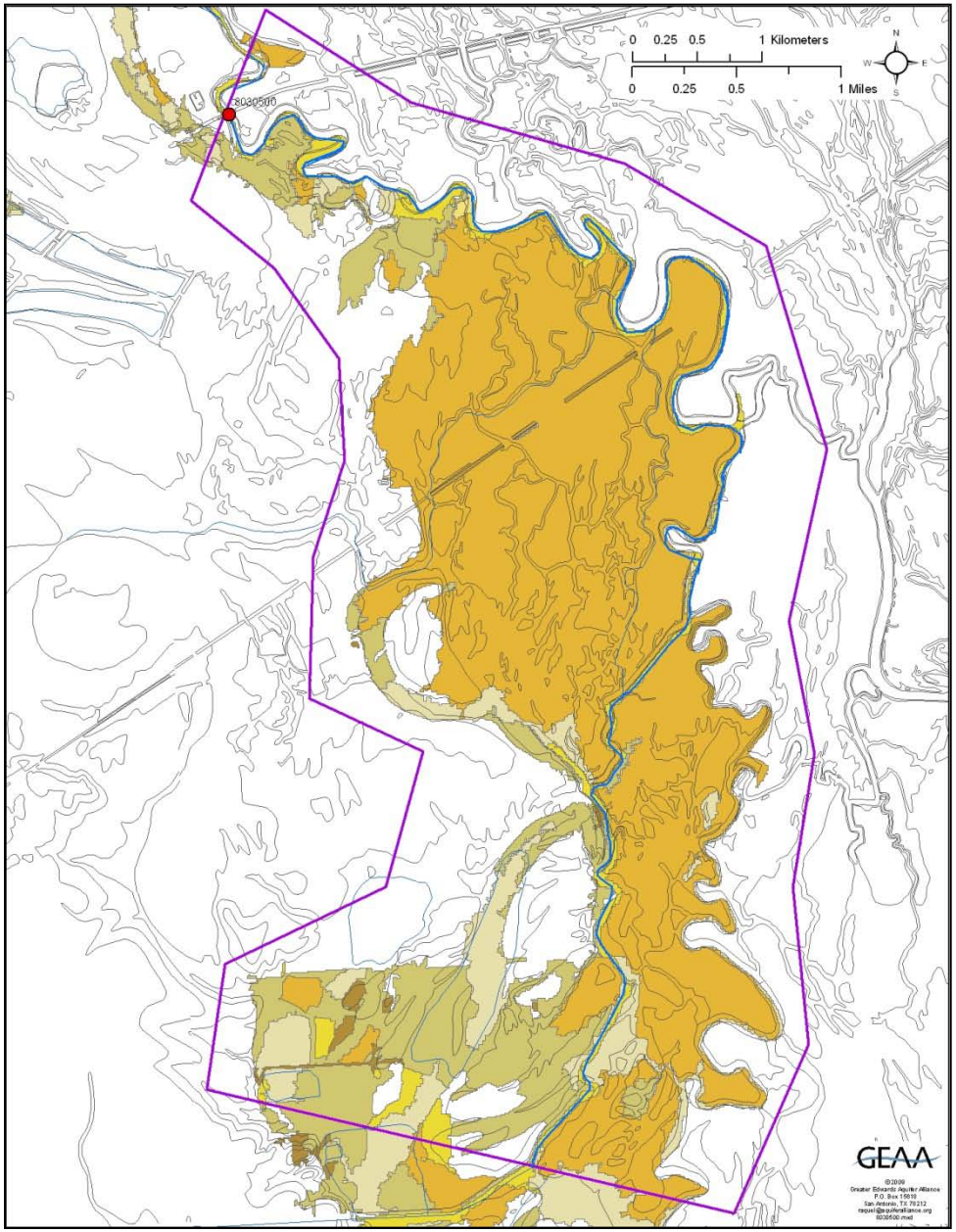


Sabine River at Ruliff
USGS Gage # 08030500

Bottomland Hardwoods
Environmental Inflows
Study Area

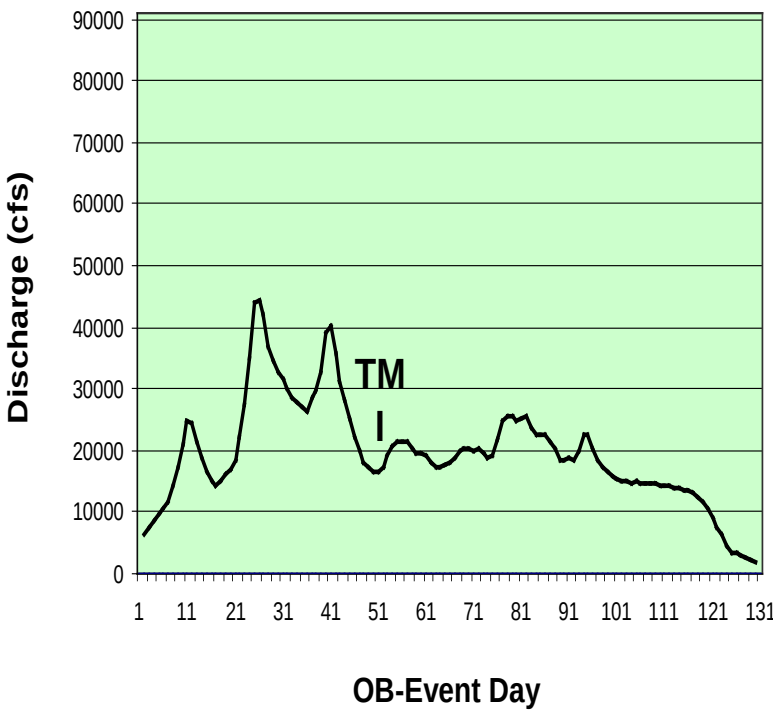
Legend

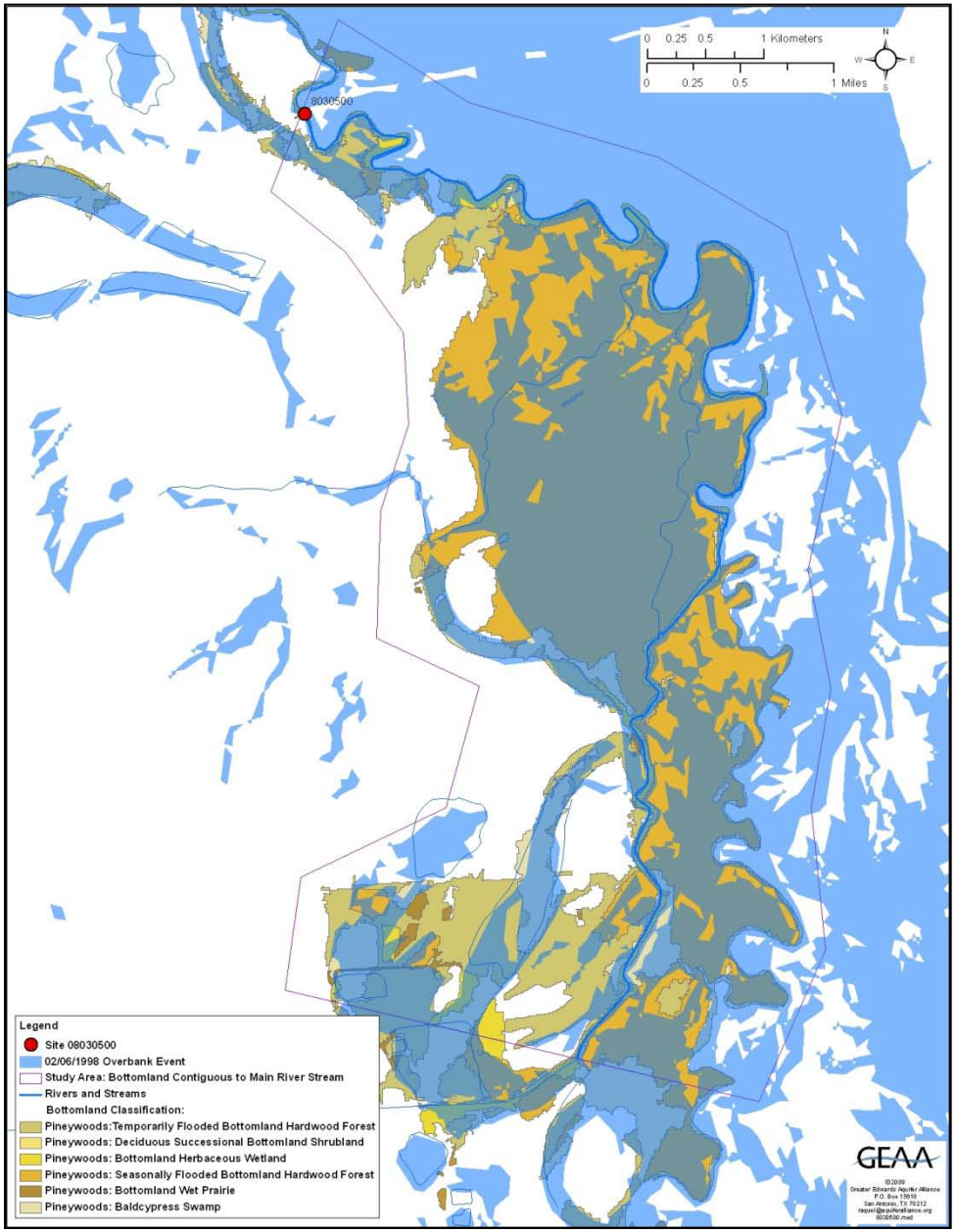
- Site 08030500
- Study Area: Bottomland Contiguous to Main River Stream
- Rivers and Streams
- Elevation Contours in 5-foot Intervals
- Bottomland Classification:
- Pineywoods:Temporarily Flooded Bottomland Hardwood Forest
- Pineywoods: Deciduous Successional Bottomland Shrubland
- Pineywoods: Bottomland Herbaceous Wetland
- Pineywoods: Seasonally Flooded Bottomland Hardwood Forest
- Pineywoods: Bottomland Wet Prairie
- Pineywoods: Baldcypress Swamp



Sabine River at Ruliff-USGS Gage # 08030500
Overbank Event: 12/18/97-4/25/98

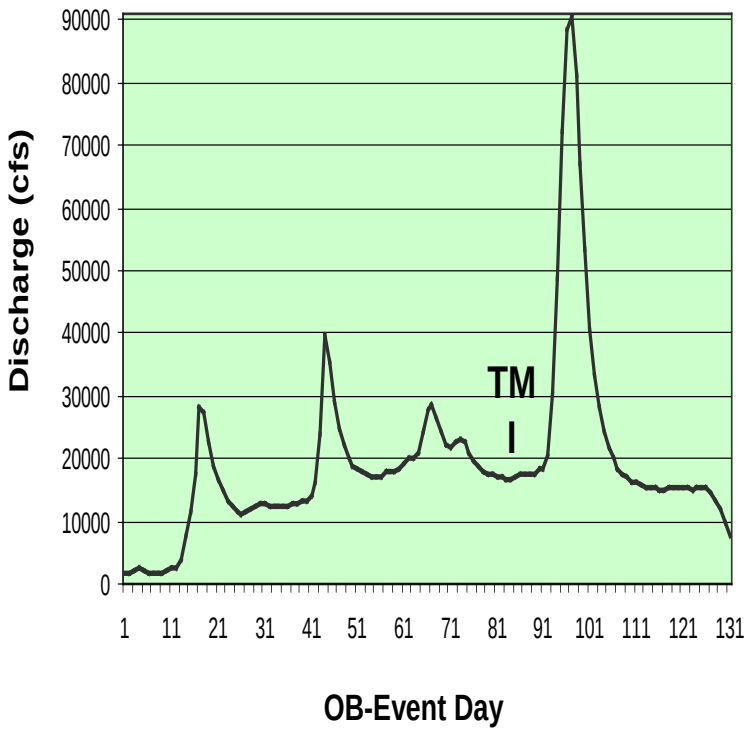
Out-of-Bank Threshold = 13,300 cfs								
TM Date	Mean Discharge (cfs)	Nearest Pre-TM Date Above Threshold	% BH Inudated	OB Event: Cumulative Discharge Volume (10^6 ac-ft)				
				Pre-TM 10d	Pre-TM 15d	Pre-TM 20d	Pre-TM 30d	Above-Threshold Days Prior to TM Date
2/6/98	**17,200**	2/6/98	**69.05%**	0.46	0.80	1.07	1.77	2.31

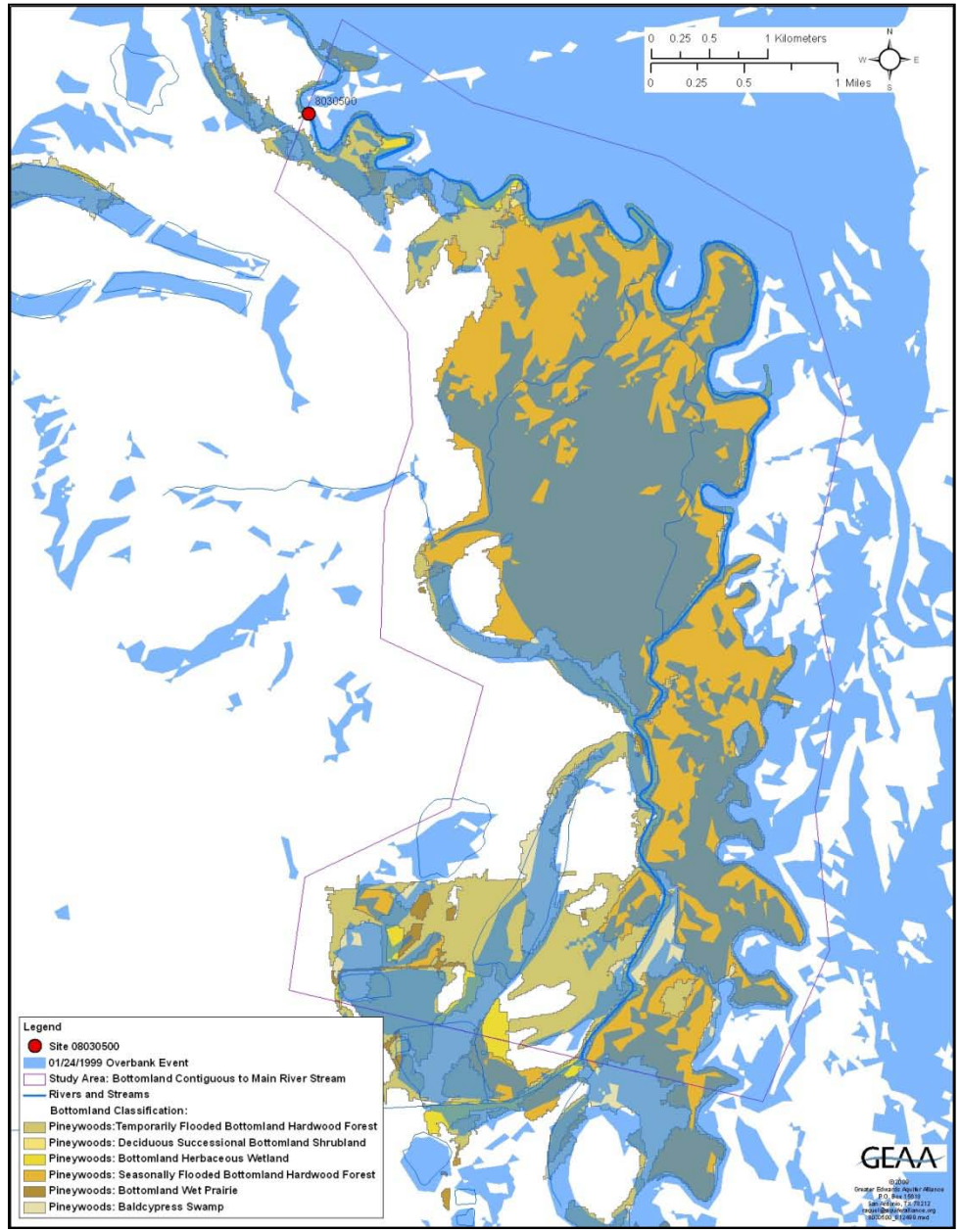




Sabine River at Ruliff-USGS Gage # 08030500
Overbank Event: 11/2/98-3/12/99

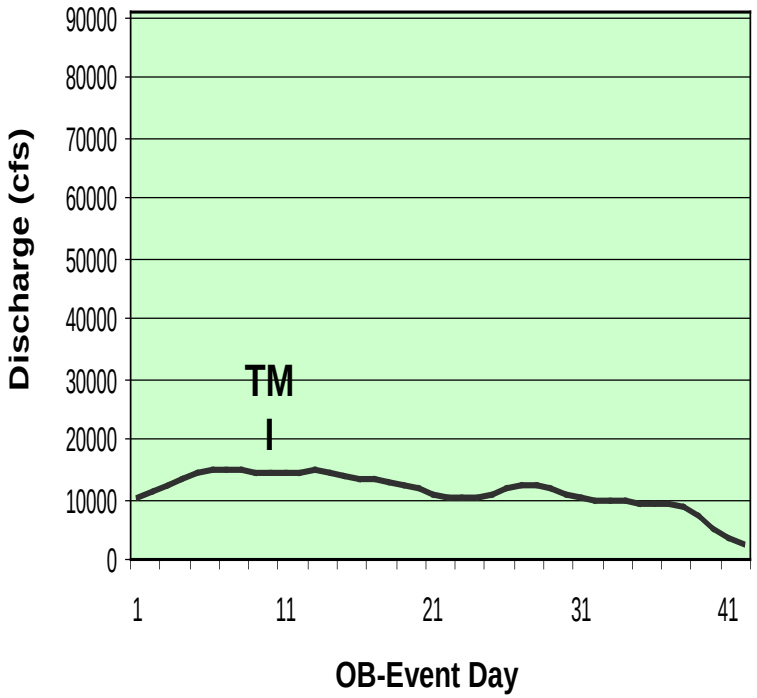
Out-of-Bank Threshold = 13,300 cfs								
TM Date	Mean Discharge (cfs)	Nearest Pre-TM Date Above Threshold	% BH Inudated	OB Event: Cumulative Discharge Volume (10^6 ac-ft)				
				Pre-TM 10d	Pre-TM 15d	Pre-TM 20d	Pre-TM 30d	Above-Threshold Days Prior to TM Date
1/24/99	**16,600**	1/24/99	**60.36%**	0.37	0.59	0.85	1.21	2.15

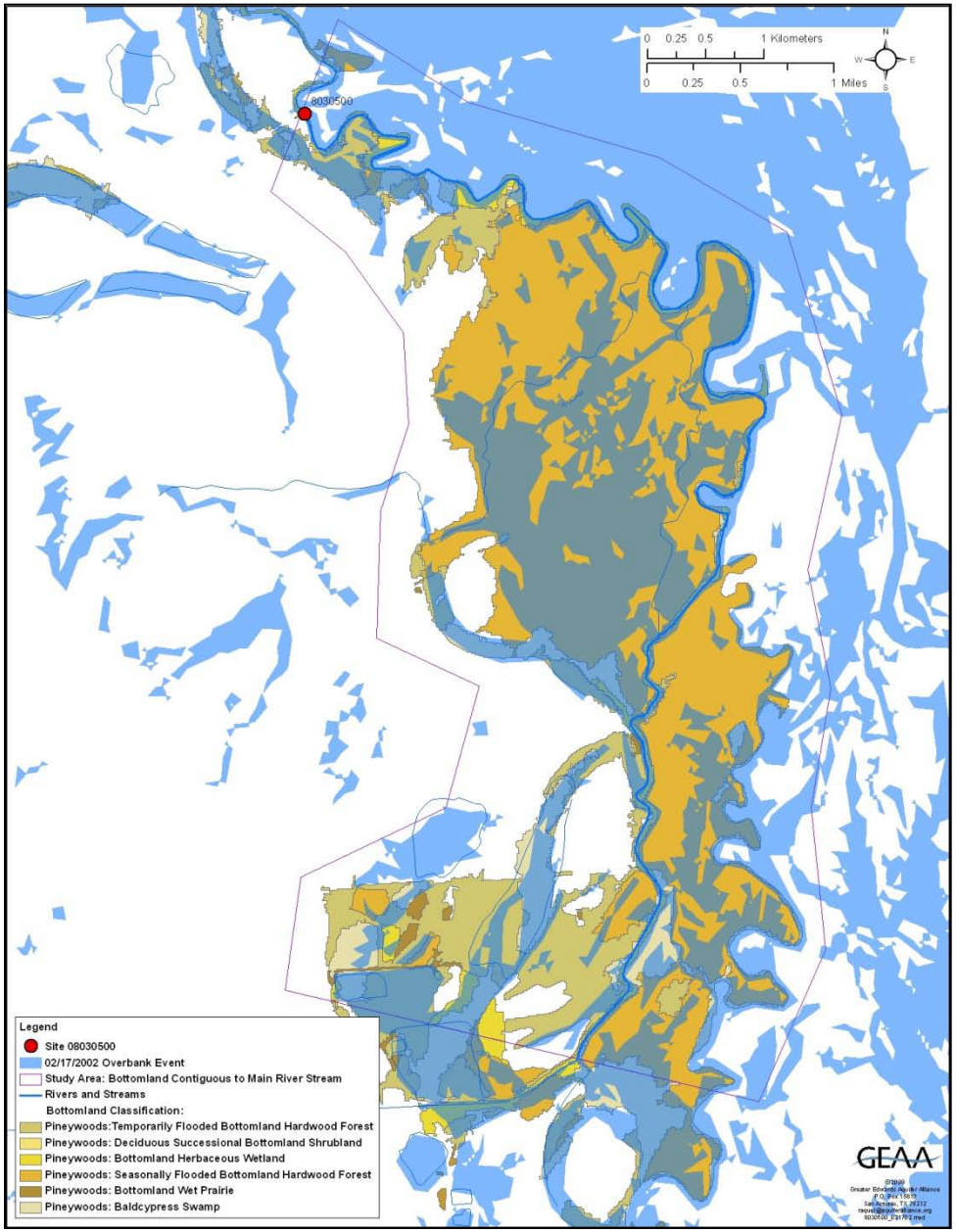




Sabine River at Ruliff-USGS Gage # 08030500
Overbank Event: 2/8/02-3/21/02

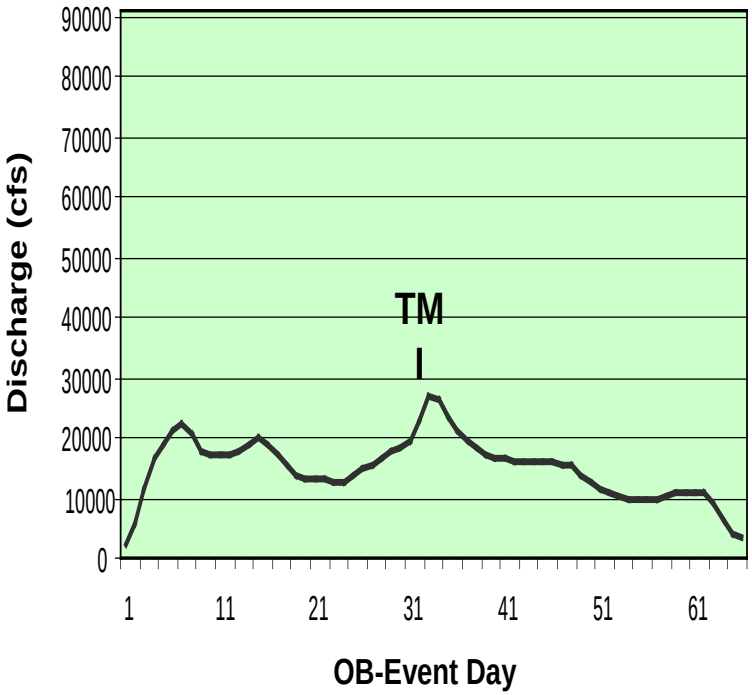
Out-of-Bank Threshold = 13,300 cfs								
TM Date	Mean Discharge (cfs)	Nearest Pre-TM Date Above Threshold	% BH Inudated	OB Event: Cumulative Discharge Volume (10^6 ac-ft)				
				Pre-TM 10d	Pre-TM 15d	Pre-TM 20d	Pre-TM 30d	Above-Threshold Days Prior to TM Date
2/17/02	**14,300**	2/17/02	**49.76%**	0.26	0.35	0.47	0.77	0.20

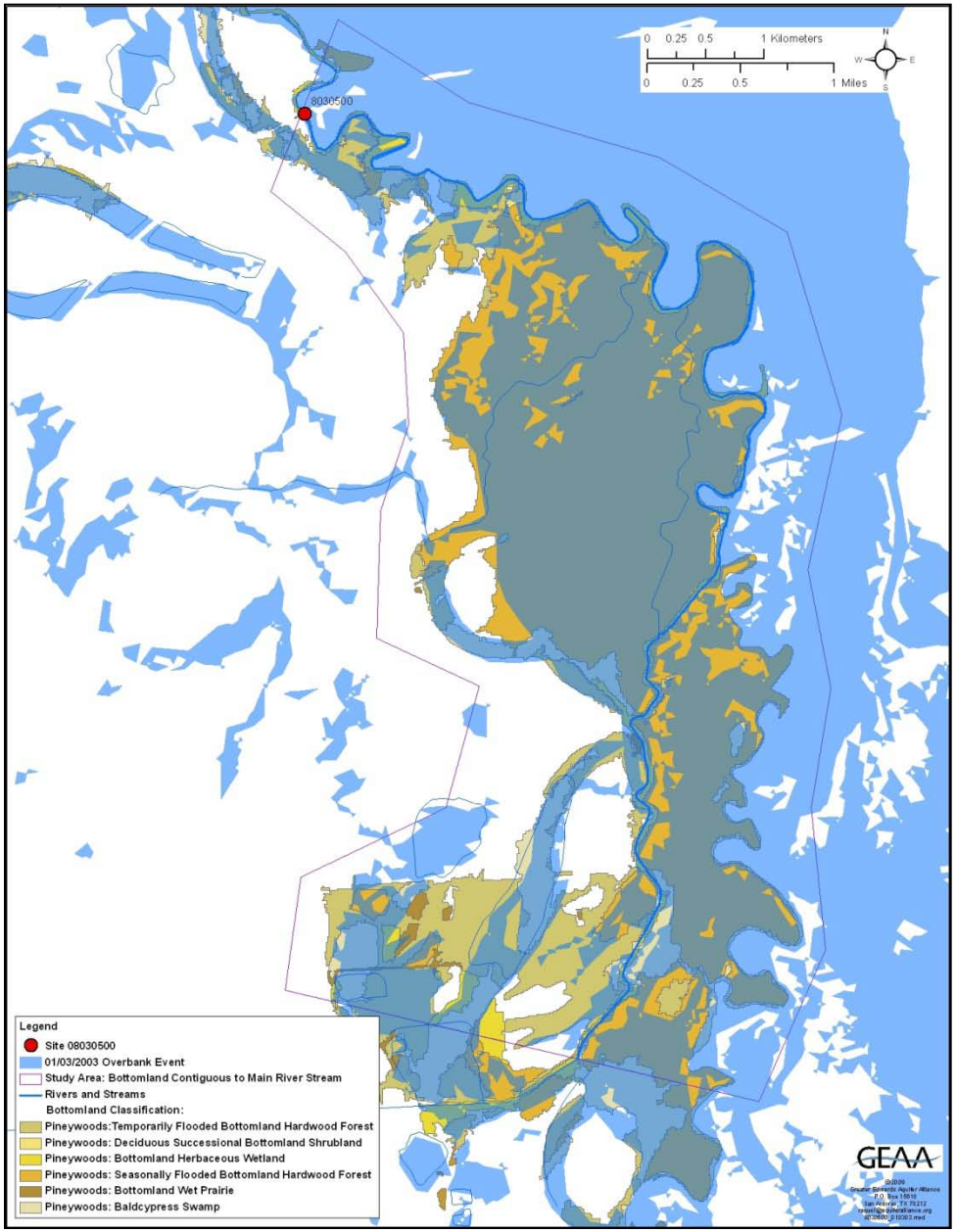




Sabine River at Ruliff-USGS Gage # 08030500
Overbank Event: 12/3/02-2/6/03

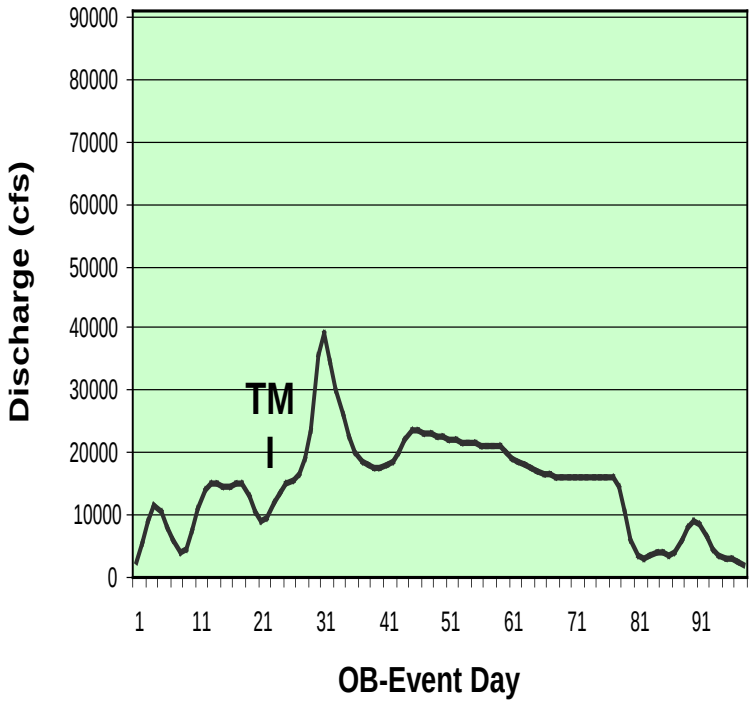
Out-of-Bank Threshold = 13,300 cfs								
TM Date	Mean Discharge (cfs)	Nearest Pre-TM Date Above Threshold	% BH Inudated	OB Event: Cumulative Discharge Volume (10^6 ac-ft)				
				Pre-TM 10d	Pre-TM 15d	Pre-TM 20d	Pre-TM 30d	Above-Threshold Days Prior to TM Date
1/3/03	**23,100**	1/3/03	**76.40%**	0.38	0.48	0.64	0.97	1.47

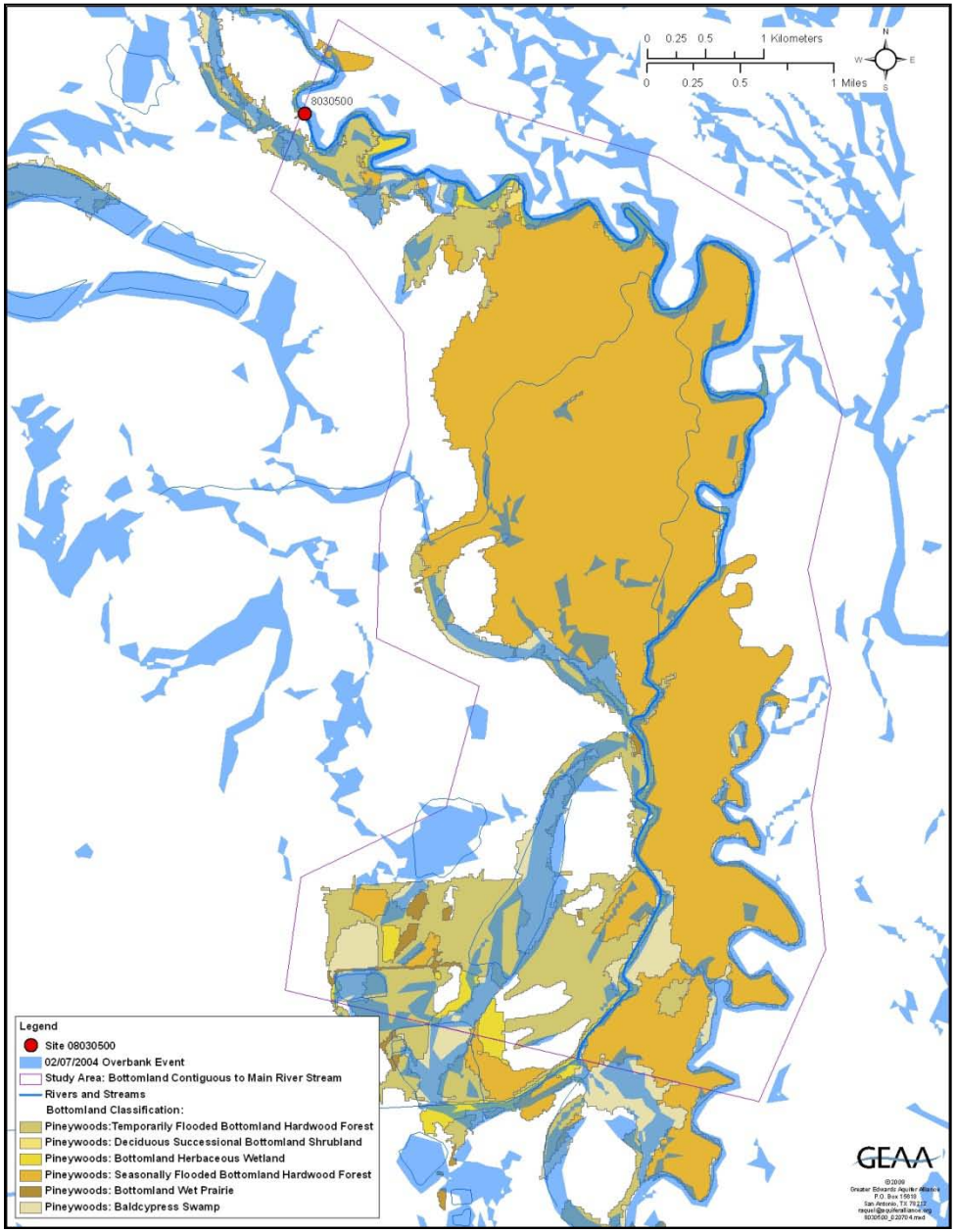




Sabine River at Ruliff-USGS Gage # 08030500
Overbank Event: 1/17/04-4/23/04

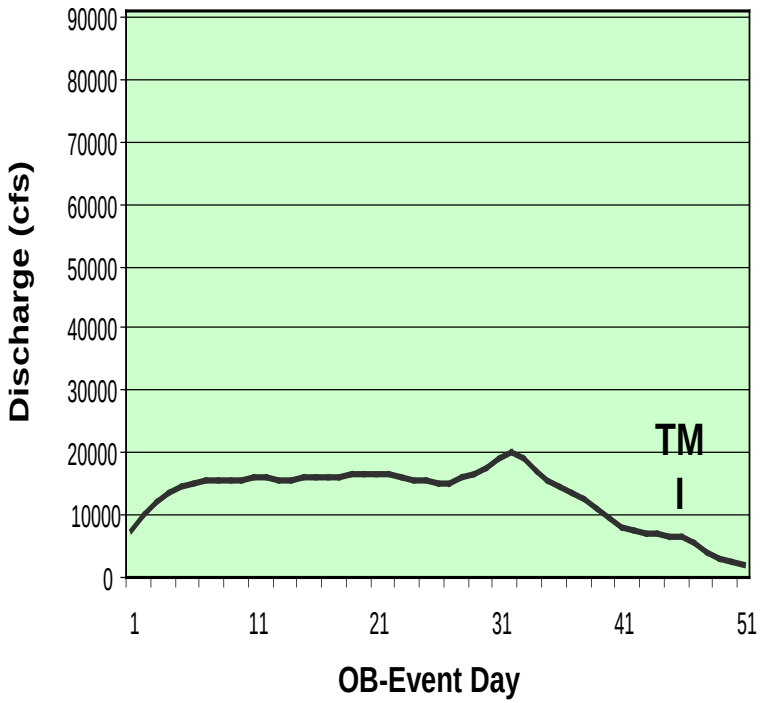
Out-of-Bank Threshold = 13,300 cfs								
TM Date	Mean Discharge (cfs)	Nearest Pre-TM Date Above Threshold	% BH Inudated	OB Event: Cumulative Discharge Volume (10^6 ac-ft)				
				Pre-TM 10d	Pre-TM 15d	Pre-TM 20d	Pre-TM 30d	Above-Threshold Days Prior to TM Date
2/7/04	**9,780**	2/3/04	**16.08%**	0.25	0.36	0.43	0.47	0.21

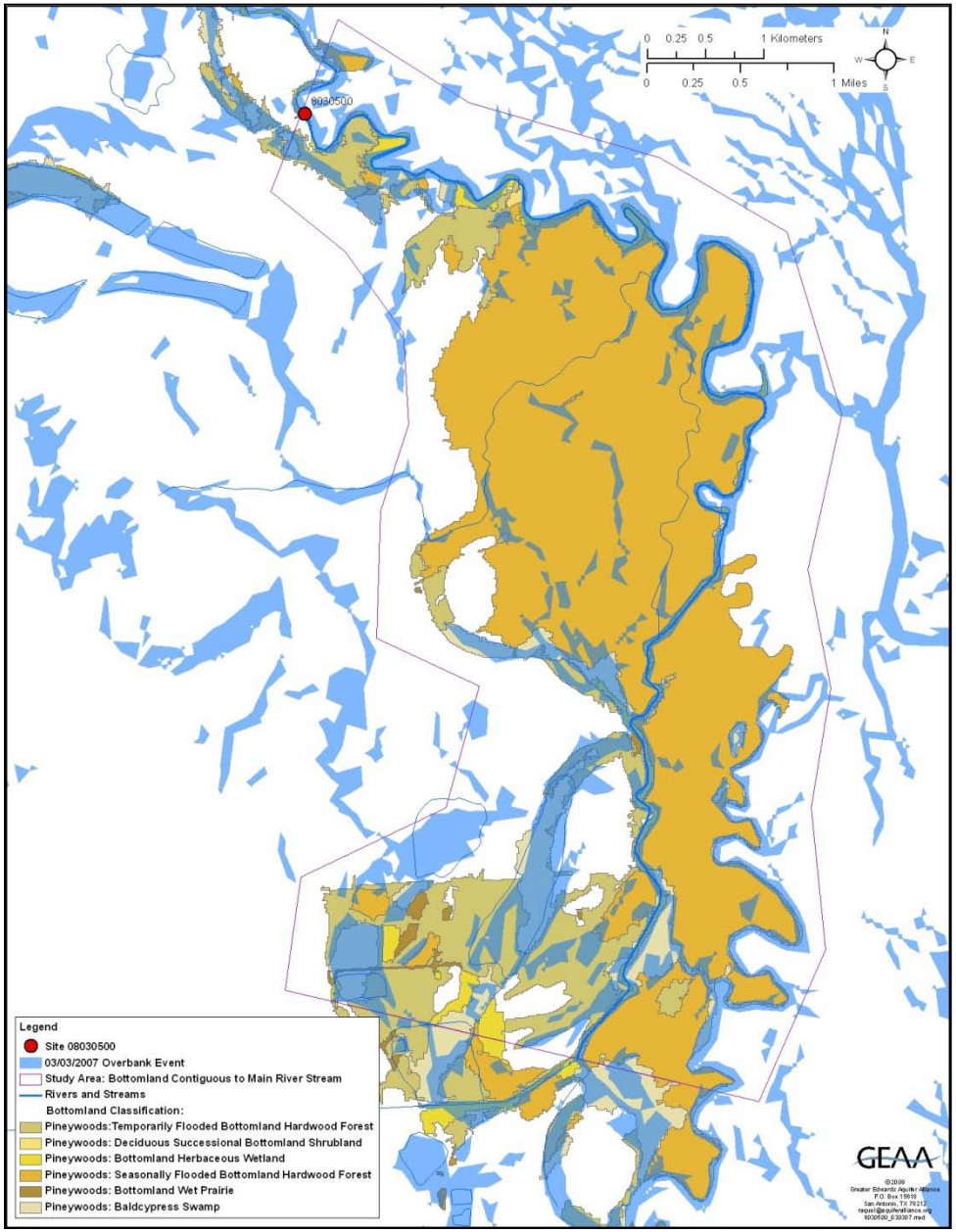




Sabine River at Ruliff-USGS Gage # 08030500
Overbank Event: 1/17/07-3/8/07

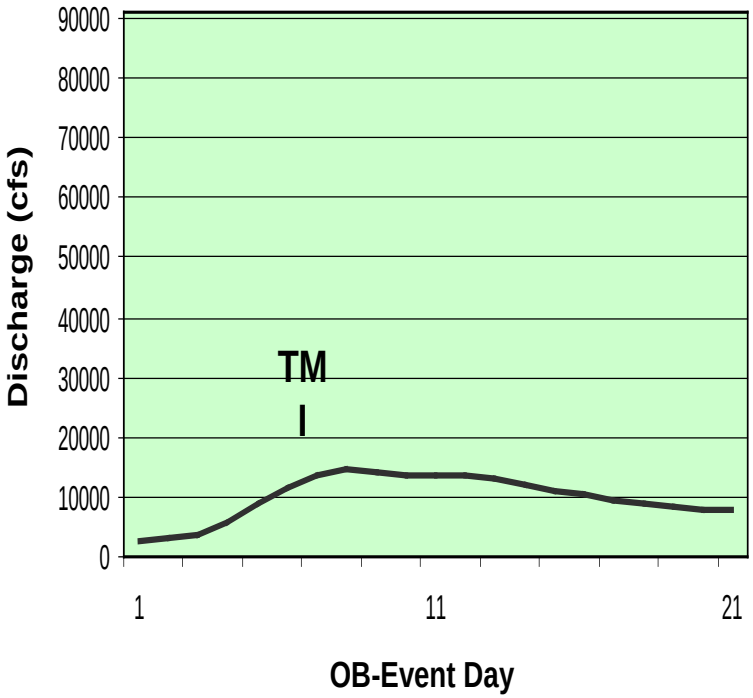
Out-of-Bank Threshold = 13,300 cfs								
TM Date	Mean Discharge (cfs)	Nearest Pre-TM Date Above Threshold	% BH Inudated	OB Event: Cumulative Discharge Volume (10^6 ac-ft)				
				Pre-TM 10d	Pre-TM 15d	Pre-TM 20d	Pre-TM 30d	Above-Threshold Days Prior to TM Date
3/3/07	**6,320**	2/22/07	**21.83%**	0.14	0.32	0.52	0.86	1.08

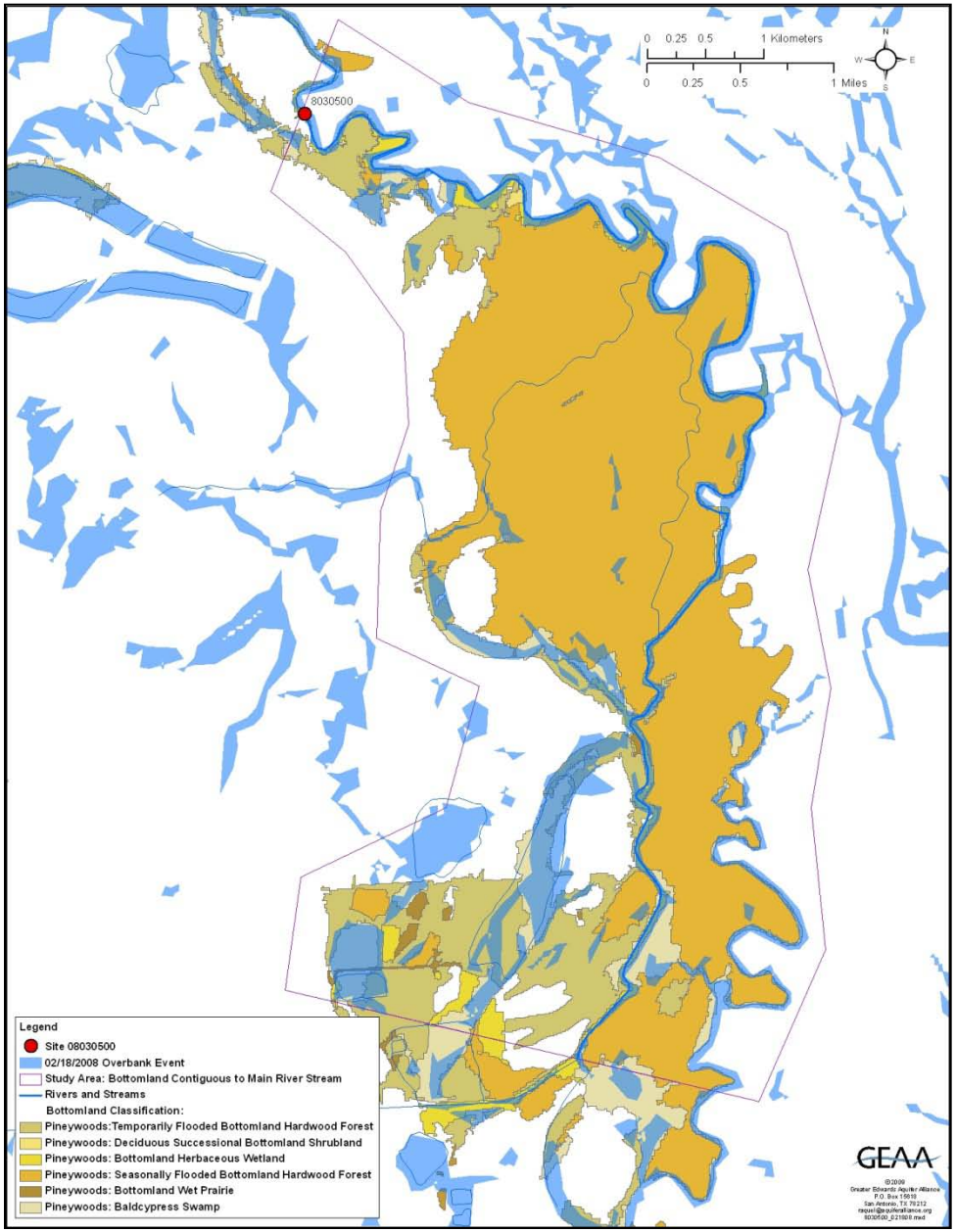




Sabine River at Ruliff-USGS Gage # 08030500
Overbank Event: 2/14/08-3/5/08

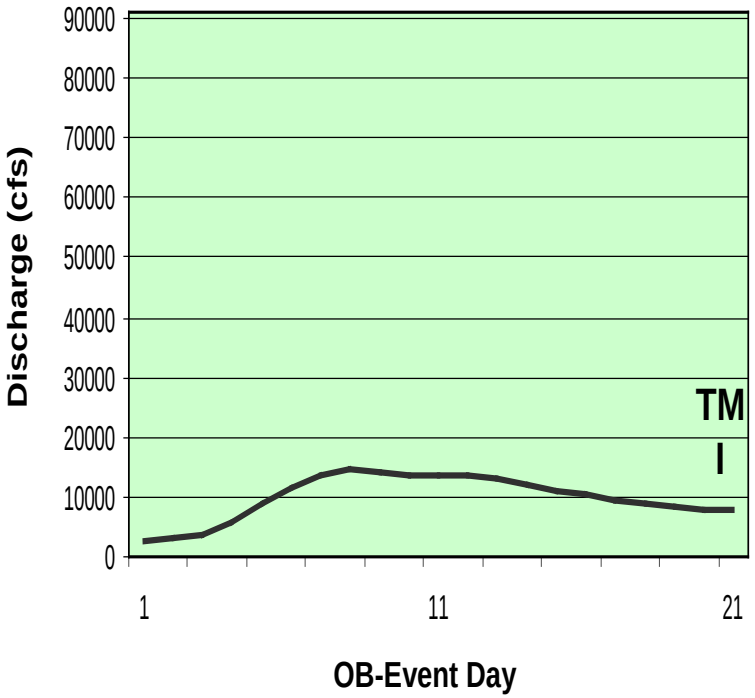
Out-of-Bank Threshold = 13,300 cfs								
TM Date	Mean Discharge (cfs)	Nearest Pre-TM Date Above Threshold	% BH Inudated	OB Event: Cumulative Discharge Volume (10^6 ac-ft)				
				Pre-TM 10d	Pre-TM 15d	Pre-TM 20d	Pre-TM 30d	Above-Threshold Days Prior to TM Date
2/18/08	**8,930**	9/19/07	**5.55%**	0.11	0.13	0.17	0.25	0.00

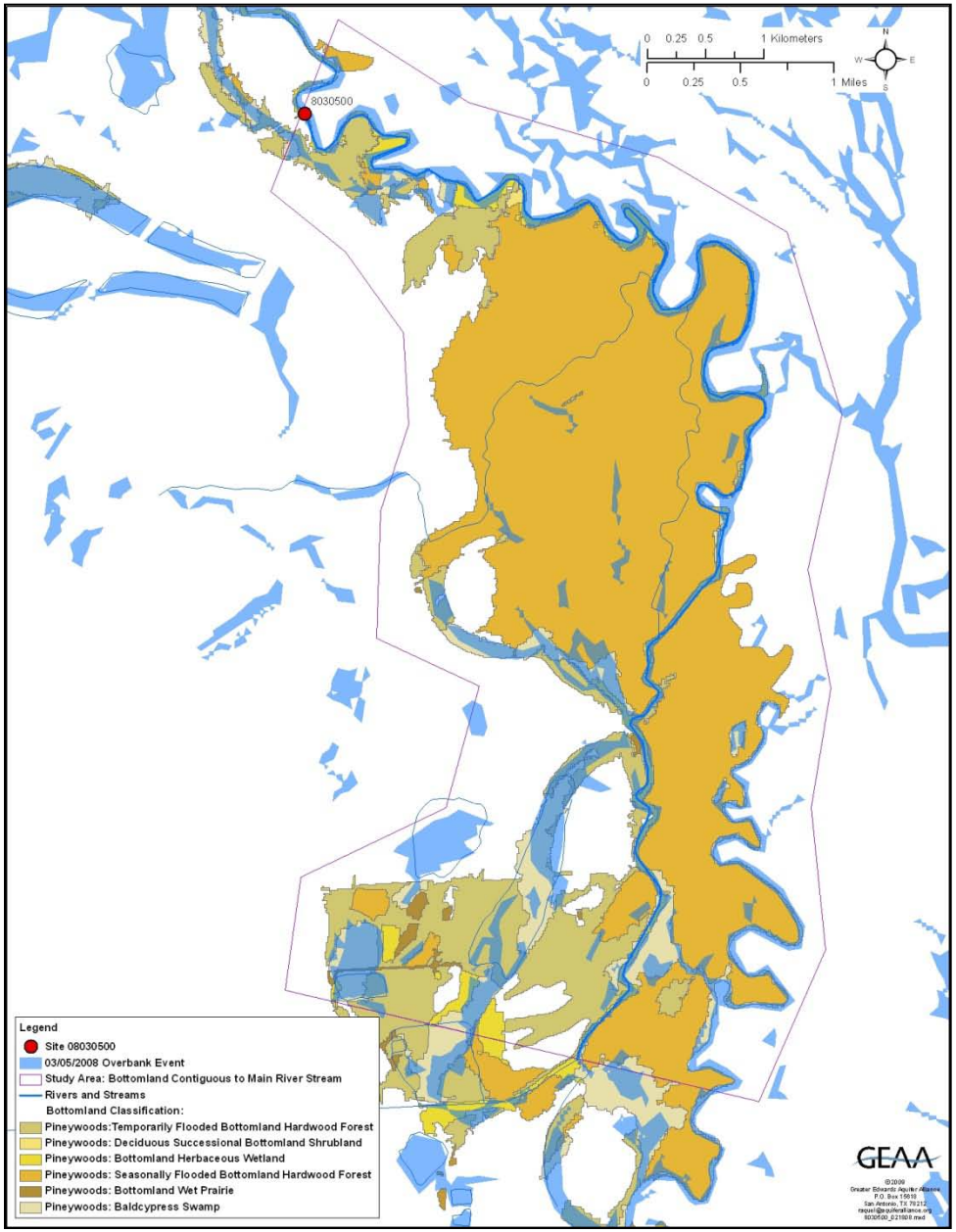




Sabine River at Ruliff-USGS Gage # 08030500
Overbank Event: 2/14/08-3/5/08

Out-of-Bank Threshold = 13,300 cfs								
TM Date	Mean Discharge (cfs)	Nearest Pre-TM Date Above Threshold	% BH Inudated	OB Event: Cumulative Discharge Volume (10^6 ac-ft)				
				Pre-TM 10d	Pre-TM 15d	Pre-TM 20d	Pre-TM 30d	Above-Threshold Days Prior to TM Date
3/5/08	**7,920**	2/25/08	**13.98%**	0.17	0.33	0.41	0.46	0.16





Neches River at Neches
USGS Gage # 08032000

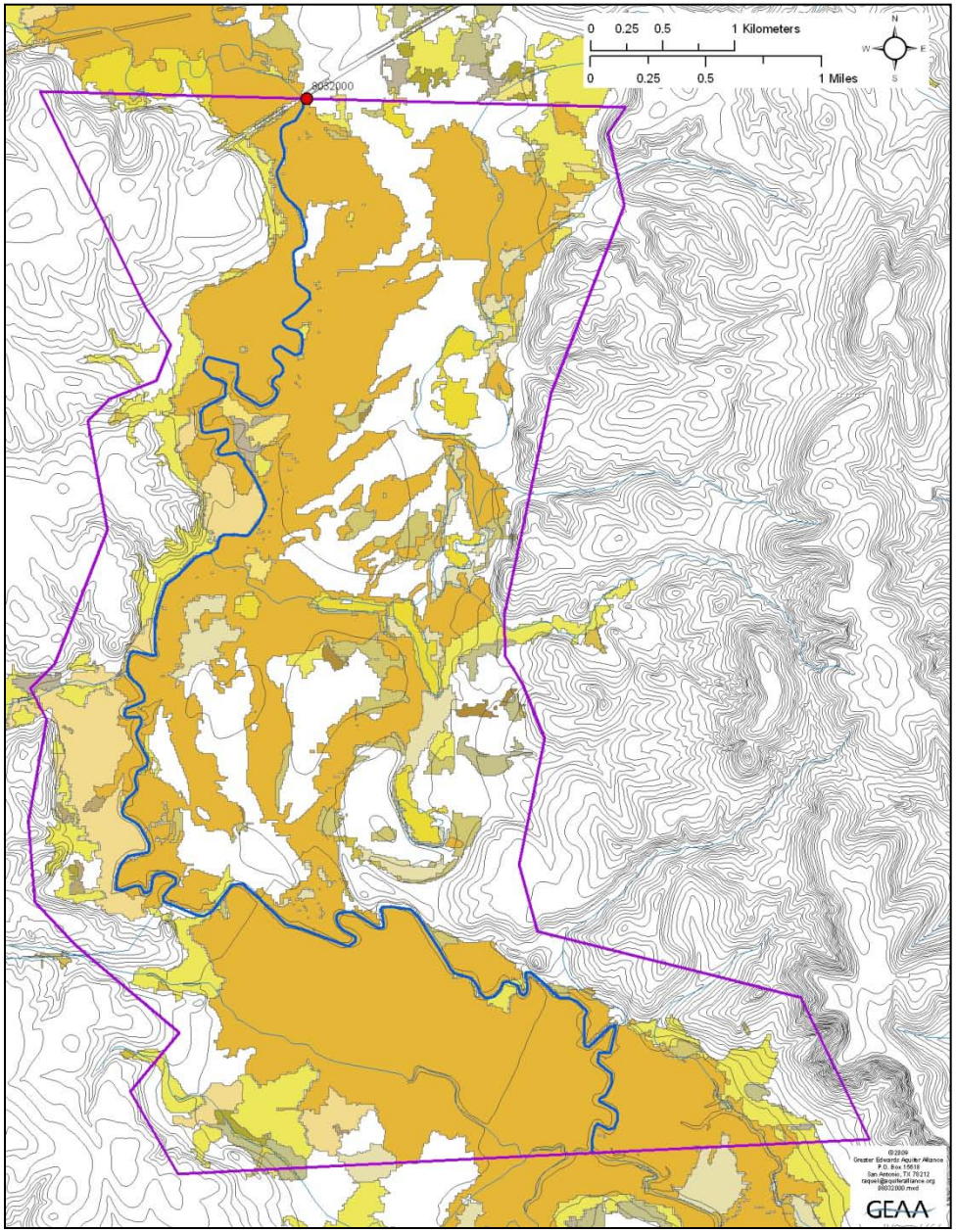
Bottomland Hardwoods
Environmental Inflows
Study Area

Legend

- Site 08032000
- Study Area: Bottomlands Contiguous to Main River Stem
- Rivers and Streams
- Elevation Contours in 5-foot Intervals

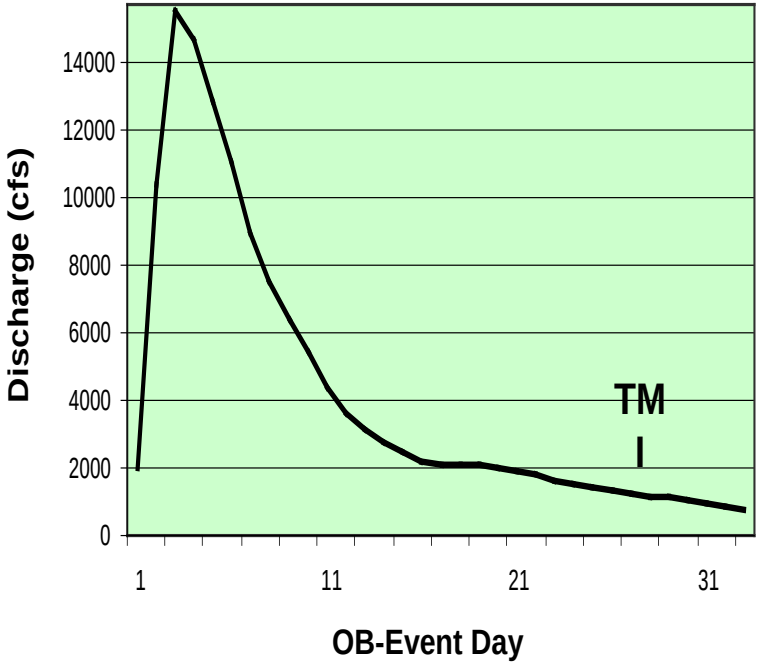
Bottomland Classification:

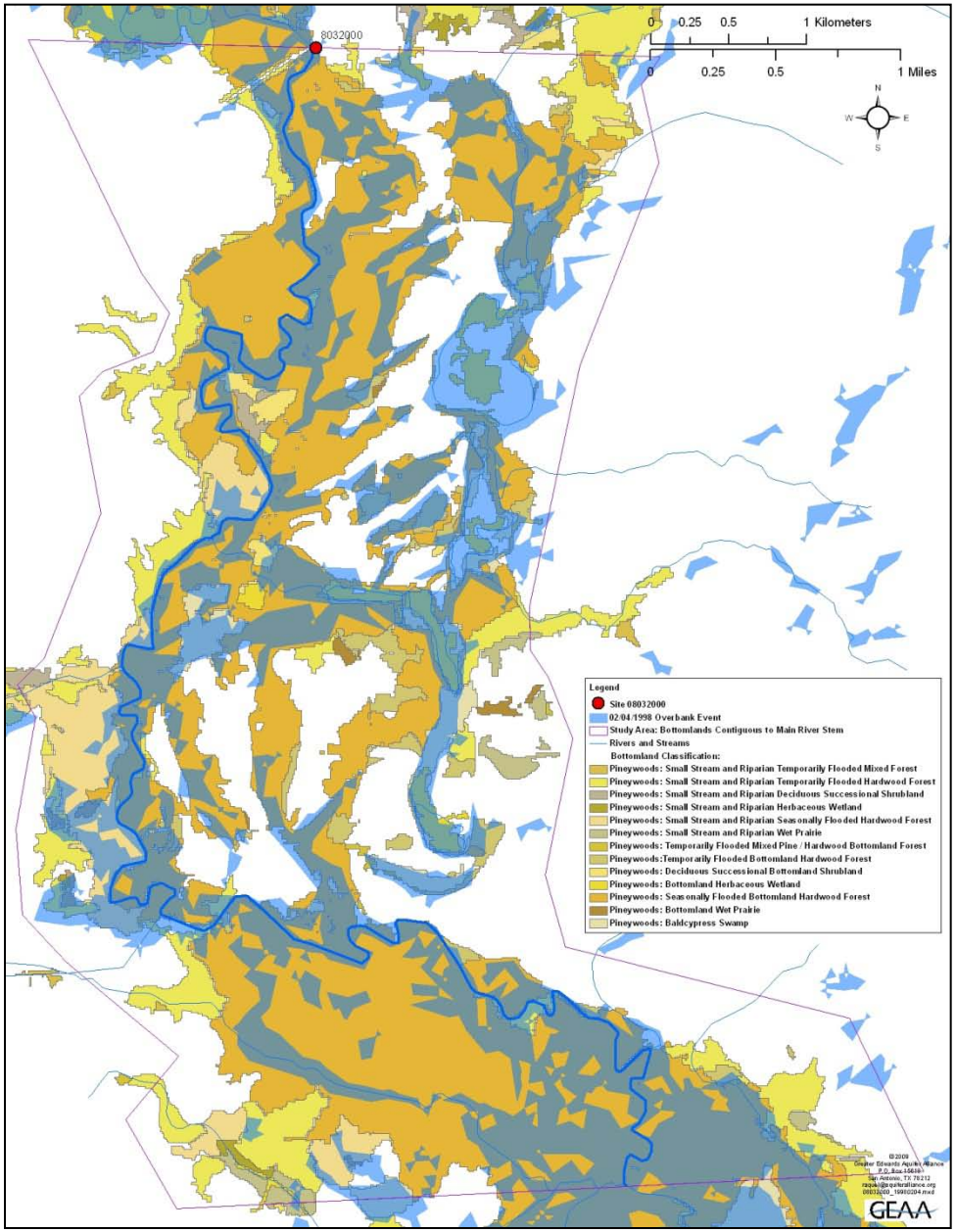
- Pineywoods: Small Stream and Riparian Temporarily Flooded Mixed Forest
- Pineywoods: Small Stream and Riparian Temporarily Flooded Hardwood Forest
- Pineywoods: Small Stream and Riparian Deciduous Successional Shrubland
- Pineywoods: Small Stream and Riparian Herbaceous Wetland
- Pineywoods: Small Stream and Riparian Seasonally Flooded Hardwood Forest
- Pineywoods: Small Stream and Riparian Wet Prairie
- Pineywoods: Small Stream and Riparian Baldcypress Swamp
- Pineywoods: Temporarily Flooded Mixed Pine / Hardwood Bottomland Forest
- Pineywoods:Temporarily Flooded Bottomland Hardwood Forest
- Pineywoods: Deciduous Successional Bottomland Shrubland
- Pineywoods: Bottomland Herbaceous Wetland
- Pineywoods: Seasonally Flooded Bottomland Hardwood Forest
- Pineywoods: Bottomland Wet Prairie
- Pineywoods: Baldcypress Swamp



Neches River at Neches-USGS Gage # 08032000
Overbank Event: 1/7/98-2/8/98

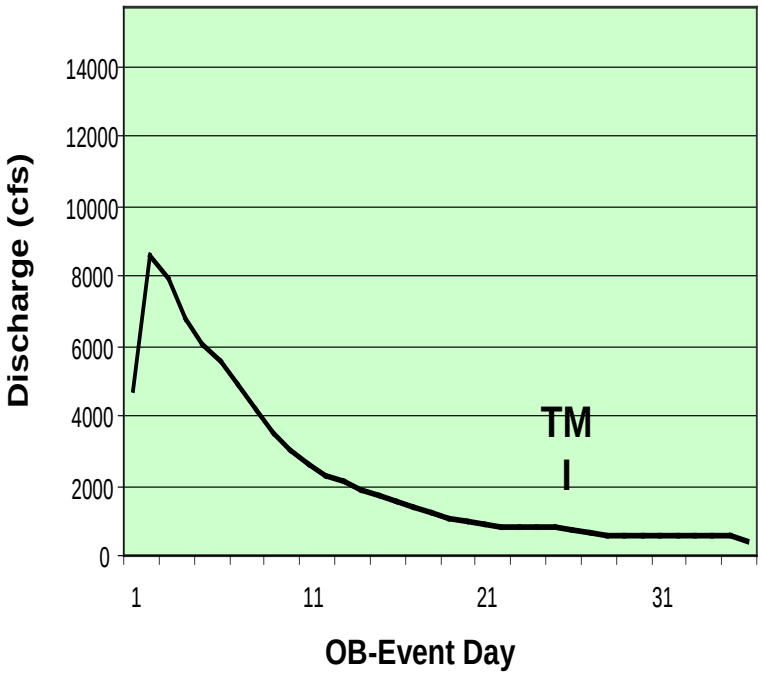
Out-of-Bank Threshold = 4,700 cfs								
TM Date	Mean Discharge (cfs)	Nearest Pre-TM Date Above Threshold	% BH Inudated	OB Event: Cumulative Discharge Volume (10^6 ac-ft)				
				Pre-TM 10d	Pre-TM 15d	Pre-TM 20d	Pre-TM 30d	Above-Threshold Days Prior to TM Date
2/4/98	**1,100**	1/16/98	**43.71%**	0.03	0.27	0.09	0.27	0.18

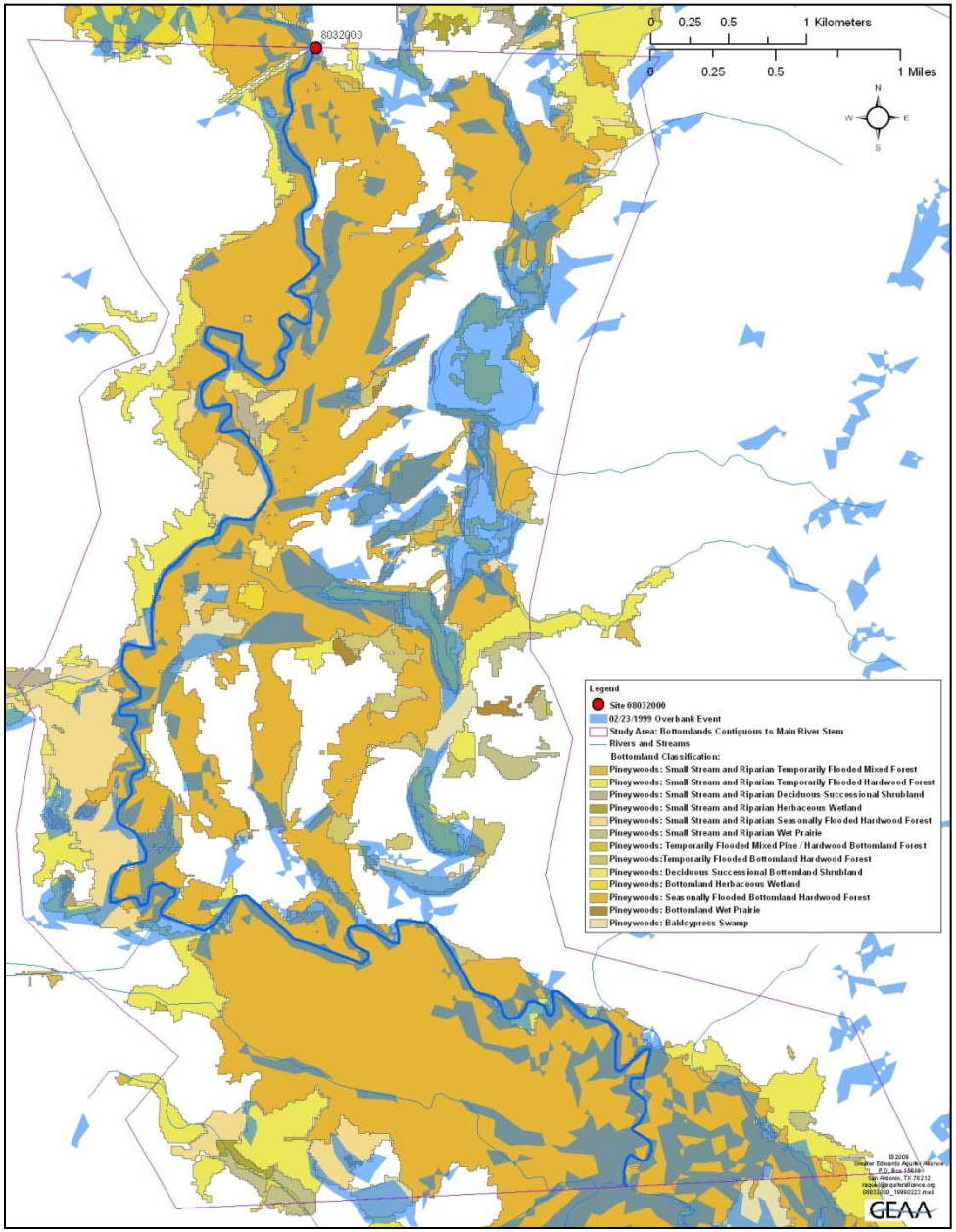




Neches River at Neches-USGS Gage # 08032000
Overbank Event: 1/29/99-3/5/99

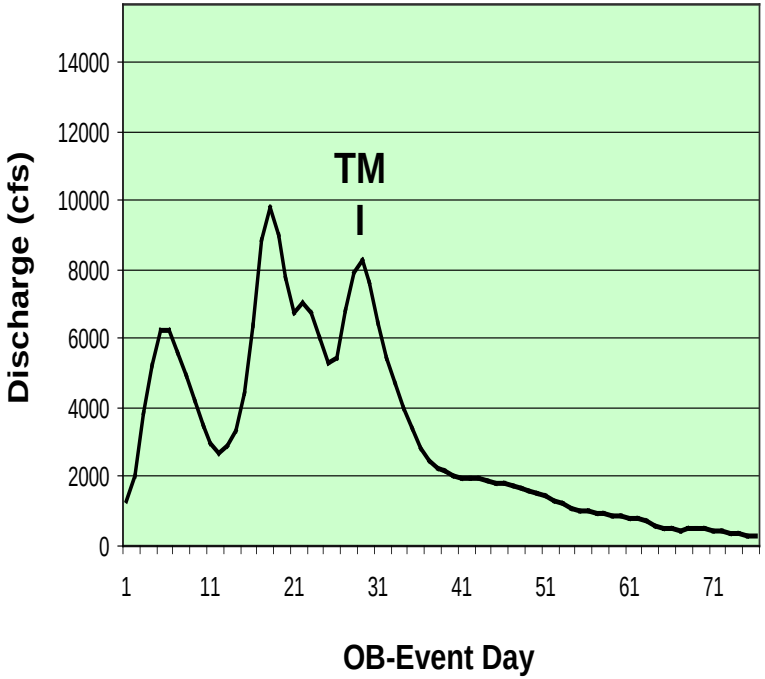
Out-of-Bank Threshold = 4,700 cfs								
TM Date	Mean Discharge (cfs)	Nearest Pre-TM Date Above Threshold	% BH Inudated	OB Event: Cumulative Discharge Volume (10^6 ac-ft)				
				Pre-TM 10d	Pre-TM 15d	Pre-TM 20d	Pre-TM 30d	Above-Threshold Days Prior to TM Date
2/23/99	**713**	2/4/99	**24.17%**	0.02	0.04	0.07	0.16	0.09

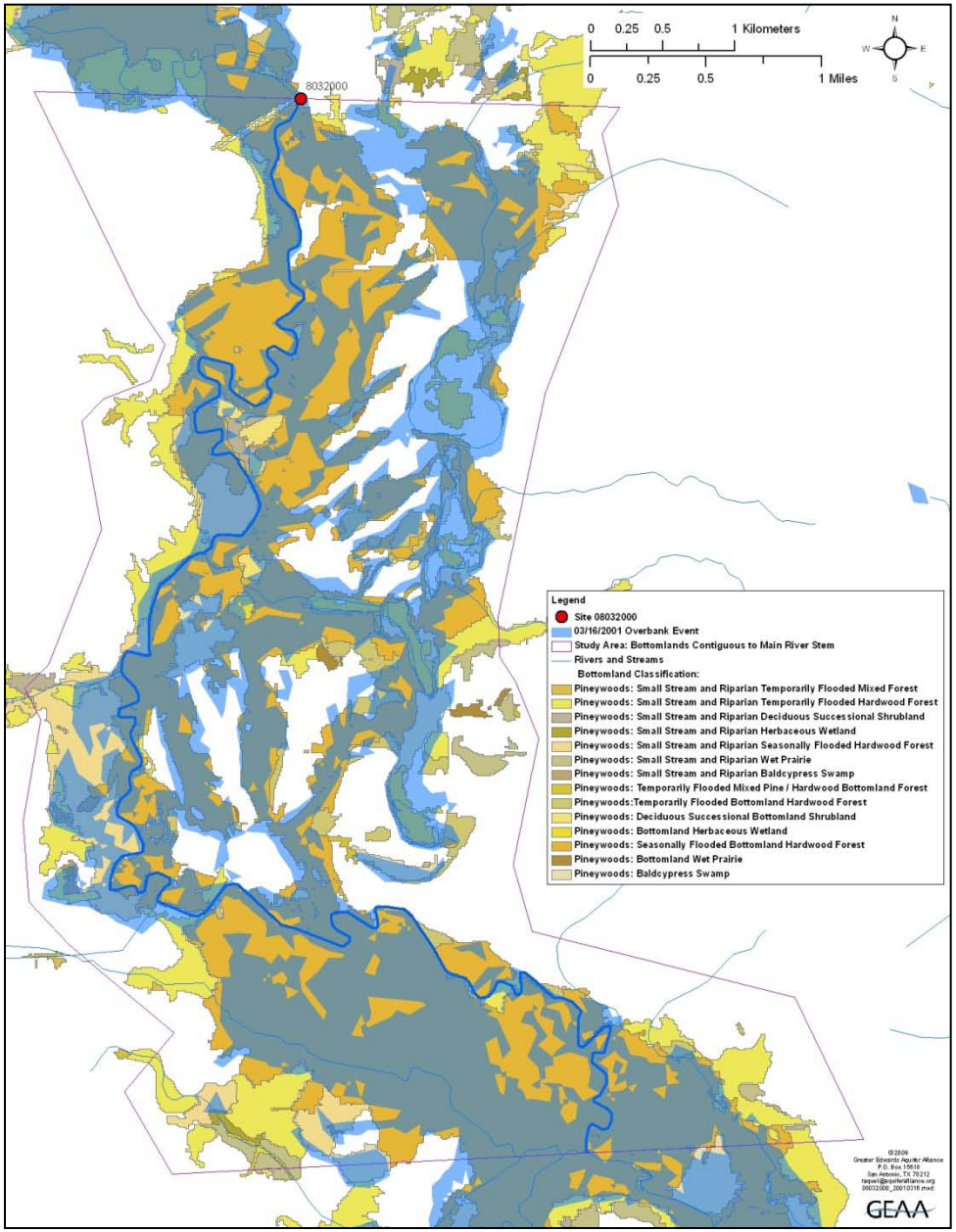




Neches River at Neches-USGS Gage # 08032000
Overbank Event: 2/16/01-5/2/01

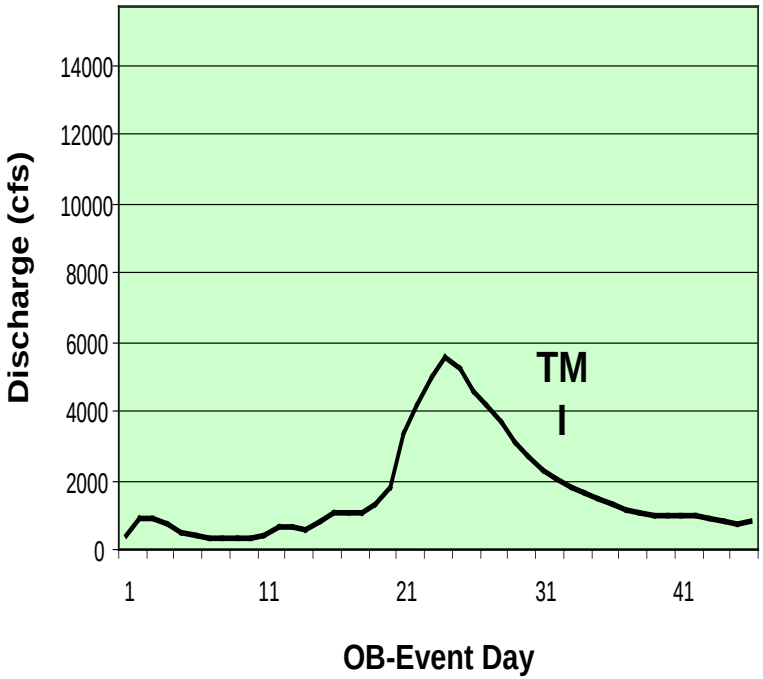
Out-of-Bank Threshold = 4,700 cfs								
TM Date	Mean Discharge (cfs)	Nearest Pre-TM Date Above Threshold	% BH Inudated	OB Event: Cumulative Discharge Volume (10^6 ac-ft)				
				Pre-TM 10d	Pre-TM 15d	Pre-TM 20d	Pre-TM 30d	Above-Threshold Days Prior to TM Date
3/16/01	**8,250**	3/16/01	**61.00%**	0.14	0.21	0.24	0.32	0.26

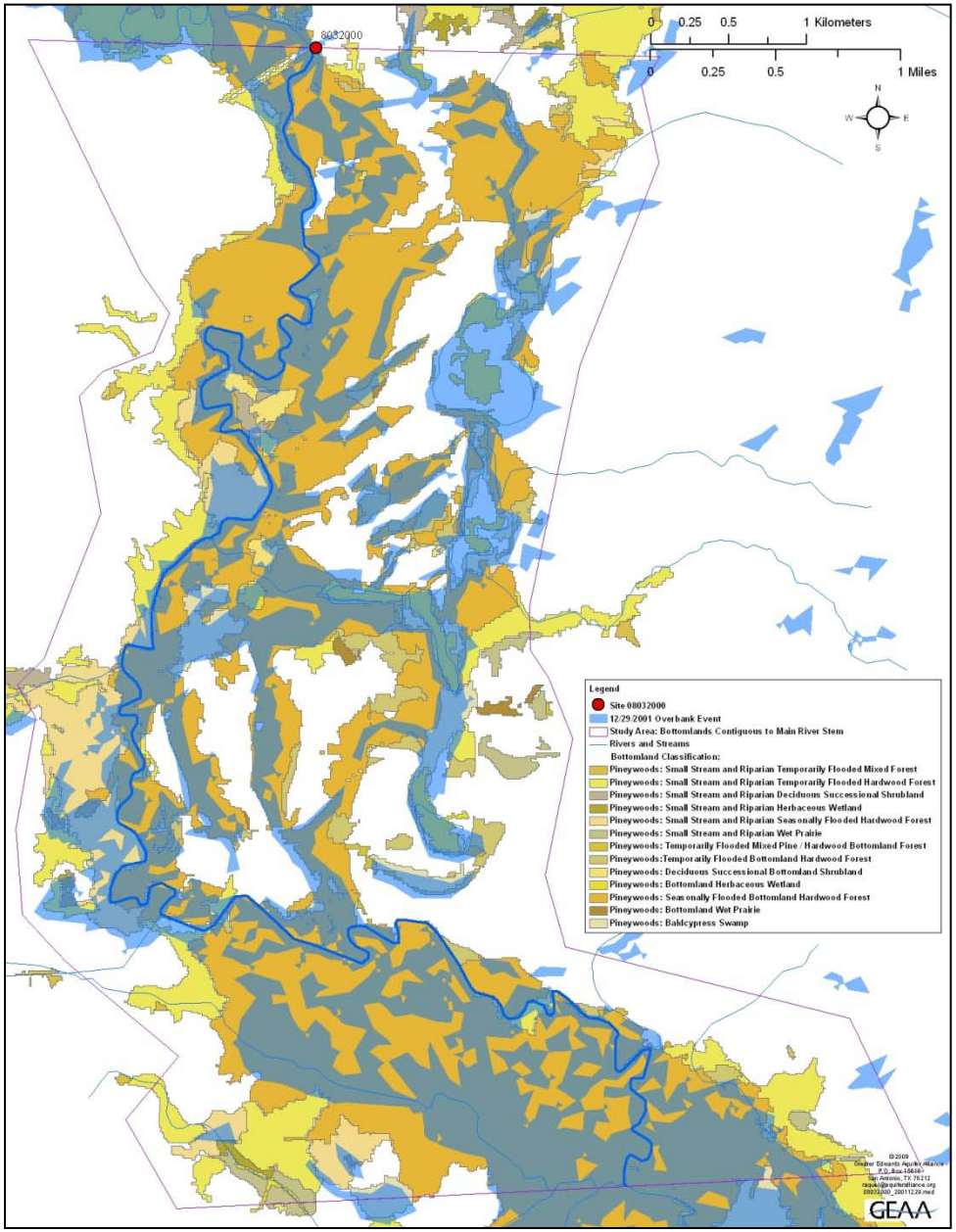




Neches River at Neches-USGS Gage # 08032000
Overbank Event: 11/28/01-1/12/02

Out-of-Bank Threshold = 4,700 cfs								
TM Date	Mean Discharge (cfs)	Nearest Pre-TM Date Above Threshold	% BH Inudated	OB Event: Cumulative Discharge Volume (10^6 ac-ft)				
				Pre-TM 10d	Pre-TM 15d	Pre-TM 20d	Pre-TM 30d	Above-Threshold Days Prior to TM Date
12/29/01	**2,020**	12/22/01	**46.80%**	0.08	0.10	0.11	0.12	0.04





Neches River at Evadale
USGS Gage # 08041000

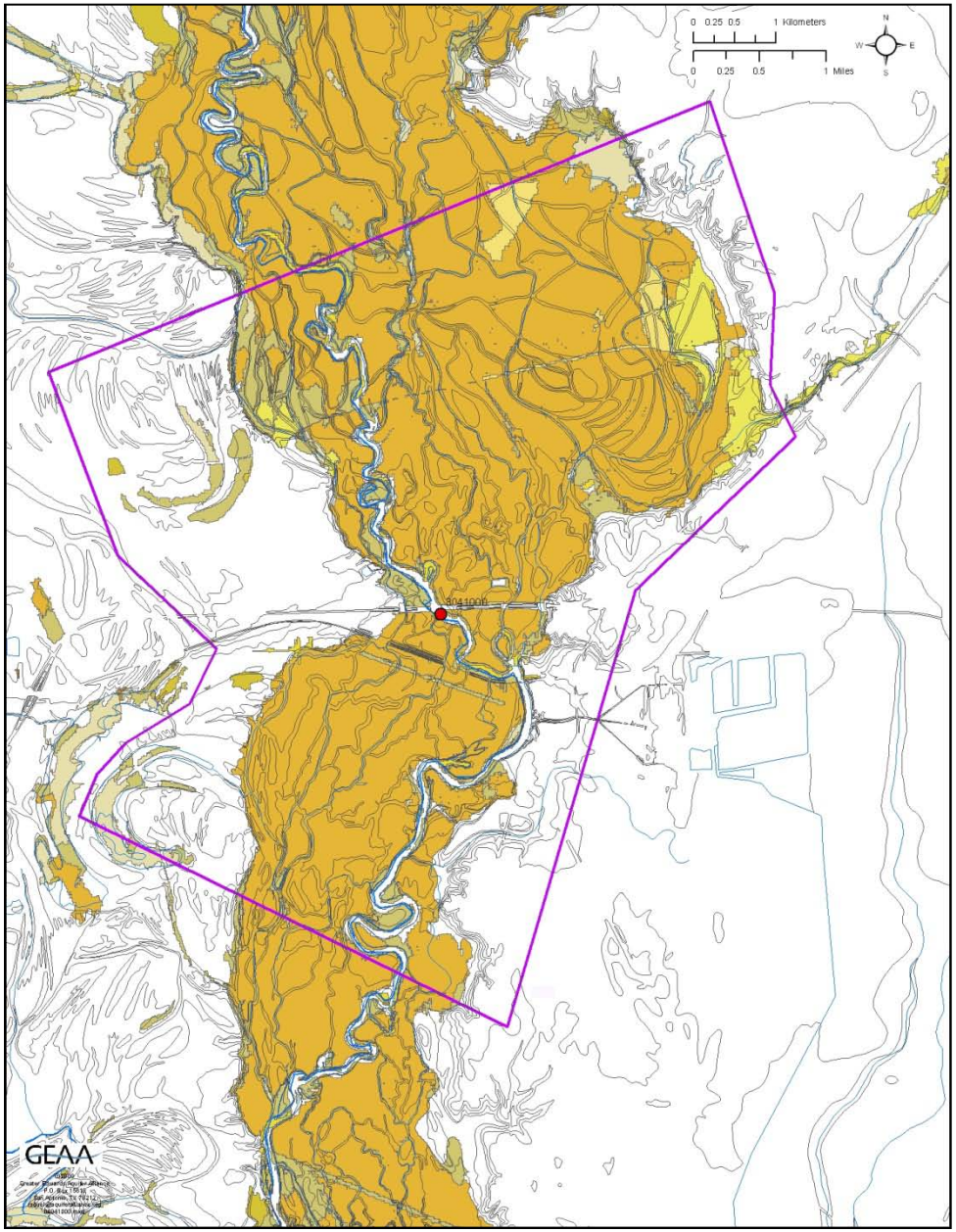
Bottomland Hardwoods
Environmental Inflows
Study Area

Legend

- Site 08041000
- Study Area: Bottomland Contiguous to Main River Stem
- Rivers and Streams
- Elevation Contours at 5-foot Intervals

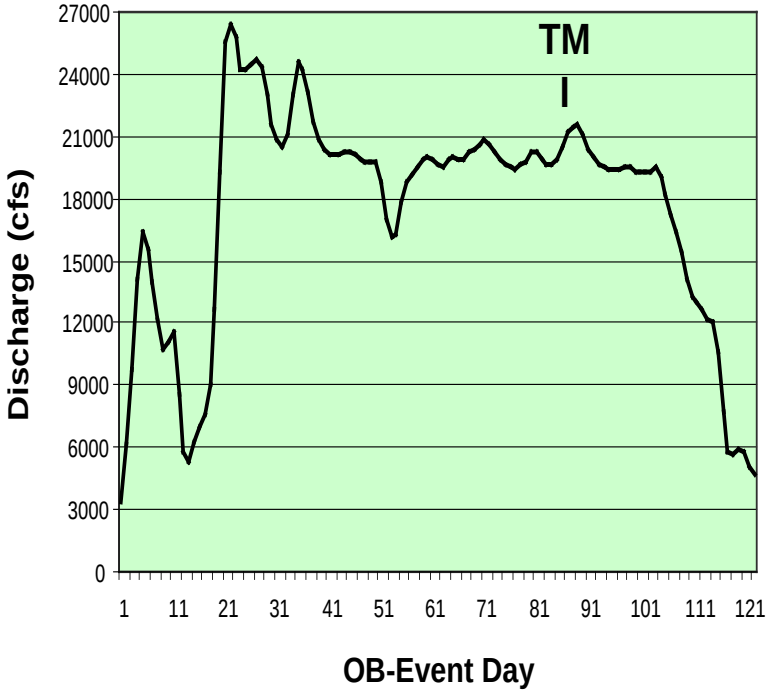
Bottomlands Classification:

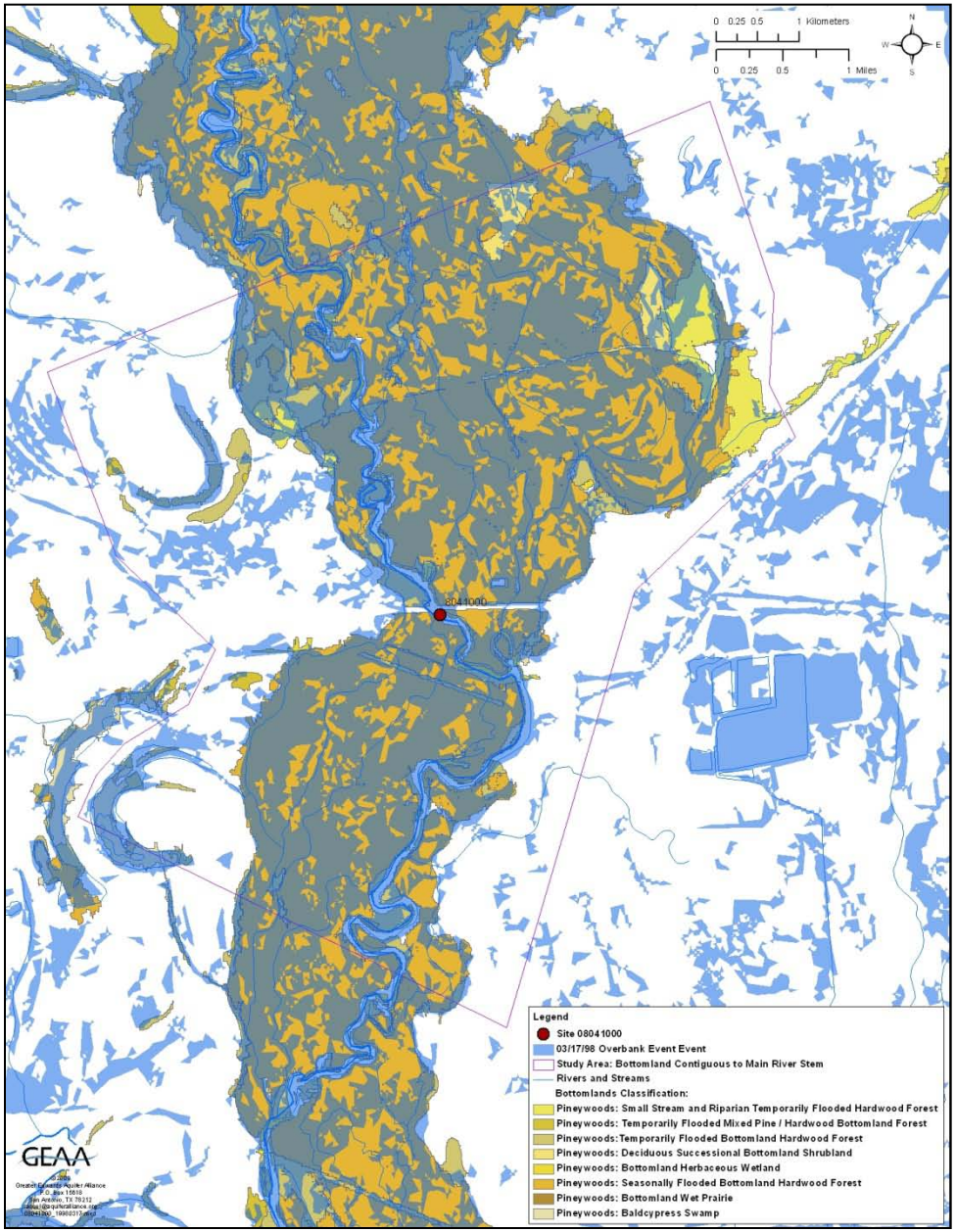
- Pineywoods: Small Stream and Riparian Temporarily Flooded Hardwood Forest
- Pineywoods: Temporarily Flooded Mixed Pine / Hardwood Bottomland Forest
- Pineywoods:Temporarily Flooded Bottomland Hardwood Forest
- Pineywoods: Deciduous Successional Bottomland Shrubland
- Pineywoods: Bottomland Herbaceous Wetland
- Pineywoods: Seasonally Flooded Bottomland Hardwood Forest
- Pineywoods: Bottomland Wet Prairie
- Pineywoods: Baldcypress Swamp



Neches River at Evadale-USGS Gage # 08041000
Overbank Event: 12/21/97-4/22/98

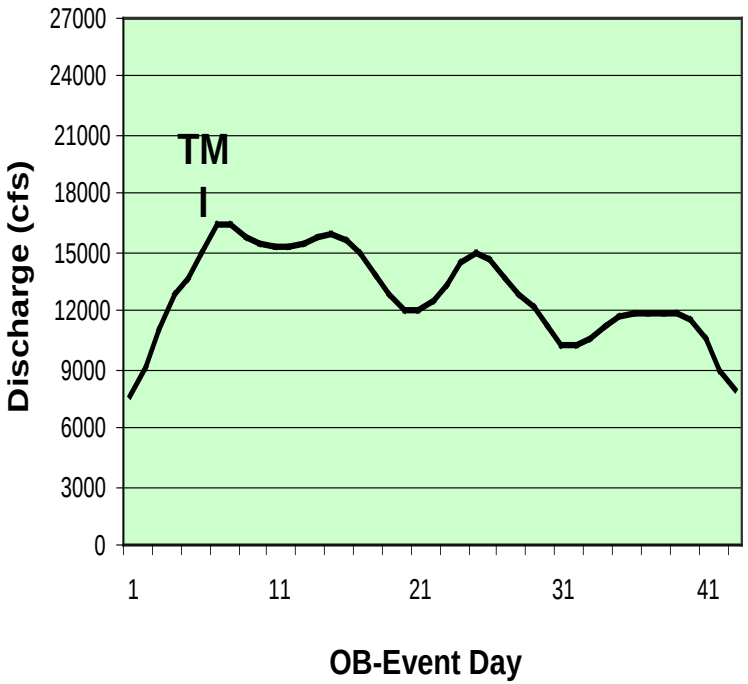
Out-of-Bank Threshold = 14,200 cfs								
TM Date	Mean Discharge (cfs)	Nearest Pre-TM Date Above Threshold	% BH Inudated	OB Event: Cumulative Discharge Volume (10^6 ac-ft)				
				Pre-TM 10d	Pre-TM 15d	Pre-TM 20d	Pre-TM 30d	Above-Threshold Days Prior to TM Date
3/17/98	**21,200**	3/17/98	**67.53%**	0.39	0.59	0.80	1.19	2.86

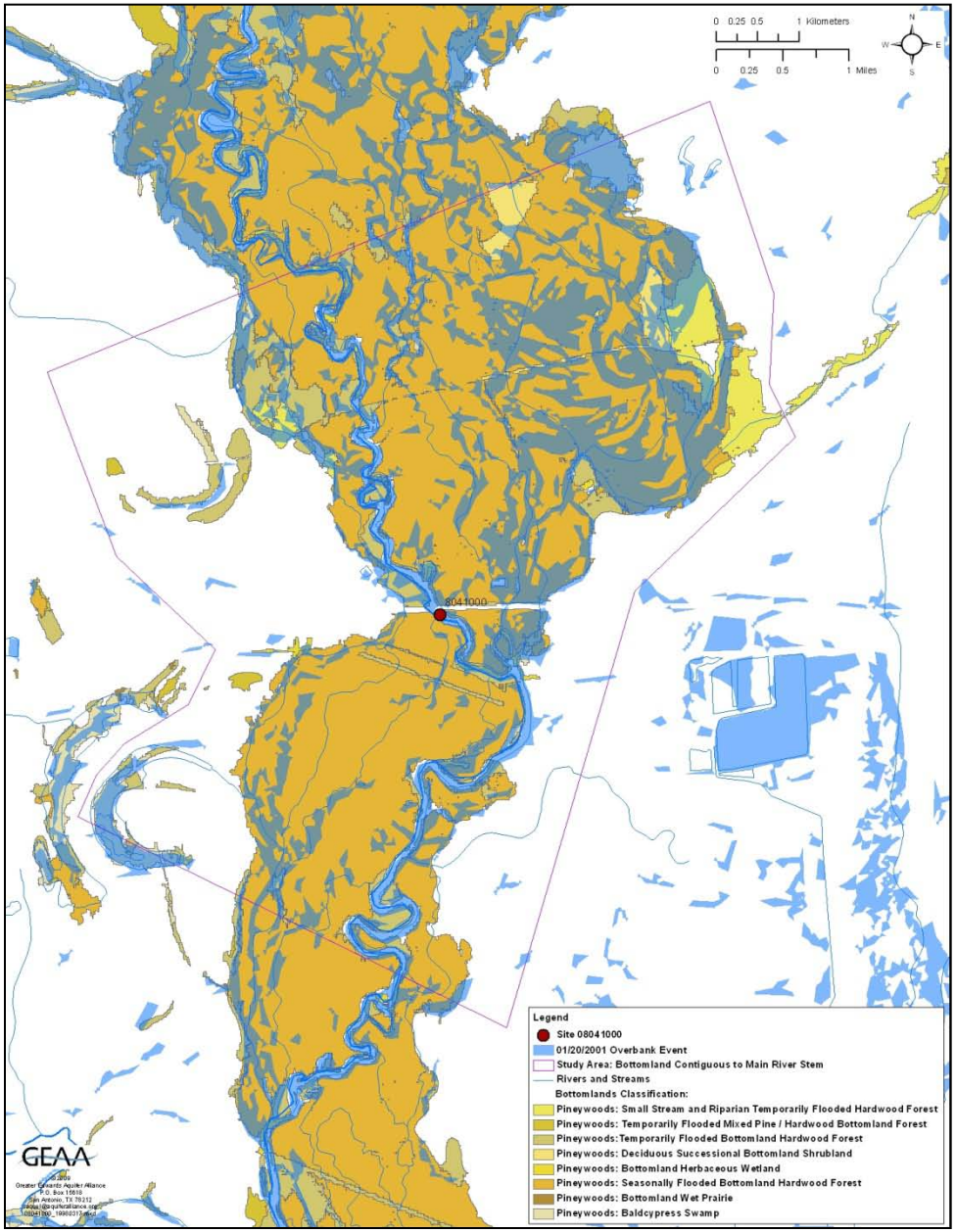




Neches River at Evadale-USGS Gage # 08041000
Overbank Event: 1/16/01-2/27/01

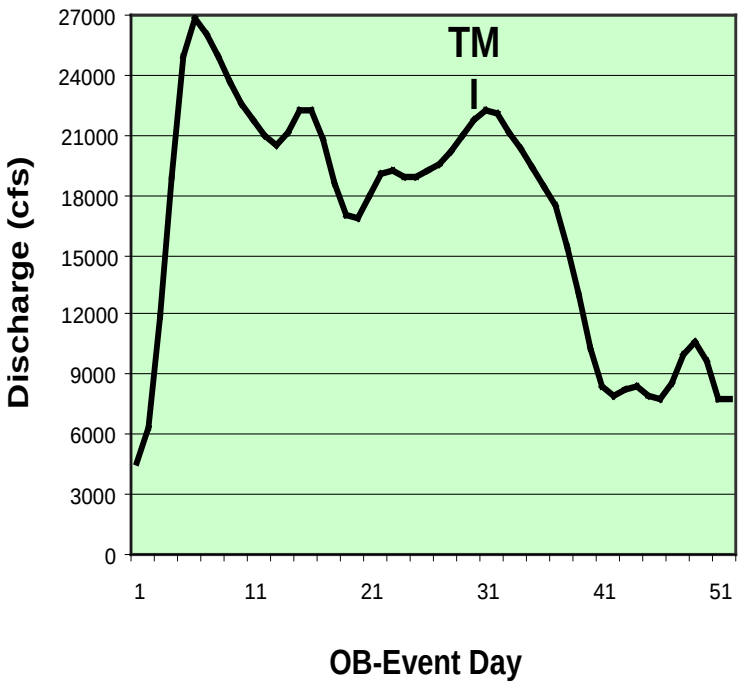
Out-of-Bank Threshold = 14,200 cfs								
TM Date	Mean Discharge (cfs)	Nearest Pre-TM Date Above Threshold	% BH Inudated	OB Event: Cumulative Discharge Volume (10^6 ac-ft)				
				Pre-TM 10d	Pre-TM 15d	Pre-TM 20d	Pre-TM 30d	Above-Threshold Days Prior to TM Date
1/20/01	**13,700**	4/27/99	**32.18%**	0.16	0.27	0.37	0.49	0.00

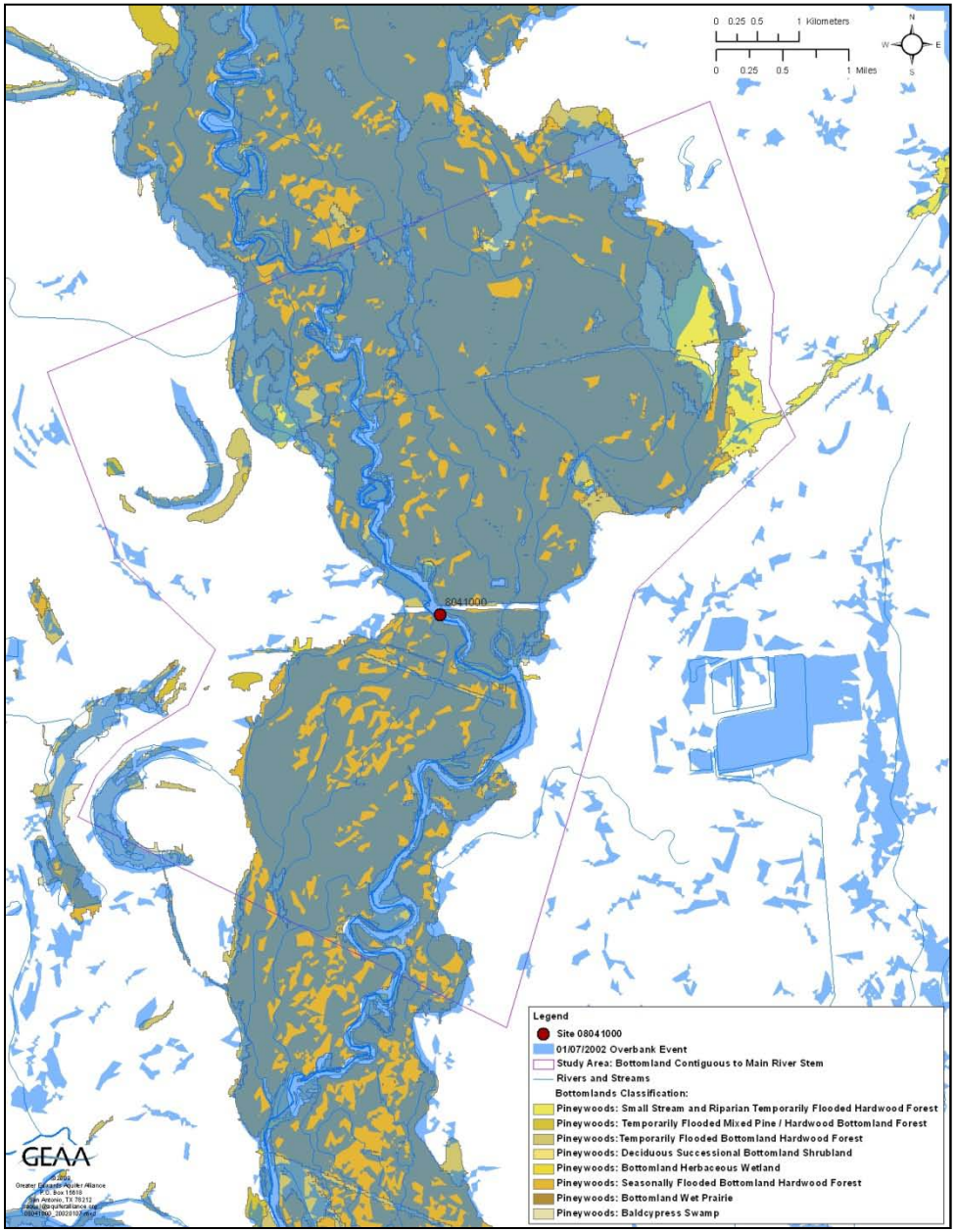




Neches River at Evadale-USGS Gage # 08041000
Overbank Event: 12/12/01-2/1/02

Out-of-Bank Threshold = 14,200 cfs								
TM Date	Mean Discharge (cfs)	Nearest Pre-TM Date Above Threshold	% BH Inudated	OB Event: Cumulative Discharge Volume (10^6 ac-ft)				
				Pre-TM 10d	Pre-TM 15d	Pre-TM 20d	Pre-TM 30d	Above-Threshold Days Prior to TM Date
1/7/02	**19,500**	1/7/02	**85.04%**	0.37	0.58	0.82	1.03	1.00





Angelina River at Alto
USGS Gage # 08036500

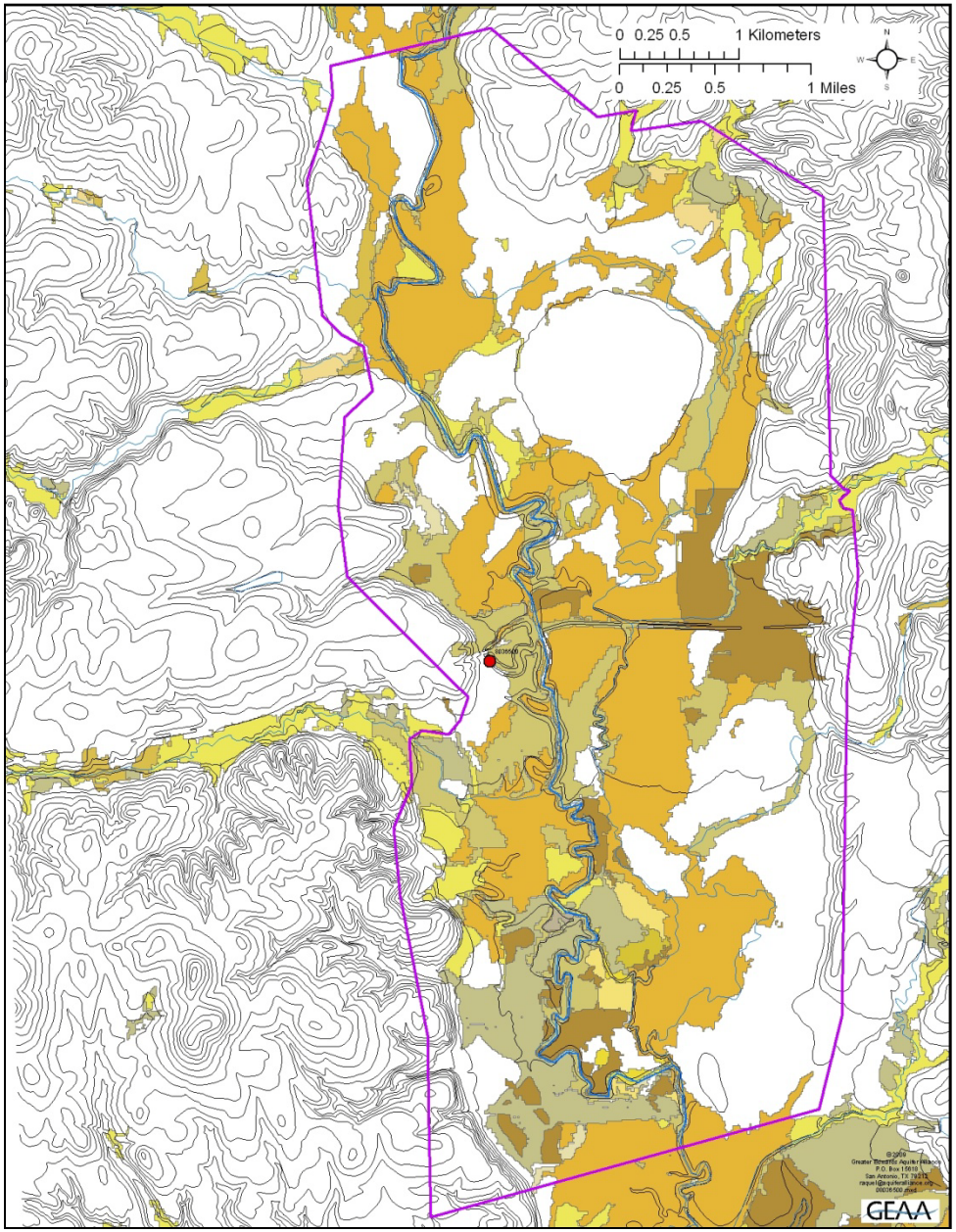
Bottomland Hardwoods
Environmental Inflows
Study Area

Legend

- Site 08036500
- Study Area: Bottomlands Contiguous to Main River Stem
- Rivers and Streams
- Elevation Contours in 5-foot Intervals

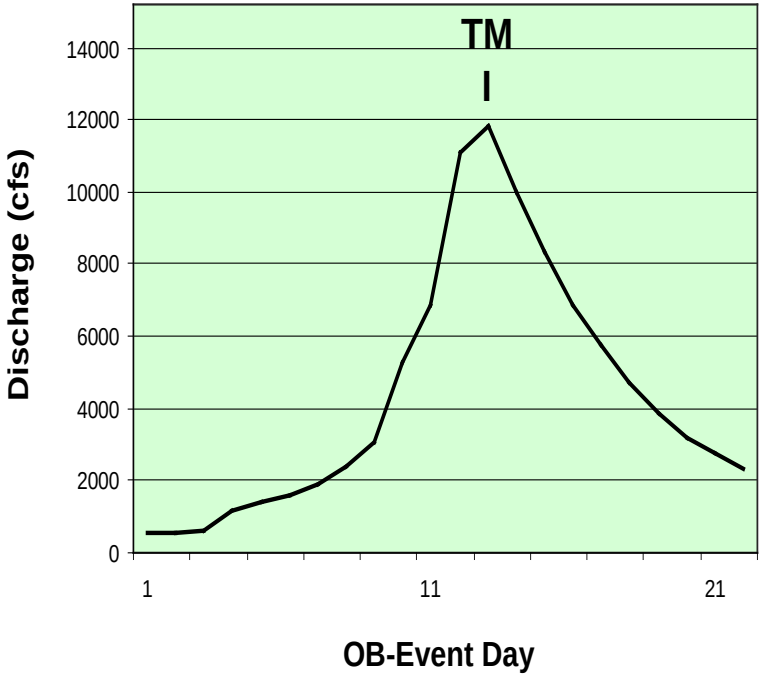
Bottomland Classifications:

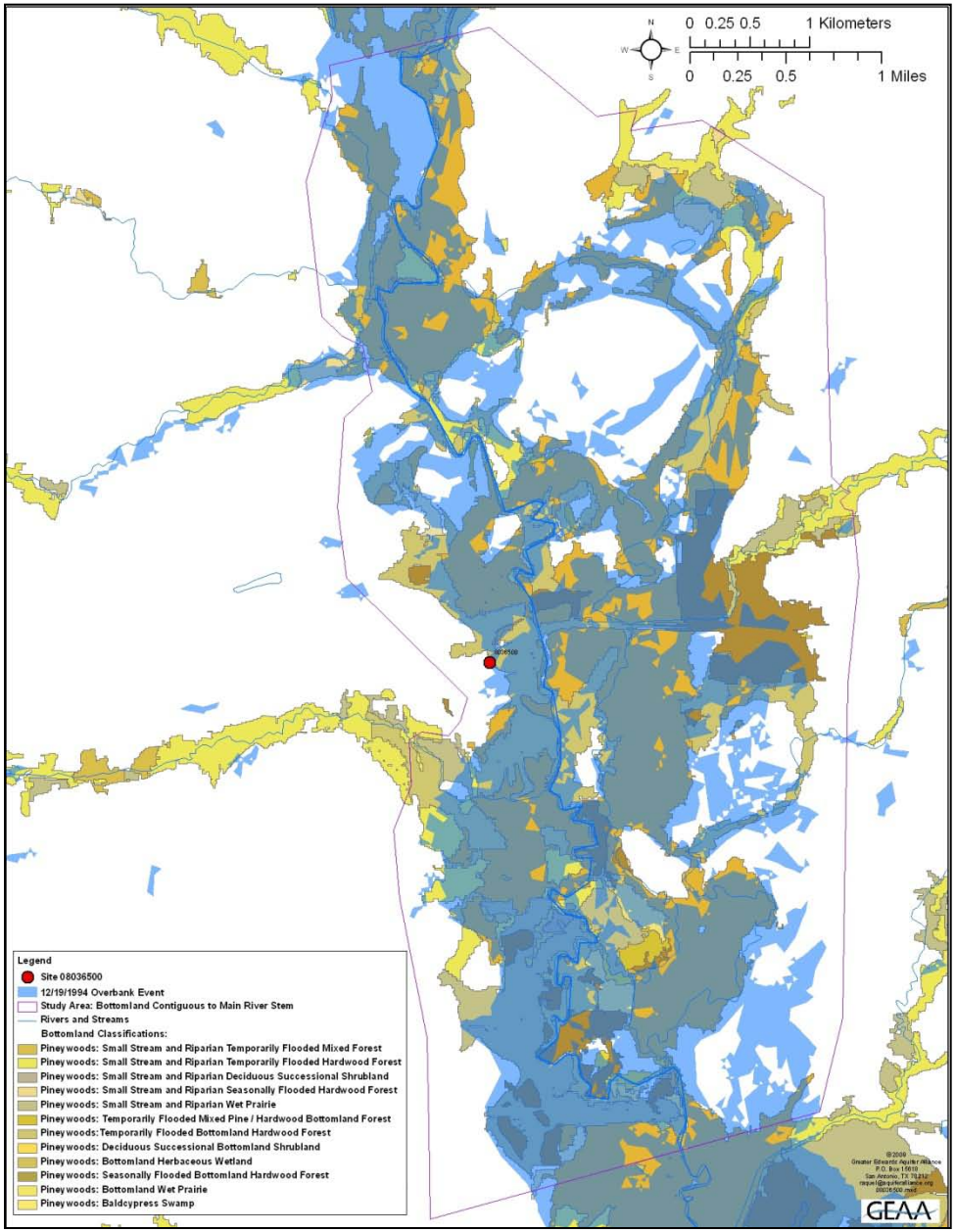
- Pineywoods: Small Stream and Riparian Temporarily Flooded Mixed Forest
- Pineywoods: Small Stream and Riparian Temporarily Flooded Hardwood Forest
- Pineywoods: Small Stream and Riparian Deciduous Successional Shrubland
- Pineywoods: Small Stream and Riparian Seasonally Flooded Hardwood Forest
- Pineywoods: Small Stream and Riparian Wet Prairie
- Pineywoods: Temporarily Flooded Mixed Pine / Hardwood Bottomland Forest
- Pineywoods:Temporarily Flooded Bottomland Hardwood Forest
- Pineywoods: Deciduous Successional Bottomland Shrubland
- Pineywoods: Bottomland Herbaceous Wetland
- Pineywoods: Seasonally Flooded Bottomland Hardwood Forest
- Pineywoods: Bottomland Wet Prairie
- Pineywoods: Baldcypress Swamp



Angelina River at Alto-USGS Gage # 08036500
Overbank Event: 12/7/94-12/28/94

Out-of-Bank Threshold = 11,200 cfs								
TM Date	Mean Discharge (cfs)	Nearest Pre-TM Date Above Threshold	% BH Inudated	OB Event: Cumulative Discharge Volume (10^6 ac-ft)				
				Pre-TM 10d	Pre-TM 15d	Pre-TM 20d	Pre-TM 30d	Above-Threshold Days Prior to TM Date
12/19/94	**11,800**	12/19/94	**71.72%**	0.09	0.10	0.10	0.11	0.02





Big Sandy Creek at Big Sandy
USGS Gage # 08019500

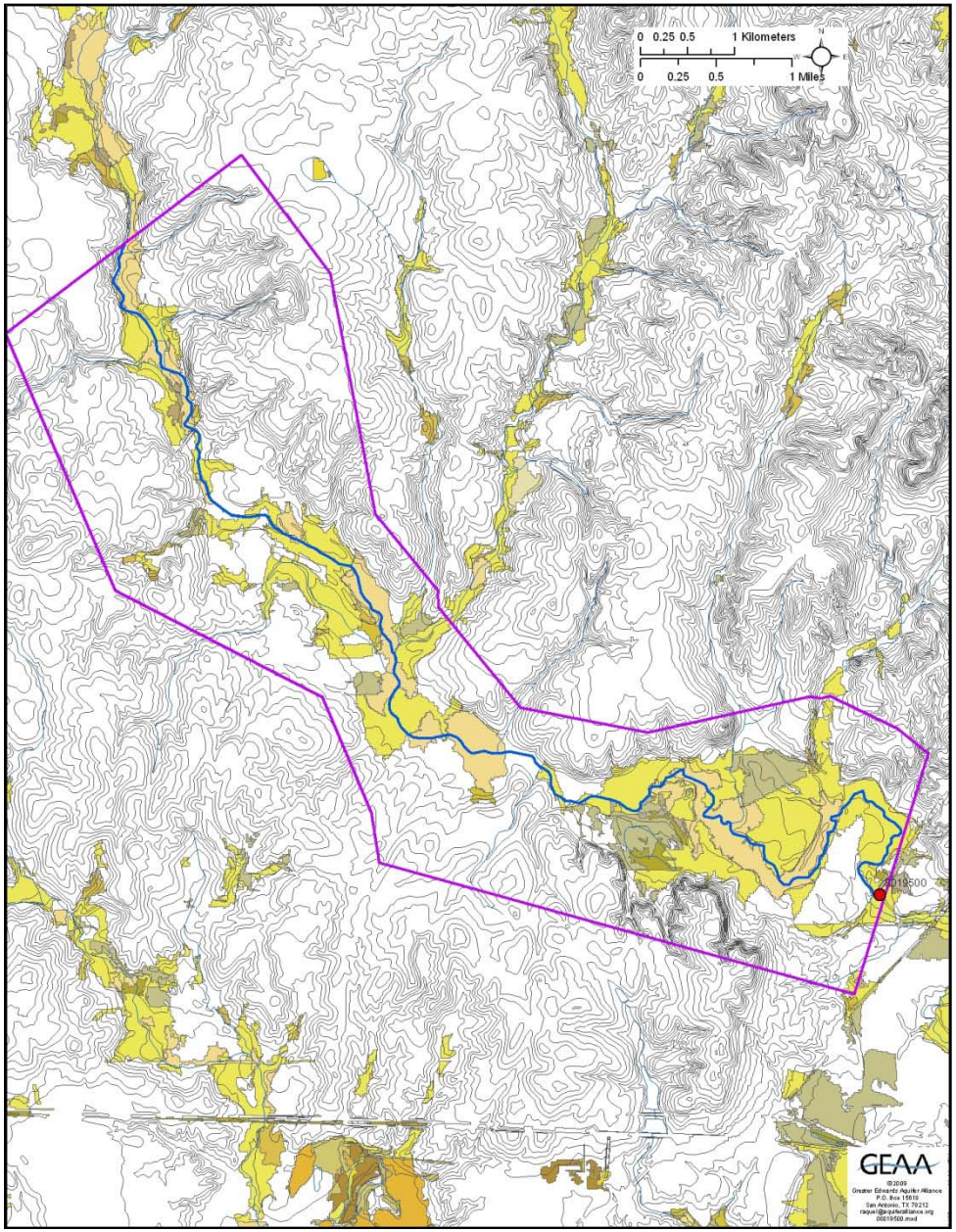
Bottomland Hardwoods
Environmental Inflows
Study Area

Legend

- Site 08019500
- Study Area: Bottomlands Contiguous to Main River Stem
- Rivers and Streams
- Elevation Contours in 5-foot Intervals

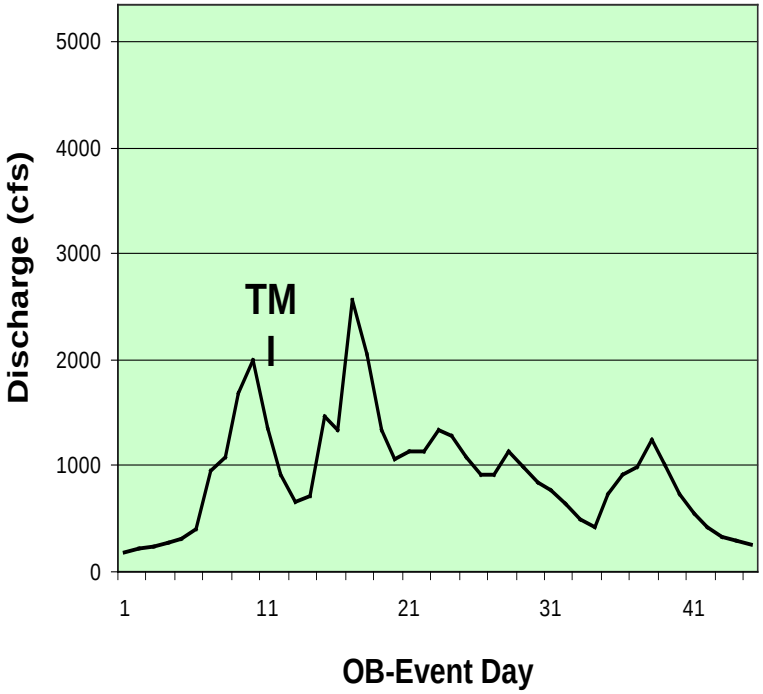
Bottomland Classification:

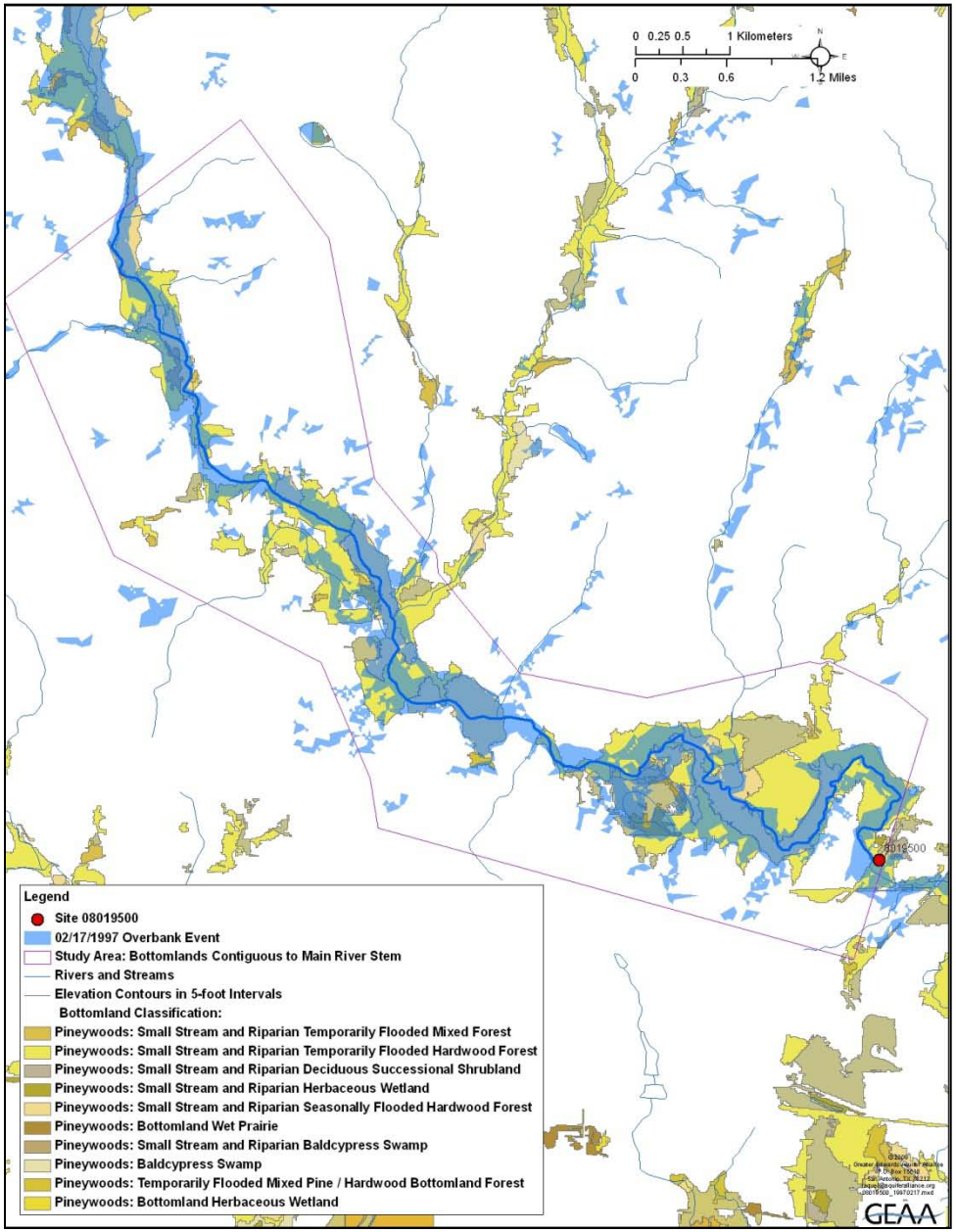
- Pineywoods: Small Stream and Riparian Temporarily Flooded Mixed Forest
- Pineywoods: Small Stream and Riparian Temporarily Flooded Hardwood Forest
- Pineywoods: Small Stream and Riparian Deciduous Successional Shrubland
- Pineywoods: Small Stream and Riparian Herbaceous Wetland
- Pineywoods: Small Stream and Riparian Seasonally Flooded Hardwood Forest
- Pineywoods: Bottomland Wet Prairie
- Pineywoods: Small Stream and Riparian Baldcypress Swamp
- Pineywoods: Baldcypress Swamp
- Pineywoods: Temporarily Flooded Mixed Pine / Hardwood Bottomland Forest
- Pineywoods: Bottomland Herbaceous Wetland



Big Sandy Creek at Big Sandy-USGS Gage # 08019500
Overbank Event: 2/7/97-3/12/97

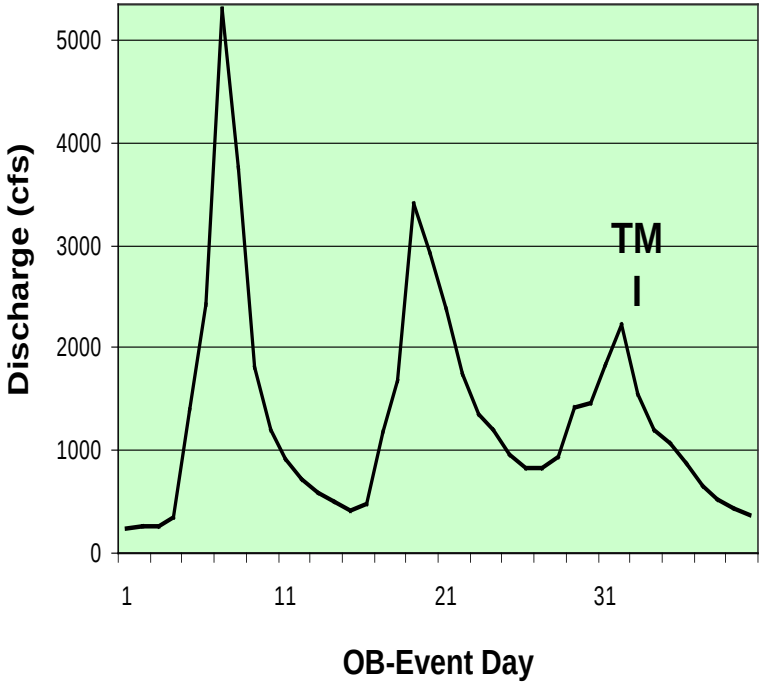
Out-of-Bank Threshold = 1,900 cfs								
TM Date	Mean Discharge (cfs)	Nearest Pre-TM Date Above Threshold	% BH Inudated	OB Event: Cumulative Discharge				
				Pre-TM 10d	Pre-TM 15d	Pre-TM 20d	Pre-TM 30d	Above-Threshold Days Prior to TM Date
2/17/97	**1,360**	2/16/97	**55.72%**	0.03	0.05	0.06	0.09	0.04

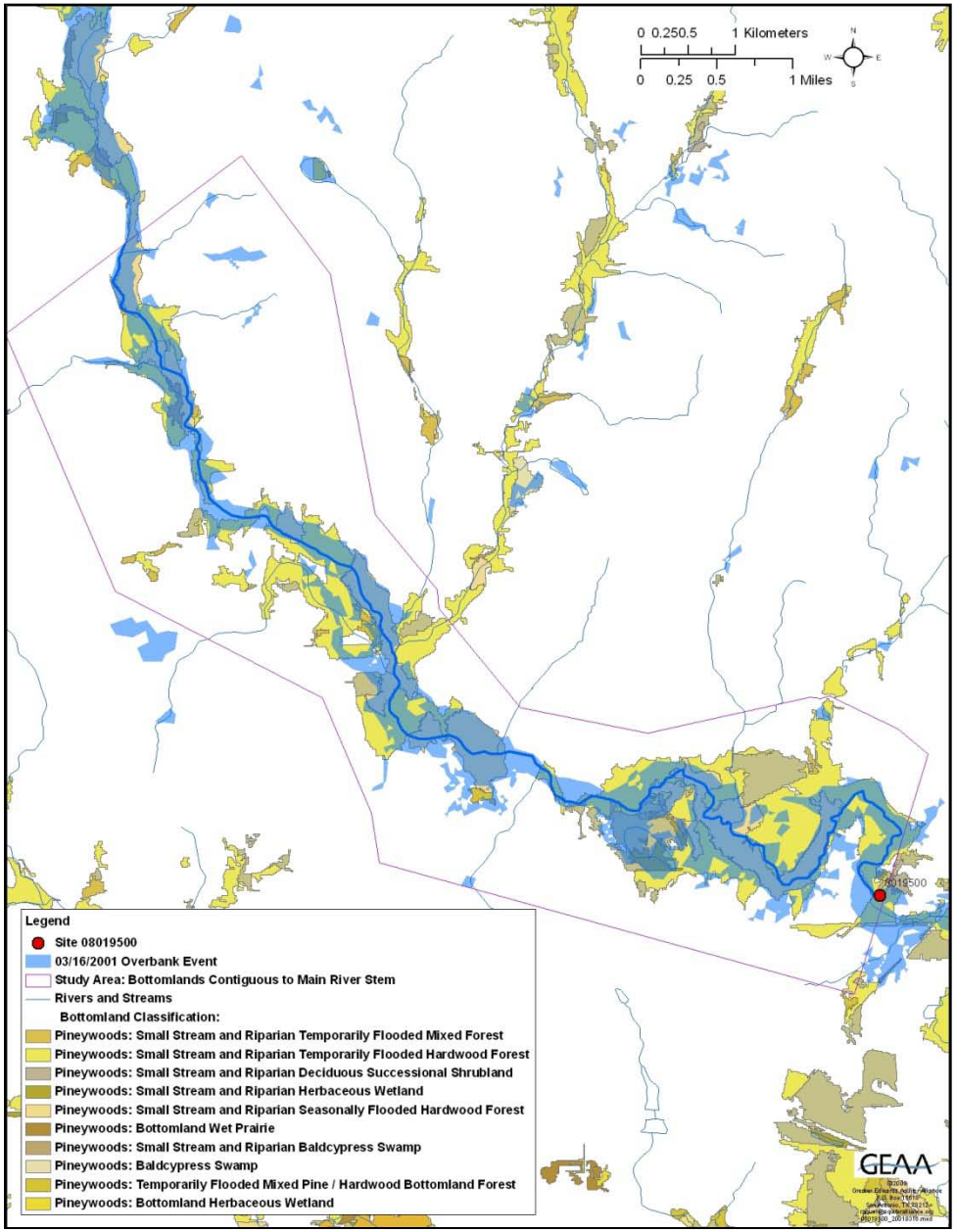




Big Sandy Creek at Big Sandy-USGS Gage # 08019500
Overbank Event: 2/12/01-3/23/01

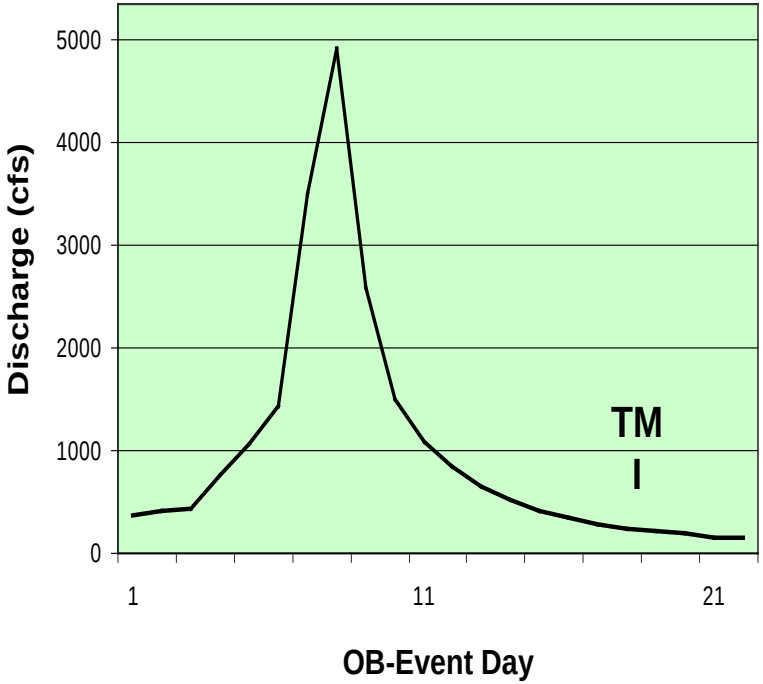
Out-of-Bank Threshold = 1,900 cfs								
TM Date	Mean Discharge (cfs)	Nearest Pre-TM Date Above Threshold	% BH Inudated	OB Event: Cumulative Discharge				
				Pre-TM 10d	Pre-TM 15d	Pre-TM 20d	Pre-TM 30d	Above-Threshold Days Prior to TM Date
3/16/01	**1,540**	3/15/01	**58.56%**	0.02	0.02	0.02	0.02	0.00

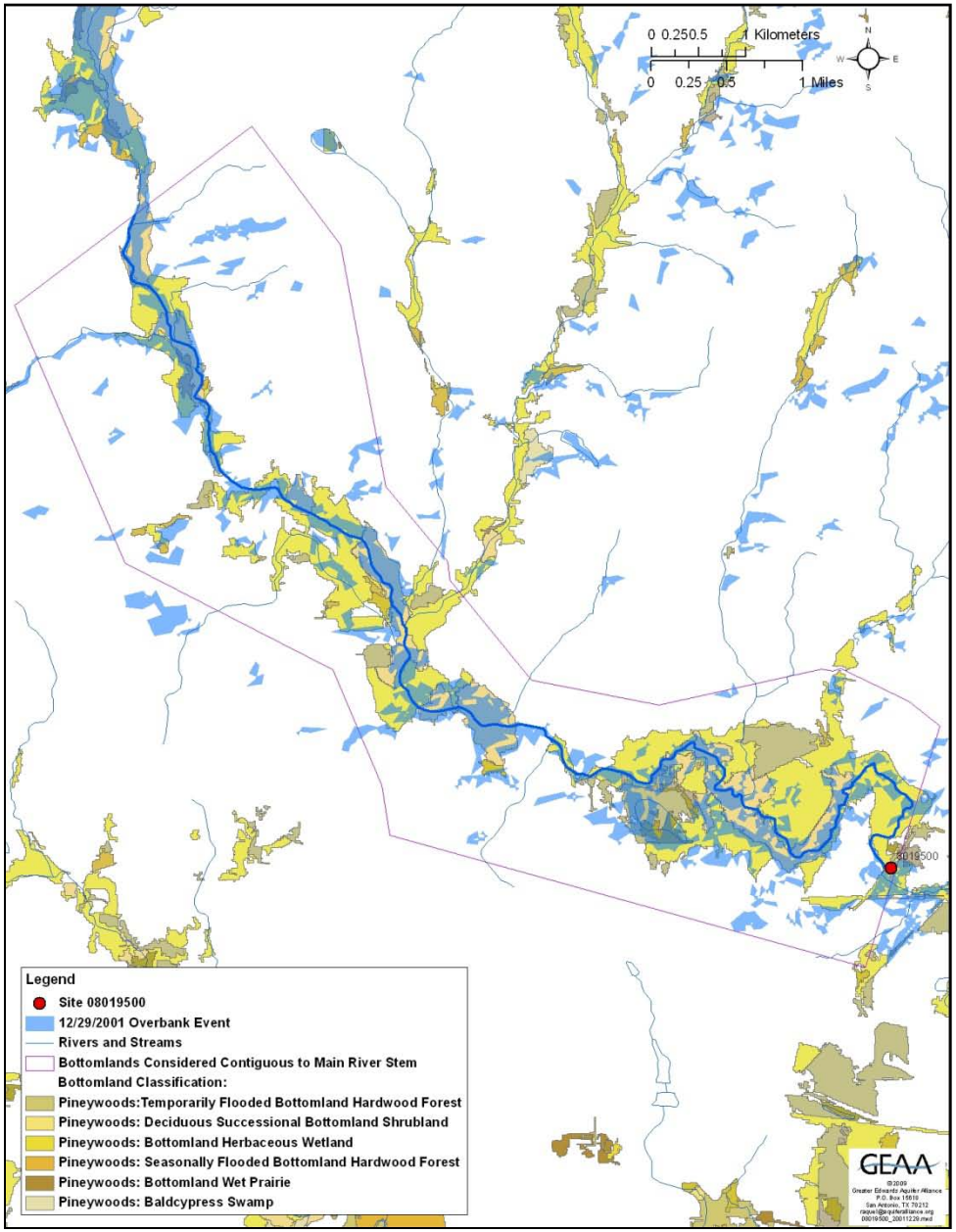




Big Sandy Creek at Big Sandy-USGS Gage # 08019500
Overbank Event: 12/12/01-1/2/02

Out-of-Bank Threshold = 1,900 cfs								
TM Date	Mean Discharge (cfs)	Nearest Pre-TM Date Above Threshold	% BH Inudated	OB Event: Cumulative Discharge				
				Pre-TM 10d	Pre-TM 15d	Pre-TM 20d	Pre-TM 30d	Above-Threshold Days Prior to TM Date
12/29/01	**245**	12/20/01	**35.82%**	0.02	0.04	0.04	0.05	0.02





Village Creek at Kountze
USGS Gage # 08041500

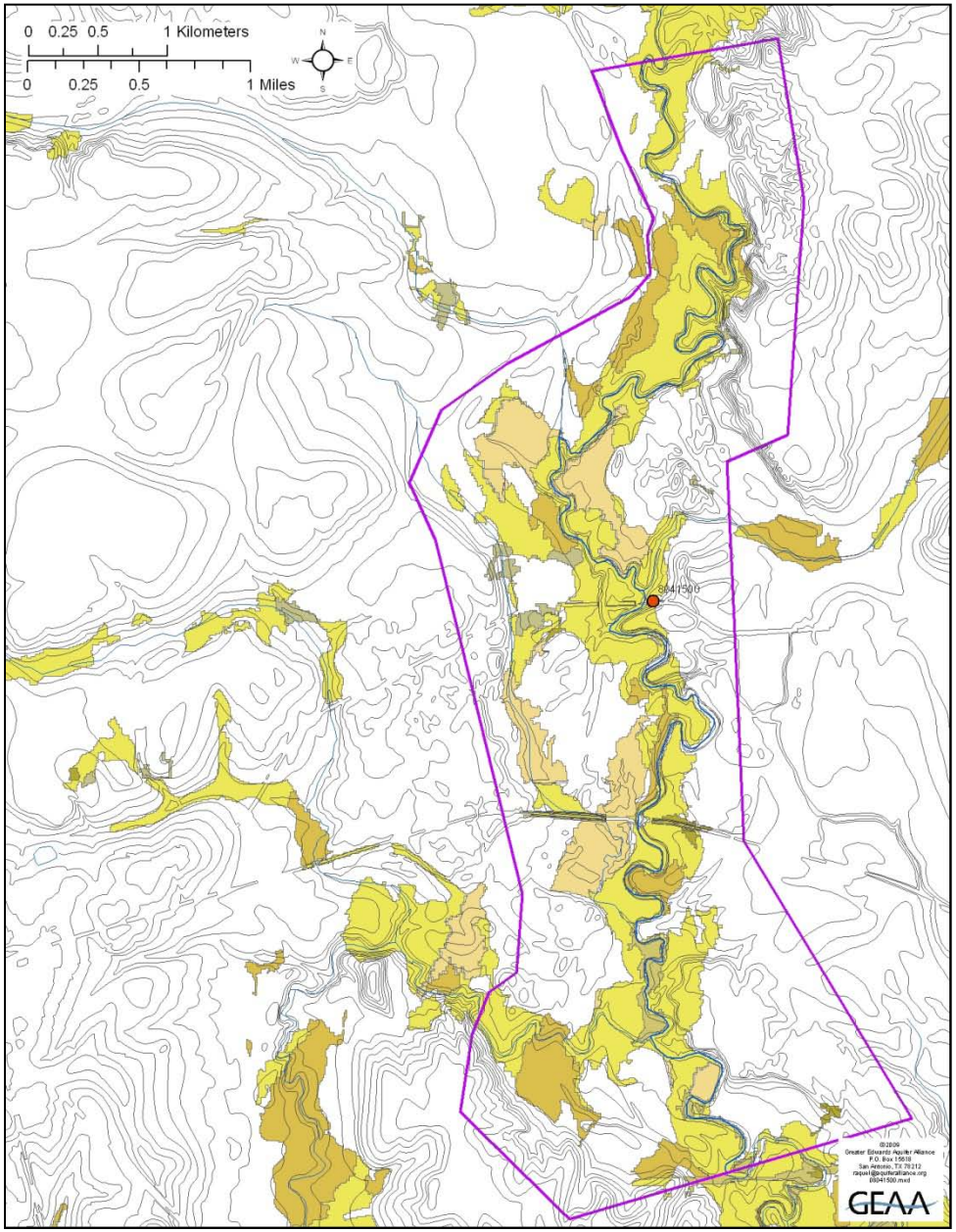
Bottomland Hardwoods
Environmental Inflows
Study Area

Legend

- Site 08041500
- Study Area: Bottomland Contiguous to Main River Stem
- Rivers and Streams
- Elevation Contours in 5-foot Intervals

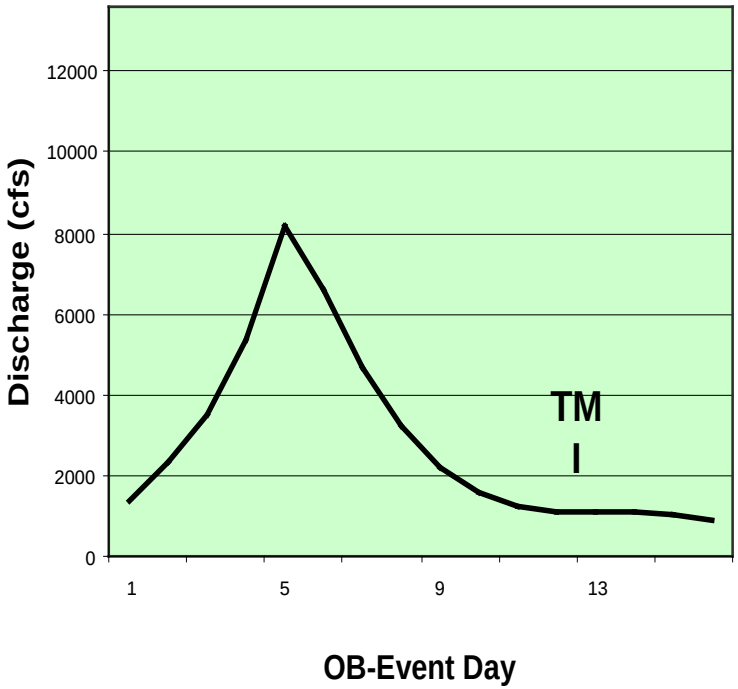
Bottomland Classification:

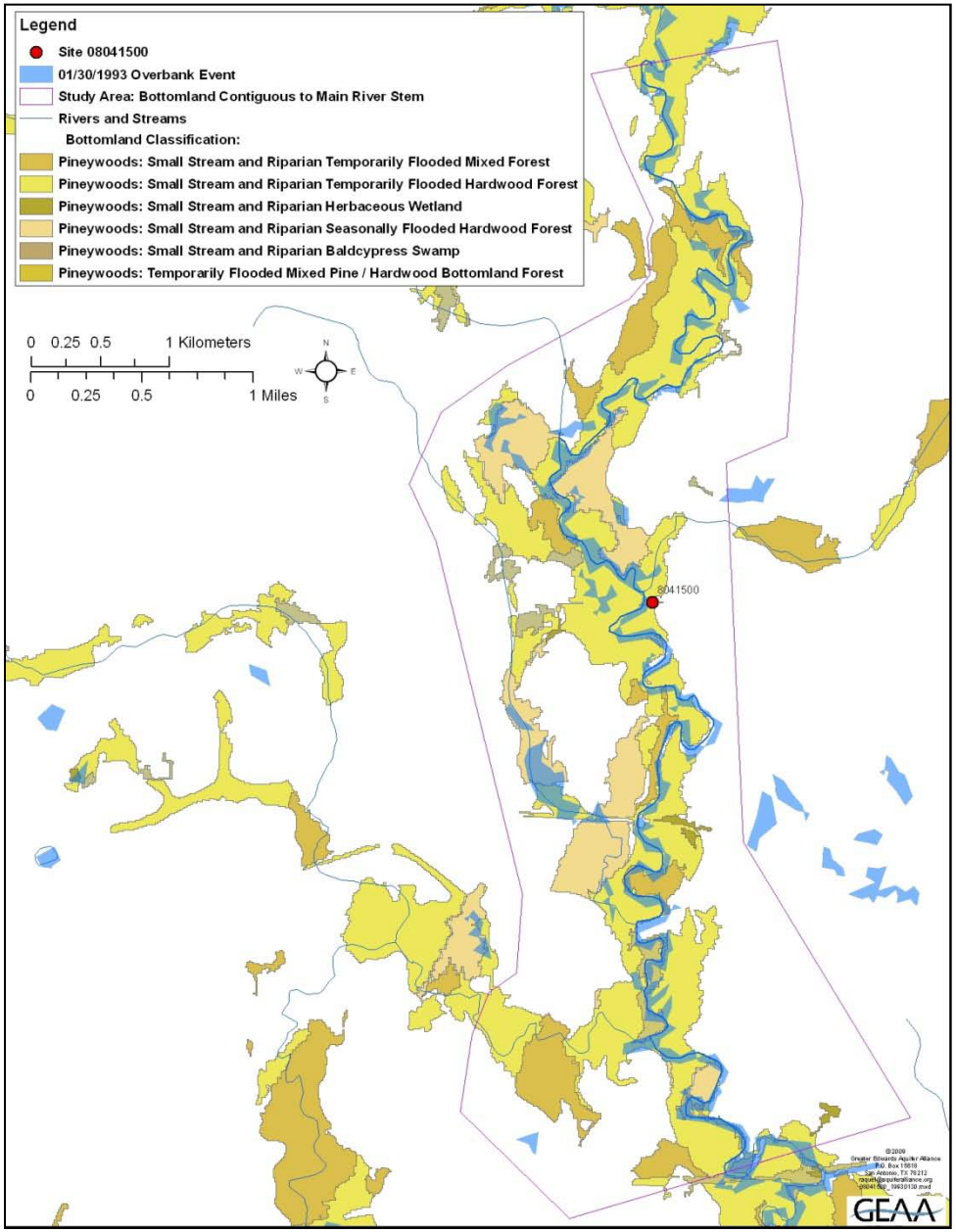
- Pineywoods: Small Stream and Riparian Temporarily Flooded Mixed Forest
- Pineywoods: Small Stream and Riparian Temporarily Flooded Hardwood Forest
- Pineywoods: Small Stream and Riparian Herbaceous Wetland
- Pineywoods: Small Stream and Riparian Seasonally Flooded Hardwood Forest
- Pineywoods: Small Stream and Riparian Baldcypress Swamp
- Pineywoods: Temporarily Flooded Mixed Pine / Hardwood Bottomland Forest



Village Creek at Kountze-USGS Gage # 08041500
Overbank Event: 1/19/93-2/3/93

Out-of-Bank Threshold = 8,150 cfs								
TM Date	Mean Discharge (cfs)	Nearest Pre-TM Date Above Threshold	% BH Inudated	OB Event: Cumulative Discharge Volume (10^6 ac-ft)				
				Pre-TM 10d	Pre-TM 15d	Pre-TM 20d	Pre-TM 30d	Above-Threshold Days Prior to TM Date
1/30/93	**1,090**	1/23/93	**14.95%**	0.07	0.09	0.11	0.14	0.02





Appendix B

Results of Analyses for Inundated Area for Selected Overbank Events Compiled by Site.

Notes on terminology in tables:
BH – Bottomland Hardwood or “floodplain” forest.
OB – Overbank or Out-of-Bank.
Out-of-Bank Threshold – the assumed level at which inundation of the Bottomland Hardwood forest should begin. Based on information within Sept. 08, 2009 Freese & Nichols memo report to the Sabine and Neches Rivers and Sabine Lake Bay Basin and Bay Expert Science Team titled “Analysis of BBEST Stream Gages”.
Mean Discharge – daily mean discharge in cubic feet per second, on the day of the Thematic Mapper imagery.

Inundation-Area Results per OB-Event: site 08022040_Sa-Beckville							
Draft Out-of-Bank Threshold = 12,600 cfs	Date:	12/30/1998		1/4/2001		2/5/2001	
Mean Discharge (cfs):		12,900		8,500		7,270	
Inundation of Total BH (ac & %)		829	15.26%	1809	33.30%	1804	33.20%
Used in BH Inflows Analysis?		Y		Y-below threshold		Y-below threshold	
BH Type:	total (ac)	ac	%	ac	%	ac	%
Pineywoods: Small Stream and Riparian Temporarily Flooded Mixed Forest	54	0	0.00%	1	1.85%	3	5.56%
Pineywoods: Small Stream and Riparian Temporarily Flooded Hardwood Forest	137	6	4.38%	17	12.41%	22	16.06%
Pineywoods: Small Stream and Riparian Herbaceous Wetland	3	1	33.33%	2	66.67%	1	33.33%
Pineywoods: Small Stream and Riparian Seasonally Flooded Hardwood Forest	423	8	1.89%	92	21.75%	67	15.84%
Pineywoods: Small Stream and Riparian Wet Prairie	82	0	0.00%	3	3.66%	0	0.00%
Pineywoods: Temporarily Flooded Mixed Pine/Hardwood Bottomland Forest	61	7	11.48%	15	24.59%	17	27.87%
Pineywoods: Temporarily Flooded Bottomland Hardwood Forest	1495	245	16.39%	591	39.53%	602	40.27%
Pineywoods: Deciduous Successional Bottomland Shrubland	79	2	2.53%	2	2.53%	7	8.86%
Pineywoods: Bottomland Herbaceous Wetland	163	30	18.40%	73	44.79%	78	47.85%
Pineywoods: Seasonally Flooded Bottomland Hardwood Forest	2614	376	14.38%	818	31.29%	822	31.45%
Pineywoods: Bottomland Wet Prairie	131	4	3.05%	30	22.90%	25	19.08%
Pineywoods: Baldcypress Swamp	191	150	78.53%	165	86.39%	160	83.77%
TOTAL ACRES	5433	829	15.26%	1809	33.30%	1804	33.20%

Inundation-Area Results per OB-Event: site 08030500_Sa-Ruliff																	
Draft Out-of-Bank Threshold = 13,300 cfs	**Date:**	**2/6/98**		**1/24/99**		**2/17/02**		**1/3/03**		**2/7/04**		**3/3/07**		**2/18/08**		**3/5/08**	
Mean Discharge (cfs):		**17,200**		**16,600**		**14,300**		**23,100**		**9,780**		**6,320**		**8,930**		**7,920**	
Inundation of Total BH (ac & %)		**2885**	**69.05%**	**2522**	**60.36%**	**2079**	**49.76%**	**3192**	**76.40%**	**672**	**16.08%**	**912**	**21.83%**	**232**	**5.55%**	**584**	**13.98%**
Used in BH Inflows Analysis?		**Y**		**Y**		**Y**		**Y**		**Y**		**Y-below threshold**		**Y-below threshold**		**Y-below threshold**	
BH Type:	**total (ac)**	**ac**	**%**	**ac**	**%**	**ac**	**%**	**ac**	**%**	**ac**	**%**	**ac**	**%**	**ac**	**%**	**ac**	**%**
Pineywoods: Temporarily Flooded Bottomland	739	296	40.05%	271	36.67%	254	34.37%	321	43.44%	160	21.65%	208	28.15%	51	6.90%	110	14.88%
Pineywoods: Deciduous Successional Bottomland Shrubland	5	4	80.00%	3	60.00%	3	60.00%	4	80.00%	1	20.00%	1	20.00%	0	0.00%	1	20.00%
Pineywoods: Bottomland Herbaceous Wetland	202	171	84.65%	161	79.70%	160	79.21%	171	84.65%	134	66.34%	144	71.29%	51	25.25%	136	67.33%
Pineywoods: Seasonally Flooded Bottomland	2834	2076	73.25%	1772	62.53%	1370	48.34%	2361	83.31%	158	5.58%	278	9.81%	39	1.38%	118	4.16%
Pineywoods: Bottomland Wet Prairie	26	5	19.23%	4	15.38%	2	7.69%	6	23.08%	1	3.85%	2	7.69%	1	3.85%	2	7.69%
Pineywoods: Baldcypress Swamp	372	333	89.52%	311	83.60%	290	77.96%	329	88.44%	218	58.60%	279	75.00%	90	24.19%	217	58.33%
TOTAL ACRES	**4178**	**2885**	**69.05%**	**2522**	**60.36%**	**2079**	**49.76%**	**3192**	**76.40%**	**672**	**16.08%**	**912**	**21.83%**	**232**	**5.55%**	**584**	**13.98%**

Inundation-Area Results per OB-Event: site 08032000_Ne-Neches									
Draft Out-of-Bank Threshold = 4,700 cfs	Date:	2/4/98		2/23/99		3/16/01		12/29/01	
Mean Discharge (cfs):		1,100		713		8,250		2,020	
Inundation of Total BH (ac & %)		1653	43.71%	914	24.17%	2307	61.00%	1770	46.80%
Used in BH Inflows Analysis?		Y		Y		Y		Y	
BH Type:	total (ac)	ac	%	ac	%	ac	%	ac	%
Pineywoods: Small Stream and Riparian Temporarily Flooded Mixed Forest	5	0	0.00%	0	0.00%	0	0.00%	0	0.00%
Pineywoods: Small Stream and Riparian Temporarily Flooded Hardwood Forest	417	48	11.51%	35	8.39%	69	16.55%	50	11.99%
Pineywoods: Small Stream and Riparian Deciduous Successional Shrubland	16	1	6.25%	1	6.25%	2	12.50%	3	18.75%
Pineywoods: Small Stream and Riparian Herbaceous Wetland	6	1	16.67%	1	16.67%	2	33.33%	1	16.67%
Pineywoods: Small Stream and Riparian Seasonally Flooded Hardwood Forest	248	81	32.66%	30	12.10%	137	55.24%	101	40.73%
Pineywoods: Small Stream and Riparian Wet Prairie	47	3	6.38%	1	2.13%	2	4.26%	2	4.26%
Pineywoods: Small Stream and Riparian Baldcypress Swamp	8	7	87.50%	6	75.00%	7	87.50%	7	87.50%
Pineywoods: Temporarily Flooded Mixed Pine / Hardwood Bottomland Forest	6	2	33.33%	2	33.33%	1	16.67%	1	16.67%
Pineywoods:Temporarily Flooded Bottomland Hardwood Forest	133	46	34.59%	42	31.58%	61	45.86%	42	31.58%
Pineywoods: Deciduous Successional Bottomland Shrubland	23	4	17.39%	1	4.35%	6	26.09%	3	13.04%
Pineywoods: Bottomland Herbaceous Wetland	112	97	86.61%	92	82.14%	105	93.75%	101	90.18%
Pineywoods: Seasonally Flooded Bottomland Hardwood Forest	2622	1251	47.71%	620	23.65%	1796	68.50%	1354	51.64%
Pineywoods: Bottomland Wet Prairie	9	0	0.00%	0	0.00%	0	0.00%	0	0.00%
Pineywoods: Baldcypress Swamp	130	112	86.15%	83	63.85%	119	91.54%	105	80.77%
TOTAL ACRES	3782	1653	43.71%	914	24.17%	2307	61.00%	1770	46.80%

Inundation-Area Results per OB-Event: site08041000-Ne-Evadale							
Draft Out-of-Bank Threshold = 14,200 cfs	**Date:**	**3/17/98**		**1/20/01**		**1/7/02**	
Mean Discharge (cfs):		**21,200**		**13,700**		**19,500**	
Inundation of Total BH (ac & %)		**5680**	**67.53%**	**2707**	**32.18%**	**7153**	**85.04%**
Used in BH Inflows Analysis?		**Y**		**Y**		**Y**	
BH Type:	**total (ac)**	**ac**	**%**	**ac**	**%**	**ac**	**%**
Pineywoods: Small Stream and Riparian Temporarily Flooded Hardwood Forest	335	131	39.10%	95	28.36%	154	45.97%
Pineywoods: Temporarily Flooded Mixed Pine/Hardwood Bottomland Forest	25	6	24.00%	1	4.00%	4	16.00%
Pineywoods: Temporarily Flooded Bottomland Hardwood Forest	733	531	72.44%	237	32.33%	532	72.58%
Pineywoods: Deciduous Successional Bottomland Shrubland	165	78	47.27%	57	34.55%	154	93.33%
Pineywoods: Bottomland Herbaceous Wetland	81	70	86.42%	57	70.37%	69	85.19%
Pineywoods: Seasonally Flooded Bottomland Hardwood Forest	6867	4671	68.02%	2106	30.67%	6045	88.03%
Pineywoods: Bottomland Wet Prairie	4	3	75.00%	3	75.00%	3	75.00%
Pineywoods: Baldcypress Swamp	201	190	94.53%	151	75.12%	192	95.52%
TOTAL ACRES	**8411**	**5680**	**67.53%**	**2707**	**32.18%**	**7153**	**85.04%**

Inundation-Area Results per OB-Event: site 08036500_Ang-Alto			
Draft Out-of-Bank Threshold = 11,200 cfs	Date:	12/19/1994	
Mean Discharge (cfs):		11,800 cfs	
Inundation of Total BH (ac & %)		3120	71.72%
Used in BH Inflows Analysis?		Y	
BH Type:	total (ac)	ac	%
Pineywoods: Small Stream and Riparian Temporarily Flooded Mixed Forest	34	23	67.65%
Pineywoods: Small Stream and Riparian Temporarily Flooded Hardwood Forest	306	134	43.79%
Pineywoods: Small Stream and Riparian Deciduous Successional Shrubland	6	6	100.00%
Pineywoods: Small Stream and Riparian Seasonally Flooded Hardwood Forest	27	20	74.07%
Pineywoods: Small Stream and Riparian Wet Prairie	448	303	67.63%
Pineywoods: Temporarily Flooded Mixed Pine/Hardwood Bottomland Forest	31	11	35.48%
Pineywoods: Temporarily Flooded Bottomland Hardwood Forest	823	535	65.01%
Pineywoods: Deciduous Successional Bottomland Shrubland	57	51	89.47%
Pineywoods: Bottomland Herbaceous Wetland	39	27	69.23%
Pineywoods: Seasonally Flooded Bottomland Hardwood Forest	2117	1712	80.87%
Pineywoods: Bottomland Wet Prairie	432	272	62.96%
Pineywoods: Baldcypress Swamp	30	26	86.67%
TOTAL ACRES	4350	3120	71.72%

Inundation-Area Results per OB-Event: site 08019500_BigSandy							
Draft Out-of-Bank Threshold = 1,900 cfs	Date:	2/17/1997		3/16/2001		12/29/2001	
Mean Discharge (cfs):		1,360		1,540		245	
Inundation of Total BH (ac & %)		1061	55.72%	1115	58.56%	682	35.82%
Used in BH Inflows Analysis?		Y		Y		Y-below threshold	
BH Type:	total (ac)	ac	%	ac	%	ac	%
Pineywoods: Small Stream and Riparian Temporarily Flooded Mixed Forest	18	1	5.56%	1	5.56%	1	5.56%
Pineywoods: Small Stream and Riparian Temporarily Flooded Hardwood Forest	1122	518	46.17%	541	48.22%	303	27.01%
Pineywoods: Small Stream and Riparian Deciduous Successional Shrubland	9	7	77.78%	9	100.00%	4	44.44%
Pineywoods: Small Stream and Riparian Herbaceous Wetland	31	22	70.97%	26	83.87%	16	51.61%
Pineywoods: Small Stream and Riparian Seasonally Flooded Hardwood Forest	499	449	89.98%	466	93.39%	316	63.33%
Pineywoods: Small Stream and Riparian Wet Prairie	198	43	21.72%	54	27.27%	29	14.65%
Pineywoods: Small Stream and Riparian Baldcypress Swamp	11	11	100.00%	11	100.00%	10	90.91%
Pineywoods: Temporarily Flooded Mixed Pine/Hardwood	15	9	60.00%	6	40.00%	2	13.33%
Pineywoods: Bottomland Herbaceous Wetlands	1	1	100.00%	1	100.00%	1	100.00%
TOTAL ACRES	1904	1061	55.72%	1115	58.56%	682	35.82%

Inundation-Area Results per OB-Event: site 08041500_Village					
Draft Out-of-Bank Threshold = 8,150 cfs	Date:	1/30/93		2/5/95	
Mean Discharge (cfs):		1,090		1,350	
Inundation of Total BH (ac & %)		225	14.95%	294	19.53%
Used in BH Inflows Analysis?		Y		Y	
BH Type:	total (ac)	ac	%	ac	%
Pineywoods: Small Stream and Riparian Temporarily Flooded Mixed Forest	214	10	4.67%	15	7.01%
Pineywoods: Small Stream and Riparian Temporarily Flooded Hardwood Forest	965	170	17.62%	222	23.01%
Pineywoods: Small stream and Riparian Herbaceous Wetland	9	0	0.00%	1	11.11%
Pineywoods: Small Stream and Riparian Seasonally Flooded Hardwood	258	29	11.24%	38	14.73%
Pineywoods: Small stream and Riparian Wet Prairie	24	0	0.00%	0	0.00%
Pineywoods: Temporarily Flooded Bottomland Hardwood	35	16	45.71%	18	51.43%
TOTAL ACRES	**1505**	**225**	**14.95%**	**294**	**19.53%**

Appendix C

Bottomland Hardwood Forest, Species Composition, Part 1

Common Name	# of Plots	Tree Cover	Shrub Cover	Herb Cover
Pineywoods: Baldcypress Swamp	7	49.071	29.714	23.143

Tree	Cover	Freq
Taxodium distichum	28.932	85.71%
Planera aquatica	7.802	42.86%
Liquidambar styraciflua	3.316	42.86%
Quercus lyrata	3.311	28.57%
Carya aquatica	2.997	14.29%
Quercus phellos	2.714	14.29%
Shrub	Cover	Freq
Planera aquatica	14.261	85.71%
Styrax americanus	4.522	28.57%
Cephalanthus occidentalis	2.783	42.86%
Taxodium distichum	2.714	14.29%
Sapium sebiferum	2.714	14.29%
Liquidambar styraciflua	0.907	14.29%
Ilex decidua	0.907	14.29%
Hibiscus mouchotus	0.907	14.29%
Herb	Cover	Freq
Polygonum sp.	4.500	14.29%
Saururus cernuus	3.311	28.57%
Tillandsia usneoides	2.979	71.43%
Saccharum baldwinii	2.714	14.29%
Onoclea sensibilis	2.714	14.29%
Carex cherokeensis	1.808	14.29%
Andropogon ternarius	0.907	14.29%
Lemna minor	0.797	28.57%

Common Name	# of Plots	Tree Cover	Shrub Cover	Herb Cover
Pineywoods: Bottomland Herbaceous Wetland	1	2.500	2.500	88.000

Tree	Cover	Freq
Taxodium distichum	1.668	100.00%
Quercus nigra	0.833	100.00%
Shrub	**Cover**	**Freq**
Taxodium distichum	1.250	100.00%
Gleditsia aquatica	0.833	100.00%
Herb	**Cover**	**Freq**
Panicum anceps	58.696	100.00%
Eleocharis sp.	29.304	100.00%

Common Name	# of Plots	Tree Cover	Shrub Cover	Herb Cover
Pineywoods: Seasonally Flooded Bottomland Hardwood Forest	16	63.000	30.969	21.875

Tree	Cover	Freq
Quercus phellos	12.978	50.00%
Quercus nigra	11.269	37.50%
Quercus lyrata	9.575	37.50%
Planera aquatica	3.541	12.50%
Celtis laevigata	3.416	18.75%
Liquidambar styraciflua	3.025	18.75%
Ulmus crassifolia	3.019	12.50%
Fraxinus pennsylvanica	2.772	18.75%
Pinus taeda	2.750	6.25%
Taxodium distichum	2.365	12.50%
Forestiera angustifolia	1.832	6.25%
Sapium sebiferum	1.832	6.25%
Salix nigra	1.582	12.50%
Carya aquatica	1.311	6.25%
Betula nigra	1.311	6.25%
Ulmus americana	1.054	12.50%
Quercus pagoda	0.919	6.25%
Quercus falcata	0.791	6.25%
Platanus occidentalis	0.791	6.25%
Nyssa aquatica	0.658	6.25%
Nyssa sylvatica	0.658	6.25%
Carya texana	0.658	6.25%
Shrub	Cover	Freq
Ilex decidua	6.187	43.75%
Cephalanthus occidentalis	2.931	25.00%
Forestiera acuminata	2.479	25.00%
Planera aquatica	2.069	12.50%
Ulmus crassifolia	1.907	25.00%
Betula nigra	1.584	12.50%
Morus rubra	1.582	12.50%
Ulmus alata	1.510	18.75%
Ostrya virginiana	1.349	18.75%

Celtis laevigata	1.190	18.75%
Ilex vomitoria	1.188	6.25%
Frangula caroliniana	1.188	6.25%
Carpinus caroliniana	1.188	6.25%
Acer negundo	1.188	6.25%
Callicarpa americana	0.791	6.25%
Fraxinus pennsylvanica	0.791	6.25%
Sapium sebiferum	0.791	6.25%
Salix nigra	0.791	6.25%
Herb	**Cover**	**Freq**
Chasmanthium latifolium	3.764	25.00%
Carex cherokeensis	3.244	31.25%
Toxicodendron radicans	2.389	25.00%
Chasmanthium laxum	2.161	25.00%
Carex hyalinolepis	1.969	6.25%
Lonicera japonica	1.214	12.50%
Ambrosia trifida	1.188	6.25%
Arundinaria gigantea	0.843	12.50%
Smilax bona-nox	0.819	18.75%
Packera glabella	0.658	6.25%
Vicia ludoviciana	0.646	6.25%

Common Name	# of Plots	Tree Cover	Shrub Cover	Herb Cover
Pineywoods: Small Stream and Riparian Baldcypress Swamp	1	38.000	38.000	

Tree	Cover	Freq
Taxodium distichum	38.000	100.00%
Shrub	**Cover**	**Freq**
Planera aquatica	19.000	100.00%
Cephalanthus occidentalis	12.654	100.00%
Alnus serrulata	6.346	100.00%

Common Name	# of Plots	Tree Cover	Shrub Cover	Herb Cover
Pineywoods: Small Stream and Riparian Herbaceous Wetland	1	38.000	38.000	38.000

Tree	Cover	Freq
Pinus palustris	19.000	100.00%
Pinus elliottii	12.654	100.00%
Pinus taeda	6.346	100.00%
Shrub	**Cover**	**Freq**
Quercus incana	19.000	100.00%
Ilex vomitoria	12.654	100.00%
Quercus falcata	6.346	100.00%
Herb	**Cover**	**Freq**
Schizachyrium scoparium	19.000	100.00%
Dichanthelium dichotomum var. ensifolium	12.654	100.00%
Andropogon ternarius	6.346	100.00%

Common Name	# of Plots	Tree Cover	Shrub Cover	Herb Cover
Pineywoods: Small Stream and Riparian Seasonally Flooded Hardwood Forest	7	70.143	29.714	21.929

Tree	Cover	Freq
Quercus nigra	19.786	71.43%
Quercus phellos	13.478	57.14%
Liquidambar styraciflua	7.183	28.57%
Ulmus americana	5.096	28.57%
Quercus similis	5.096	28.57%
Fraxinus pennsylvanica	4.500	14.29%
Betula nigra	4.500	14.29%
Quercus falcata	4.500	14.29%
Celtis laevigata	2.997	14.29%
Salix nigra	1.503	14.29%
Ulmus alata	1.503	14.29%
Shrub	**Cover**	**Freq**
Betula nigra	5.629	42.86%
Carpinus caroliniana	5.259	42.86%
Ilex decidua	3.084	28.57%
Ulmus crassifolia	2.893	42.86%
Ulmus alata	2.714	14.29%
Ostrya virginiana	2.714	28.57%
Acer negundo	2.714	14.29%
Fraxinus pennsylvanica	1.927	28.57%
Callicarpa americana	0.907	14.29%
Ligustrum sinense	0.907	14.29%
Celtis laevigata	0.907	14.29%
Herb	**Cover**	**Freq**
Chasmanthium laxum	5.629	42.86%
Chasmanthium latifolium	4.559	42.86%
Lonicera japonica	2.178	28.57%
Toxicodendron radicans	1.644	28.57%
Ampelopsis arborea	1.107	14.29%
Smilax rotundifolia	1.107	28.57%
Saururus cernuus	1.107	14.29%
Brunnichia ovata	1.107	28.57%

Arundinaria gigantea	1.107	14.29%
Tripsacum dactyloides	0.907	14.29%
Panicum hemitomon	0.737	14.29%

Common Name	# of Plots	Tree Cover	Shrub Cover	Herb Cover
Pineywoods: Small Stream and Riparian Temporarily Flooded Hardwood Forest	62	64.952	31.806	19.048

Tree	Cover	Freq
Quercus nigra	12.173	48.39%
Liquidambar styraciflua	8.968	38.71%
Fraxinus pennsylvanica	5.923	19.35%
Betula nigra	5.584	19.35%
Celtis laevigata	5.313	20.97%
Quercus falcata	5.065	20.97%
Ulmus americana	4.602	22.58%
Pinus taeda	2.789	12.90%
Quercus phellos	2.781	17.74%
Taxodium distichum	2.097	6.45%
Ulmus crassifolia	1.675	9.68%
Ulmus alata	1.016	6.45%
Shrub	Cover	Freq
Quercus nigra	3.197	20.97%
Ulmus alata	2.743	27.42%
Liquidambar styraciflua	2.503	17.74%
Celtis laevigata	2.454	25.81%
Acer negundo	2.085	12.90%
Carpinus caroliniana	1.736	11.29%
Betula nigra	1.686	16.13%
Ulmus crassifolia	1.174	14.52%
Ligustrum sinense	1.068	11.29%
Ilex decidua	1.057	8.06%
Quercus phellos	1.028	9.68%
Ostrya virginiana	0.811	9.68%
Callicarpa americana	0.803	11.29%
Acer rubrum	0.696	6.45%
Maclura pomifera	0.517	6.45%
Fraxinus pennsylvanica	0.516	9.68%
Herb	Cover	Freq
Chasmanthium latifolium	3.219	51.61%
Chasmanthium laxum	1.341	14.52%

Arundinaria gigantea	1.066	19.35%
Smilax rotundifolia	0.843	16.13%
Smilax bona-nox	0.766	14.52%
Carex cherokeensis	0.718	8.06%
Polygonum hydropiperoides	0.709	6.45%
Lonicera japonica	0.703	14.52%
Toxicodendron radicans	0.659	19.35%
Cynodon dactylon	0.615	8.06%
Aster subulatus	0.601	6.45%

Common Name	# of Plots	Tree Cover	Shrub Cover	Herb Cover
Pineywoods: Small Stream and Riparian Temporarily Flooded Mixed Forest	4	81.750	32.375	5.750

Tree	Cover	Freq
Quercus nigra	27.223	100.00%
Pinus taeda	17.304	75.00%
Nyssa aquatica	11.000	25.00%
Ulmus alata	11.000	25.00%
Fagus grandifolia	7.875	25.00%
Acer rubrum	7.348	50.00%
Shrub	Cover	Freq
Sambucus nigra	6.337	50.00%
Ilex opaca	6.327	50.00%
Acer rubrum	5.397	75.00%
Carpinus caroliniana	4.750	25.00%
Ilex vomitoria	4.750	25.00%
Nyssa aquatica	1.938	25.00%
Ulmus alata	1.587	25.00%
Magnolia virginiana	1.290	25.00%
Herb	Cover	Freq
Chasmanthium latifolium	1.938	25.00%
Lonicera japonica	1.290	25.00%
Woodwardia virginica	0.647	25.00%

Common Name	# of Plots	Tree Cover	Shrub Cover	Herb Cover
Pineywoods: Small Stream and Riparian Wet Prairie	9	8.111	2.556	78.500

Tree	Cover	Freq
Acer rubrum	3.500	11.11%
Liquidambar styraciflua	2.331	11.11%
Quercus nigra	1.169	11.11%
Shrub	**Cover**	**Freq**
Juniperus virginiana	1.046	22.22%
Ulmus alata	0.666	22.22%
Gleditsia triacanthos	0.556	22.22%
Herb	**Cover**	**Freq**
Cynodon dactylon	32.589	66.67%
Paspalum notatum	6.661	33.33%
Ambrosia psilostachya	6.522	22.22%
Lolium perenne	6.512	22.22%
Sorghastrum nutans	4.889	11.11%
Sorghum halepense	3.266	22.22%
Ambrosia trifida	3.256	11.11%
Schizachyrium scoparium	3.256	11.11%
Zanthium strumarium	3.256	11.11%
Polygonaum lapathifolium	3.256	11.11%
Paspalum floridanum	1.633	11.11%
Cucurbita foetidissima	1.633	11.11%
Aristida oligantha	1.633	11.11%

Common Name	# of Plots	Tree Cover	Shrub Cover	Herb Cover
Pineywoods: Temporarily Flooded Bottomland Hardwood Forest	18	56.472	33.556	23.944

Tree	Cover	Freq
Liquidambar styraciflua	9.937	44.44%
Quercus nigra	5.822	16.67%
Ulmus crassifolia	5.603	38.89%
Quercus lyrata	4.292	22.22%
Fraxinus pennsylvanica	3.905	22.22%
Ulmus alata	3.691	16.67%
Quercus phellos	2.916	11.11%
Platanus occidentalis	2.797	11.11%
Quercus laurifolia	2.444	5.56%
Populus deltoides	1.772	11.11%
Taxodium distichum	1.750	5.56%
Quercus michauxii	1.633	11.11%
Acer rubrum	1.628	5.56%
Salix nigra	1.309	11.11%
Celtis laevigata	1.169	11.11%
Nyssa sp.	1.056	5.56%
Pinus taeda	0.816	5.56%
Ulmus rubra	0.703	5.56%
Ulmus americana	0.703	5.56%
Gleditsia aquatica	0.585	5.56%
Carya illinoinensis	0.585	5.56%
Shrub	Cover	Freq
Ilex decidua	4.759	44.44%
Planera aquatica	3.500	11.11%
Ulmus alata	2.814	16.67%
Salix nigra	2.684	11.11%
Fraxinus pennsylvanica	2.509	22.22%
Acer negundo	2.109	16.67%
Cephalanthus occidentalis	2.037	11.11%
Forestiera acuminata	2.027	16.67%
Ulmus americana	1.750	5.56%
Ulmus crassifolia	1.566	27.78%

Ilex vomitoria	1.224	16.67%
Ilex opaca	0.847	11.11%
Ostrya virginiana	0.816	5.56%
Celtis laevigata	0.783	11.11%
Crateagus sp.	0.703	5.56%
Platanus occidentalis	0.703	5.56%
Acer rubrum	0.585	5.56%
Herb	**Cover**	**Freq**
Arundinaria gigantea	3.907	22.22%
Chasmanthium latifolium	3.416	33.33%
Carex cherokeensis	3.366	27.78%
Toxicodendron radicans	2.005	22.22%
Vicia ludoviciana	1.166	5.56%
Carex sp.	1.102	11.11%
Aster ericoides	1.056	5.56%
Berchemia scandens	0.847	11.11%
Solidago gigantea	0.717	11.11%
Carex amphibola	0.703	5.56%
Carex hyalinolepis	0.703	5.56%
Potamogeton nodosus	0.703	5.56%
Rubus arvensis	0.639	11.11%
Campsis radicans	0.631	11.11%

Appendix D

Bottomland Hardwood Forest, Species Composition, Part 2

Common Name	# Plots	Stems/acre	BA sq ft/acre
Pineywoods: Deciduous Successional Bottomland Shrubland	3	120.36	41.72

Species	Relative BA	Relative Density	Frequency
Tilia americana	46.58%	13.33%	33.33%
Quercus pagoda	26.86%	6.67%	33.33%
Pinus taeda	21.31%	46.67%	66.67%
Acer barbatum	3.76%	13.33%	33.33%
Carya aquatica	1.37%	13.33%	33.33%

Common Name	# Plots	Stems/acre	BA sq ft/acre
Pineywoods: Seasonally Flooded Bottomland Hardwood Forest	194	155.35	88.55

Species	Relative BA	Relative Density	Frequency
Taxodium distichum	13.13%	4.23%	8.76%
Quercus phellos	12.11%	10.94%	26.29%
Quercus lyrata	11.97%	6.15%	22.16%
Liquidambar styraciflua	10.37%	10.46%	29.38%
Fraxinus pennsylvanica	7.90%	11.26%	25.26%
Quercus pagoda	4.23%	1.52%	7.22%
Pinus taeda	3.86%	1.92%	4.64%
Celtis laevigata	3.80%	6.87%	19.07%
Nyssa aquatica	3.74%	1.36%	3.09%
Quercus nigra	3.70%	3.59%	12.89%
Ulmus crassifolia	3.14%	4.87%	15.46%
Carya aquatica	2.61%	2.32%	9.79%
Acer rubrum	1.80%	2.00%	6.70%
Planera aquatica	1.70%	3.27%	5.67%
Triadica sebifera	1.63%	5.19%	13.92%
Quercus michauxii	1.52%	0.80%	4.64%
Carpinus caroliniana	1.33%	4.55%	15.98%
Nyssa sylvatica	1.30%	1.52%	7.73%
Ulmus americana	1.28%	2.72%	14.43%
Quercus laurifolia	1.11%	0.96%	3.09%

Common Name	# Plots	Stems/acre	BA sq ft/acre
Pineywoods: Small Stream and Riparian Baldcypress Swamp	15	128.39	47.59

Species	Relative BA	Relative Density	Frequency
Liquidambar styraciflua	36.72%	28.75%	46.67%
Quercus laurifolia	15.42%	11.25%	20.00%
Salix nigra	8.58%	2.50%	13.33%
Planera aquatica	6.86%	13.75%	20.00%
Quercus lyrata	6.34%	3.75%	20.00%
Nyssa sylvatica	6.34%	6.25%	26.67%
Quercus phellos	5.33%	6.25%	13.33%
Gleditsia aquatica	4.04%	6.25%	6.67%
Fraxinus pennsylvanica	3.24%	5.00%	20.00%
Acer rubrum	2.27%	2.50%	13.33%
Quercus nigra	2.27%	1.25%	6.67%
Ulmus crassifolia	0.98%	1.25%	6.67%

Common Name	# Plots	Stems/acre	BA sq ft/acre
Pineywoods: Small Stream and Riparian Herbaceous Wetland	5	154.06	43.07

Species	Relative BA	Relative Density	Frequency
Taxodium distichum	52.92%	28.13%	40.00%
Fraxinus caroliniana	21.02%	50.00%	60.00%
Quercus phellos	8.93%	3.13%	20.00%
Quercus lyrata	6.10%	3.13%	20.00%
Salix nigra	5.75%	6.25%	20.00%
Betula nigra	2.05%	3.13%	20.00%
Triadica sebifera	1.71%	3.13%	20.00%
Ulmus crassifolia	1.52%	3.13%	20.00%

Common Name	# Plots	Stems/acre	BA sq ft/acre
Pineywoods: Small Stream and Riparian Seasonally Flooded Hardwood Forest	109	169.83	76.81

Species	Relative BA	Relative Density	Frequency
Quercus nigra	16.29%	11.31%	34.86%
Liquidambar styraciflua	15.51%	18.34%	48.62%
Fraxinus pennsylvanica	7.53%	8.71%	28.44%
Quercus phellos	7.07%	3.12%	14.68%
Quercus lyrata	6.04%	4.03%	16.51%
Pinus taeda	6.02%	3.25%	5.50%
Ulmus americana	5.94%	7.15%	25.69%
Taxodium distichum	3.54%	4.42%	3.67%
Ulmus crassifolia	3.13%	2.60%	8.26%
Salix nigra	3.13%	2.08%	6.42%
Betula nigra	3.08%	2.86%	8.26%
Platanus occidentalis	3.08%	0.39%	2.75%
Carpinus caroliniana	2.77%	8.19%	31.19%
Celtis laevigata	2.37%	2.73%	11.01%
Ulmus alata	1.82%	3.25%	13.76%
Nyssa sylvatica	1.39%	2.21%	12.84%
Acer barbatum	1.28%	1.30%	4.59%
Planera aquatica	1.17%	1.82%	4.59%
Triadica sebifera	1.02%	1.69%	7.34%
Ilex opaca	1.00%	1.30%	4.59%

Common Name	# Plots	Stems/acre	BA sq ft/acre
Pineywoods: Small Stream and Riparian Temporarily Flooded Hardwood Forest	351	165.62	77.66

Species	Relative BA	Relative Density	Frequency
Liquidambar styraciflua	16.71%	19.50%	46.15%
Quercus nigra	13.07%	8.41%	33.05%
Pinus taeda	11.48%	10.56%	19.37%
Quercus pagoda	3.95%	1.49%	8.26%
Celtis laevigata	3.72%	3.64%	12.54%
Quercus phellos	3.67%	2.57%	9.97%
Betula nigra	3.61%	2.82%	8.55%
Quercus falcata	3.57%	1.90%	11.40%
Quercus alba	3.01%	1.16%	6.55%
Quercus stellata	2.77%	1.86%	8.26%
Fraxinus pennsylvanica	2.67%	5.18%	12.25%
Nyssa sylvatica	2.56%	1.99%	11.11%
Ulmus americana	2.48%	3.73%	16.52%
Ulmus alata	2.46%	5.05%	21.65%
Quercus laurifolia	1.88%	1.28%	4.84%
Quercus lyrata	1.58%	0.70%	4.84%
Taxodium distichum	1.52%	0.75%	3.13%
Carpinus caroliniana	1.37%	4.06%	15.95%
Salix nigra	1.29%	1.28%	4.56%
Ulmus crassifolia	1.26%	1.66%	5.13%
Fagus grandifolia	1.23%	0.54%	2.28%
Acer rubrum	1.22%	2.53%	9.97%
Pinus echinata	1.06%	0.66%	2.85%
Carya cordiformis	1.05%	0.79%	3.99%
Juniperus virginiana	0.99%	1.28%	4.56%

Common Name	# Plots	Stems/acre	BA sq ft/acre
Pineywoods: Small Stream and Riparian Temporarily Flooded Mixed Forest	32	200.10	99.13

Species	Relative BA	Relative Density	Frequency
Pinus taeda	40.69%	30.45%	46.88%
Pinus elliottii	11.66%	6.39%	12.50%
Quercus nigra	9.26%	10.15%	46.88%
Liquidambar styraciflua	6.82%	11.28%	50.00%
Quercus pagoda	4.89%	1.13%	12.50%
Fagus grandifolia	4.05%	1.88%	9.38%
Betula nigra	3.07%	3.76%	6.25%
Quercus laurifolia	2.90%	2.26%	12.50%
Nyssa sylvatica	2.78%	3.76%	18.75%
Magnolia virginiana	1.62%	1.13%	12.50%
Ulmus americana	1.53%	1.88%	12.50%
Juglans nigra	1.11%	1.50%	3.13%
Carya glabra	1.06%	0.75%	3.13%
Carpinus caroliniana	1.05%	8.27%	18.75%
Quercus lyrata	1.01%	0.75%	3.13%
Acer rubrum	1.00%	1.13%	9.38%
Quercus alba	0.96%	1.50%	9.38%

Common Name	# Plots	Stems/acre	BA sq ft/acre
Pineywoods: Small Stream and Riparian Wet Prairie	9	149.78	97.44

Species	Relative BA	Relative Density	Frequency
Pinus taeda	37.34%	8.93%	22.22%
Quercus nigra	32.98%	33.93%	66.67%
Liquidambar styraciflua	19.20%	33.93%	55.56%
Juglans nigra	3.32%	1.79%	11.11%
Acer barbatum	3.00%	3.57%	11.11%
Quercus phellos	1.67%	3.57%	22.22%
Ulmus americana	1.39%	5.36%	33.33%
Salix nigra	1.00%	5.36%	22.22%

Common Name	# Plots	Stems/acre	BA sq ft/acre
Pineywoods: Temporarily Flooded Bottomland Hardwood Forest	122	161.80	82.78

Species	Relative BA	Relative Density	Frequency
Taxodium distichum	18.23%	7.07%	12.30%
Liquidambar styraciflua	10.00%	13.17%	34.43%
Quercus nigra	7.90%	7.07%	26.23%
Celtis laevigata	7.01%	8.05%	22.95%
Triadica sebifera	6.38%	13.78%	18.03%
Fraxinus pennsylvanica	6.12%	7.32%	22.95%
Quercus phellos	6.05%	1.95%	8.20%
Nyssa aquatica	4.94%	1.83%	4.10%
Quercus lyrata	3.08%	1.71%	9.02%
Platanus occidentalis	2.95%	1.83%	7.38%
Carya aquatica	2.79%	1.71%	9.84%
Ulmus americana	2.78%	3.29%	16.39%
Quercus pagoda	2.58%	0.73%	4.10%
Pinus taeda	2.10%	1.83%	8.20%
Carya illinoinensis	1.71%	1.22%	4.10%
Quercus laurifolia	1.67%	1.34%	5.74%
Ulmus crassifolia	1.36%	1.95%	5.74%
Quercus alba	1.17%	0.24%	0.82%
Salix nigra	1.13%	1.34%	4.10%
Acer rubrum	1.11%	2.20%	8.20%
Populus deltoides	1.10%	0.12%	0.82%

Common Name	# Plots	Stems/acre	BA sq ft/acre
Pineywoods: Temporarily Flooded Mixed Pine / Hardwood Bottomland Forest	7	154.75	53.46

Species	Relative BA	Relative Density	Frequency
Pinus taeda	32.05%	26.67%	57.14%
Quercus laurifolia	19.66%	6.67%	42.86%
Liquidambar styraciflua	18.27%	6.67%	28.57%
Magnolia virginiana	9.80%	13.33%	14.29%
Quercus phellos	9.52%	17.78%	28.57%
Quercus nigra	5.81%	4.44%	28.57%
Carpinus caroliniana	2.19%	2.22%	14.29%
Ilex opaca	1.31%	2.22%	14.29%
Quercus stellata	1.03%	6.67%	14.29%

Common Name	# Plots	Stems/acre	BA sq ft/acre
Red River: Floodplain Hardwood Forest	16	159.48	94.40

Species	Relative BA	Relative Density	Frequency
Populus deltoides	41.64%	5.66%	18.75%
Acer negundo	14.02%	21.70%	31.25%
Juniperus virginiana	10.44%	9.43%	25.00%
Carya illinoinensis	6.16%	2.83%	6.25%
Quercus shumardii	5.70%	1.89%	12.50%
Salix nigra	4.57%	1.89%	12.50%
Celtis laevigata	4.44%	10.38%	31.25%
Quercus michauxii	3.43%	4.72%	18.75%
Fraxinus pennsylvanica	3.28%	16.04%	31.25%
Maclura pomifera	2.53%	6.60%	6.25%
Platanus occidentalis	1.30%	1.89%	12.50%
Acer barbatum	0.92%	1.89%	12.50%

Section	Page	Subsection	SectionParagraph	CommentBy	Comment	AcceptReason	RejectReason	ActionOnComment	ID
1	6	1.2.3	next to last sentence	SH	"Opinions and recommendations by the report authors were not always agreed upon by consensus..." seems contradict the last sentence that "report… reflects the consensus…" If the main report is the consensus and the sub-committee or discipline reports in the app. are not always concensus, then a little clarification is needed here	Agree with comment; consistency		Handled due to a previously addressed comment	244
1	1	1.1	na	RHH	move last two sentences of the paragraph (beginning: SB3 created…) to a position afer [sic] the word environment in the 6th line of the paragraph. Then start a new paragraph at the next sentence that begins: "Prior to SB1…"	Agree with comment; clarification		Change made as suggested	55
1	1	NA	last line	RHH	the phrase at the end of the last sentence about Louisiana seems to just be dropped in here without the ability of the reader to understand what it means. I suggest either providing additional information here or deleting the reference here and bringing it up in more detail later.	Agree with comment; clarification		Added clarifying language	60
1	1	NA	line 5	RHH	The sentence that begins on this line is very long. Suggest breaking it into two sentences for ease of reading.	Partially agree with comment		Accepted with modification; shortened sentence.	56
1	1	NA	line 10	RHH	end of line needs a comma after manner	Accept comment; grammar fix		change made as suggested	57
1	1	NA	line 8	RHH	Sabine Lake (Sabine-Neches Estuary) Member notes: Throughout the document there are various ways we refer to the estuary. We either should be consistent, or we should at the outset provide all the various ways of naming the estuary; that is, at this point.		Correction ID #56 removes this text	N/A due to another change	58
1	1	NA	first line	RHH	Correct the name of the BBEST: Sabine and Neches and Sabine Lake Bay Basin and Bay Expert Scient [sic] Team	Accept comment; correction		change made as suggested	59
1	3	1.2	end of page	RHH	need to add a short paragraph explaining that two consultants were retained for the purpose of providing technical suppor [sic] for the process.	Agree with comment; helpful addition		Change made as suggested	63
1	3	1.2	second paragraph	RHH	Move the first sentence in the second paragraph to the beginning of the section (in front of the first sentence of the first paragraph).		Disagree with comment	None	61
1	3	1.2	first paragraph	RHH	THEN, add the following sentence after the new first sentence of the section: Table 1 provides a list of the Sabine-Neches BBEST members and the Sabine-Neches BBASC representatives that nominated them.	Agree with comment		Added recommended sentence and modified preceeding sentence to be consistent with the change	62
1	4		Table 1	SKV	Replace "V.P., Project Manager" with "Vice President" for my affiliation.	Agree with comment; correction		change made as suggested	148
1	4	1.2	Table 1	RHH	can you use "Principal" instead of "Sr. Project Manager" on my name?	Agree with comment; correction		change made as suggested	64
1	5	1.2	Figure 2	RHH	This table [sic] is close but needs some work. Will try to work something up.	Agree with comment; helpful addition		Change made as suggested	65
1	6	1.2.1	third paragraph	RHH	lower case on "environmental flow regime"	Agree with comment; grammar		change made as suggested	66
1	6	1.2.2	na	RHH	period at the end of the paragraph	Agree with comment; grammar		change made as suggested	67
1	6	1.2.3	first line	RHH	add comma: …composed of a main body, which is…	Agree with comment; grammar		change made as suggested	69
1	6	1.2.3		RHH	Suggest deleting the sentence "Opinions and recommendations by the report authors were not always agree upon by consensus of the …" This sentence is not needed and I don't really know what to make of it	Agree with comment; consistency		N/A due to another change	70

Section	Page	Subsection	SectionParagraph	CommentBy	Comment	AcceptReason	RejectReason	ActionOnComment	ID
1	6	1.2.3	7th line	SKV	Replace "not always" with "generally"	Agree with comment; correction		Change made as suggested	149
1	6	1.2.3	second line	RHH	semicolon afer [sic] recommendations; delete the word "finally"; add comma after appendices; delete the "s" in includes.	Agree with comment; clarification		Change made with one modification: "includes" changed to "include the"	68
1	7		Figure 3	RHH	Add a Contributor's box in the left hand side and put the NWF reports in there;	Agree with comment; helpful addition		change made as suggested	71
1	7	1.2.2	Figure 3	SKV	Remove "NOT RECOMMENDED: Recognized" for High Flow Pulses	Agree with comment; correction		change made as suggested	150
1	9	1.2.5		RHH	Correct reference to Sabine-Neches estuary		We agree that the reference is not correct, but this text box is a literal quotation of what was agreed upon by the BBEST as its Goal.	None	72
2	13	2.1		RHH	Following are eight recommendations adopted by the Sabine-Neches BBEST regarding an environmental flow regime for the Saine [sic] and Neches Basins and the Sabine-Neches Estuary. Each recommendation includes a brief summary of the rationale associated with the recommendation	Agree with comment; helpful addition		change made as suggested	73
2	13	2.1		RHH	Add the paragraph on the addendum tab for Section 2.1 to the end of this section "Following are eight recommendations adopted by the Sabine-Neches BBEST regarding an environmental flow regime for the Saine [sic] and Neches Basins and the Sabine-Neches Estuary. Each recommendation includes a brief summary of the rationale associated with the recommendation"	Agree with comment; helpful addition		Change made as suggested	74
2	13	2.1.1	Last sentence	SKV	Insert "fully" before "control"	Agree with comment; helpful addition		change made as suggested	152
2	13	2.1.1	Next to last sentence.	SKV	Delete "direct"	Agree with comment; correction		change made as suggested	151
2	13	2.1.1		RHH	Suggest putting the recommendation in the heading (like most are) in the following manner: RECOMMENDATION 1: THE SAC DEFINITION OF A SOUND ECOLOGICAL ENVIRONMENT (SEE SECTION 1.2.4) APPLIES TO THE SABINE AND NECHES RIVERS AND THE SABINE-NECHES ESTUARY		Good point; alternate correction to issue made	Added clarifying language	75
2	13	2.1.1		RHH	Delete the repeated definition of a sound ecological requirement [sic; perhaps environment] from the text. It is not needed since it was discussed previously in section 1.2.4	Agree with comment; report organization		Change made as suggested	76
2	13	2.1.1		RHH	Add a bold "Rationale" ahead of the parapgraph [sic] beginning "The Sabine-Neches BBEST recognizes…"	Agree with comment; correction		change made as suggested	77
2	13	2.1.1	line 5	RHH	modify this line to read: "etc.) unelated [sic] to and unaffected by direct instream flows. Therefore, while recommended instream flow regimes may have a"	Agree with comment; helpful addition		change made as suggested	78
2	13	2.1.1	last line	RHH	modify this line to read: "does not have the ability to control these systems."	Agree with comment; clarification		Alternate revision	79
2	13	2.1.2	line 3	RHH	change to Appendix XII-1	Agree with comment; report organization		change made as suggested (globally for all 3 WQ appendices)	82
2	13	2.1.2	line 2	RHH	modify the sentence to read: "…(TSWQS) at the 12 gages selected for SB3 consideration within the range of flows for…"	Agree with comment; clarification		change made as suggested	81
2	13	2.1.2	Recommendation heading	RHH	delete the parenthetical: (Sabine Lake), as it has already been defined.	Agree with comment; correction		change made as suggested	80
2	13	2.1.2	4th line	SKV	Insert "segments including the" before "12 gages"	Agree with comment; helpful addition		change made as suggested	153

Section	Page	Subsection	SectionParagraph	CommentBy	Comment	AcceptReason	RejectReason	ActionOnComment	ID
2	14	2.1.2	line 1	RHH	delete the first part of the line: "selected for SB3 consideration"		Good point; alternate correction to issue made	Alternate revision	83
2	14	2.1.2	line 5	RHH	add to the end of the sentence: "…page 132) despite the influence that the Sabine-Neches Waterway and Gulf Intracoastal Canal have on salinity in the estuary."	Agree with comment; correction		Change made as suggested with correction to Gulf Intracoastal Waterway	84
2	14	2.1.3	7th line	SKV	Replace "recommends" with "believes"	Agree with comment; clarification		change made as suggested	154
2	14	2.1.3	Recommendation heading	RHH	Suggest rewrite:"RECOMMENDATION 3: ACKNOWLEDGE THAT FLOWS IN THE SABINE AND NECHES RIVERS AND INFLOWS TO THE SABINE-NECHES ESTUARY WILL CHANGE OVER TIME"	Agree with comment; clarification		change made as suggested	85
2	14	2.1.3	line 7	RHH	rplace [sic] "recommends" with "understands"		N/A due to another change	Used "believes" rather than "understands"	86
2	14	2.1.4	line 7	RHH	delete "likely"	Agree with comment; clarification		change made as suggested	87
2	14	2.1.4	line 8	RHH	replace "may be largely" with "is"	Agree with comment		change made as suggested	88
2	14	2.1.4	line 11	RHH	add phrase after the word process: "and other overlay disciplines"	Agree with comment; helpful addition		change made as suggested	89
2	15	2.1.5	7th line	SKV	Replace "median" with "25th - 75th"	Agree with comment; correction		change made as suggested	156
2	15	2.1.5	1st line	SKV	Delete "water supply"	Agree with comment; clarification		change made as suggested	155
2	15	2.1.6	Rationale paragraph line 5	RHH	replace "seasonal" with "limited"	Agree with comment		change made as suggested	91
2	15	2.1.6	Recommendation heading	RHH	rewrite heading: "RECOMMENDATION 6: SUBSISITENCE FLOWS ARE DEFINED ON A SEASONAL BASIS FROM MBFIT/HEFR, UNLESS: <then add the two numbered items, all in the heading caps"		Disagree with comment; heading too long to appear in TOC	None	90
2	16	2.1.6	Rationale paragraph on page 16; line 4	RHH	rewrite: "….called DFLOW by EPA),…"	Agree with comment; clarification		Added clarifying language	92
2	16	2.1.7	1st sentence	SKV	Replace "levels" with "storage" at 3 locations	Agree with comment; clarification		change made as suggested	157
2	16	2.1.7	1st sentence	SKV	Replace "50th percentile" with "25th - 75th percentiles"	Agree with comment; correction		change made as suggested	158
2	16	2.1.7	Recommendation heading	RHH	rewrite heading to read: BASE FLOWS, DEFINED ON A SEASONAL BASIS REPRESENT THRESHOLDS FOR ENVIRONMENTAL PROTECTION BASED ON…." <include the entire bolded part of this section as part of the recommendation heading>		Disagree with comment; suggested change would make TOC entry cumbersome	None	93
2	16	2.1.8	RECOMMENDATION 8: first paragraph	RCH	Mention gaged inflows that are not included in analysis for SB3 selected gages: Pine Island Bayou (Neches) and Cow Bayou (Sabine).	Agree with comment; helpful addition		Change made as suggested	205
2	16	2.1.8	Title	SKV	Renumber subsection from "2.1.8" to "2.1.9" and change recommendation "8" to "9"	Agree with comment; report organization		change made as suggested	159
2	16	2.1.8	New subsection	SKV	Insert attached file "S&N_Pulse_Recommendation_SKV_11-16-2009_v2.doc" as new Recommendation 8.	Agree with comment; correction		change made as suggested	160
2	17	2.2.1		SKV	Delete sub-section re: Recognition 1 and renumber following sub-sections and Recognitions	Agree with comment; correction		change made as suggested	161
2	17	2.2.1	last sentence, second paragraph	SH	may consider another word rather than "acceptable environmental risk", would consider using "environmental change" or "fluctuation" or "variance" as opposed to "risk"		Disagree with comment; Specific terminology used based on SNBBEST discussion	None	245
2	17	2.2.1	Heading	RHH	add to the end of the recognition heading: "AS FLOWS THAT MUST BE PRESCRIBED"		N/A due to another change	None	94
2	18 AND 19	2.2.3, 2.2.4, 2.2.5		RHH	These Recognitions are addressed later under unique conditions and should not be in this section. Delete them from here		Recognitions introduced here for specific purpose	None	95

Section	Page	Subsection	SectionParagraph	CommentBy	Comment	AcceptReason	RejectReason	ActionOnComment	ID
2	19	2.2.4	Paragraph above Rationale; and Rationale	JWT	Above rationale – add - All free water (free water means all waters other than stored water) and stored water in the stateline reach, without reference to origin, will be divided equally between the two states. Add to rationale – "Stateline" means the point on the Sabine River where its waters in downstream flow first touch the states of both Louisiana and Texas.	Agree with comment; helpful addition		Change made as suggested	206
2	19	2.2.5	Rationale	JWT	This section leaves the reader hanging; need to strengthen it. Move recognitions part down into rationale and add into recommendation – Environmental flows as well as the diversions for the water supply canal system in Texas are adversely affected by migration of channel flow to the Old River Channel in Louisiana during low and average flow condtions [sic].	Agree with comment; helpful addition		Change made as suggested	207
2, 5 and 6	17, 64 & 95	2.2.1, 5.2.2.3 and 6.1.2.3		SH	the report begins with a summary of "recommendations" and "recognitions" then goes on to elaborate on each item and include foreseeable implementation senarios. There seems to be a contradition as to whether high pulses are recommended or not and later in the report has high pulses would be prescribed	Agree with comment; clarification		N/A due to another change	246
3	20	3.1.1	section heading	RHH	delete section heading (only one in section)	Agree with comment; report organization		change made as suggested	96
3	20	3.1.2	section heading	RHH	delete section heading (only one in section)	Agree with comment; report organization		change made as suggested	97
3	21	3.2.1	Last sentence, 1st paragraph	SKV	Add "Upper Neches River Municipal Water Authority (UNRMWA)" to the list.	Agree with comment; correction		change made as suggested	162
3	21	3.2.1	last paragraph	SH	strike the word "lower" from the first sentence and rewrite last sentence as "In accordance with its permit as issued by TCEQ, there is a minimum pass-through flow requirement of 400 cfs for the saltwater barrier."	Agree with comment; helpful addition		Change made as suggested	247
3	23	3.3.1	1st sentence	SKV	54,000 acres doesn't match Table 16 (60,000 acres)	Agree with comment; clarification		Alternate revision	163
3	27-35	3.4 - 3.4.4	All text	KW	I suggest moving sections 3.4 Regional Water Planning, 3.4.1. 2007 State Water Plan, 3.4.2 Unique Stream Segments, 3.4.3 Unique Reservoir Sites, and 3.4.4 Sabine-Neches Area Unique Issues to the back of the document (to page 137, just in front of the Glossary). Member note: I'd like to suggest that we move some of this material that is not directly related to our analyses and environmental flow recommendations to a position that follows our presentation of 1) what we were assigned to do, 2) what we did, and 3) what our recommendations are.		Disagree with comment	Reduced size of this section, per comment in revised draft	256
3	28	3.4.1	first paragraph on page 28	RHH	delete parenthetical phrase: (including water conservation)	Agree with comment; delete unnecessary text		change made as suggested	98
3	29	3.4.2.	second full paragraph on page 29	RHH	line 8: Delete the phrase "While a very small portion of the Neches Rvier [sic] basin falls within Region H…" and begin the sentence with "Recommended unique…."	Agree with comment; delete unnecessary text		change made as suggested	99
3	30	3.4.3	second paragraph	RHH	incorrect citation of legislation; Member notes: we wrote this and I will get the corrected citation	Agree with comment; clarification		Change made as suggested	101
3	30	3.4.3	last paragraph; last sentence	RHH	rewrite sentence: "….sites taken by RWPGs in Regions I and D."	Agree with comment; clarification		Change made as suggested	100

Section	Page	Subsection	SectionParagraph	CommentBy	Comment	AcceptReason	RejectReason	ActionOnComment	ID
3	30	3.4.3.1		RHH	The Region I RWPG is planning to address the status of future unique reservoir sites for the 2011 update of the regional water plan in December 2009. All currently proposed reservoirs in the region will be considered.	Agree with comment; helpful addition		Change made as suggested	102
3	31	3.4.3.1	new paragraph to add to end of section	RHH	Please add this text: "The Region I RWPG is planning to address the status of future unique reservoir sites for the 2011 update of the regional water plan in December 2009. All currently proposed reservoirs in the region will be considered."	Agree with comment; helpful addition		Change made as suggested	104
3	31	3.4.3.1	line6, second paragraph on page 31	RHH	after designated, add phrase: "a portion of"	Agree with comment; helpful addition		change made as suggested	103
3	32	3.4.4	Sections and subsections	RHH	Elevate the Section from 3.4.4 to 3.5 and elevate each subsection accordingly. This section is not peculiar to regional water planning and should stand on its own.	Agree with comment; report organization		change made as suggested	105
3	34	3.4.4.7	first paragraph	SH	strike the word "lower" from the first sentence		Disagree with comment	None	248
4	36	4.2	End of paragraph	RHH	add the following sentence: "The Sabine-Neches BBEST utilized information provided in the initial drafts of the guidance documents to the extent practical."	Agree with comment; helpful addition		change made as suggested	106
5	38	5.1.1	Heading	RHH	rename: GAGE SELECTION AND GEOGRAPHIC COVERAGE	Agree with comment; helpful addition		change made as suggested	107
5	39	5.1.1	last line of first paragraph on page 39	RHH	add "appropriated" after the word "few"	Agree with comment; clarification		change made as suggested	108
5	39	5.1.1	second paragraph	RHH	Correct reference to Sabine Neches Estuary	Agree with comment; correction		change made as suggested	109
5	39	5.1.1.1	Heading	RHH	delete the subsection heading (not necessary since it's the only one)		Good point; alternate correction to issue made	Added heading for Section 5.1.1.1 Gage Selection; previous 5.1.1.1 now 5.1.1.2	110
5	41	5.1.6	next to last paragraph	KW	Change to: Because of these disadvantages, the hydrologic methods are only recommended when sufficient data to define flow alteration–ecological response relationships are unavailable. In Texas, the only documented sources of such data are from the lower Colorado River, San Marcos River, lower Sabine River, lower Neches River, and Big Cypress Bayou. Member notes: Expand list of examples, as there are other instream flow studies of the IFIM-PHabSim type performed in Texas (refs are available). Member note: Expand list of examples, as there are other instream flow studies of the IFIM-PHabSim type performed in Texas (refs are available).	Accepted		Added clarifying language	257
5	42	5.1.7	lines 1 and 2 of second paragraph	RHH	rewrite first part of the sentence: "Based on recommendations from the SAC in 2003, TCEQ created…."		Disagree with comment	None	111
5	44	5.1.10	first paragraph	RHH	Correct reference to Sabine Neches Estuary	Agree with comment; correction		change made as suggested	112
5	44	5.1.10	line 3 of third paragraph	RHH	Correct reference to Sabine Neches Estuary	Agree with comment; correction		change made as suggested	113
5	44	5.1.9	last line of first paragraph on page 39	RHH	rewrite last line: "reasonable and scientifically defensible approach in the contect [sic] of SB3.	Agree with comment; helpful addition		change made as suggested	114
5	50	5.1.10	Next to last paragraph, last line	SKV	Insert "of base" after "percentile"	Agree with comment; consistency		change made as suggested	164

Section	Page	Subsection	SectionParagraph	CommentBy	Comment	AcceptReason	RejectReason	ActionOnComment	ID
5	50	5.1.10.1	Heading	RHH	delete the subsection heading (not necessary since it's the only one)		Good point; alternate correction to issue made	Promoted this to Section 5.1.11	115
5	52	5.1.10	last paragraph on page 52	RHH	rewrite: "….called DFLOW by EPA),…"	Agree with comment; clarification		Change made as suggested	116
5	53	5.1.10.1	Next to last paragraph, last sentence	SKV	Delete sentence beginning with "Recommendations may in some cases . . ."	Agree with comment; delete unnecessary text		change made as suggested	165
5	53	5.1.10.1	1st sentence of second paragraph on page	KW	Change to: Other flow selection methods, including the 95th percentile of historic flows, were considered, and the BBEST concluded that each has certain strengths and weaknesses. Member note: At one point, the biology subcommittee recommended the 95th percentile of flows as the subsistence threshold (the account and rationale is given in the Biological Overlay document), but this was later rejected in favor of the HEFR subsistence estimates (by consensus).	Agree with comment; clarification		Change made as suggested	258
5	53 and 54	5.1.11	throughout the section	RHH	Correct reference to Sabine Neches Estuary	Agree with comment; correction		change made as suggested	117
5	53-54	5.1.11	2nd to last paragraph	KW	Define in the text what MinQ, MaxQ and MaxC are. Member note: This is the first appearance of the acronyms in our document.	Agree with comment; clarification		Added clarifying language	259
5	57	5.2.1	line 1	RHH	delete the "s" from Overlay	Agree with comment; grammar fix		change made as suggested	118
5	57	5.2.2	last line of paragraph	RHH	Correct the references to the appendices (should be Appendices VIII and VII).	Agree with comment; correction		Change made as suggested	214
5	58	5.2.2.1	4th line of third paragraph	RHH	Move parenthesis: BIO-WEST (2009b)	Agree with comment; correction		Change made as suggested	217
5	58	5.2.2.1	6th line of third paragraph	RHH	Wording of the sentence beginning "A trend…" needs work. See Additional Text Tab Proposed text is: "A trend in the lower reaches of the maintems [sic] of both the Sabine and Neches Rivers is toward higher flow during exceptionally dry summers, as compared to historical flows under the same conditions."	Agree with comment; clarification		Change made as suggested	218
5	58	5.2.2.1	line 1 of second paragraph	RHH	Capitalize "River"	Agree with comment; correction		Change made as suggested	216
5	58	5.2.2.1	line 1 of first paragraph	RHH	word addition:"….flow requirements necessary to maintain…"		Disagree with comment	None	215
5	59	5.2.2.1	2nd paragraph under Subsistence Flow Recommendations	SKV	Replace the sentence beginning with "In most cases, . . ." with "Initial adoption of the summer seasonal subsistence flow from HEFR for the entire year resulted in seasonal flows well below levels ever recorded for the segment in the winter."	Agree with comment; clarification		change made as suggested	168
5	59	5.2.2.1	last line of 2nd paragraph	RHH	add "River" between "Sabine" and "segments"	Agree with comment; clarification		Change made as suggested	220
5	59	5.2.2.1	2nd paragraph under Subsistence Flow Recommendations	SKV	Replace "This was especially true for winter," with "Winter is"	Agree with comment; delete unnecessary text		change made as suggested	166
5	59	5.2.2.1	2nd paragraph under Subsistence Flow Recommendations	SKV	In the sentence beginning with "Second, . . . ", replace "lowest" with "summer" and delete ", 7Q10,"	Agree with comment; clarification		change made as suggested	167

Section	Page	Subsection	SectionParagraph	CommentBy	Comment	AcceptReason	RejectReason	ActionOnComment	ID
5	59	5.2.2.1	9th line of third paragraph	RHH	use "including" instead of "included"	Agree with comment; correction		Change made as suggested	221
5	59	5.2.2.1	next to last line of third paragraph	RHH	"ectothermic", not "ecothermic"	Agree with comment; correction		Change made as suggested	222
5	59	5.2.2.1	2nd paragraph under Subsistence Flow Recommendations	SKV	At the end of the sentence beginning with "Second, ...", append "though such subsistence flow levels are comparable to available 7Q10 values (Table 6) for the full period of record"	Agree with comment; clarification		change made as suggested	169
5	59	5.2.2.1	line 1 of 4th paragraph	RHH	add "of all recorded flows" after "5th percentile"	Agree with comment; clarification		Change made as suggested	219
5	59 - 60	5.2.2.1	line 1 of last paragraph on page 59 AND in next to last paragraph on page 6	RHH	delete the " 's" from Sbucommitee [sic]	Agree with comment; grammar fix		change made as suggested	119
5	60	5.2.2.1	3rd paragraph under Subsistence Flow Recommendations	SKV	At the end of the paragraph, append the following sentence. "It is noted, however, that treated effluent comprises a significant component of the subsistence and base flows of the San Antonio River."	Agree with comment; clarification		change made as suggested	170
5	61	5.2.2.2	Figure 13	KW	I think the figure caption got split up (above and below the figure)?	Agree with comment; formatting fix		Alternate revision	260
5	62	5.2.2.3		SKV	Include caps in subtitle "Responses of aquatic focal species to high flow pulses."	Agree with comment; clarification		change made as suggested	171
5	63	5.2.2.3	line 1 of second paragraph	RHH	rewrite first sentence; see Additional Text tab Among alligator gars and other gar species, adults and juveniles (particularly juveniles) commonly move into flooded plains to feed…	Agree with comment; clarification		Change made as suggested	223
5	63	5.2.2.3	2nd paragraph under Pulse Flow and Overbanking Recommendations	SKV	In the 1st sentence, add "and overbanking events" after "high flow pulses"	Agree with comment; clarification		change made as suggested	172
5	63	5.2.2.3	line 3 of 1st paragraph	RHH	rewrite: "Our terrestrial focal species that have aspects of their…."	Agree with comment; clarification		Added clarifying language	224
5	63	5.2.2.3	2nd paragraph under Pulse Flow and Overbanking Recommendations	SKV	In the 2nd sentence add "and overbank flow" after "High flow pulse"	Agree with comment; clarification		change made as suggested	173
5	63	5.2.2.3	Responses of Focal Species to Overbanking Flows	MWM	Sharitz and Mitsch 1993 reference. Change sentence to "These bottomland hardwood tree species require periodic flooding (including occasional growing season overbank flows) for successful…" Member notes: Recognize importance of occasional growing season overbanking flows. Not all of the functions listed will be satisfied by dormant season flows only.	Agree with comment; clarification		Change made as suggested	201
5	64	5.2.2.3	line 4 of second paragraph	RHH	Capitalize "Rivers"	Agree with comment; grammar fix		Change made as suggested	226
5	64	5.2.2.3	line 3 of 1st paragraph	RHH	rewrite: "…and correlation (i.e., R2) for all four models was high."	Agree with comment		Change made as suggested	225

Section	Page	Subsection	SectionParagraph	CommentBy	Comment	AcceptReason	RejectReason	ActionOnComment	ID
5	65	5.2.2.3	Closing paragraph in bold text	SKV	Insert the following sentence to replace the existing bold text. "Climatic conditions and flood events are expected to produce these levels of flow even with full use of existing water rights and realistic projections of water supply development."	Agree with comment; clarification		Change made as suggested	176
5	65	5.2.2.3	Closing paragraph in bold text	SKV	Before language in draft, insert the following sentence. "Seasonal high flow pulses have recognized ecological benefits and are recommended for protection with certain reservations associated with environmental and operational liability risks."	Agree with comment; clarification		change made as suggested	174
5	65	5.2.2.3	Closing paragraph in bold text	SKV	Insert the following sentence immediately before existing bold text. "The Sabine-Neches BBEST also recognizes the ecological functions and benefits of overbank flows, but does not recommend actions be taken to produce such flows.	Agree with comment; clarification		change made as suggested	175
5	65	5.2.3	15th line of second paragraph	RHH	reference at the end of the line to the State Methodology is missing part of the title.	Agree with comment; clarification		Change made as suggested	227
5	66	5.2.3	3rd line second paragraph under NWF discussion	RHH	delete "specific"	Agree with comment; delete unnecessary text		change made as suggested	228
5	66	5.2.3	middle of 6th paragraph of section	SH	In listing the key species, "These key species and communities are:…" oysters were omitted in this sentence	Agree with comment; correction		Change made as suggested	249
5	66	5.2.3	entire section	RCH	Key species and communities are: Rangia cuneata larvae --- The larval stage of Rangia is not suitable as a focus or key species, it is present for only a short time period after spawning. It is very stenotolerant to everything, but after a few days it is benthic and after a few months it is eurytolerant to nearly everything.	Agree with comment		Added clarifying language	210
5	66	5.2.3.1		RHH	5.2.3.1 NATIONAL WILDLIFE FEDERATION (NWF) ANALYSIS OF HABITAT SUITABILITY…..	Agree with comment; report organization		change made as suggested	120
5	66 plus 68, 71 and other pages	5.2.3	Rangia references in second and third paragraphs and thereafter	RHH	Rangia cuneata should be italicized and abbreviated version of the mussel's name should be "R.cuneata" (italicized).	Agree with comment; consistency		Change made as suggested	229
5	66-71	5.2.3	NWF habitat suitability section	RHH	Suggest deleting most of this as it is all repeated in the discipline appendix. keep the first four paragraphs of this section and delete everything after to the section on the State methodology.		Disagree with comment	None	121
5	66-72	5.2.3	formatting of subsections	RHH	several subsection numbers should be added as follows:	Agree with comment; report organization		Change made as suggested	122
5	67	5.2.3	just below Figure 14	SH	there appears to be a remnant of a sentence "with the synthetic inflow record… Village Creek." that was moved or copied to another location and should be deleted	Agree with comment; clarification		Good point; alternate correction to issue made; the original NWF figure title included this text, but is too long for the auto-generated TOC. Re-wrote it as a sentence.	250
5	71	5.2.3	3rd paragraph on this page	SKV	After the first sentence, insert the following sentence. "Assumed subsistence flows did not include periodic dry base flows."	Agree with comment; helpful addition		Change made as suggested	177
5	71	?	1st line of last paragraph on page 71	RHH	rewrite beginning of sentence: "For the salinity-inflow relationship…."	Agree with comment; clarification		Change made as suggested	230
5	71	5.2.3.2		RHH	5.2.3.2 THE STATE METHODOLOGY FOR ESTIMATING FRESHWATER INFLOW NEEDS OF BAYS AND ESTUARIES	Agree with comment; report organization		change made as suggested	123
5	72	5.2.3	second paragraph, second sentence	RCH	USGS gages on Pine Island Bayou and Cow Bayou were used.		N/A	None	211
5	72	5.2.3.4		RHH	5.2.3.3 COMPARISON OF HEFR-GENERATED FRESHWATER INFLOWS TO…..	Agree with comment; report organization		change made as suggested	124

Section	Page	Subsection	SectionParagraph	CommentBy	Comment	AcceptReason	RejectReason	ActionOnComment	ID
5	72	5.2.3.4		RHH	5.2.3.4 IMPACTS OF OIL AND GAS EXPLORATION AND SHIP CHANNEL…..	Agree with comment; report organization		change made as suggested	125
5	74	5.2.3	Adaptive Management	RHH	Give this subsection a 5.2.4 Adaptive Management and Biological Considerations	Agree with comment; report organization		change made as suggested	126
5	74	5.2.4	Renumber	RHH	Renumber to 5.2.5 BIO-WEST ECOLOGICAL REVIEW. Also the subsection numbers	Agree with comment; report organization		change made as suggested	127
5	74	5.2.4	1st sentence	SKV	Replace "development" with "identification"	Agree with comment; correction		change made as suggested	178
5	76	5.2.4.1	Fluvial Table 8. third line from bottom	RCH	Tritogonia (pistolgrip) not a good indicator, it is too rare. Should use Amblema plicata or Quadrula mortoni, these are both common to abundant.		N/A	None	212
5	77	?	line 2 of first paragraph in Sabine-Neches Estuary Focal Species section	RHH	rewrite beginning of sentence: "The list of focal species was collectively…."	Agree with comment; grammar fix		Change made as suggested	231
5	78	5.3	line 9	RHH	end sentence after transport."	Agree with comment; delete unnecessary text		change made as suggested	128
5	78	5.3	end of paragraph	RHH	Add new sentence: "Appendix XIV contains the complete Geomorphic Overlay discipline report for the Sabine-Neches BBEST.	Agree with comment; helpful addition		change made as suggested	129
5	78	5.3	line 7	RHH	replace "which" with "that"	Agree with comment; grammar fix		change made as suggested	130
5	78	5.3	line 6	RHH	Correct reference to Sabine Neches Estuary		Don't see specific reference	None	131
5	78	5.3	line 9	RHH	Start next sentence with "The analyses…."; and delete "also" at the beginning of the next line.		Don't see reference	None	132
5	79	?	1st paragraph on page 79	RHH	format problem at third to last line	Agree with comment; formatting fix		Change made as suggested	232
5	79	5.3.1.1	sediment discharge section	RHH	format problem near end of paragraph	Agree with comment; formatting fix		change made as suggested	133
5	80	5.3.1.1	2nd paragraph on this page	SKV	Remove "-" from exponent for meters ("m") at two locations.	Agree with comment; correction		change made as suggested	179
5	83	5.3.3	flow senario 2	SH	present day operations is TCEQ Run 8, rather than Run 3	Agree with comment; correction		Change made as suggested	251
5	83	5.3.3	flow senario 3	SH	this should be identified as TCEQ WAM Run 3 so that references to Runs 3 and 8 would be understood in later text	Agree with comment; correction		Change made as suggested	252
5	85	5.3.4	middle of 2nd paragraph	SH	change the word "is" to "in" at "… 30% and the channel in this area could be…"	Agree with comment; correction		Change made as suggested	253
5	85	5.4	1 paragraph	SKV	Replace "6.4" with "5.4"	Agree with comment; correction		change made as suggested	180
5	85	5.4	entire section	RCH	All of the water quality stations are from the freshwater USGS gages, none from the industrialized reaches of the rivers or from Sabine Lake. TCEQ has sample stations in Segment 0601 in the lower Neches. TPWD has years of data from Sabine Lake and the Keith Lake system.	Agree with comment; helpful addition		Change made as suggested (as a footnote)	213
5	86	5.4.1	last line of first paragraph on page 86	RHH	rewrite: "…to say that water quality cannot be maintained at flows lower than 7Q2, or should not be considered."	Agree with comment; clarification		change made as suggested	136
5	86	5.4.1	line 1 of third paragraph on 86	RHH	Appendix XII-1	Agree with comment; formatting fix		change made as suggested	135
5	86	5.4.1	line 3 of third paragraph on 86	RHH	add "expected to be" after the word "be"	Agree with comment; formatting fix		change made as suggested	134
5	87	5.4.3	line 3 of third paragraph on 87	RHH	Appendix XII-2	Agree with comment; clarification		change made as suggested	137

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5	90	5.4.4	line 3 of 4th paragraph	RHH	Appendix XII-2	Agree with comment; report organization		change made as suggested	138
5	90	5.4.5	line 5 of first paragraph	RHH	Appendix XII-2	Agree with comment; report organization		change made as suggested	139
5	90	5.4.5	line 3 of first paragraph	RHH	replace comma after "however" with a colon	Agree with comment; grammar fix		change made as suggested	140
6		na	photographs	RHH	na; The TPWD is a good source of photographs of the Neches River. You might see if they can get some to replace the Google Earth photos		Due to time limitations unable to replace the photographs	None	233
6	101	6.1.5	2nd paragraph, 9th line	SKV	Delete "conservation" and add "at the top of the conservation pool" after "acre-feet."	Agree with comment; clarification		change made as suggested	189
6	103	6.1.5	Figure 19	SKV	Replace with revised version found in attached file "Revised_Fig_19.pdf."	Agree with comment; correction		change made as suggested	190
6	104	6.1.5	Figure 20	SKV	Replace with revised version found in attached file "Revised_Fig_20.pdf."	Agree with comment; correction		change made as suggested	191
6	105	6.1.5	Figure 21	SKV	Replace with revised version found in attached file "Revised_Fig_21.pdf."	Agree with comment; correction		change made as suggested	192
6	106	6.1.5	Figure 22	SKV	Replace with revised version found in attached file "Revised_Fig_22.pdf."	Agree with comment; correction		change made as suggested	193
6	107	6.1.5	Attainment Frequencies in Flow Regime Applications, last sentence	MWM	1. Change "clearly indicative" to "suggests" 2. Delete "is, however" 3. Break into two sentences, with a period after "locations". 4. Delete “even though” 5. Make second sentence read "However, since frequencies of attainment for various flows will be less than observed historically, additional study will be required to ascertain potential environmental effects of these recommendations. Member notes: Better reflects our scientific uncertainty, lack of actual risk assessment, and recommendations for more study.	Agree with comment; clarification		Change made as suggested	202
6	114	6.2.1.4	Text to add in a new section (perhaps).	JWT	Add to Section 6.2.1.4: In the HEFR analyses for Sabine-Neches BBEST, the gage with the most discrepancies was the Bon Wier gage relative to the downstream (59 river miles) Ruliff gage. In most cases, it is expected that the downstream gage would have higher values than the upstream gage. However, the HEFR values for Bon Wier are almost always significantly higher than Ruliff. The reason for this discrepancy may stem from NWS bankfull and flood stage discharges, but it is unclear based on available information if threshold parameters should be changed and how this would translate into environment needs. The current FERC relicense studies may shed more light on this issue at the Bon Wier gage.	Agree with comment; helpful addition		Change made as suggested	203
6	120	6.2.2.1		SKV	Replace photograph with attached file "Neches_River_nr_Neches_7-1-2005.JPG."	Agree with comment; helpful addition		change made as suggested	194
6	126	6.2.2.4		SKV	Consider replacement of Google map with photo from TPWD (2005).		Unable to implement due to time constraints	None	195
6	128	6.2.2.5		SKV	Consider replacement of Google map with photo from TPWD (2005).		Unable to implement due to time constraints	None	196
6	130	6.2.2.6		SKV	Consider replacement of Google map with photo from TPWD (2005).		Unable to implement due to time constraints	None	197
6	134	6.2.3.1	1st paragraph after bullets	SKV	Add following sentence. "Furthermore, the NWF study did not include passage of seasonal base flows under dry hydrologic conditions."	Agree with comment; helpful addition		Change made as suggested	198

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6	92	preamble	third and fourth bullets	RHH	I do not see these as being different. Unresolved issues here can't be finalized b/c data are not there to do so; therefore future studies are needed. I suggest combining these two under the heading "Future Studies." SUGGEST taking the term "unresolved issues" out of this discussion and focusing on the need for future studies.	Disagree with comment		None	234
6	92	preamble	first bullet	RHH	either delete the quote marks or cite where the quote comes from	Agree with comment; formatting fix		Change made as suggested	235
6	93	6.1.1	line 2	RHH	delete "instream" (redundent next to "environmental")	Agree with comment; delete unnecessary text		Change made as suggested	236
6	93	6.1.1	line 1	RHH	"Recommendations" (plural needed)	Agree with comment; grammar fix		Change made as suggested	237
6	93,94,95	6.1.2.1, 6.1.2.2, 6.1.2.3, 6.1.2.4	line 1 of last paragraph and applicable paragraphs of 6.1.2.2, 6.1.2.3, and 6.1.2.4	RHH	rewrite first sentence; see Additional Text tab Analysis of available hydrologic, biologic, geomorphic, and water quality data; and the exercise of best professional judgment, suggest that….	Agree with comment; clarification		Change made as suggested	238
6	94	6.1.2.2	3rd paragraph	SKV	At the end of the sentence beginning with "However," append "except under dry hydrologic conditions."	Agree with comment; clarification		change made as suggested	182
6	94	6.1.2.2	3rd paragraph	SKV	In the first sentence, delete "a great deal of"	Agree with comment; correction		change made as suggested	181
6	94	6.1.2.2	line 5 of third paragraph	RHH	replace "likely will" with "may"	Agree with comment; clarification		Change made as suggested	239
6	95	6.1.2.3	beginning 11th line of 3rd paragraph	RHH	suggest rewriting the bolded section of this paragraph for clarity; see Additional Text tab The Sabine-Neches BBEST recognizes such reductions in high flow pulses will be a consequence of the interaction between water use and natural variation in precipitation. The Sabine-Neches BBEST views these reductions as an acceptable environmental risk at this time and accepts that they are subject to review as new studies and information become available.	Agree with comment; clarification		Change made as suggested	240
6	95	6.1.2.3	end of 3rd paragraph	SH	same note as for section 2.2.1 re use of "acceptable risk"		Disagree with comment; Specific terminology used based on SNBBEST discussion	None	254
6	96	6.1.3	bolded section at end of the section	RHH	rewrite the beginning of the bolded section: "The Sabine-Neches BBEST recommends that …."	Agree with comment; clarification		Change made as suggested	241
6	96	6.1.3	2nd paragraph	SKV	In the first sentence, move "cumulative" from its present location to a new location after "of" and before "water."	Agree with comment; clarification		change made as suggested	183
6	96	6.1.3	2nd paragraph	SKV	In the last sentence, change "recommended" to "recommends."	Agree with comment; grammar fix		change made as suggested	184
6	96	6.1.3	1st sentence, 2nd paragraph	SH	First sentence seems that it should also be bold to highlight the recommended way of determining hydrologic condition	Agree with comment; consistency		Change made as suggested	255
6	96	6.1.4	first sentence and beginning of second sentence	RHH	rewrite as shown in Additional Text tab An important consideration in providing recommendations of environmental flow regimes is the understanding of how such regimes might be applied to new surface water appropriations. Hence, the Sabine-Nechess BBEST's understanding…	Agree with comment; clarification		Change made as suggested	242
6	97	6.1.4	Table 15	SKV	Replace Table 15 with attached file "Implementation_Example_v3.pdf."	Agree with comment; correction		change made as suggested	185
6	98	6.1.4.1		SKV	Replace entire subsection with revised version found in the attached file "Revised_6.1.4.1-6.1.4.3_11-16-2009_SKV.docx."	Agree with comment; correction		change made as suggested	186

Section	Page	Subsection	SectionParagraph	CommentBy	Comment	AcceptReason	RejectReason	ActionOnComment	ID
6	98	6.1.4.2		SKV	Replace entire subsection with revised version found in the attached file "Revised_6.1.4.1-6.1.4.3_11-16-2009_SKV.docx."	Agree with comment; correction		change made as suggested	187
6	99	6.1.4.3		SKV	Replace entire subsection with revised version found in the attached file "Revised_6.1.4.1-6.1.4.3_11-16-2009_SKV.docx."	Agree with comment; correction		change made as suggested	188
Appendices				RHH	SUGGEST CHANGE THE NUMBERS ON THESE APPENDICES TO APPENDIX XII-1, APPENDIX XII-2, AND APPENDIX, XII-3 (RATHER THAN WQ-1, WQ-2, AND WQ-3	Agree with comment; report organization		Change made as suggested	243
Signature Page	na	na	na	RHH	those of us who are PE's are going to have to deal with this issue that we are supposed to seal virtually anything we sign. I am planning to contact the board of registration about this.			No action required in report that can be taken at this time	48
ToC	ii	2.2.5		SKV	Replace "6" with "5"	Agree with comment; grammar fix		change made as suggested	141
ToC	ii	3.4.4		SKV	Consider changing Section 3.4.4 to Section 3.5	Agree with comment; grammar fix		handled due to a previously addressed comment	142
TOC	ii	NA	na	RHH	suggest de-denting the Sabine Neches Study Area section to be 3.5 and its subsections up by a level. This section is not peculiar to Regional water planning but is its own issue.	Agree with comment; report organization		change made as suggested	49
ToC	iii	5.2.2.3		SKV	Stray "-"	Agree with comment; grammar fix		change made as suggested	143
ToC	iii	5.3.1.2		SKV	Format.	Agree with comment		Change made as suggested	144
TOC	iii	NA	na	RHH	Subsection 5.3.1: Recent Senate Bill 2 Studies (spell out SB)	Agree with comment; use of abbreviations		change made as suggested	50
TOC	ii-iv	na	na	RHH	should not have single subsections within a section: eliminate headings for 3.2.1; 5.1.0.1; 6.2.3.1;	Partially agree with comment; report organization		3.2.1 change made as suggested; 5.1.0.1 up-dented to 5.1.11 rather than eliminated; this is a major section that should be in the TOC; added new 6.2.3.1 "Estuary Description"; 6.2.3.2 is "SAC Guidance …"; and added 6.2.3.3 "U.S. Army Corps of Engineers …"	51
ToC	iv	6.2.2.6		SKV	Add ", TX"	Agree with comment; correction		change made as suggested	145
ToC	iv	6.2.3.1		SKV	Format.				146
TOC	iv	NA	na	RHH	The first appendix should the [sic] the applicable Texas Water Code legislation		Disagree with comment	None	52
ToC	v	9.3.3		SKV	Format.				147
TOC	v	NA	na	RHH	subsection 9.3.1: suggest renaming the water quality appendices XII-1, XII-2, and XII-3.	Agree with comment; report organization		change made as suggested	54
TOC	v	NA	na	RHH	subsection 9.2.2: its Freese and Nichols, not Freese-Nichols	Agee with comment; correction		change made as suggested	53
ToC	v	9.3.3		SKV	Format.				147
TOC	v	NA	na	RHH	subsection 9.2.2: its Freese and Nichols, not Freese-Nichols	Agee with comment; correction		change made as suggested	53
TOC	v	NA	na	RHH	subsection 9.3.1: suggest renaming the water quality appendices XII-1, XII-2, and XII-3.	Agree with comment; report organization		change made as suggested	54