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

SAC Members

Robert Brandes, Ph.D, P.E., Vice-Chair
Robert Huston, Chair
Paul Jensen, Ph.D, P.E.
Mary Kelly
Fred Manhart
Paul Montagna, Ph.D
George Ward, Ph.D
James Wiersema

Document Version Date: August 31, 2009

Report # SAC-2009-05

Table of Contents

SECTION 1. INTRODUCTION AND BACKGROUND 1
1.1 Intersection of Senate Bills 2 and 3 2
1.2 Overview of Texas Rivers and Streams 3
1.3 Instream Flow Science 4
1.3.1 Biology 4
1.3.2 Hydrology 5
1.3.3 Geomorphology 6
1.3.4 Water Quality 6
1.4 Instream Flow Regime Components 6
SECTION 2. DEVELOPMENT OF INFORMATION FOR BIOLOGICAL OVERLAY 11
2.1 River Basin, Regional and Ecoregion Data Resources 12
2.2 Information Sources Habitat Requirements 13
2.2.1 Current Velocity and Depth 14
2.2.2 Instream Cover 15
2.2.3 Substrate Composition 15
2.2.4 Instream Vegetation 15
2.2.5 Riparian Vegetation 15
2.2.6 Floodplain Habitat 16
2.2.7 Fish Migration Barriers 16
2.3 Water Quality 16
2.4 Strategies for Synthesis of Available Information 17
2.4.1 Preliminary Data Synthesis and Analysis 18
2.4.2 Confounding Factors 19
SECTION 3. DEVELOPMENT OF GEOGRAPHIC SCOPE FOR FLOW REGIME RECOMMENDATIONS 29
3.1 Realistic Expectations Concerning Geographic Input 30
3.2 Specific Procedures for Developing Geographic Input 31
3.2.1 River Type 31
3.2.2 Use of Available Data Sources and Maps 32
3.2.3 Maps 34
3.3 Summary and Recommendations 36
SECTION 4. BIOLOGICAL INPUT FOR HEFR 44
4.1 HEFR Decision Points 44
4.2 Biological Input to IHA and MBFIT 47
4.3 Biological Input to HEFR 48
4.4 Example Application 49
4.4.1 Default Method 49
4.4.2 Available Biological Data 50
4.4.3 Application of Biological Data During Pre-Processing 52
4.4.4 Biological Input to Hydrographic Separation 54
4.5 Biological Input to HEFR 55
4.5 Summary 56
SECTION 5. OVERLAY OF BIOLOGICAL INFORMATION: REFINING THE FLOW REGIME MATRIX 58

5.1 Integration is a Multi-disciplinary Process 58
5.2 Subsistence Flows 59
5.3 Base Flows 60
5.4 High Flow Pulses 62
5.5 Overbank Flows 63
5.6 Adaptive Management 63
SECTION 6. SUMMARY AND RECOMMENDATIONS 65
SECTION 7. REFERENCES 71
SECTION 8. INSTREAM BIOLOGY WORKGROUP 83

List of Tables

Table 1. Some ecological functions performed by instream flow regime components 9
Table 2. Selected key ecological related questions that should be addressed. 20
Table 3. Characteristics of Aquatic Life Use Subcategories 45
Table 4. Pre-Processing Decision Points 46
Table 5. Biological Input for the IHA Hydrographic Characterization 47
Table 6. Biological Input for the MBFIT Hydrographic Characterization 48
Table 7. Biological Input to HEFR 49
Table 8. Lower San Antonio Instream Flow Guidelines 50

List of Figures

Figure 1. Trinity River Basin- Basin and Sub Basins 38
Figure 2. Trinity River Basin- Biotic Provinces and Ecological Zones 39
Figure 3. Vegetation Types Requiring Overbanking 40
Figure 4. Trinity River System with Associated Vegetation Types 41
Figure 5. Trinity River System- Exampleof Inundation Areas 42
Figure 6. Trinity River System- Example of Marsh/Swamp Areas 43
Figure 7. Conceptual Model depicting stage of change in biological conditions 45
Figure 8. Flow Regime Matrix Generated With Default Values 50
Figure 9. Habitat Types vs. Discharge 51
Figure 10. Predicted Fish Habitat per Guild or Species 51
Figure 11. Percent of maximum habitat vs. simulated discharge at Smithville 53
Figure 12. Input for IHA Hydrographic Separation 54
Figure 13. Modified HEFR Inputs 55
Figure 14. Modified Flow Regime Matrix 56
Figure 15. Flow Duration Curve Generated Using the Default Method 57
Figure 16. Modified Flow Duration Curve Based on Biological Input 57
Figure 17. Wetted width relationships to spring flow in the San Marcos River 60
Figure 18. Paddlefish life cycle in relation to seasonal flow in Big Cypress Bayou 62

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.

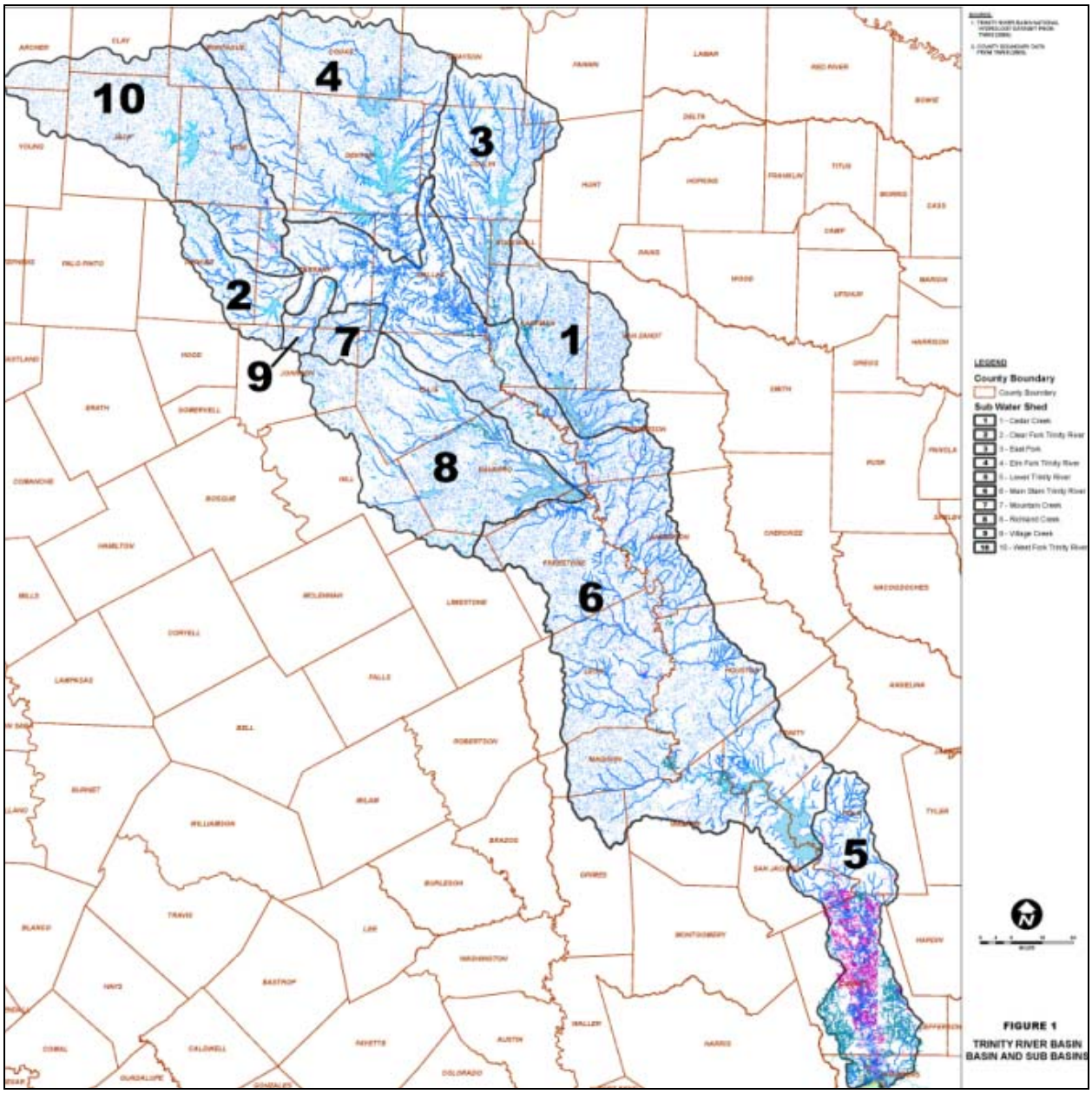

Figure 1. Trinity River Basin- Basin and Sub Basins

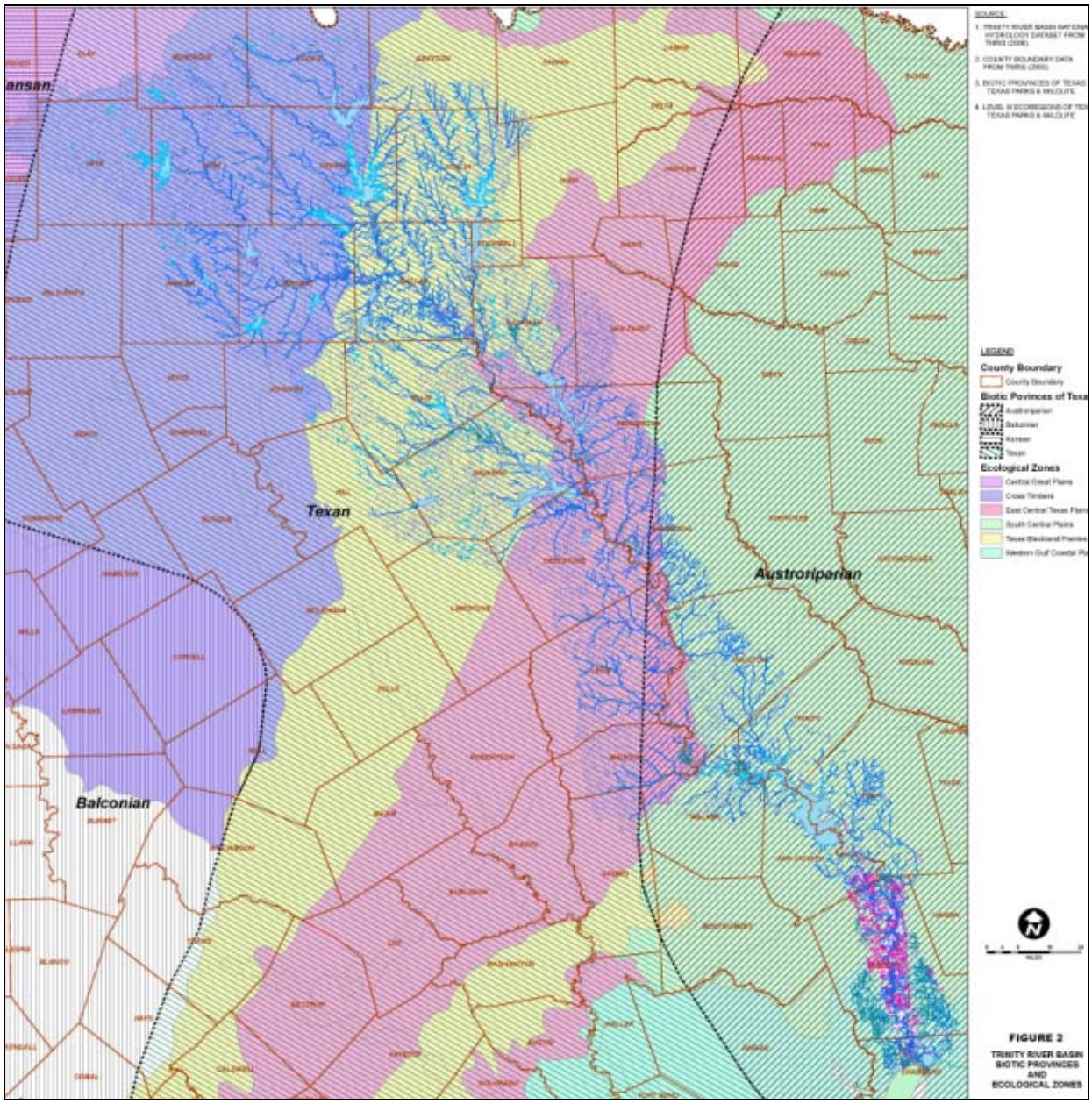

Figure 2. Trinity River Basin- Biotic Provinces and Ecological Zones

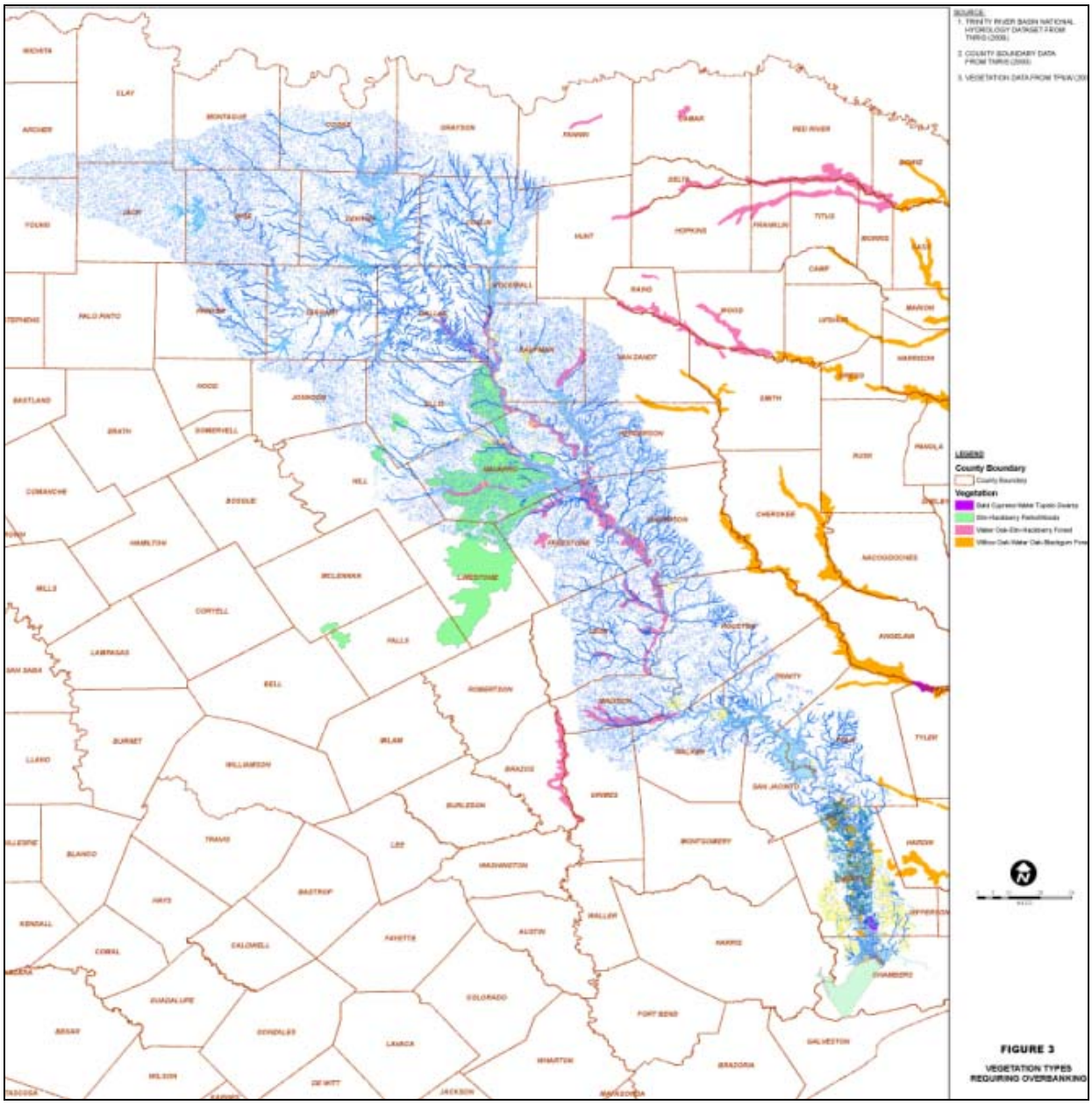

Figure 3. Vegetation Types Requiring Overbanking

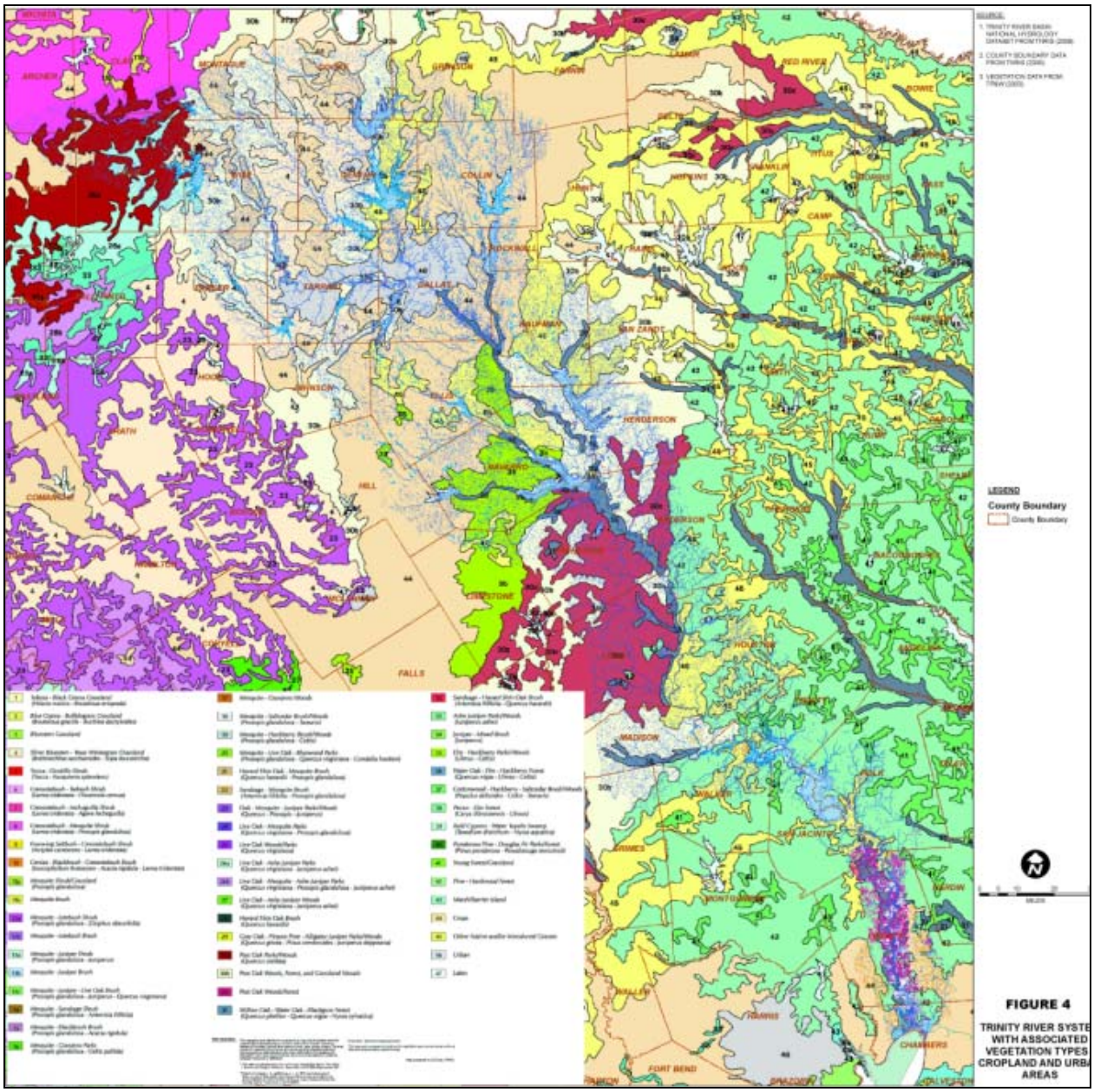

Figure 4. Trinity River System with Associated Vegetation Types Cropland and Urban Areas

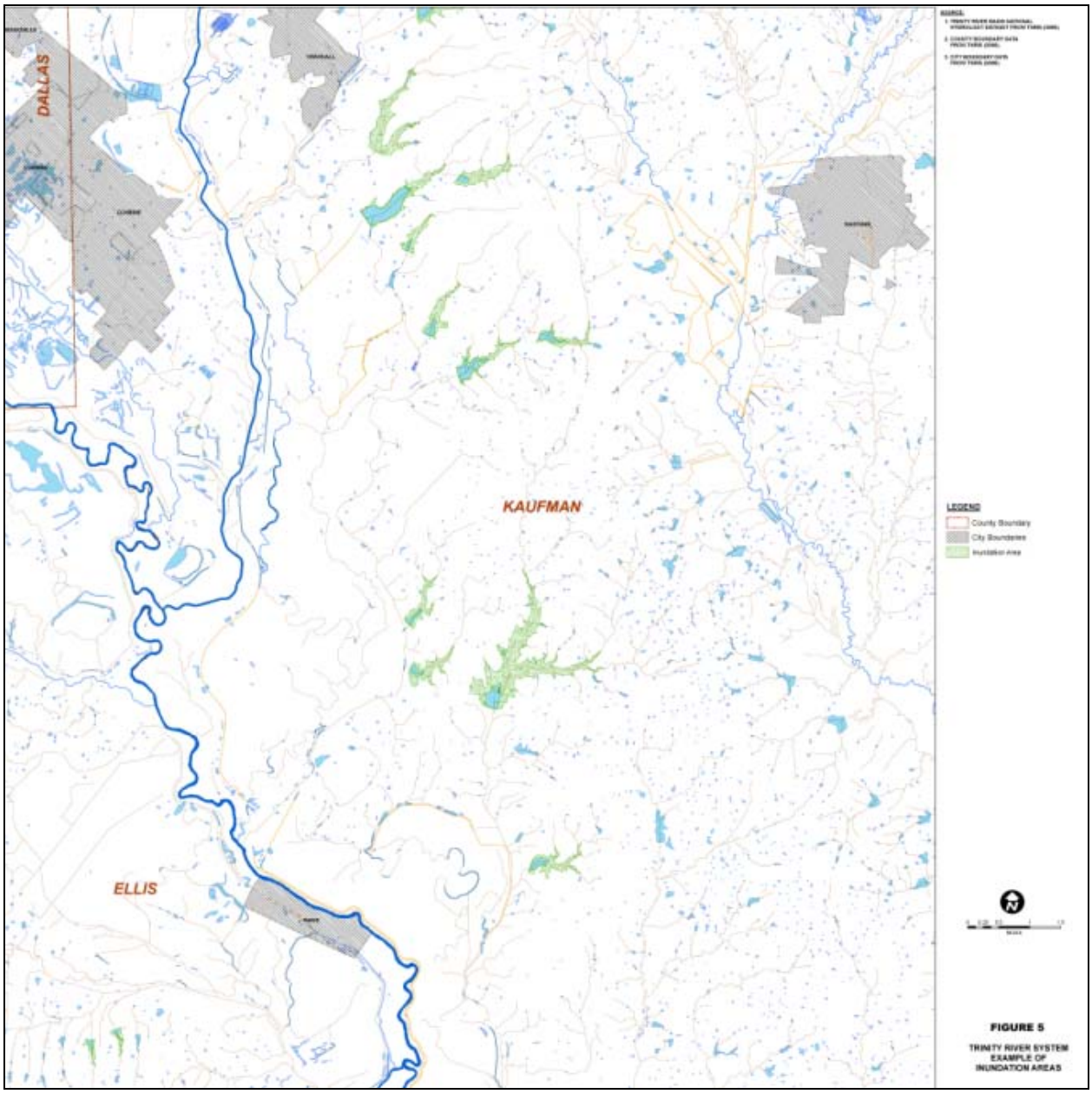

Figure 5. Trinity River System- Example of Inundation Areas

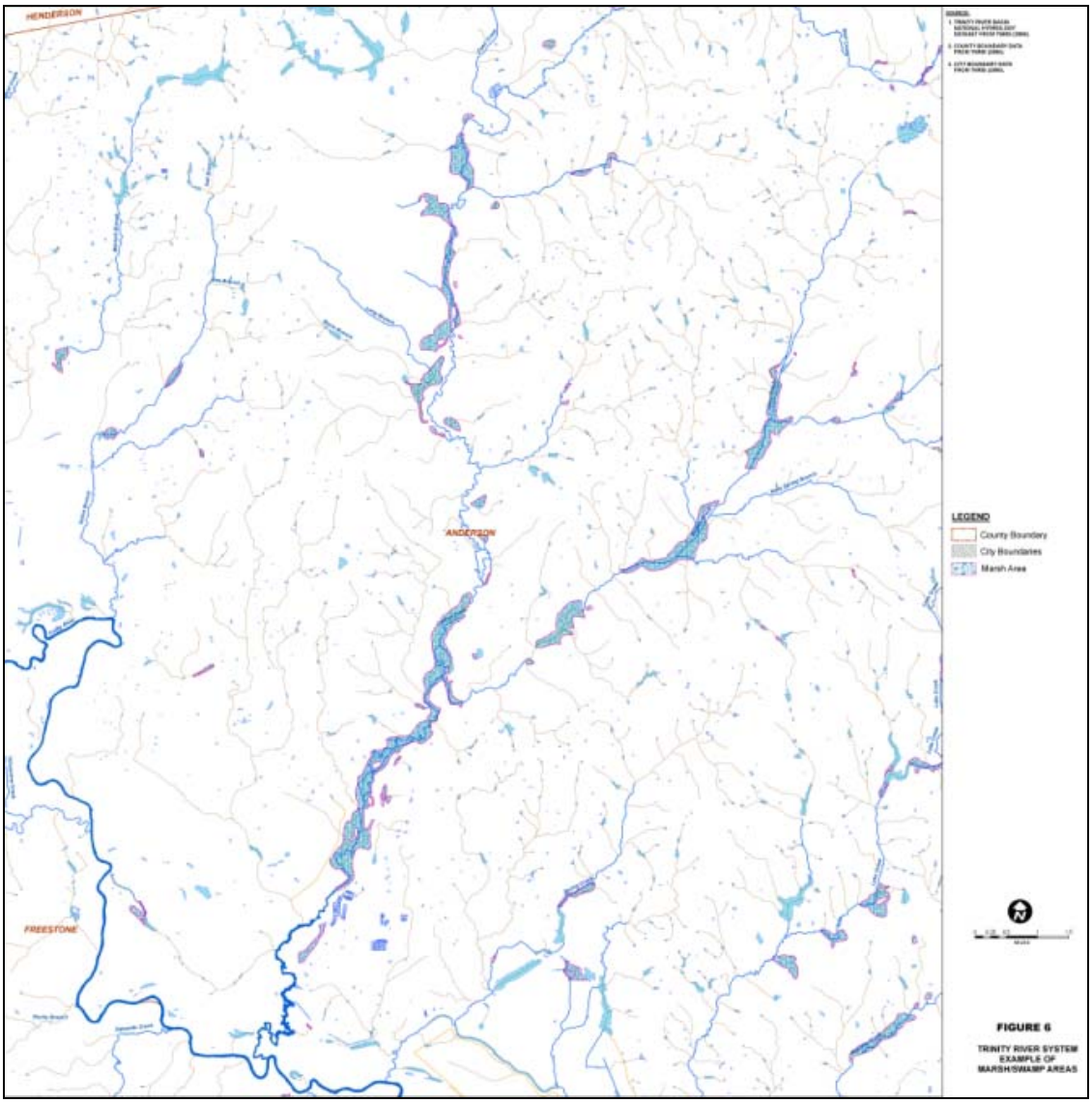

Figure 6. Trinity River System- Example of Marsh/Swamp Areas

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

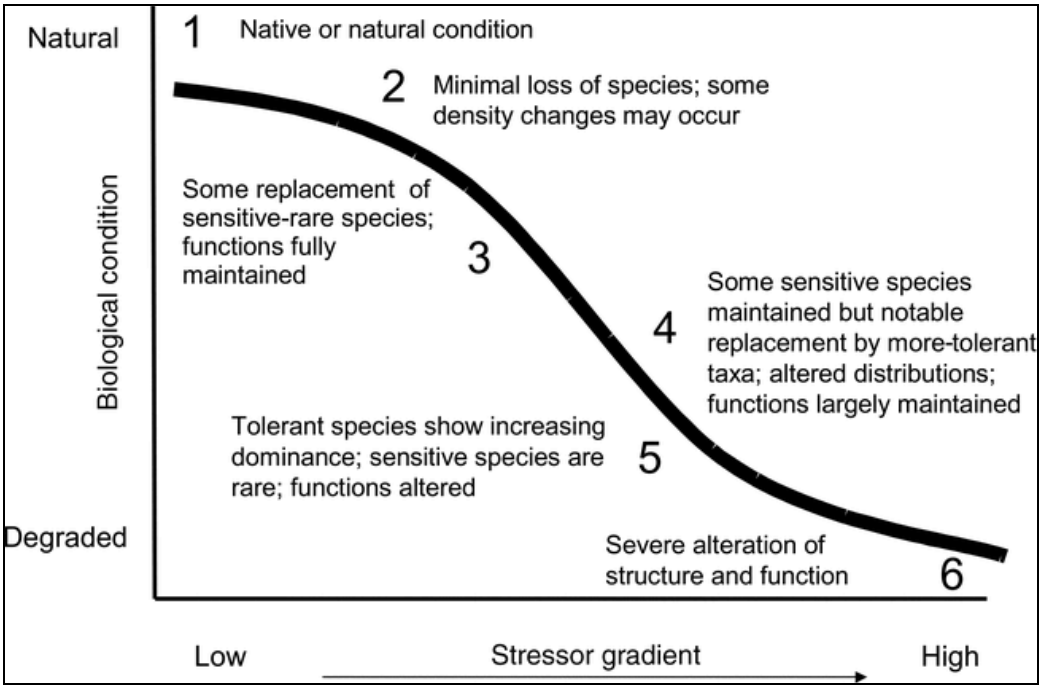

Figure 7. Conceptual Model Depicting Change in Biological Conditions in Response to an Increasing Stressor Gradient (from Davies and Jackson 2006)

[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.

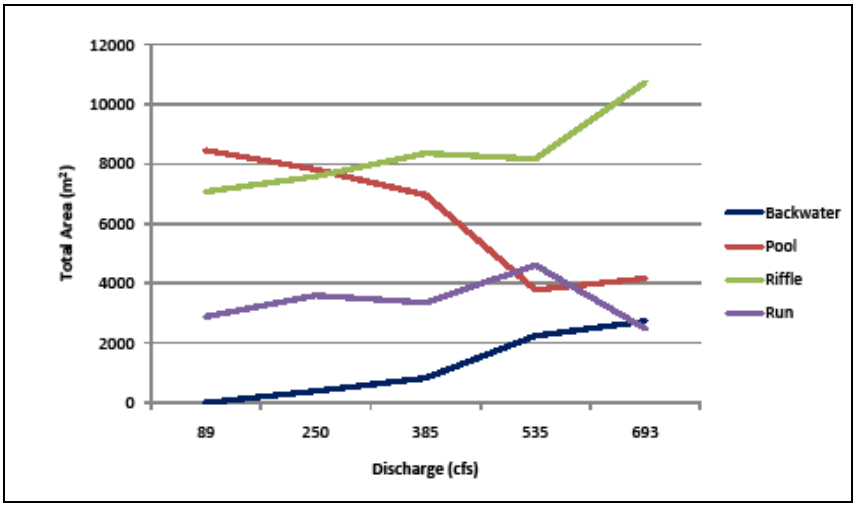

Figure 9. Habitat Types vs. Discharge (from BIO-WEST 2008, Figure 5.5, Page 36)

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.

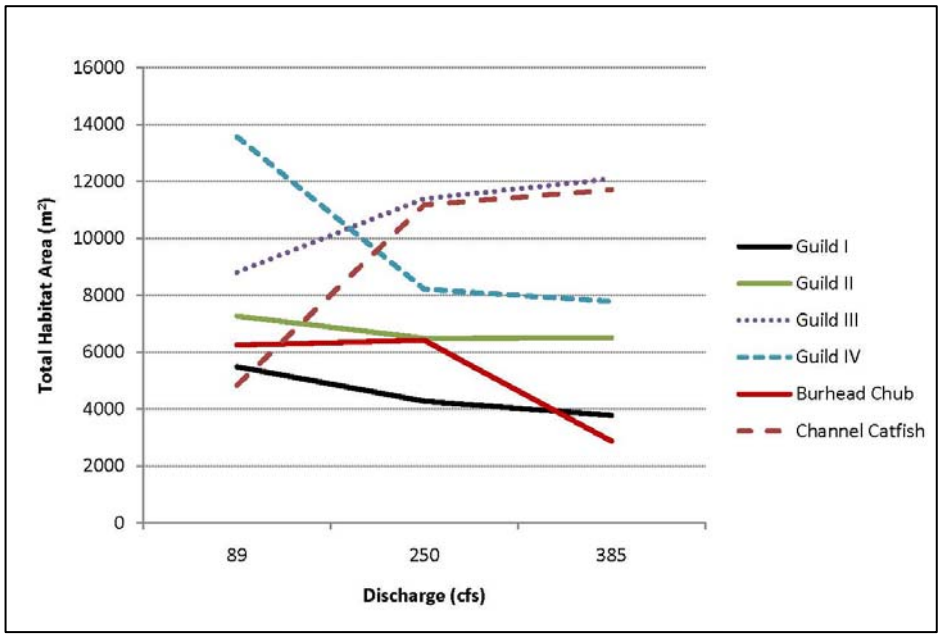

Figure 10. Predicted Fish Habitat per Guild or Species (from Bio-West 2008, Figure 6.8, Page 77)

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).

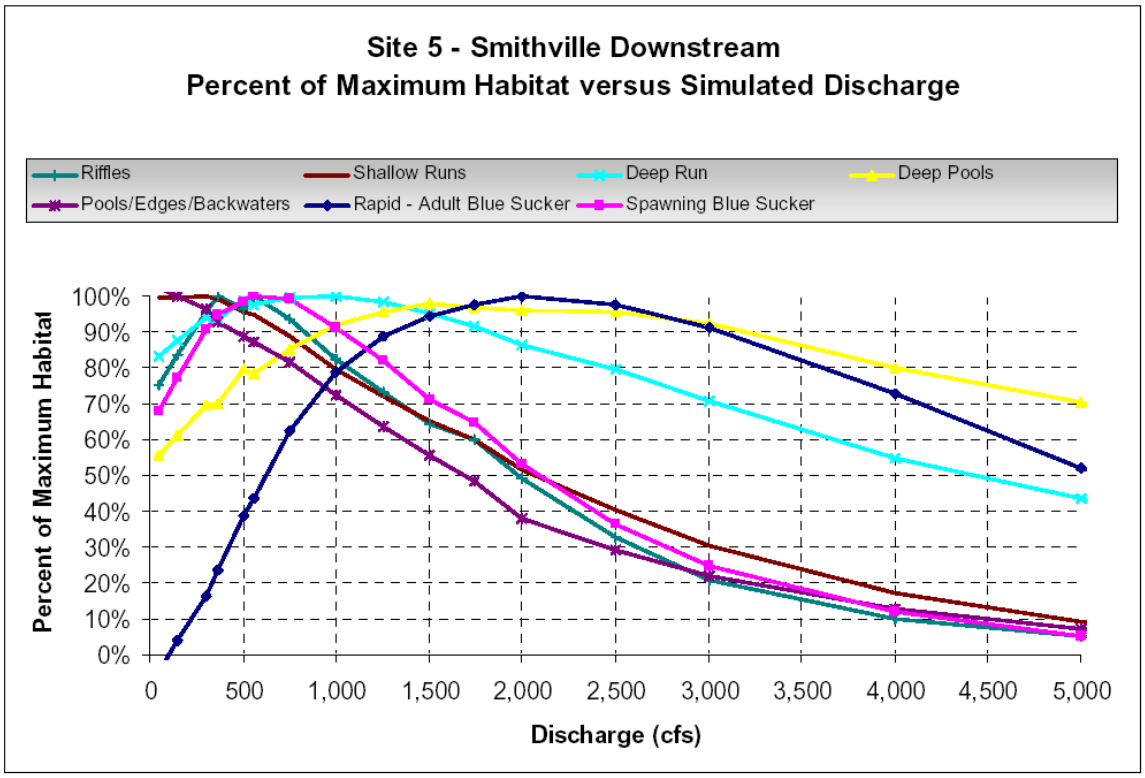

Figure 11. Percent of Maximum Habitat vs. Simulated Discharge at Smithville (from BIO-WEST 2007, Figure C10, Page C6)

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.

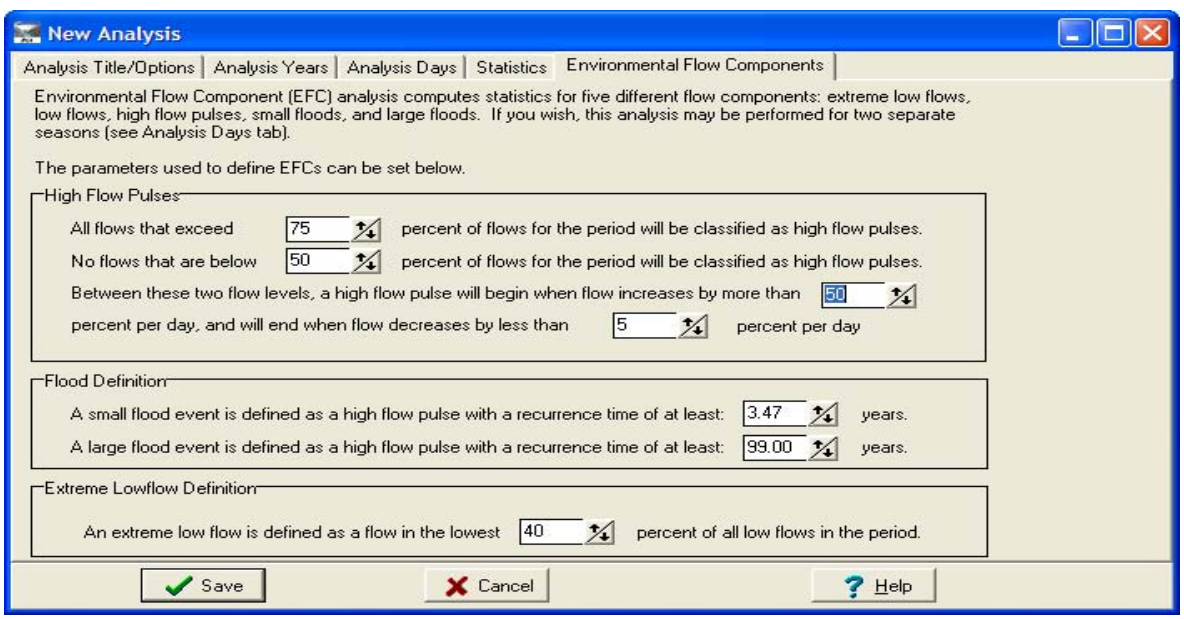

Figure 12. Input for IHA Hydrographic Separation

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.

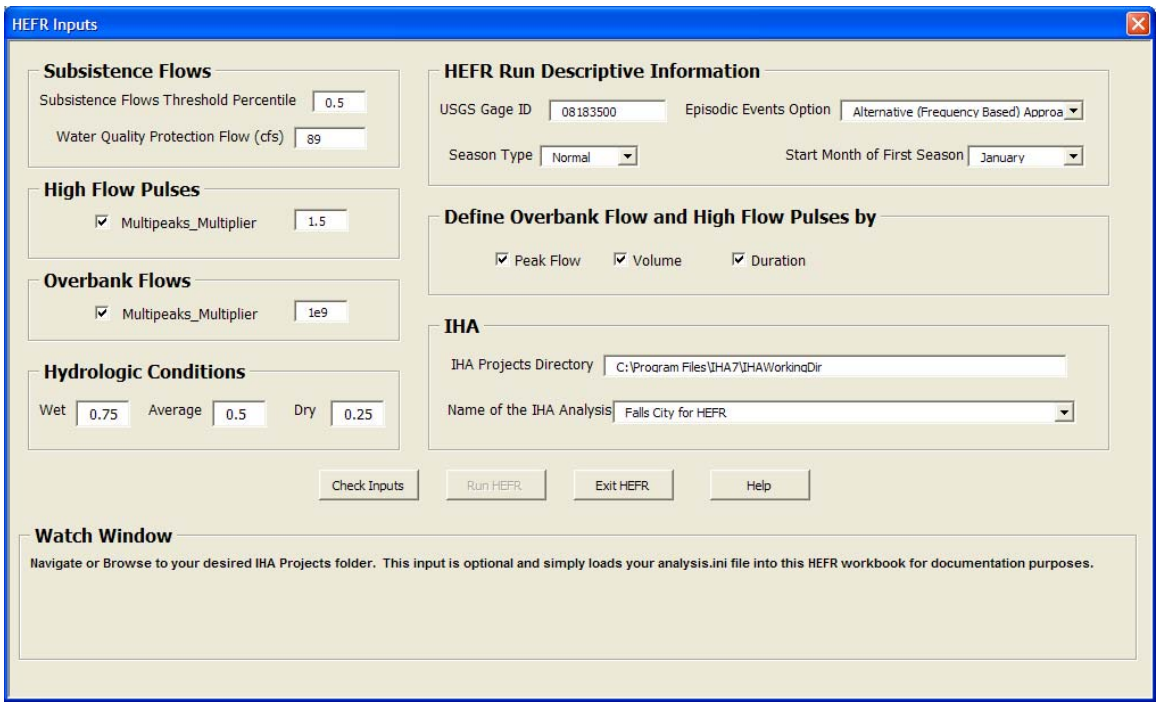

Figure 13. Modified HEFR Inputs

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.

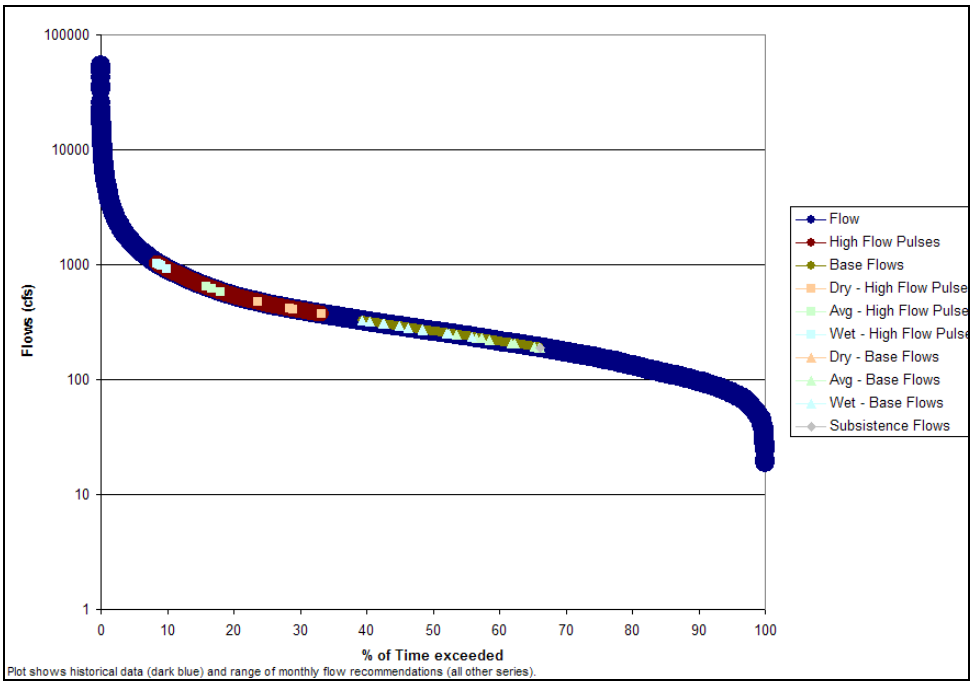

Figure 15. Flow Duration Curve Generated Using the Default Method

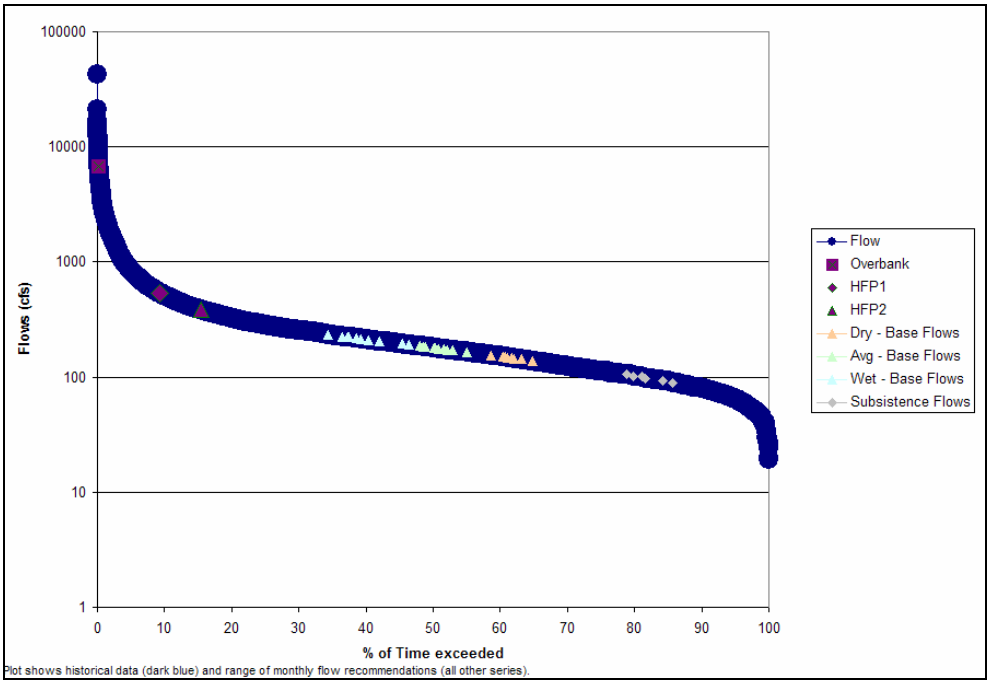

Figure 16. Modified Flow Duration Curve Based on Biological Input

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).

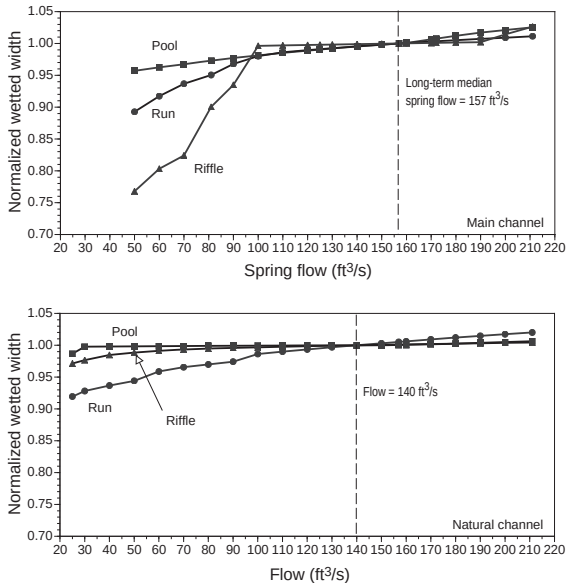

Figure 17. Wetted Width Relationships to Spring Flow in the San Marcos River (from Saunders et al. 2001)

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.

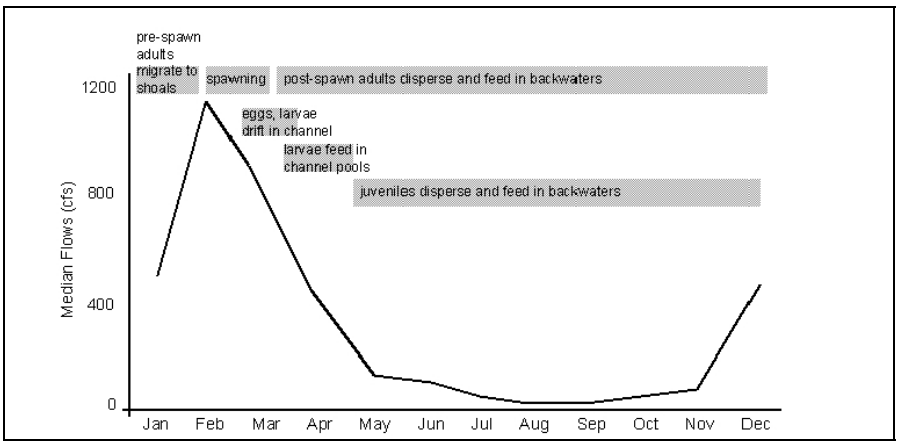

Figure 18. Paddlefish Life Cycle in Relation to Seasonal Flow in Big Cypress Bayou (from Winemiller et al. 2005)

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).

SECTION 7. REFERENCES

Abell, R.A., D.M. Olson, E. Dinerstein, P.T. Hurley, J.T. Diggs, W.Eichbaum, S. Walters, W. Wettengel, T. Allnutt, C.J. Loucks, and P. Hedao. 2000. Freshwater ecoregions of North America: a conservation assessment. Island Press, Washington, D.C.

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.

Angermeier, P.L. 1987. Spatiotemporal variation in habitat selection by fishes in small Illinois streams. Pages 52-60 *in* W.J. Matthews and D.C. Heins, editors. Community and evolutionary ecology of North American stream fishes. University of Oklahoma Press, Norman, Oklahoma.

Annear, T., I. Chisholm, H. Beecher, A. Locke and 12 other authors. 2004. Instream flows for riverine resource stewardship, revised edition. Instream Flow Council, Cheyenne, Wyoming.

Apse, C., M. DePhilip, J. Zimmerman, and M. P. Smith. Developing instream flow criteria to support ecologically sustainable water resource planning and management. Final report to the Pennsylvania Instream Flow Technical Advisory Committee: 196. 2008.

Armour, C.L. 1991. Guidance for evaluating and recommending temperature regimes to protect fish. U.S. Fish and Wildlife Service Biological Report 90(22). 13 p.

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.

Arrington, D.A., K.O. Winemiller, and C.A. Layman. 2005. Community assembly at the patch scale in a species rich tropical river. *Oecologia* 144:157-167.

Arthington, A. H., S. E. Bunn, N. L. Poff and R. J. Naiman. 2006. The challenge of providing environmental flow rules to sustain river ecosystems. Ecological Applications 16: 1311-1318.

Balon, E. 1975. Reproductive guilds of fishes: a proposal and definition. Journal of the Fisheries Research Board of Canada 32(6): 821-864.

Balon, E. 1981. Additions and amendments to the classification of reproductive styles in fishes. Environmental Biology of Fishes 6(3/4): 377-389.

BIO-WEST. 2007. Draft Instream Flow Guidelines Development. Colorado River Flow Relationships to Aquatic Habitat and State Threatened Species: Blue Sucker. Prepared for Lower Colorado River Authority and San Antonio Water System. April 23, 2007. Available at http://www.lcra.org/library/media/public/docs/lswp/findings/BIO_Draft_ifguidelines_2007.pdf

BIO-WEST. 2008. Preliminary Instream Flow Assessment for the Lower San Antonio River (Interim Subsistence and Base-Dry Instream Flow Guidelines Development). Prepared for San Antonio River Authority. September 2008.

BIO-WEST. 2009. Instream Flow Guidelines - Relationships to Aquatic Habitat and State Threatened Species: Blue Sucker.

Blair, W.F. 1950. The Biotic Provinces of Texas. The Texas Journal of Science, Volume 2, No. 1. University of Texas.

Bonner, T. and D. Runyan. 2007. Fish Assemblage Changes in Three Western Gulf Slope Drainages. Report to TWDB, Austin, TX.

Bovee, K.D., B.L. Lamb, J.M. Bartholow, C.D. Stalnaker, J. Taylor, and J. Henriksen. 1998. Stream habitat analysis using the instream flow incremental methodology. Information and Technical Report USGS/BRD-1998-0004. U.S. Geological Survey, Biological Resources Division, Fort Collins, Colorado. 131p.

Bowles, D.E., K. Aziz, and C.L. Knight. 2000. *Macrobrachium* (Decapoda: Caridea: Palaemonidae) in the contiguous United States: a review of the species and an assessment of threats to their survival. Journal of Crustacean Biology 20:158-171.

Brierly, G.J. and Fryirs, K., 2000. River styles, a geomorphic approach to catchment characterization: Implications for river rehabilitation in Bega catchment, New South Wales, Australia. Environmental Management 6, 661-679.

Brierly, G.J. and Fryirs, K., 2005. Geomorphology and river management: applications of the River Styles Framework. Wiley-Blackwell.

Bunn, S.E. and A.H. Arthington. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environmental Management 30:492-507.

Busch, D.E., and M.L. Scott. 1995. Western Riparian Ecosystems. In: LaRoe, E.T., G.S. Farris, C.E. Puckett, P. D. Doran, and M.J. Mac. Our Living Resources: A report to the Nation on the distribution, abundance, and health of U.S. plants, animals, and ecosystems. Washington, DC: U.S. Geological Survey. p. 286-290.

Camp Dressser & McKee Inc., B.D. Bledsoe, W.J. Miller, N.L. Poff, J.S. Sanderson and T.K. Wilding. 2009. Watershed Flow Evaluation Tool pilot study for Roaring Fork and Fountain Creek watersheds and site-specific quantification pilot study for Roaring Fork watershed (draft). Colorado Water Conservation Board, Denver, CO. http://cwcb.state.co.us/IWMD/COsWaterSupplyFuture/

Campbell., L. 2003. Endangered and threatened animals of Texas: their life history and management. Texas Parks and Wildlife Department. Austin, Texas.

Carlander, K.D. 1969. Handbook of Freshwater Fishery Biology - Life History Data on Freshwater Fishes of the United States and Canada, Exclusive of the Perciformes (Volume One) . Iowa State University Press. Ames, Iowa.

Carlander, K.D. 1977. Handbook of freshwater fishery biology. Volume 2. Life history data on Centrachid fishes of the United States and Canada. Iowa State University Press. Ames, Iowa.

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. Iowa State University Press. Ames, Iowa.

Connor, J.V. and R.D. Suttkus. 1986. Zoogeography of freshwater fishes of the western Gulf Slope of North America. pp: 413-456. In: Hocutt, C.H. and E.O. Wiley eds. The Zoogeography of North American Freshwater Fishes. Wiley Interscience. New York, New York.

Cooke, S.J. and D.P. Philipp. 2009. Centrachid fishes: diversity, biology, and conservation. Wiley-Blackwell. West Sussex, UK.

Davies, S. and S. Jackson. 2006. The Biological Condition Gradient: A Descriptive Model for Interpreting Change in Aquatic Ecosystems. Ecological Applications 16(4): 1251-1256.

Dixon, J.R. 2000. Amphibians and Reptiles of Texas: With Keys, Taxonomic Synopses, Bibliography, and Distribution Maps (W.L. Moody, Jr., Natural History Series, No. 8. 2nd edition. Texas A&M University Press.

Douglas, N.H. 1974. Freshwater Fishes of Louisiana. Claitors Publisher

Eastman, J. and A. Hansen. 1999. Birds of Lake, Pond and Marsh: Water and Wetland Birds of Eastern North America Stackpole Books. Birds of Field and Shore: Grassland and Shoreline Birds of Eastern North America.

Edwards, R.J., G. Longley, R. Moss, J. Ward, R. Matthews, and B. Stewart. 1989. A classification of Texas aquatic communities with special consideration toward the

conservation of endangered and threatened taxa. Texas Journal of Science 41:231-240.

Edwards, R.J. 1997. Ecological profiles for selected stream-dwelling Texas freshwater fishes. TWDB Report. Contract 95-483-107. UT Pan American. Edinburg, Texas.

Ehrlich, P., D. Dobkin and D. Wheye. 1988. The Birder's Handbook: A Field Guide to the Natural History of North American Birds. Fireside.

Engel, F.L., and J.C. Curran. Geomorphic Classification of the Lower San Antonio River, Texas. Texas Water Development Board Project 0604830637. 2008.

Fischer, R.A. 2000. Width of riparian zones for birds. EMRRP Technical Notes Collections (TN EMRRP-SI-09). U.S. Army Engineer Research and Development Center, Vicksburg, MS.

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.

Froese, R. and D. Pauly. Editors. 2000. FishBase 2000. Concepts, design and data sources. FAO Makati City, Philippines. Electronic Source: http://www.fishbase.org

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.

Gorman, O.T. and J.R. Karr. 1978. Habitat structure and stream fish communities. Ecology 59:507-515.

Gorman. O.T. 1988. The dynamics of habitat use in a guild of Ozark minnows. Ecological Monographs 58(1) 1-18.

Griffith, G., S. Bryce, J. Omernik, and A. Rogers. 2007. Ecoregions of Texas. AS-199 (12/07). Project Report to Texas Commission on Environmental Quality.

Guillen, G., and J. Wrast. 2009. Trinity River Basin Literature Review. Annotated Bibliography. Work to date: January 6, 2009. Environmental Institute of Houston.

Harris, N. M., A.M. Gurnell, D.M. Hannah, and G.E. Petts. Classification of river regimes: a context for hydroecology. Hydrol. Processes 14: 2831-2848. 2000.

Hassan-Williams, C. and T. Bonner. 2009. Texas Freshwater Fishes Website. Available at http://www.bio.txstate.edu/~tbonner/txfishes/index.htm

Henriksen, J. Hydroecological Integrity Assessment Process (HIP) for Texas: Stream Classification Tool for Texas (TxSCT). US Geological Survey. 2008.

Henriksen, J. A., J. Heasley, J. G. Kennen, and S. Nieswand. Users' Manual for the Hydroecological Integrity Assessment Process Software (including the New Jersey Assessment Tools). U.S. Geological Survey Open-File Report 2006-1093: 71. 2006.

Hersh, E., and D. Maidment. An Integrated Stream Classification System for Texas. CRWR Online Report 07-02. Available at <http://www.crwr.utexas.edu/online.shtml>. 2007.

Higgins, J.V., M.T. Bryer, M.L. Khoury, and T.W. FitzHugh. A Freshwater Classification Approach for Biodiversity Conservation Planning. Conservation Biology 19: 432-435. 2005.

Howells, R.G., R.W. Neck, and H.D. Murray. 1996. Freshwater mussels of Texas. Texas Parks and Wildlife Department, Austin, Texas.

Hubbs, C. 1985. Darter reproductive seasons. Copeia 1985(1):56-68.

Hubbs, C., R.J. Edwards and G.P. Garrett. 2008. An annotated checklist of the freshwater fishes of Texas, with keys to identification of species. Texas Academy of Science. Available at http://www.texasacademyofscience.org/

Hubert, W.A., S.H. Anderson, P.S.Southall and J.H. Crance. 1984. Habitat suitability index models and instream flow suitability curves: paddlefish. FWS/OBS-82/10.80. Fort Collins, Colorado.

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.

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.

Knighton, D. 1998. Fluvial forms and processes: a new perspective. Oxford University Press

Kuehne, R.A. and R.W. Barbour. 1983. The American Darters. University Press of Kentucky. Frankfort, Kentucky.

Johnson, E. The Natural Regions of Texas. University of Texas Bulletin 3113. Bureau of Business Research. The University of Texas. 1931.

Johnston, C.E. 1999. The relationship of spawning mode to conservation of North American minnows (Cyprinidae). Environmental Biology of Fishes 55:21-30.

Junk, W.J., P.B. Bayley & R.E. Sparks. 1989. The flood pulse concept in river-floodplain systems, p.110-127 In D.P. Dodge (ed) Proceedings of the International Large River Symposium. Canadian Special Publication of Fisheries and Aquatic Sciences 106.

Lee, D., C.R. Gilbert, C. H. Hocutt, R. E. Jenkins, D.E. McAllister, and J.R. Stauffer, Jr. 1980. Atlas of North American Freshwater Fishes. Publication 1980-12. North Carolina State Museum.

Leftwich, K.N., P.L. Angermeier and C. A. Dolloff. 1997. Factors influencing behavior and transferability of habitat models for benthic stream fish. Transactions of the American Fisheries Society 126(5): 725-734.

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.

Linam, G.W., L.J. Kleinsasser, and K.B. Mayes. 2002. Regionalization of the index of biotic integrity for Texas streams. River Studies Report No. 17. Texas Parks and Wildlife Department, Austin, Texas.

Locke, A., C. Stalnaker, S. Zellmer, K. Williams, H. Beecher, T. Richards, C. Robertson, A. Wald, A. Paul and T. Annear. 2008. Integrated approaches to riverine resource stewardship: case studies, science, law, people, and policy. Instream Flow Council. Cheyenne, Wyoming.

Lytle, D.A., and N.L. Poff. Adaptation to natural flow regimes. Trends in Ecology and Evolution 19: 94-100. 2004.

Matthews, W.J. and D.C. Heins.editors 1987. Community and evolutionary ecology of North American Stream Fishes. University of Oklahoma Press. Norman, Oklahoma.

Mayden, R.L. editor. 1992. Systematics, historical ecology, and North American Freshwater Fishes. Stanford University Press. Stanford, California

McCafferty, W.P. 1983. Aquatic Entomology: The Fishermen's Guide and Ecologists' Illustrated Guide to Insects and Their Relatives. Jones and Bartlett Publishers, Inc.

Merritt, R.W., K.W. Cummins and M. Berg. 2008. An introduction to the aquatic insects of North America. 4th edition.Kendall Hunt Publishing.

Michigan Groundwater Conservation Advisory Council. Report to the Michigan Legislature in response to Public Act, 34: 37. 2007.

Miller, R.J. and H.W. Robison. 2004. Fishes of Oklahoma. University of Oklahoma Press. Norman, Oklahoma.

Miller, R.R., W. L. Minckley, and S.M. Norris. 2006. Freshwater fishes of Mexico. University Of Chicago Press.

Morrow, J.V. and C. Fischenich. 2000. Habitat requirements for freshwater fishes. ERDC TN-EMRRP-SR-06. U.S. Army Corp of Engineers. Vicksburg, MS.

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. Austin, Texas

Naiman, R.J., H. Décamps, and M.E. McClain. 2005, Riparia: ecology, conservation, and management of streamside communities. Elsevier Academic Press. San Diego, California.

National Weather Service Advanced Hydrologic Predictions Services (NWASHPS): USGS 08183500 San Antonio Rv nr Falls City, TX. 2009. Available at http://ahps.srh.noaa.gov/ahps2/hydrograph.php?wfo=ewx&gage=fact2&view=1,1,1,1,1,1,1,1&toggles=10,7,8,2,9,15,6&type=2.

NRC (National Research Council). 2002. Riparian areas. National Academy Press.Washington, D.C.

NRC (National Research Council). 2005. The science of instream flows: a review of the Texas Instream Flow Program. National Academies Press, Washington, D.C. Available online: http://books.nap.edu/catalog/11197.html.

Olden, J. D. and N. L. Poff. 2003. Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. River Research and Applications 19: 101-121.

Page, L.M. 1983. Handbook of darters. TFH Publications. Neptune City, N.J.

Phillips, J. 2006. Field Data Collection In Support of Geomorphic Classification of the lower Brazos And Navasota Rivers. Phase 2 of the project: Geomorphic Context, Constraints, and Change in the lower Brazos and Navasota Rivers, Texas. Final report to the Texas Water Development Board.

Phillips, J.D., and M.C. Slattery. 2007. Geomorphic Processes, Controls, and Transition Zones in the Lower Sabine River.

Phillips, J.D. 2008b. Geomorphic Units Of the Lower Sabine River. Project Report for the Texas Water Development Board and Texas Instream Flow Program, TWDB contract number 0704830782.

Piegay, H. 2003. Dynamics of wood in large rivers. American Fisheries Society Symposium 37:109-133.

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 46:1805-1818.

Poff, N. L., B. Richter, A. H. Arthington, S. E. Bunn, R. J. Naiman, E. Kendy, M. Acreman, C. Apse, B. P. Bledsoe, M. Freeman, J. Henriksen, R. B. Jacobson, J. Kennen, D. M. Merritt, J. O'Keefe, J. Olden, K. Rogers, R. E. Tharme, and A. Warner. (in press). The Ecological Limits of Hydrologic Alteration (ELOHA): A new framework for developing regional environmental flow standards. Freshwater Biology.

Richter, B.D., J.V. Baumgartner, J. Powell, and D.P. Braun. 1996. A method for assessing hydrologic alteration within ecosystems. Conservation Biology 10:1163-1174.

Richter, B.D., A.T. Warner, J. L. Meyer and K. Lutz. 2006. A collaborative and adaptive process for developing environmental flow recommendations. River Res. Applic. 22: 297–318.

Rinne, J.N. R.M. Hughes and B. Calamusso. Editors. 2005. Historical changes in large river fish assemblages of the Americas. American Fisheries Society Symposium 45. American Fisheries Society.. Bethesda, MD.

Robison, H.W. and T.M. Buchanan. 1989. Fishes of Arkansas. University of Arkansas Press.

Rosgen, D.L. 1994. A classification of natural rivers. Catena 22:169-199.

Rosgen, D.L. 1996. Applied river morphology. 2nd edition. Wildland Hydrology. Pagosa Springs, Colorado.

Schmidly, D. 2004. The Mammals of Texas (Corrie Herring Hooks Series University of Texas Press. Revised edition.

Saunders, K. S., Mayes, K.B., Jurgensen, T.A., Trungale, J.F., Kleinsasser, L.J., Aziz, K., Fields, J.R., Moss, R.E. 2001. An Evaluation of Spring Flows to Support the

Upper San Marcos River Spring Ecosystem, Hays County, Texas. River Studies Report No. 16. Resource Protection Division, Texas Parks and Wildlife, Austin, TX.

Science Advisory Committee (SAC). 2009a. 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.

Science Advisory Committee (SAC). 2009b. Fluvial Sediment Transport as an Overlay to Instream Flow Recommendations for the Environmental Flows Allocation Process. Report # SAC-2009-04. May 29, 2009.

Science Advisory Committee(SAC). 2009c. Geographic Scope of Instream Flow Recommendations. Report # SAC-2009-02. April 3, 2009. Available at: http://www.tceq.state.tx.us/assets/public/permitting/watersupply/water_rights/eflows/

Simon, T.P. 1999. Assessment of Balon's reproductive guilds with application to Midwestern North American freshwater fishes.pp: 97-121. In: Simon, S.P. ed. Assessing the sustainability and biological integrity of water resources using fish communities. CRC Press.

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. (Part of a 6 volume series on this topic).

Smith, D.G. 2001. Pennak's Freshwater Invertebrates of the United States: Porifera to Crustacea, 4th Edition. Wiley.

Snelder, T. H., R. Woods, and B. J. F. Biggs. Improved eco-hydrological classification of rivers. River Research and Applications 21: 609-628. 2005.

Stalnaker, C.B., Bovee, K.D., and Waddle, T.J. 1996. Importance of the temporal aspects of habitat hydraulics to fish population studies. Regulated Rivers: Research & Management 12:145-153.

Stein, B. 2002. States of the union: ranking America's biodiversity. NatureServe, Arlington, Virginia.

Stutzenbaker, C.D.. 1999. Aquatic and Wetland Plants of the Western Gulf Coast. 1999. Texas Parks and Wildlife Press. Austin, Texas

Sublette, J.E., M.D. Hatch and M. Sublette. 1990. Fishes of New Mexico. University of New Mexico Press. (out of print).

Texas Commission on Environmental Quality. 2008. 2008 Texas Water Quality Inventory and 303(d) List. Available at http://www.tceq.state.tx.us/assets/public/compliance/monops/water/08twqi/2008_303d.pdf

Texas Commission on Environmental Quality, Texas Parks and Wildlife Department, Texas Water Development Board, 2008: *Texas Instream Flow Studies: Technical Overview*. Report 369, Texas Water Development Board, Austin.

Texas Parks and Wildlife Department (TPWD). 1984. The Vegetation Types of Texas. http://www.tpwd.state.tx.us/landwater/land/maps/gis/map_downloads/map_gallery/bio/. Accessed July 9, 2009.

Texas Parks and Wildlife Department(TPWD). 2009a. Endangered and Threatened Species: State and Federal Regulations. http://www.tpwd.state.tx.us/huntwild/wild/species/endang/index.phtml

Texas Parks and Wildlife Department (TPWD). 2009b. Ecologically Significant Stream Segments. http://www.tpwd.state.tx.us/landwater/water/environconcerns/water_quality/sigsegs/. Accessed July 9, 2009.

Texas Parks and Wildlife Department (TPWD). 2009c. Level III Ecoregions of the Continental United States, US Environmental Protection Agency, 2000. Revision of Omernik 1987.

Thomas, C., T.H. Bonner, and B.G. Whiteside. 2007. Freshwater Fishes of Texas: A Field Guide. College Station, Texas. Texas A&M University Press.

Thorp, J.H., M.C. Thoms and M.D. Delong. 2008. The riverine ecosystem sythesis: towards conceptual cohesiveness in river science. Academic Press. San Diego, California.

TRG (Technical Review Group). 2008. Review of desk-top methods for establishing environmental flows in Texas rivers and streams – final report to the Texas Commission on Environmental Quality. Austin, Texas.

University of Texas at Austin, 2009. Texas Natural History Collections Fishes of Texas Project database (http://www.utexas.edu/tmm/tnhc/fish/index.html)

USACE. 1994 Red River Waterway Project, Shreveport, LA to Daingerfield, TX Reach, Reevaluation Study, In-Progress Review.

USDA (U.S. Department of Agriculture). 2009. NRCS. Plants Database. Wetland Indicator Status. http://plants.usda.gov/wetinfo.html

USFWS (U.S. Fish and Wildlife Service). 1988. National list of vascular plant species that occur in wetlands. U.S. Fish & Wildlife Service Biological Report 88 (26.9).

USFWS (U.S. Fish and Wildlife Service). 1993. 1993 supplement to list of plant species that occur in wetlands: Northwest (Region 9). Supplement to U.S. Fish & Wildlife Service Biological Report 88 (26.9).

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

van den Belt, Marjan and T. Dietz. 2004. Mediated Modeling: A System Dynamics Approach To Environmental Consensus Building. Island Press

Voshell, J.R. 2002. A Guide to Common Freshwater Invertebrates of North America McDonald and Woodward Publishing Company.

Walsh, M.C., J. Deeds, and B. Nightengale. 2007. Classifying Lotic Systems for Conservation: Methods and Results of the Pennsylvania Aquatic Community Classification. Pennsylvania Natural Heritage Program, Western Pennsylvania Conservancy, Middletown, PA and Pittsburgh, PA.

Willis, S.C., K.O. Winemiller, and H. López-Fernández. 2005. Habitat structural complexity and morphological diversity of fish assemblages in a Neotropical floodplain river. *Oecologia* 142:284-295.

Winemiller, K.O., F.P. Gelwick, T. Bonner, S. Zeug, and C. Williams. 2004. Response of oxbow lake biota to hydrologic exchanges with the Brazos River channel. Report to the Texas Water Development Board. 59 pp.

Winemiller, K.O., A. Chin, S.E. Davis, D.L. Roelke, L.M. Romero, and B.P. Wilcox. 2005. Summary Report Supporting the Development of Flow Recommendations for the Stretch of Big Cypress Creek below Lake O' the Pines Dam. Final Project Report to the Caddo Lake Institute and The Nature Conservancy.

Wolock, D. M. 2003. Hydrologic landscape regions of the United States. Open-File Report 03–145. U.S. Geological Survey, Washington, D.C. Digital data set, accessed June 16, 2008, at URL <http://water.usgs.gov/lookup/getspatial?hlrus>.

Wootton, R.J. 1990. Ecology of teleost fishes. Chapman and Hall, London.

Zeug, S.C. and K. O. Winemiller. 2008. Relationships between hydrology, spatial heterogeneity, and fish recruitment dynamics in a temperate floodplain river. *River Research and Applications* 24:90-102.

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., Winemiller, K.O., and S. Tarim. 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.

SECTION 8. INSTREAM BIOLOGY WORKGROUP

TPWD:
John Botros, John.Botros@tpwd.state.tx.us
David Bradsby, David.Bradsby@tpwd.state.tx.us
Lynne Hamlin, Lynne.Hamlin@tpwd.state.tx.us
Kevin Mayes, Kevin.Mayes@tpwd.state.tx.us
Clint Robertson, Clint.Robertson@tpwd.state.tx.us

TCEQ:
Kathy Alexander, kalexand@tceq.state.tx.us
Christopher Loft, cloft@tceq.state.tx.us
Gregg Easley, geasley@tceq.state.tx.us
Dakus Geeslin, pgeeslin@tceq.state.tx.us
Leonard Oliver, loliver@tceq.state.tx.us

OTHERS:
[1] Jim Wiersema, jim_wiersema@horizon-esi.com
[2] George Guillen, Guillen@uhcl.edu
[2] Joe Trungale, jftrungale@sbcglobal.net
[2] Kirk Winemiller, k-winemiller@tamu.edu
Ryan Smith, ryan_smith@TNC.ORG
Norman Johns, johns@nwf.org

[1]SAC Member
[2] BBEST Member