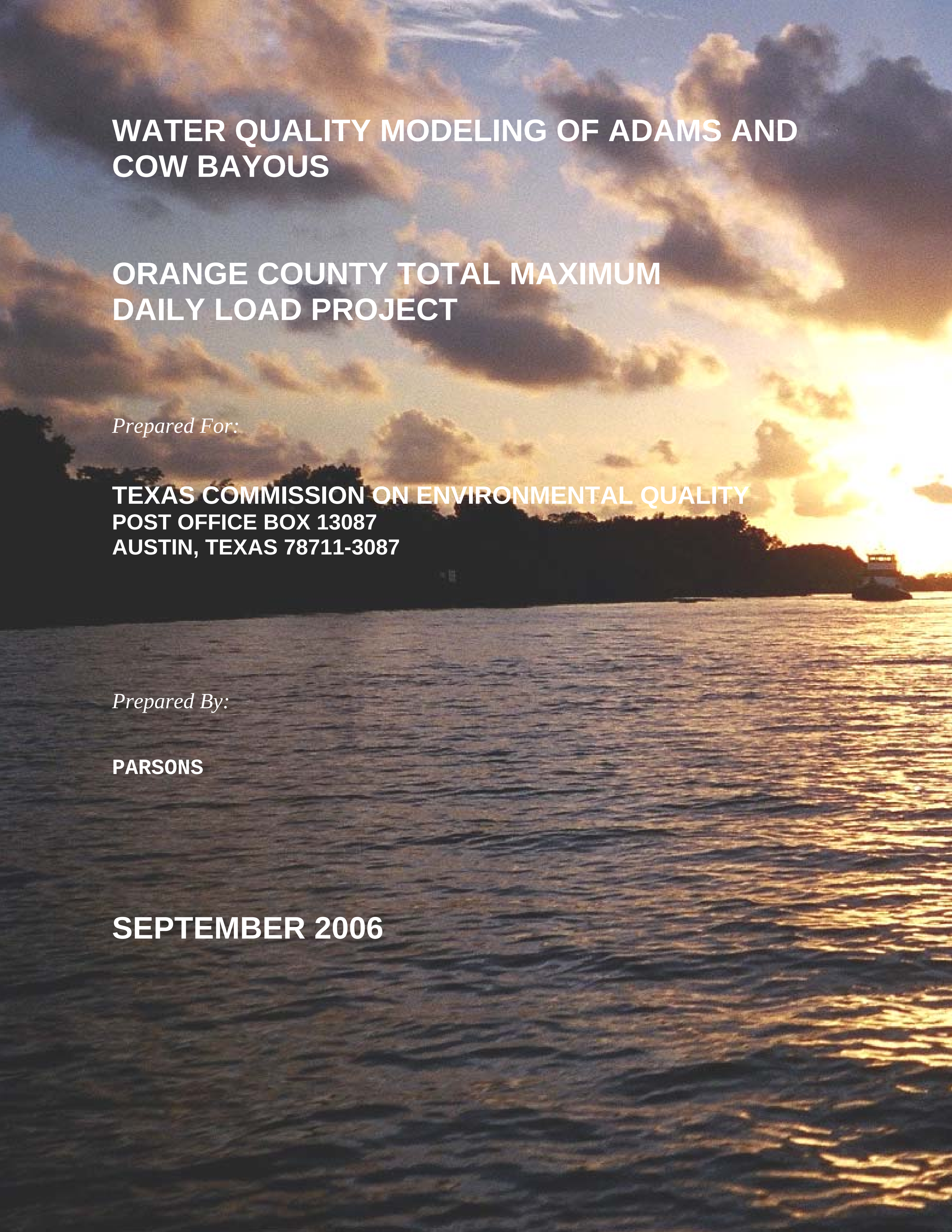

WATER QUALITY MODELING OF ADAMS AND COW BAYOUS

ORANGE COUNTY TOTAL MAXIMUM DAILY LOAD PROJECT

Prepared For:

TEXAS COMMISSION ON ENVIRONMENTAL QUALITY
POST OFFICE BOX 13087
AUSTIN, TEXAS 78711-3087

Prepared By:

PARSONS

SEPTEMBER 2006

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Acronyms and Abbreviations

cBOD – carbonaceous biochemical oxygen demand (ultimate)
cBOD5 - 5-day carbonaceous biochemical oxygen demand
CFR – code of federal regulations
cfs – cubic feet per second
ChlA – chlorophyll a
cms – cubic meters per second, m^3/s
EC – Escherichia coli, or E. coli
HSPF – Hydrologic Simulation Program-Fortran
IH – interstate highway
km – kilometer
l – liter
m^2 – square meters
m^3 – cubic meters
mg – milligrams
mgd – million gallons per day
MPN – most probable number, i.e., the most likely count of bacteria in a water sample
m/s – meters per second
N/A – not applicable
NH_3N – ammonia (as nitrogen)
NO_3N – nitrate (as nitrogen)
OrgN – organic nitrogen (dissolved)
OrgP – organic phosphorus (dissolved)
PO_4P – phosphate (as phosphorus)
RMSE – root mean square error
SH – state highway
SOD – sediment oxygen demand
SRA – Sabine River Authority of Texas
TCEQ – Texas Commission on Environmental Quality
TKN – total Kjeldahl nitrogen (ammonia + organic nitrogen)
TMDL – total maximum daily load
TPDES – Texas Pollutant Discharge Elimination System
TSS – total suspended solids
USEPA – United States Environmental Protection Agency
USGS – United States Geological Survey
VSS – volatile suspended solids
WASP – Water Analysis Simulation Program
WWTP – wastewater treatment plant

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Introduction

This report summarizes the development of linked hydrodynamic and water quality models of Adams and Cow Bayous. Because Adams Bayou and most of Cow Bayou are tidal streams, with reversing flows, in-stream hydrodynamics and water quality were simulated with RMA2 and Water Quality Analysis Simulation Program (WASP) models, respectively. The output from the Hydrologic Simulation Program-Fortran (HSPF) watershed models was linked to the in-stream models of Adams and Cow Bayous and their tributaries, for use in developing total maximum daily loads (TMDLs) for fecal bacteria and dissolved oxygen. The models will be useful for several purposes:

- to aid understanding of the processes affecting water quality,
- to quantify pollutant loadings to the bayous and allocate them among sources,
- to link in-stream water quality impairments to pollutant loadings,
- to quantify the loading reductions required to achieve water quality standards, and
- to evaluate the benefits of various water quality management options.

This report addresses only the instream hydrodynamic and water quality models of Adams and Cow Bayou. A separate report (Parsons 2006) describes development and results of the HSPF watershed models.

Regulatory Background

Water quality standards serve the dual purposes of establishing the water quality goals for a specific water body and serve as the regulatory basis for the establishment of water-quality-based treatment controls and strategies (40 CFR 131.10). Water quality standards are comprised of designated uses and water quality criteria. The federal Clean Water Act requires that states designate for each water body desirable and appropriate uses to be achieved and protected. These designated uses of water bodies include recreation in and on the water, public water supply, navigation, agricultural and industrial water supply, and protection and propagation of fish, shellfish and wildlife. States must then set water quality criteria necessary to protect those designated uses. Criteria are expressed as constituent concentrations, levels, or narrative statements, representing a quality of water that supports a particular use. When criteria are met, water quality will generally protect the designated use (40 CFR 131.3).

Section 303(d) of the Federal Clean Water Act and U.S. Environmental Protection Agency (USEPA) regulations (40 CFR Part 130) require states to develop TMDLs for water bodies that do no meet water quality standards. A TMDL is an allocation of allowable point and nonpoint source pollutant loadings that will enable the water body to meet water quality standards when implemented.

The Texas Commission on Environmental Quality (TCEQ) has determined that Adams Bayou, Cow Bayou, and several of their tributaries do not meet water quality standards and require TMDLs (TCEQ 2002). Adams and Cow Bayous are adjacent streams that flow into the Sabine River just upstream of Sabine Lake in Orange County, in the southeast corner of Texas (Figure

1). The unsupported designated uses include contact recreation, aquatic life support, and general uses.

The TCEQ has divided Adams and Cow Bayous and their tributaries into multiple segments for water quality management purposes. The segments not meeting water quality standards are described as follows:

- Segment 0508 (Adams Bayou Tidal) - from the confluence with the Sabine River in Orange County to a point 1.1 kilometers (km) (0.7 miles) upstream of IH-10 in Orange County (a classified tidal stream of 8 miles in length). Does not support aquatic life or contact recreation uses.

- Segment 0508A (Adams Bayou above Tidal) - from a point 1.1 km (0.7 miles) upstream of IH-10 in Orange County to the upstream perennial portion of the stream northwest of Orange in Orange County (an unclassified freshwater stream of 8 miles in length). Does not support aquatic life or contact recreation uses.

- Segment 0508B (Gum Gully) - From the confluence of Adams Bayou to the upstream perennial portion of the stream northwest of Orange in Orange County (an unclassified freshwater stream of 3.5 miles in length). Does not support aquatic life or contact recreation uses.

- Segment 0508C (Hudson Gully) - From the confluence with Adams Bayou to the headwaters near US 890 in Pinehurst in Orange County (an unclassified tidal stream of 0.5 miles in length). Does not support aquatic life or contact recreation uses.

- Segment 0511 (Cow Bayou Tidal) - from the confluence with the Sabine River in Orange County to a point 4.8 km (3.0 miles) upstream of IH-10 in Orange County (a classified tidal stream of 20 miles in length). Does not support aquatic life, contact recreation, or general uses.

- Segment 0511A (Cow Bayou above Tidal) – from a point 4.8 km (3.0 miles) upstream of IH-10 in Orange County to the upstream perennial portion of the stream northeast of Vidor in Orange County (an unclassified freshwater stream of 10.6 miles in length). Does not support aquatic life use.

- Segment 0511B (Coon Bayou) – from the confluence with Cow Bayou up to the extent of tidal limit in Orange County (an unclassified tidal stream of 4.7 miles in length). Does not support aquatic life or contact recreation uses.

- Segment 0511C (Cole Creek) – from the confluence with Cow Bayou west of Orange in Orange County to the upstream perennial portion of the stream south of Mauriceville in Orange County (an unclassified tidal stream of 9.5 miles in length). Does not support aquatic life or contact recreation uses.

- Segment 0511E (Terry Gully) – from the confluence with Cow Bayou in Orange County to the headwaters northeast of Vidor in Orange County (an unclassified freshwater stream of 8.6 miles in length). Does not support contact recreation use.

The specific criteria used to determine non-support of the contact recreation use in these bayous were based on levels of fecal coliform and E. coli bacteria. The assessment of nonsupport of the aquatic life use was based on levels of dissolved oxygen. Non-support of general uses was determined from measurements of pH. A more thorough review of water quality standards and assessment of water quality conditions in these bayous can be found in a prior report of this project "*Assessment of Water Quality Impairments in Adams Bayou Tidal (Segment 0508), Cow Bayou Tidal (Segment 0511) and their Tributaries*" (Parsons 2002).

Watershed Overview

Adams and Cow Bayous are sluggish streams that flow into the Sabine River (USGS Hydrologic Unit Code 12010005) just upstream of Sabine Lake in Orange County, Texas. Adams Bayou extends from its confluence with the Sabine River in a northerly direction across Orange County to near the Newton County Line. Adams Bayou previously extended into southern Newton County, but this flow has been redirected eastward through a ditch to the Sabine River. Cow Bayou extends from its confluence with the Sabine River in a northerly direction, roughly parallel to but west of Adams Bayou, across Orange County to Buna in southern Jasper County (Figure 1).

The lower portions of both bayous have been channelized, straightened, and dredged for navigation, creating numerous oxbows in the former, more sinuous, channels. Both bayous are under tidal influence below and a short distance above Interstate Highway (IH)-10. The tidal portions of Adams and Cow Bayous extend approximately 8 and 20 miles, respectively, above their confluences with the Sabine River.

A U.S. Geological Survey (USGS) gaging station measured flow in Cow Bayou at the State Highway (SH) 12 bridge near Mauriceville from 1952 to 1986, and was re-activated in October of 2002. The annual average, maximum, and 7-day, 2-year minimum flow (7Q2) at this site were 104.4 cubic feet per second (cfs), 4600 cfs, and 0.05 cfs, respectively, over the period of record.

There is no flow gaging station on Adams Bayou, but field surveys indicate that under low-flow conditions there is essentially no base flow (TWC 1986). Under these conditions, water movement occurs due to tidal ebb and flow, downstream water diversions, and wastewater discharges to the bayou. Upper reaches of Adams Bayou and non-tidal tributaries are intermittent streams.

The Adams Bayou watershed of approximately 37 square miles lies almost entirely within Orange County, though it includes a small portion of southern Newton County. The Cow Bayou watershed comprises approximately 199 square miles covering substantial portions of Orange and Jasper Counties, as well as a small corner of Newton County. The combined watersheds cover 41% of Orange County, 8% of Jasper County, and 0.3% of Newton County.

Further details of watershed properties are described in the HSPF modeling report (Parsons 2006).

Objectives

Following their determination that the water quality standards of Adams and Cow Bayous were not supported, the TCEQ selected Parsons and the Sabine River Authority (SRA) as contractors to assist in developing TMDLs. An assessment of existing water quality data (Parsons 2002) concluded with a high degree of confidence that water quality in Adams and Cow Bayou did not meet water quality standards, but that the sources of pollutants were not adequately quantified, and the impacts of sources were not known with sufficient confidence to develop a TMDL. The assessment also indicated that, because both nonpoint sources and in-stream conditions likely contributed to the impairment, it was advisable to develop and calibrate both a watershed model and an in-stream model to aid in identifying the TMDLs and allocating the allowable load among various point and nonpoint sources of pollutants. A "point source" pollutant is one that originates from a specific point, such as a wastewater discharge pipe of a wastewater treatment plant, or a large confined animal feeding lot. In practice, the term "point source" is applied to facilities required to have a Texas Pollutant Discharge Elimination System (TPDES) permit for wastewater discharges to water. Nonpoint source pollutants are those not released from pipes but originating over a large land area. Examples of nonpoint sources include failing septic tanks, improper animal husbandry practices, soil erosion, and urban runoff.

Parsons prepared a model selection technical memorandum (Parsons 2003a) that evaluated the capabilities of the available models to simulate water quality in Adams and Cow Bayous, as well as the loadings of pollutants from their watersheds. The HSPF model was recommended for its capacity to simulate watershed loading processes in both urban and rural areas. The WASP water quality model, coupled with the DYNHYD hydrodynamic model and the HSPF watershed model, was recommended as the best available model system to simulate water quality processes in the bayous. It was later discovered that DYNHYD was not able to accurately simulate the tidal cycles occurring in the bayous during the intensive surveys of May through August of 2004. Therefore, hydrodynamic models of Adams and Cow Bayou were developed using RMA2, a more full-featured hydrodynamic model developed by the U.S. Army Corps of Engineers.

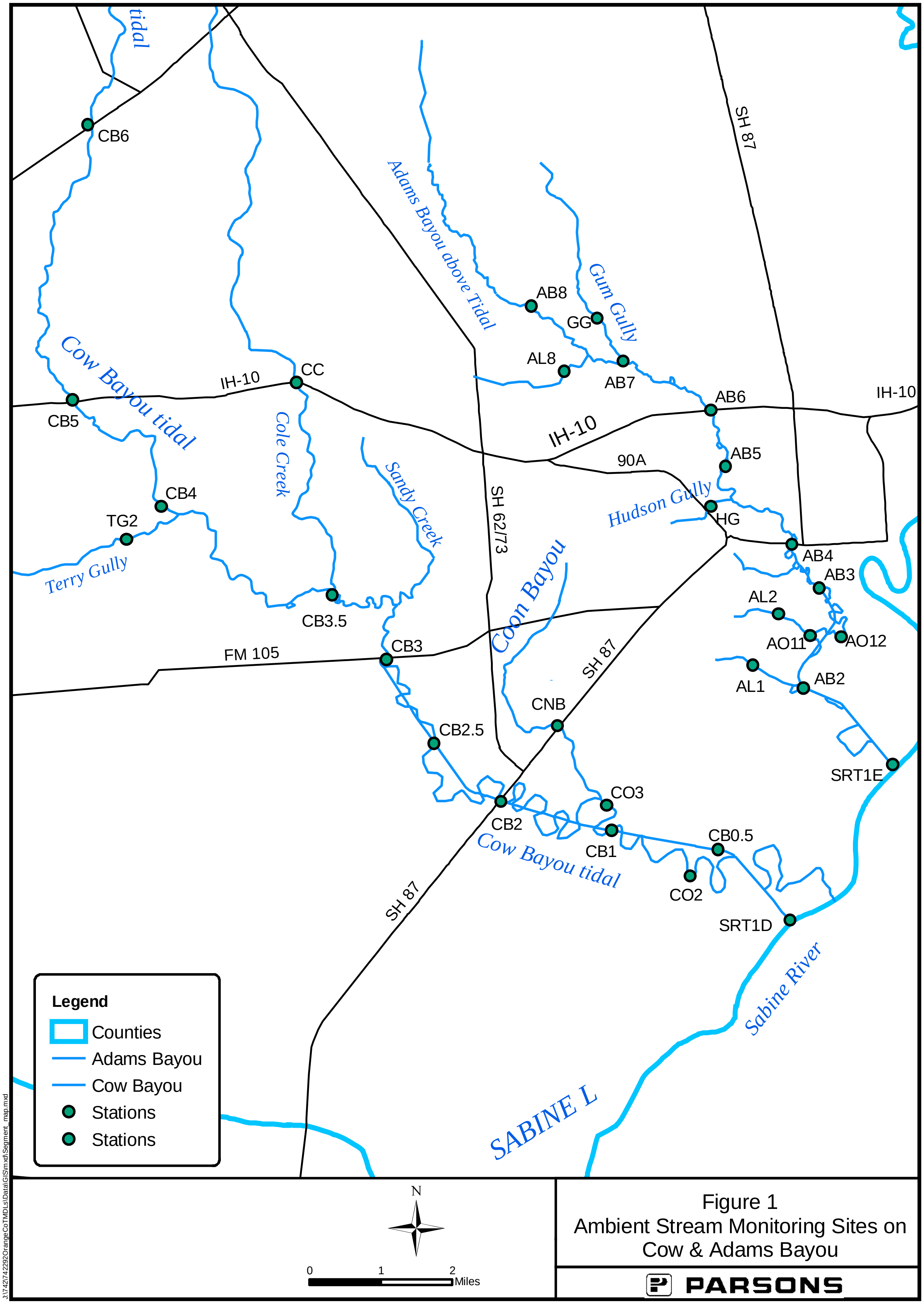

Figure 1
Ambient Stream Monitoring Sites on
Cow & Adams Bayou

PARSONS

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Field Data Collection

A water quality monitoring plan (Parsons 2003b) and quality assurance project plan (Parsons 2003c) were developed to collect data necessary to develop and calibrate the watershed, hydrodynamic, and water quality models. This data was collected by Parsons and the SRA between January and November 2004. The data collection effort consisted of 1) runoff sampling to calibrate pollutant loading factors for the watershed model, 2) sediment oxygen demand surveys, and 3) several intensive surveys addressing instream flows, water quality, and pollutant loading from wastewater discharges in Adams and Cow Bayou. The runoff sampling provided data for calibration of the HSPF nonpoint source model, and is described in the report *Nonpoint source modeling of the watersheds of Adams and Cow Bayous* (Parsons 2006).

Sediment Oxygen Demand

Sediment oxygen demand was believed to be a key factor controlling dissolved oxygen levels in the bayous, based on the QUAL-TX modeling reports of the Texas Water Commission from the 1980s (Texas Water Commission 1986, 1988). Therefore sediment oxygen demand was measured at a number of sites in each bayou using *in situ* respirometers. The respirometers, or SOD chambers, monitored the dissolved oxygen depletion in a confined volume of water overlying bed sediments over the course of one to three hours. An example result is given in figure 2. Two to six SOD measurements were made at each of six sites in the main stem of Adams Bayou and six sites in the main stem of Cow Bayou during August 2004. Water temperatures ranged from 22 to 31 °C. Measured SOD levels for individual measurements ranged from 0.7 to 5.3 g O_2/m^2/day, with an average (± standard deviation) of 2.3 (± 1.3) in Adams Bayou and 2.2 (± 1.2) in Cow Bayou. These levels are not unusual for estuaries, but are much lower than values assumed in the Texas Water Commission’s waste load evaluations.

Figures 3 and 4 illustrate the spatial patterns of SOD in Adams and Cow Bayou. The highest SOD measurements in each bayou were observed in upper portions of the dredged and straightened/widened sections of the bayous, where the reduction in water speeds and increasing salinity causes fine suspended particles to coagulate and settle out of the water column

Because temperature is expected to exert a significant effect on SOD, these SOD levels were normalized to 20°C for use in the WASP model, using a temperature coefficient of 1.04 from literature values. Normalized 20°C SOD levels for individual chambers ranged between 0.5 to 4.0 g O_2/m^2/day

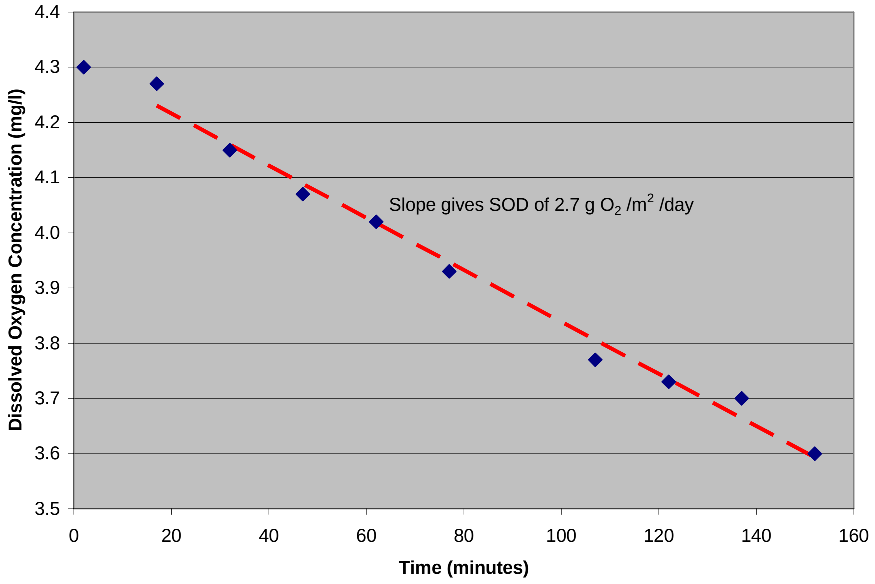


Figure 2. An example sediment oxygen demand measurement at site CB5

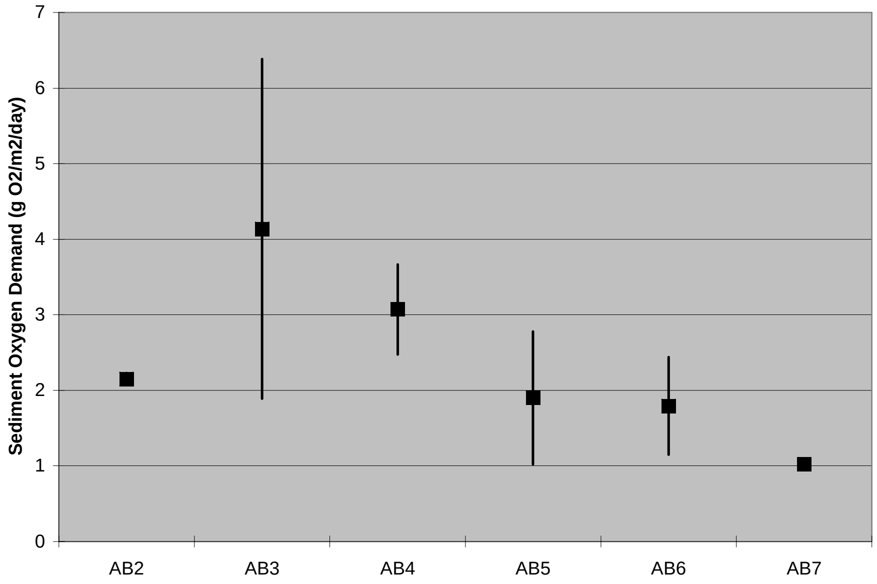


Figure 3. Average measured SOD levels in Adams Bayou. Squares represent average values and vertical bars represent one standard deviation.

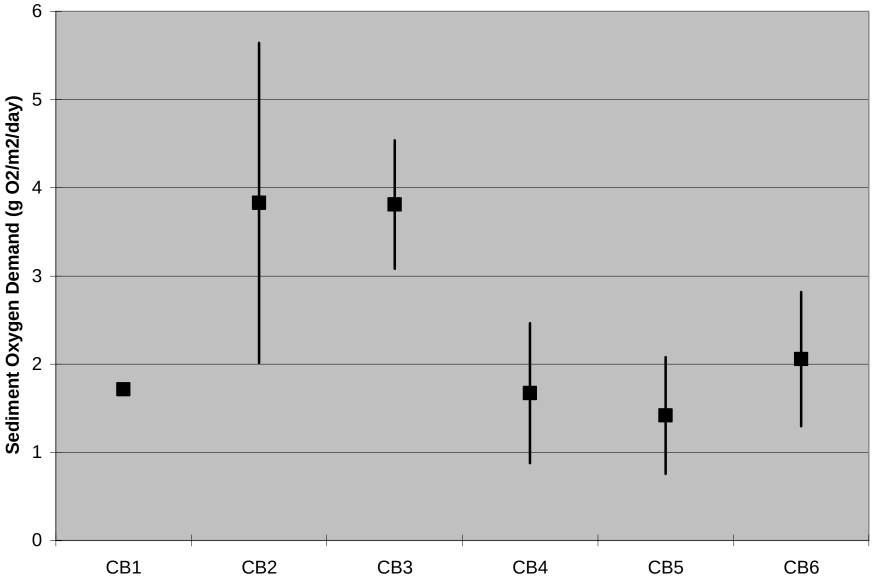


Figure 4. Average measured SOD levels in Cow Bayou. Squares represent average values and vertical bars represent one standard deviation.

Intensive Surveys

Two 48-hour intensive surveys were performed on each bayou during the summer of 2004 to provide data for calibration and verification of the hydrodynamic and water quality models. Summer is the season when dissolved oxygen levels have historically been very low. The surveys were performed approximately one month apart. The Adams Bayou intensive surveys were performed from May 26-28 and June 29–July 1. The Cow Bayou intensive surveys were performed from July 20-22 and from August 24-26. Ambient monitoring sites from the intensive surveys are depicted in figure 1. Each ambient monitoring site was visited five to nine times over the course of each 48-hour intensive survey for measurement of flow, water depth and velocity, dissolved oxygen, salinity/conductivity, water temperature, and pH. Flow and velocity measurements were made using acoustic Doppler current profilers and Marsh-McBirney electronic current meters. Water surface elevations were continuously monitored and recorded at a few locations using tide gages. Multi-parameter sondes were deployed at one or two depths at many sites to record water depth, salinity/conductivity, temperature, dissolved oxygen, and pH every 15 minutes over the course of each survey.

Water quality samples were collected three to five times from each ambient monitoring site during each survey. Samples were analyzed for chlorophyll A (ChlA), nitrate nitrogen (NO3N), ammonia nitrogen (NH3N), total Kjeldahl nitrogen (TKN), orthophosphate phosphorus (PO4P), 5-day carbonaceous biochemical oxygen demand (cBOD5), total dissolved solids, total suspended solids (TSS), volatile suspended solids (VSS), E. coli (EC), and alkalinity. Additional water quality samples were collected on a daily basis from the permitted water quality discharges to the bayous, and analyzed for the same suite of parameters.

cBOD is typically measured as cBOD5, the oxygen demand from oxidation of organic matter over a five day period. However, the WASP model simulates ultimate cBOD, the oxygen demand from biochemical oxidation of essentially all organic matter. In order to estimate ultimate cBOD from cBOD5, cBOD was measured after 5, 15, and 20 days in fourteen ambient samples from various locations in each bayou. The 20-day cBOD measurements were considered to represent ultimate cBOD. The ratio of ultimate cBOD to cBOD5 ranged from 1.0 to 3.9 with an overall average of 2.3 and a standard deviation of 0.7. This ratio was not significantly different between bayous or intensive survey period. Therefore, for the WASP model input, all cBOD5 measurements were multiplied by 2.3 to represent ultimate cBOD.

Further details of the intensive surveys and other data collection can be found in the Sampling Plan (Parsons 2003b) and the Quality Assurance Project Plan (Parsons 2003c). The measured water quality data is too voluminous to be included in this report. The quality-assured data can be obtained from the TCEQ surface water quality monitoring database (http://www.tceq.state.tx.us).

RMA2 Hydrodynamic Model Description

RMA2 is a two-dimensional, vertically averaged, finite element hydrodynamic model supported by the U.S. Army Corps of Engineers. It computes water surface elevations and horizontal velocities for subcritical, free-surface two-dimensional flows (Donnell et al., 2005). The RMA2 model is comprised of elements and nodes. Elements represent a finite stretch of the channel of a bayou, and hold water. Each element is composed of three or more nodes. Nodes are the points where water surface elevation and velocity calculations are performed, and all linkages between elements occur at nodes. The elements have a trapezoidal shape with characteristic channel bottom width and side slope, which may vary by element to reflect the local shape of the channel. Elements may also have off-channel water storage, which is useful for simulating inundated areas such as wetlands, or oxbow channels and reservoirs linked to the bayous. The depth-dependent geometry of the off-channel storage may also be varied to reflect the actual geometry. The RMA models also utilize marsh porosity, which allows partial wetting and partial drying of shallow elements with water level changes.

Model Segmentation and Key Parameters

Separate hydrodynamic models were developed for the Adams and Cow Bayou systems. The RMA2 models were developed using SMS (Surface-Water Modeling System) version 9 software, which provides a graphical user interface for RMA2 and other models. SMS is not required to run RMA2, and primarily aids in model development.

Both models extended from the Sabine River (the downstream boundary) to the upstream limits of tidal influence of each bayou and their tributaries. Oxbow channels were also included in the model, either explicitly modeled as discrete elements or included as off-channel water storage attached to the main channel. Figures 5 and 6 illustrate the RMA2 model segmentation of Adams and Cow Bayous, respectively. Adams and Cow bayous were simulated with 1-dimensional model elements for simplicity and concordance with the DYNHYD model originally proposed. The Adams Bayou system hydrodynamic model was comprised of 312 nodes and 154 elements. The Cow Bayou system was comprised of 224 nodes and 111 elements.

The bottom elevations of the bayous were estimated from measurements made during the field intensive surveys. The model was run with a 6-minute time step. Surface roughness was varied with stream depth, and calibrated values of Manning’s N ranged from 0.017 to 0.035.

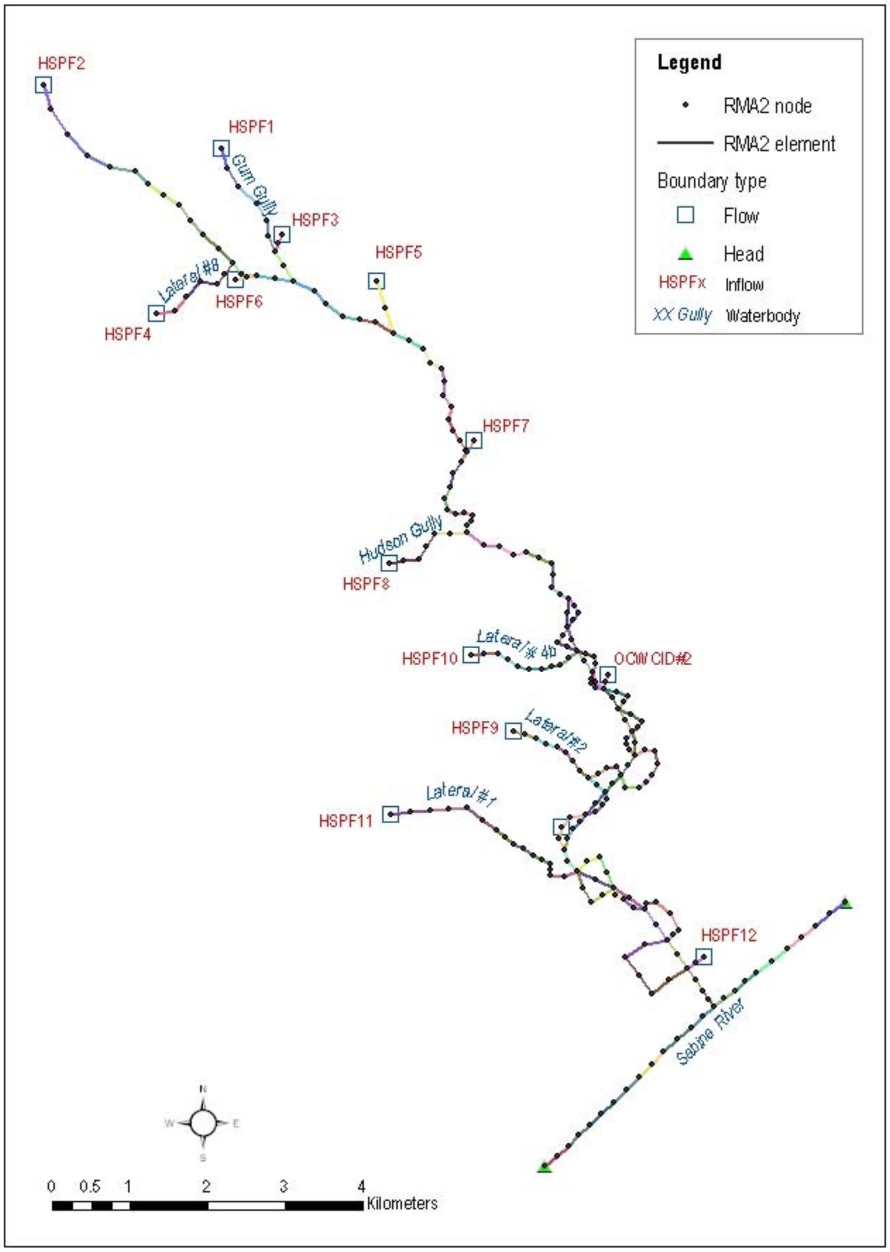


Figure 5. Adams Bayou RMA2 Model Segmentation

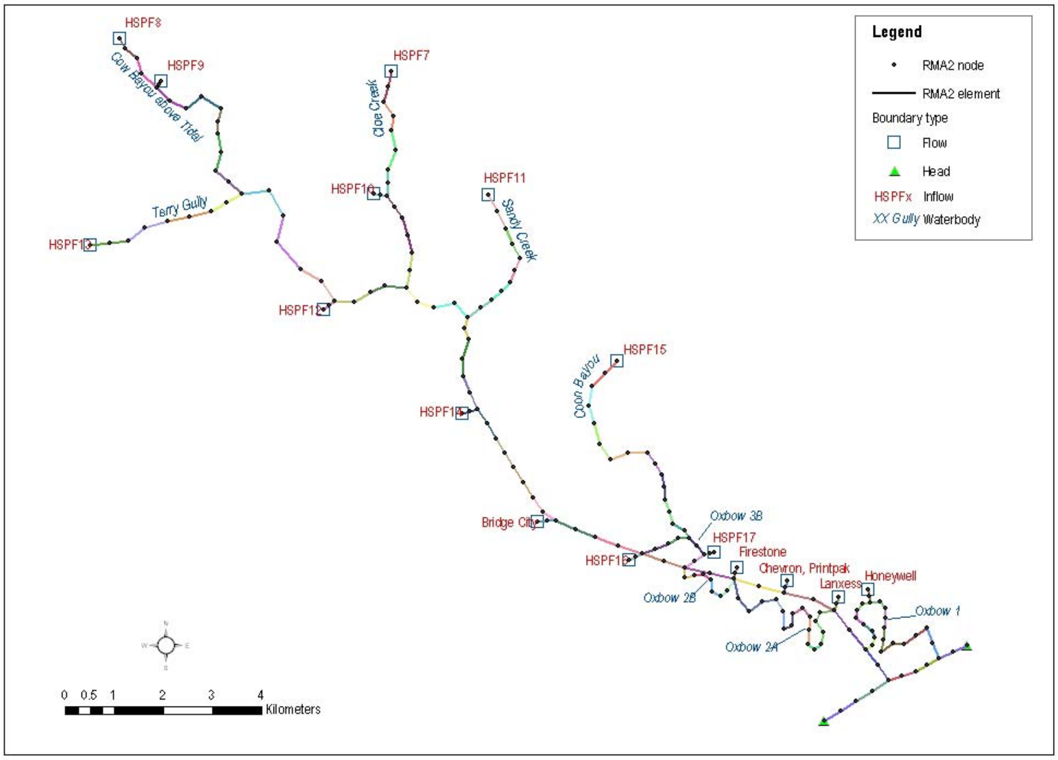


Figure 6. Cow Bayou RMA2 Model Segmentation

Model Input Data

Tidal water surface oscillations in the Sabine River drive tidal water movements through the Adams and Cow Bayou systems. Tide height data from a continuous gage at the Rainbow Bridge (where SH 87 crosses the Neches River just upstream from Sabine Lake) were used as the Sabine River downstream boundary water surface elevation condition in the models. Water elevations measured with tide gages deployed near the mouth of Adams and Cow Bayou during the field intensive surveys were not significantly different from those recorded at the Rainbow Bridge gage. The average daily tidal range at the Rainbow Bridge is 0.284 m (0.93 feet).

Upstream inflows to the model from above tidal reaches were predicted by the calibrated HSPF watershed model and entered as boundary inflows to a number of tributaries. The HSPF inputs are shown in Figures 5 and 6. Large (>0.3 mgd) point source discharge inflows were also included in the RMA2 model as boundary inflows, and are illustrated in Figures 5 and 6.

Model Calibration and Verification

The RMA2 models for each bayou were calibrated to a six day period. The calibration was then verified with a second six-day period. These six day calibration and verification periods consisted of three days of “spin-up” time for the model to equilibrate, followed by the three days when the intensive surveys were performed. The model dates were:

	Calibration Period	Verification Period
Adams Bayou:	May 23-28, 2004	June 26 – July 1, 2004
Cow Bayou:	July 17-22, 2004	August 21-26, 2004

The model was first calibrated to measured water surface elevations, then to measured water velocities and flows. The parameters adjusted in calibration included the channel geometry, off-channel storage area, and Manning’s N surface roughness. Calibration performance was judged first visually, then based on the root mean square error (RMSE), and essentially adjusted until no further improvement could be obtained.

$$RMSE = \sqrt{\frac{\sum \left(\Pr edicted - Observed\right)^2}{count\ of\ \ observations}}$$

Water Level

Figures 4 and 5 compares the measured and modeled water surface elevations at stations where tide gages or multi-parameter sondes recorded water depth during the Adams Bayou intensive surveys. Because the primary purpose of the sondes was to measure dissolved oxygen and other water quality parameters, they were deployed between an anchor and a buoy in mid-channel. In this configuration, the sondes were able to move around somewhat. Some of the difference between measured and modeled water elevations was likely due to movement of the sondes. Table 1 displays the model calibration and verification statistics for water elevation at Adams Bayou locations. On average, the RMSE was approximately 0.12 foot, or 1.5 inch. The error in the verification model run was higher than that from the calibration period, but still within acceptable limits given a tidal range of more than one foot. It was also noticeable that the model error tended to be greater in the more upstream tidal portions of the system during the verification run. In part this may be due to a major rainfall event before the second intensive survey, which caused large freshwater inflows. It appears that the HSPF model may not have simulated accurately the runoff from this rainfall event due to differential rainfall between the Adams Bayou watershed and the rain gage northwest of Vidor. The influence of runoff and tributary inflow, relative to tide-driven flow, is greater in the narrow and shallow upstream reaches of the bayous.

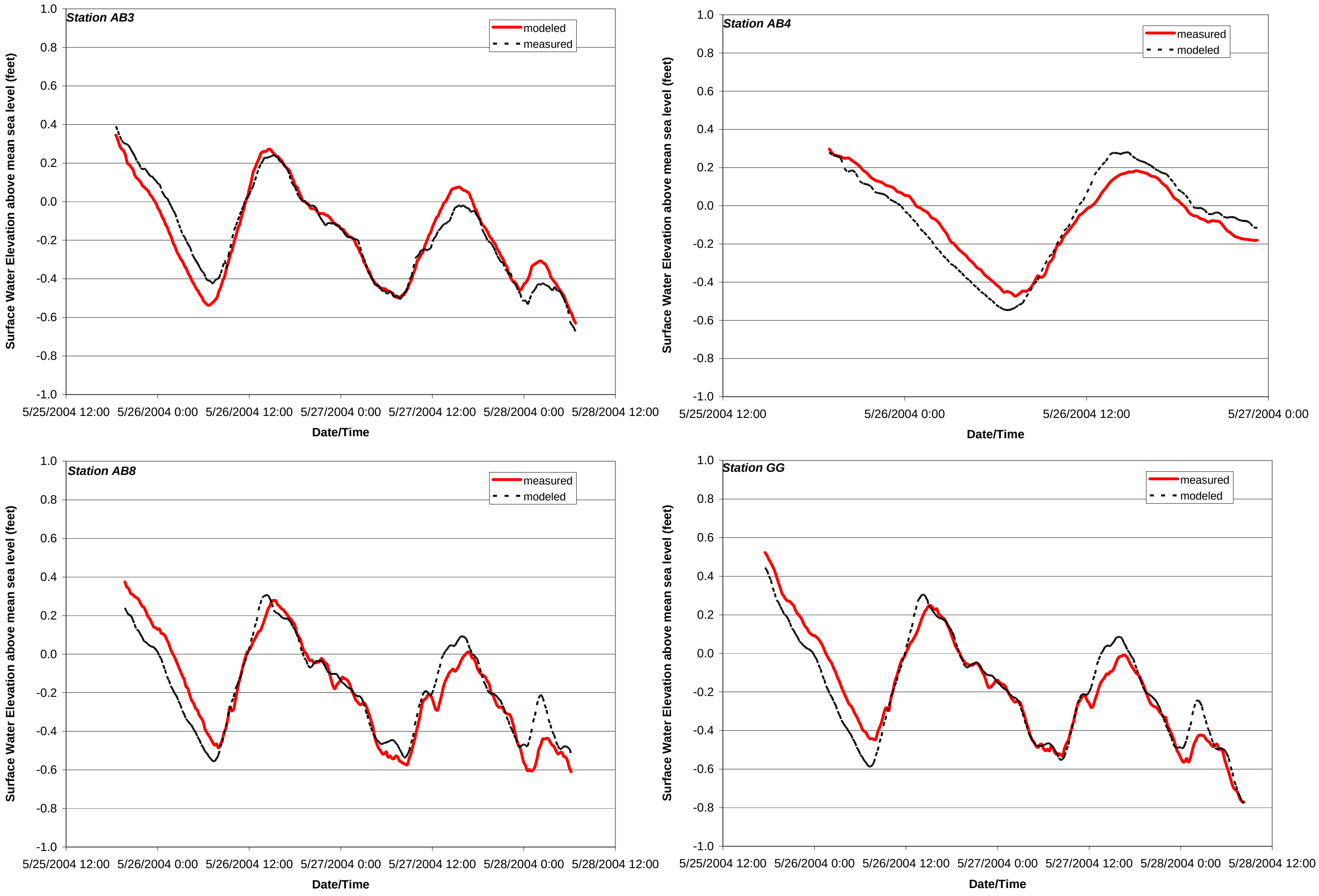


Figure 4. Predicted vs measured water levels in Adams Bayou – 1st event

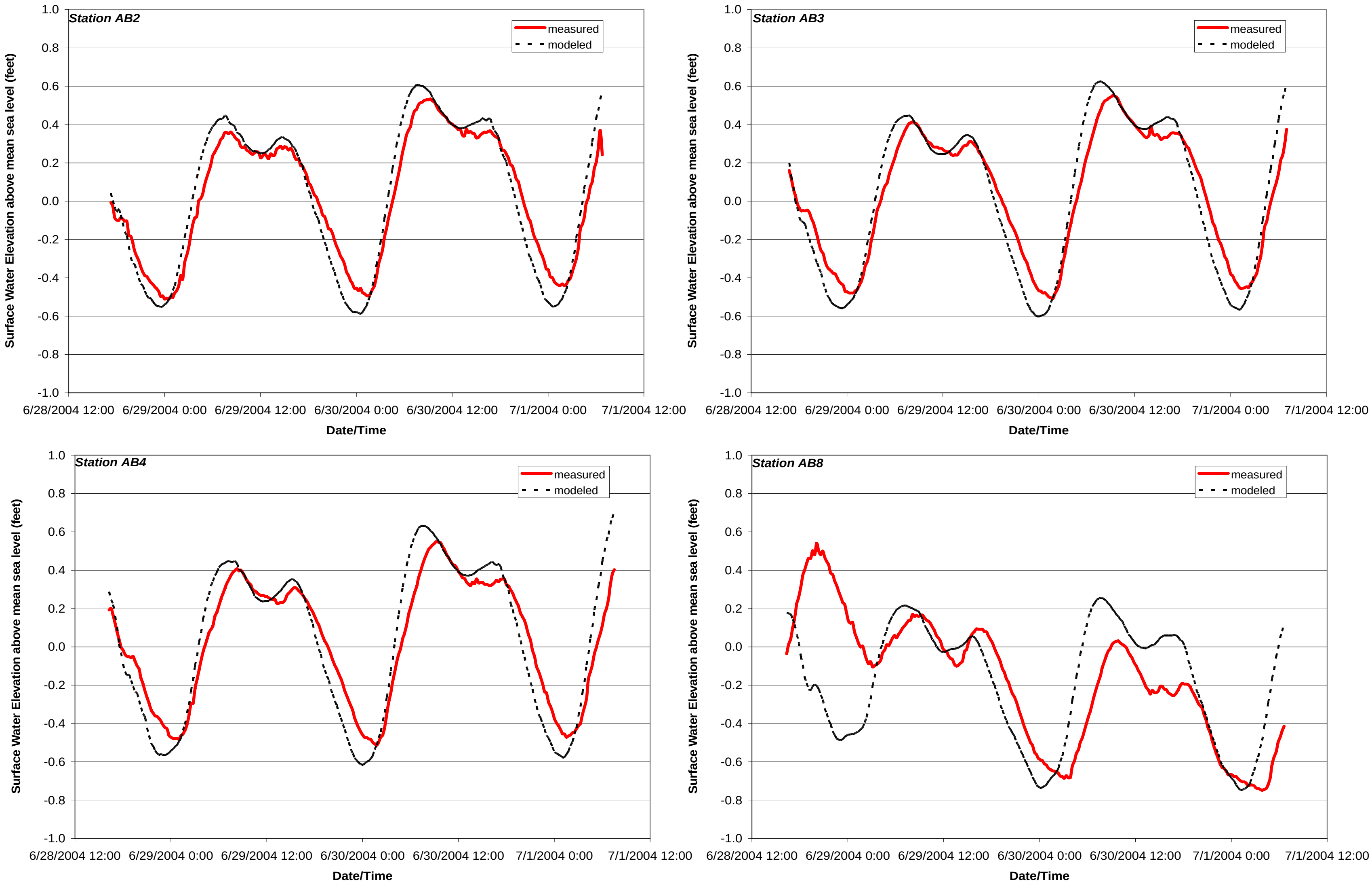


Figure 5. Predicted vs measured water levels in Adams Bayou – 2nd event

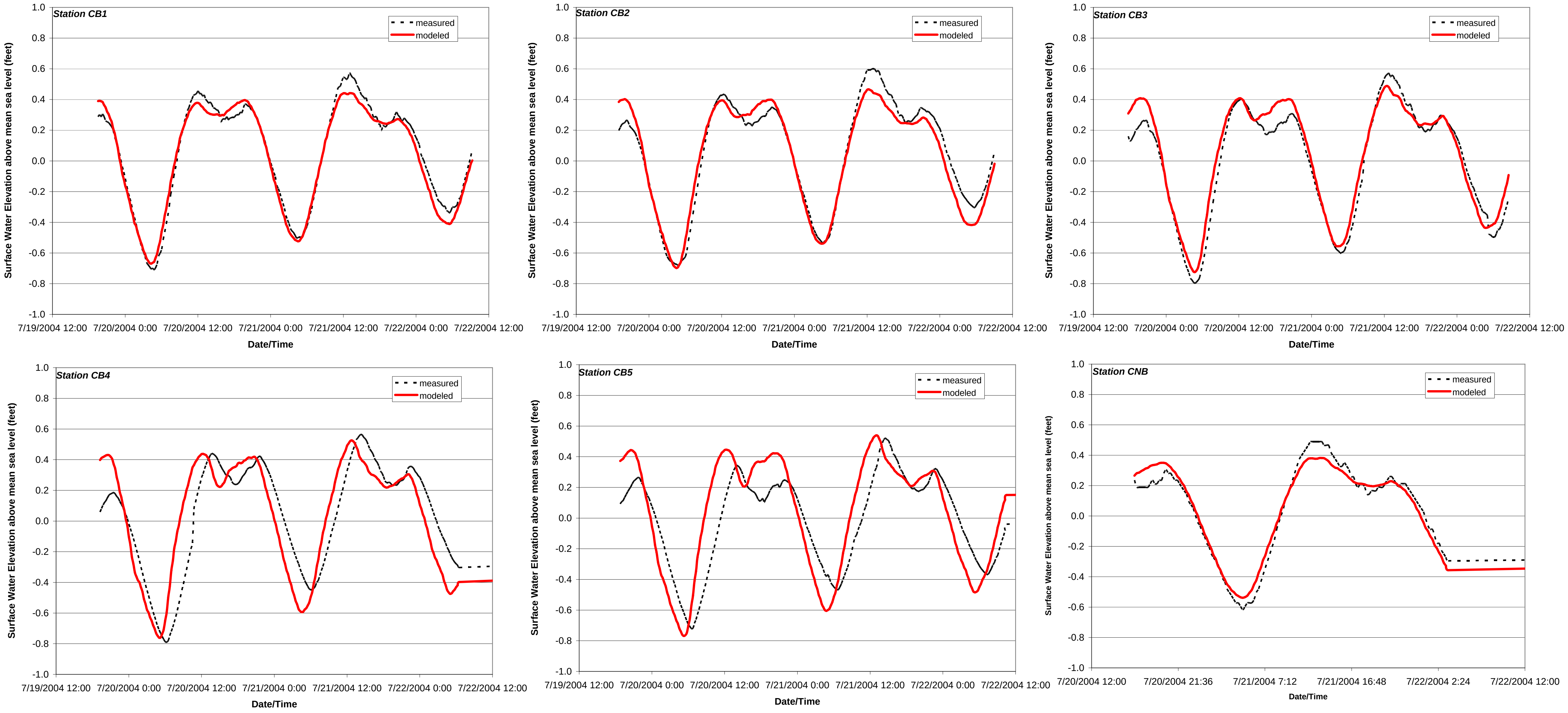
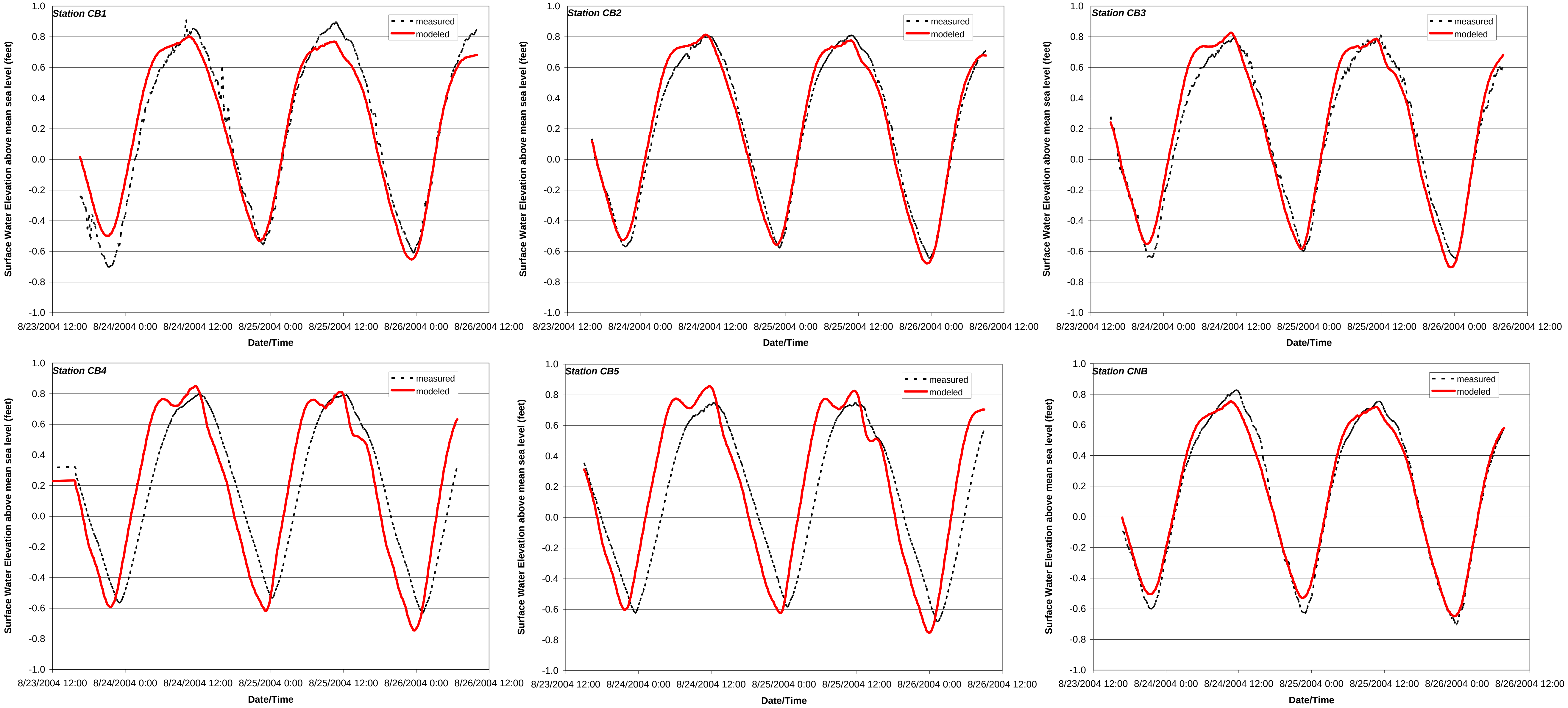


Figure 6. Predicted vs measured water levels in Cow Bayou – 1st event


Station CB1

Station CB2

Station CB3

Station CB4

Station CB5

Station CNB

Figure 7. Predicted vs measured water levels in Cow Bayou – 2nd event

Table 1. Average model error (RMSE, in feet) summary for water levels in the Adams Bayou system

	AB2	AB3	AB4	AB8	GG
Intensive Survey #1 – Calibration	NA	0.08	0.08	0.10	0.09
Intensive Survey #2 – Verification	0.11	0.12	0.15	0.31	NA
All	0.11	0.10	0.13	0.23	0.09

Figures 6 and 7 compare the measured and modeled water surface elevations at stations where tide gages or multi-parameter sondes recorded water depth during the Cow Bayou intensive surveys. Table 2 displays the model calibration and verification statistics for water elevation at Cow Bayou locations. On average, the RMSE was approximately 0.13 foot, or 1.5 inch, similar to that for the Adams Bayou model. Also similar to the Adams Bayou model, error was greater in the upstream portions of the model.

Table 2. Average model error (RMSE, in feet) summary for water levels in the Cow Bayou system

	CB1	CB2	CB3	CB4	CB5	CNB
Intensive Survey #1 – Calibration	0.06	0.08	0.09	0.21	0.21	0.06
Intensive Survey #2 – Verification	0.11	0.07	0.09	0.24	0.25	0.06
All	0.09	0.08	0.09	0.22	0.23	0.06

Flow

Water flow through the bayous was the most important hydrodynamic calibration target because it controls the movement of water quality constituents in the WASP water quality model. The measurement of flow in the bayous was not as precise as that of water level, and flow was measured only 1 to 4 times per day at each site during the intensive surveys. Individual flow measurements at a site required from ten to thirty minutes to complete, during which time the flows were changing. For these reasons the error in flow calibration was expected to be higher. Tables 3 and 4 present the root mean square error summary for model flow predictions for Adams and Cow Bayous, respectively. At most sites the model errors were small relative to the range of flows observed. It was interesting to note that all Adams Bayou sites, including sites considered by the TCEQ to be representative of Adams Bayou above tidal, exhibited tidal flow patterns.

Table 3. Average model error (RMSE) summary for water flow in the Adams Bayou system. All values are in cubic meters per second (cms).

Site		Intensive Survey #1 Model Calibration	Intensive Survey #2 Model Verification	Both Surveys
AB2	RMSE Flow Range	8.0 -22.4 – 16.3	3.1 -29.2 – 31.0	6.0 -29.2 – 31.0
AB3	RMSE Flow Range	6.6 -30.7 – 13.9	4.2 -38.8 – 26.2	5.4 -38.8 – 26.2
AB4	RMSE Flow Range	2.2 -18.7 – 10.4	4.4 -22.4 – 22.7	3.8 -22.4 – 22.7
AB5	RMSE Flow Range	2.7 -6.7 – 4.8	3.9 -4.4 – 14.9	3.6 -6.7 – 14.9
AB6	RMSE Flow Range	1.1 -3.7 – 4.7	3.0 0.3 – 15.2	2.2 -3.7 – 15.2
AB7	RMSE Flow Range	0.8 -2.3 – 2.2	1.6 1.2 – 10.7	1.3 -2.3 – 10.7
AB8	RMSE Flow Range	0.3 -1.0 – 0.9	0.9 0.8 – 6.9	0.7 -1.0 – 6.9
HG	RMSE Flow Range	0.03 -0.05 – 0.31	0.06 0.00 – 0.76	0.04 -0.05 – 0.76
GG	RMSE Flow Range	0.09 -0.2 – 1.7	0.28 0.4 – 2.3	0.20 -0.2 – 2.3
AL1	RMSE Flow Range	0.16 -0.8 – 0.6	0.34 -0.8 – 0.7	0.27 -0.8 – 0.7
AL2	RMSE Flow Range	0.09 -0.2 – 0.6	0.19 -0.2 – 1.3	0.15 -0.2 – 1.3
AO11	RMSE Flow Range	1.2 -3.9 – 2.9	1.0 -4.2 – 5.0	1.1 -4.2 – 5.0
AO12	RMSE Flow Range	0.9 -2.6 – 2.0	1.2 -3.0 – 3.8	1.0 -3.0 – 3.8

Table 4. Average model error (RMSE) summary for water flow in the Cow Bayou system
All values are in cubic meters per second (cms).

Site		Intensive Survey #1 Model Calibration	Intensive Survey #2 Model Verification	Both Surveys
CB0.5	RMSE Flow Range	6 -117 – 87	12 -102 – 82	10 -117 – 87
CB1	RMSE Flow Range	10 -80 – 61	7 -69 – 57	8 -80 – 61
CB2	RMSE Flow Range	5 -50 – 44	6 -44 – 42	6 -50 – 44
CB2.5	RMSE Flow Range	4 -31 – 29	4 -28 – 27	4 -31 – 29
CB3	RMSE Flow Range	3 -16 – 17	4 -16 – 16	3 -16 – 17
CB3.5	RMSE Flow Range	2.7 -10.4 – 10.8	2.8 -10.2 – 9.8	2.8 -10.4 – 10.8
CB4	RMSE Flow Range	1.4 -3.6 – 4.2	0.9 -4.3 – 3.7	1.2 -4.3 – 4.2
CB5	RMSE Flow Range	0.5 -1.2 – 1.6	0.6 -1.5 – 1.6	0.6 -1.5 – 1.6
CNB	RMSE Flow Range	0.4 -0.8 – 0.9	0.3 -0.8 – 0.9	0.3 -0.8 – 0.9
TG2	RMSE Flow Range	0.5 -0.8 – 1.1	0.5 -1.1 – 1.1	0.5 -1.1 – 1.1
CC	RMSE Flow Range	0.4 -0.8 – 0.6	No measurable flow	0.4 -0.8 – 0.6
CO2	RMSE Flow Range	3 -21 – 18	5 -19 – 17	5 -21 – 18
CO3	RMSE Flow Range	0.9 -8.0 – 8.6	3.0 -7.6 – 8.2	2.5 -8.0 – 8.6

WASP Water Quality Model Description

WASP is a generalized framework for simulating water quality in surface waters and the underlying benthos. It can be applied in one, two or three dimensions. The time-varying processes of advection, dispersion, point- and nonpoint-source pollutant loading, and boundary exchange are included in the basic program. Four WASP modules are provided. The EUTRO module is designed to simulate nutrients, dissolved oxygen, and eutrophication. The TOXI module simulates organic contaminant fate and transport. The HEAT module simulates temperature and salinity. The mercury module simulates various mercury species and sediment balances.

For this project, the EUTRO module in WASP version 7.1 was applied to simulate both dissolved oxygen (DO) and E. coli (EC). Separate models were developed for each bayou system, and for DO and EC. Thus, a total of four WASP models were developed.

In WASP version 7.1, EUTRO can be run with various levels of complexity, simulating the transport and transformations of up to thirteen state variables: dissolved oxygen (DO), carbonaceous biochemical oxygen demand (cBOD), ammonia nitrogen (NH3N), nitrate nitrogen (NO3N), organic nitrogen (OrgN), orthophosphate phosphorus (PO4P), organic phosphorus (OrgP), phytoplankton chlorophyll a (ChlA), benthic algae, detritus (nonliving particulate organic matter), suspended and bed solids, salinity, and sediment oxygen demand (SOD). In the Adams and Cow Bayou DO models, all of these parameters were simulated except benthic algae.

Because EC is not included among the constituents simulated by the EUTRO module, EC was simulated as ammonia nitrogen. Ammonia is a useful analog because it similarly degrades via a first order rate, can adsorb to suspended sediments, and can settle to and resuspend from bottom sediments when adsorbed on sediments. However, some additional ammonia processes in EUTRO were inactivated in the EC model: uptake by algae and aquatic plants, and production by decay of organic matter, among others. Other processes affect EC but not ammonia behavior in streams, and are not directly simulated in WASP but incorporated into an overall die-off or disappearance rate: direct sedimentation of free bacteria (i.e., not associated with particles), bacterial re-growth, photolysis or inactivation caused by light, grazing by zooplankton and flagellates, phagotrophy by algae, and cell lysis caused by bacteriophagic viruses. It was therefore assumed that EC die-off and disappearance rates can vary spatially. In the EC models, this was simulated using the model parameters for inhibition of ammonia decay via nitrification at low DO levels. However, instead of simulating DO, DO concentrations were specified for each model reach to spatially adjust the nitrification rate, which is actually a reduction in the EC mortality rate.

Model Segmentation

While a large number of small model elements were used in the RMA2 hydrodynamic models to simulate the sinuosity and bottom elevation change of natural channels, There was no need for high spatial resolution simulations in the WASP water quality model, both from a water quality management perspective and because field measurements of water quality for calibration were not of high spatial resolution. The WASP model segmentation was developed by aggregating RMA2 elements to reaches to minimize the volume differences between adjacent reaches, while maintaining the minimum segmentation required for water quality management purposes. Additionally, an attempt was made to locate the WASP reaches so that the monitoring stations were near the center of the model reach, so that calibration data would be representative of typical conditions in the reach. Each WASP model reach consisted of a single surface water segment overlying a single benthic sediment segment. Figures 8 and 9 illustrate the segmentation of the WASP models of Adams and Cow Bayous, respectively. Tables 5 and 6 describe the physical dimensions of WASP reaches.

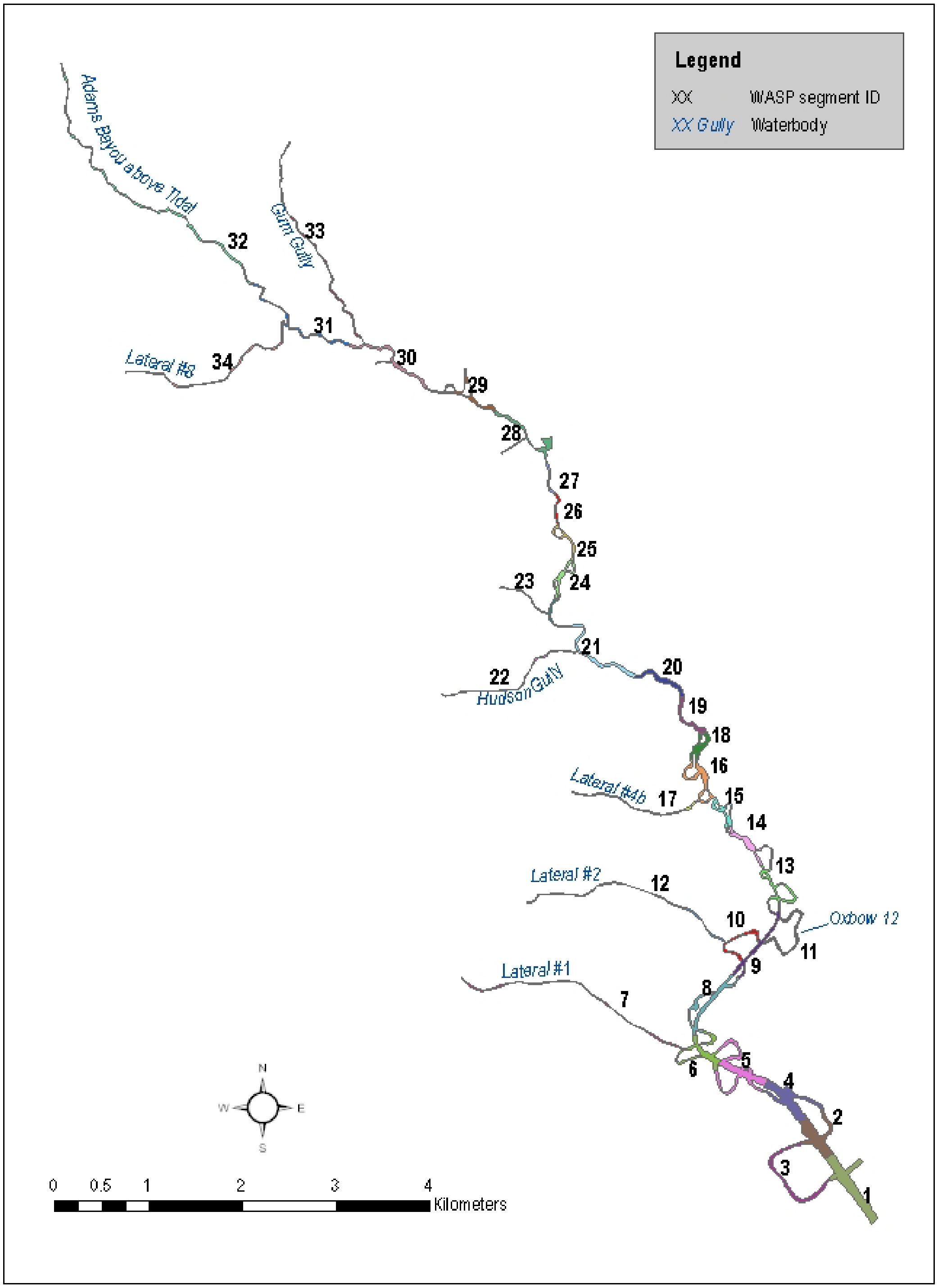


Figure 8. Adams Bayou WASP model segmentation

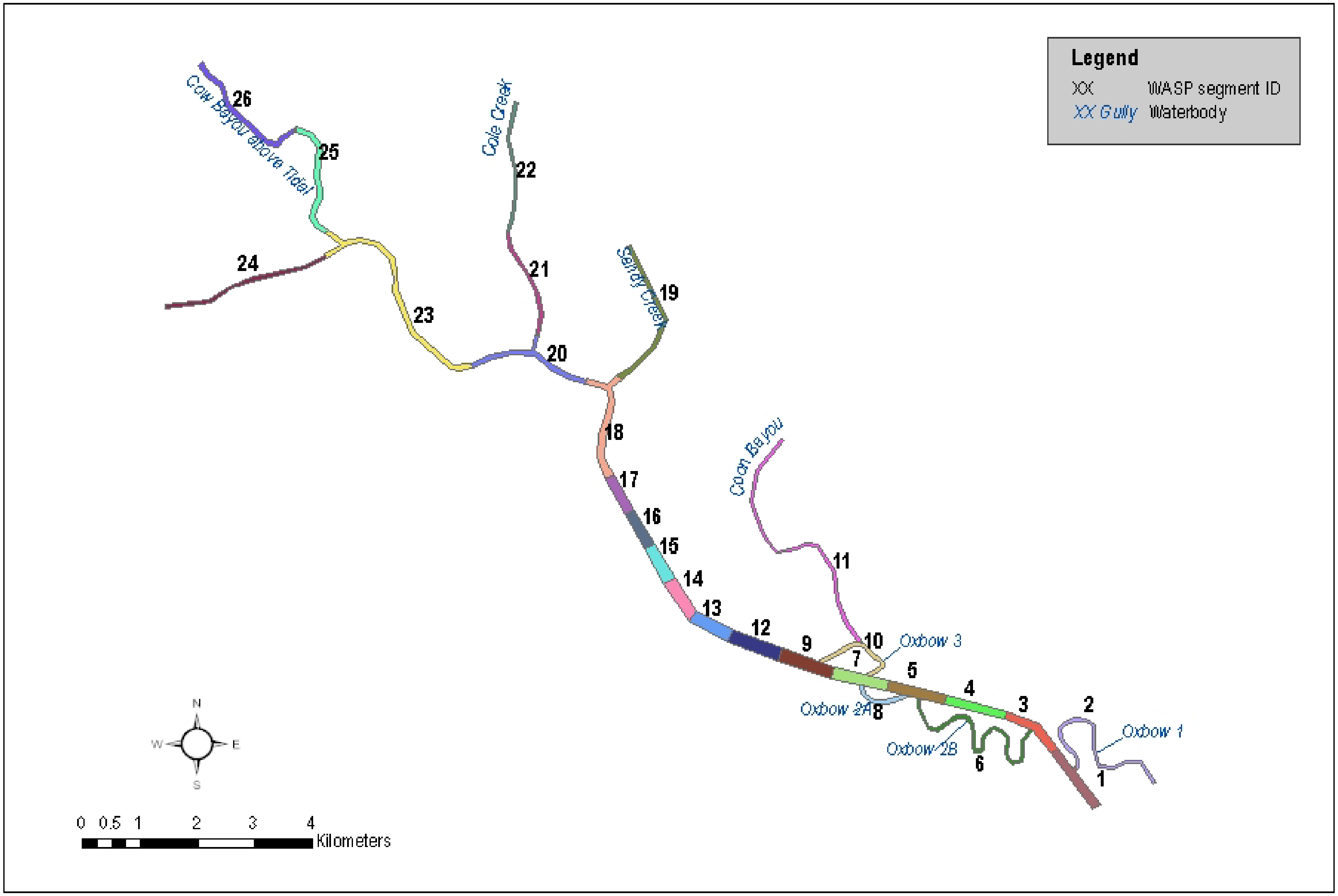


Figure 9. Cow Bayou WASP model segmentation

Table 5. Physical properties of Adams Bayou WASP model reaches

Reach	Reach Name	Monitoring Site ID	Approximate volume cubic meters	Depth meters	Length meters	Width meters
1	Rch 1		532,000	5.1	1,109	95
2	Rch 2		270,000	4.2	1,200	60
3	Oxbow #1		108,000	3.4	1,155	29
4	Rch 3		203,000	3.9	1,353	41
5	Rch 4		253,000	3.7	1,770	39
6	Rch 5	AB2	252,000	5.1	1,009	55
7	Lateral #1	AL1	48,000	2.3	2,375	10
8	Rch 6		195,000	4.0	1,923	27
9	Rch 7		177,000	4.1	1,870	26
10	Oxbow 11	AO11	33,000	2.1	670	24
11	Oxbow 12	AO12	62,000	2.6	883	29
12	Lateral #2	AL2	6,000	1.6	873	6
13	Rch 8	AB3	138,000	3.9	1,420	28
14	Rch 9		94,000	3.1	1,028	30
15	Rch 10		57,000	4.4	524	30
16	Rch 11		96,000	3.0	1,191	28
17	Lateral #4b		7,000	1.5	1,179	5
18	Rch 12	AB4	97,000	3.0	818	42
19	Rch 13		102,000	4.0	715	41
20	Rch 14		95,000	4.0	676	39
21	Rch 15		143,000	4.0	1,395	29
22	Hudson Gully	HG	6,000	1.4	788	7
23	Rch 16		30,000	4.0	278	30
24	Rch 17	AB5	61,000	4.2	356	45
25	Rch 18		80,000	4.2	494	44
26	Rch 19		41,000	4.2	304	35
27	Rch 20		73,000	4.2	672	28
28	Rch 21	AB6	62,000	4.0	756	23
29	Rch 22		75,000	3.8	1,258	18
30	Rch 23	AB7	68,000	3.4	1,263	18
31	Rch 24		57,000	2.8	1,695	15
32	Rch 25	AB8	42,000	1.9	2,395	12
33	Gum Gully	GG	10,000	1.6	1,612	5
34	Lateral #8	AL8	5,000	1.5	891	5

Table 6. Physical properties of Cow Bayou WASP model reaches

Reach	Reach name	Monitoring Site ID	Approximate Volume cubic meters	Depth meters	Length meters	Width meters
1	Rch 1		585,667	4.7	1,060	118
2	Oxbow 1		507,968	3.0	3,267	52
3	Rch 2		483,538	3.4	1,515	94
4	Rch 3	CB0.5	399,086	3.5	1,208	94
5	Rch 4		740,937	5.0	1,755	84
6	Oxbow 2A	CO2	365,092	2.4	3,083	49
7	Rch 5	CB1	697,715	6.2	1,353	83
8	Oxbow 2B		167,839	3.9	854	50
9	Rch 6		775,915	7.0	1,410	79
10	Oxbow 3	CO3	143,270	1.8	1,737	47
11	Coon Bayou	CNB	62,949	1.4	4,359	12
12	Rch 7		594,377	8.2	940	77
13	Rch 8	CB2	572,114	8.6	947	70
14	Rch 9		434,417	8.6	698	73
15	Rch 10		454,485	8.0	712	79
16	Rch 11	CB2.5	443,421	8.0	695	80
17	Rch 12		310,656	5.5	876	65
18	Rch 13	CB3	353,972	2.9	2,275	53
19	Sandy Creek		55,913	2.4	2,381	10
20	Rch 14	CB3.5	206,417	2.6	2,509	32
21	CClower		69,696	1.9	2,046	18
22	CCupper	CC	21,956	1.1	2,006	10
23	Rch 15		187,781	2.2	4,404	19
24	Terry Gully	TG2	33,135	1.1	2,565	11
25	Rch 16	CB4	47,641	1.8	2,099	12
26	Rch 17	CB5	34,042	1.1	2,285	13

Model Input Data

In addition to system geometry and segmentation, additional input data required by WASP include hydrodynamic data (water depth, flow, velocity), meteorology, initial conditions, boundary conditions, point and nonpoint source pollutant loads, and rate constants and coefficients for model processes.

Hydrodynamic Linkage

The WASP model cannot read an RMA2 hydrodynamic file directly. Therefore, a Fortran program was written to convert the RMA2 model output to the output format of the DYNHYD model, which can be read by WASP. The DYNHYD format conveys the essential hydrodynamic information required by WASP, including element volumes, inflows and outflows, water velocities, and depths. A second Fortran program was written to aggregate RMA2 elements in order to reduce the detailed segmentation of the RMA2 model to the level necessary for WASP. This involved summing the volumes and averaging depths and water velocities of the RMA2 elements comprising the WASP reaches. Next, a program provided with WASP converted the DYNHYD file, in ASCII format, to the binary hydrodynamic file read directly by the WASP 7.1 model.

Meteorology

Hourly meteorological data collected by the TCEQ from the continuous air monitoring station (CAMS 9/141) at 2700 Austin Avenue in West Orange were used as WASP model input. Parameters used by the model were air temperature, solar radiation, and wind speed.

Point Source Pollutant Loads

Point source loads were measured daily at discharge points during the intensive surveys for model input for the calibration period. Loads included NH3N, NO3N, OrgN, PO4P, cBOD, EC, and suspended solids. For long-term simulations, point source loadings were estimated based on a combination of self-reported effluent data (from January 2000 through March 2005) and effluent measurements made during the intensive surveys. Most facilities with permitted discharges to the bayous are required to report each month the average measured flow rate of their discharge. Most facilities are also required to report on a monthly basis either the monthly total loads or average concentrations of one or more specific pollutants or other parameters in their wastewater discharge to the bayous. In cases where the facility did not self-report a pollutant concentration or load, that load was estimated using the self-reported monthly average flow and the average concentration measured during the intensive surveys. Point source loads to Adams and Cow Bayou are summarized in *Nonpoint Source Modeling of the Watersheds of Adams and Cow Bayou* (Parsons 2006).

Non-Point Source Pollutant Loads

Nonpoint source pollutant loads from the HSPF watershed model were summarized on a daily basis by subwatershed. Loads included NH3N, NO3N, OrgN, PO4P, cBOD, EC, and suspended solids. These loads were then input by subwatershed to the WASP reaches. The nonpoint source pollutant sources and loads are described in detail in *Nonpoint Source Modeling of the Watersheds of Adams and Cow Bayou* (Parsons 2006).

Initial and Boundary Conditions

Reach-specific initial concentrations of ChlA, DO, NH3N, NO3N, OrgN, PO4P, cBOD, EC, salinity, and suspended solids were estimated from average measured values of these parameters from from January 2000 through March 2005. OrgN concentrations were calculated as the difference between TKN and NH3N. For WASP reaches lacking direct monitoring data, concentrations were interpolated from the nearest monitoring stations. The concentrations at the lower boundary, at the Sabine River, were measured during the intensive surveys in the Sabine River at its confluence with each bayou.

Water temperature is not simulated in the EUTRO module, but specified as an external time series based on measured data. For model calibration and verification periods, measured reach-specific temperatures from the intensive surveys were used. For long-term water quality simulations, a seasonal curve was developed and fit to long-term air and water temperature measurements in Adams and Cow Bayous and adjacent sections of the Sabine River.

Calibration

Dispersion

Longitudinal dispersive mixing and exchange between reaches was first calibrated to measured salinity data. The WASP dispersion formulation is based on the cross-sectional area between adjacent reaches and a characteristic mixing length, taken to be the distance between midpoints of the adjacent reaches. Due to rainfall, there was no significant salinity gradient during either intensive survey of Adams Bayou (in May and June), when due to freshwater inflows the total dissolved solids concentrations remained below 100 mg/l throughout the bayou (Figure 10). Therefore it was not possible to calibrate to salinity in Adams Bayou. However, there were pronounced salinity gradients in Cow Bayou from the Sabine confluence to its upper tidal reaches, ranging from 3 down to 0.2 parts per thousand (ppt). Calibrated dispersion coefficients for surface waters ranged from 10 to 2000 m^2/s in the Cow Bayou system, and the average RMSE was 0.4 ppt (Table 13). These dispersion coefficients were applied to reaches of similar dimensions (length and cross-sectional area) in Adams Bayou.

A dispersion coefficient of 5×10^{-9} m^2/s and a mixing length of 0.5 m were applied to predict vertical dispersive exchange between sediments and the water column throughout each bayou. The dispersion coefficient was estimated from literature values (Roychoudhury, 2001).

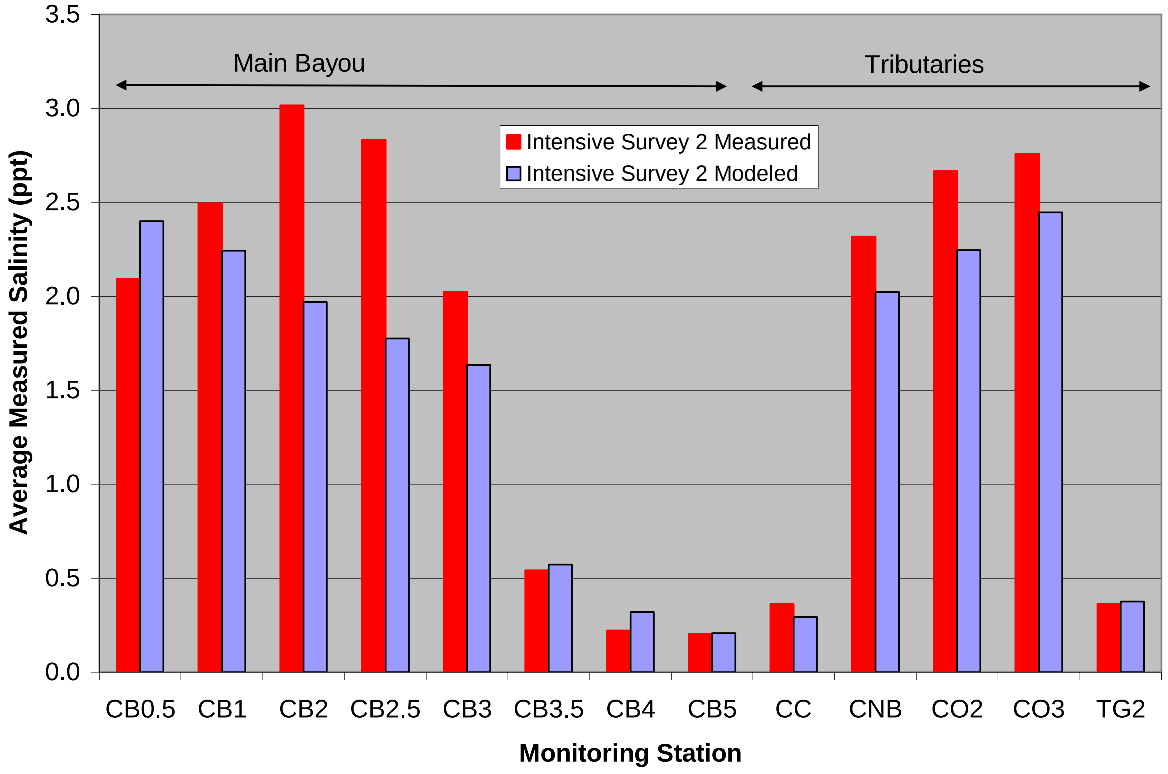


Figure 10. Cow Bayou salinity verification for the second intensive survey – August 24-26, 2004

Model Constants and Coefficients

The constants and coefficients governing the water quality constituents in the WASP model can be divided into those held constant throughout each bayou system and those with specific values for each reach within a given bayou system. Each of these groups can be further divided into constants and coefficients that were measured, those estimated based on the scientific and technical literature, and those whose values were selected by calibrating the model to observed data. For those parameters adjusted by calibration, the model goodness of fit was evaluated by the RMSE.

System-wide constants and coefficients for processes that were simulated in the dissolved oxygen models are listed in Table 7 along with their measured, literature, or calibrated values used in each model. For values estimated from the literature, an effort was made to identify typical values from similar systems. The sources of these values included the WASP user manual (Wool et al. 2001), EPA guidance (Bowie et al. 1985), and references in both of these documents such as Thomann and Fitzpatrick (1982). Calibrated values were adjusted (to optimize model fit to observed data) within ranges considered realistic based on a review of this same literature. Table 8 lists values of reach-specific parameters for the Adams Bayou DO model. Table 9 lists values of reach-specific parameters for the Cow Bayou DO model.

For the EC models, it was assumed that EC die-off and disappearance rates from the water column could vary with stream reach, and that EC die-off rates in the sediments are much slower than those in the water column. Some of the factors affecting the water column disappearance rate of EC include water temperature, predation, hydrodynamic factors that lead to increased sedimentation or resuspension from sediments, suspended solids levels, and vegetative canopy coverage. Reach-specific EC die-off rates were implemented in the WASP model using 1) a system-wide maximum die-off rate, implemented via the ammonia nitrification rate, 2) a system-wide half-saturation constant for EC die-off, implemented via the DO half-saturation for nitrification, and 3) a reach-specific constant DO concentration. Tables 10 and 11 list the values of reach-specific die-off rates (at 20°C) and sediment exchange rates for EC in the Adams and Cow Bayou models, respectively. In addition to these reach-specific parameters, a literature-derived temperature coefficient of 1.09 and partition coefficient of 1000 to suspended and bed sediments were applied for EC universally.

A review of first order coliform disappearance rates from twelve rivers and streams (Mitchell and Chamberlin 1978) revealed rates ranging from 0.1 to 26 day^{-1}, with an average rate of 1.03 day^{-1}. The calibrated rates from Adams and Cow Bayou reaches compare well with these literature values. In some cases the calibrated EC decay rates may not only reflect the rates of instream decay, but also correct for inaccurate estimations of bacterial loads from some sub-watersheds in the HSPF watershed model. Fluxes to and from the sediments were used to further calibrate the model predictions at some sites. While the magnitude of daily benthic fluxes of EC may appear large, they represent a very small fraction of the total load of EC in the system.

Carbonaceous BOD decay rates were estimated from 20-day laboratory incubations. For the first five days, the measured decay rates ranged from 0.04 – 0.57 day^{-1}, with an average of 0.13 day^{-1} and a standard deviation of 0.14 day^{-1}. From five to fifteen days, the cBOD decay rates ranged from 0.00 – 0.13 day^{-1}, with an average value of 0.07 day^{-1} and a standard deviation of 0.03 day^{-1}. From fifteen to twenty days, the cBOD decay rates declined further, ranging from 0.00 to 0.07

day^{-1}, with an average of 0.02 day^{-1} and a standard deviation of 0.02 day^{-1}. When adjusted to the ambient bayou water temperatures of 25 – 30 °C observed during the intensive surveys, clearly the majority of cBOD degradation will occur during the first five days. Thus, it is not surprising that the calibrated cBOD decay rates at 20 °C were close to the measured laboratory 5-day cBOD decay rate.

Table 7. Values of system-wide model constants and coefficients for dissolved oxygen models

Process	Source	Adams Bayou	Cow Bayou
atmospheric deposition rate of NH3N (mg/m^2/day)	ed	0.54	0.54
atmospheric deposition rate of NO3N (mg/m^2/day)	ed	0.56	0.56
ammonia nitrification rate constant @ 20°C (day^{-1})	C	0.5	0.2
nitrification temperature coefficient	lv	1.08	1.08
half-saturation for nitrification (mg O_2/L)	C	0	3
ammonia partition coefficient to suspended solids	C	1000	not used
ammonia partition coefficient to benthic sediments	C	1000	not used
denitrification rate constant @ 20°C (day^{-1})	C	2	0.5
denitrification temperature coefficient	lv	1.08	1.08
half-saturation for denitrification (mg O_2/L)	lv	5	5
OrgN mineralization rate constant (dissolved) @ 20°C (day^{-1})	C	0.5	0.4
OrgN mineralization (dissolved) temperature coefficient	lv	1.07	1.07
OrgN mineralization rate constant (sediments) @ 20°C (day^{-1})	fm	0.0004	0.0004
OrgN mineralization (in sediments) temperature coefficient	lv	1.047	1.047
fraction of phytoplankton death recycled to OrgN	C	not used	1
OrgP mineralization rate constant (dissolved) @ 20°C (day^{-1})	C	0.22	0.2
OrgP mineralization (dissolved) temperature coefficient	lv	1.08	1.08
OrgP mineralization rate constant (sediments) @ 20°C (day^{-1})	fm	0.0004	0.0004
OrgP mineralization rate (sediments) temperature coefficient	lv	1.08	1.08
fraction of phytoplankton death recycled to OrgP	lv	1	1
phytoplankton maximum growth rate constant @ 20°C (day^{-1})	C	1.8	1.8
phytoplankton growth temperature coefficient	lv	1.066	1.066
algal self-shading coefficient	lv	1	not used
algal self-shading exponent	lv	0.048	not used
phytoplankton carbon to chlorophyll ratio	C_1	30	20
phytoplankton half-saturation constant for nitrogen uptake (mg N/l)	C	0.025	0.05
phytoplankton half-saturation constant for phosphorus uptake (mg N/l)	C	0.001	0.01
phytoplankton endogenous respiration rate constant @ 20°C (day^{-1})	C	0.17	0.05
phytoplankton respiration temperature coefficient	lv	1.045	1.045
phytoplankton non-predatory mortality rate constant (day^{-1})	lv	0.02	0.02
phytoplankton zooplankton grazing rate constant (day^{-1})	lv	1.5	1.5
phytoplankton decay rate constant in sediments (day^{-1})	lv	0.02	0.02

Process	Source	Adams Bayou	Cow Bayou
phytoplankton decay in sediments temperature coefficient	lv	1.08	1.08
phytoplankton phosphorus to carbon ratio	lv	0.02	0.02
phytoplankton nitrogen to carbon ratio	lv	0.25	0.25
phytoplankton half-saturation for recycle of nitrogen and phosphorus (mg C/l)	lv	1	1
phytoplankton light formulation method	N/A	Steele	Steele
phytoplankton maximum quantum yield constant	lv	720	720
phytoplankton optimal light saturation	lv	360	360
detritus and solids light extinction multiplier	C	0.052	0.040
waterbody type for wind-driven reaeration	N/A	2	2
reaeration calculation method	N/A	Covar	Covar
elevation above sea level (meters)	N/A	0	0
global reaeration rate constant @ 20°C (day^{-1})	lv	0.5	not used
reaeration temperature coefficient	lv	1.022	1.022
oxygen to carbon stoichiometric ratio	lv	3.2	3.2
cBOD decay rate constant @ 20°C (day^{-1})	C_1	0.14	0.14
cBOD decay temperature coefficient	lv	1.047	1.047
cBOD decay rate constant in sediments @ 20°C (day^{-1})	fm	0.0004	0.0004
cBOD decay in sediments temperature coefficient	lv	1.08	1.08
detritus dissolution rate constant @ 20°C (day^{-1})	lv	0.02	0.02
detritus dissolution temperature coefficient	lv	1.047	1.047
fraction of detritus dissolution to cBOD	lv	1	1
fraction of cBOD carbon source for denitrification	lv	not used	1
sediment oxygen demand temperature coefficient	lv	1.047	1.047

C = calibrated within literature ranges; C_1 = calibrated within range of field-derived estimates; lv = literature values were used; fm = based on field measurements; ed = estimated based on measurements collected outside of this project; N/A = not applicable

Table 8. Reach-specific parameters for the Adams Bayou dissolved oxygen model

Reach Name	Scale factor for wind	Light Extinction	cBOD Decay Rate Scale Factor	Benthic Ammonium Flux mg/m^2/day	Benthic Phosphate Flux mg/m^2/day	Sediment Oxygen Demand g/m^2/day	Zooplankton Population
Rch 1	0.8	10	1	200	100	4	0.2
Rch 2	0.6	10	1	200	100	4	0.2
Oxbow #1	0.4	10	1	200	100	4	0.2
Rch 3	0.6	10	1	200	100	4	0.2
Rch 4	0.6	10	1	200	100	4	0.2
Rch 5	0.6	10	1	200	100	4	0.2
Lateral #1	0.4	3	1	-100	100	4	0.01
Rch 6	0.4	10	1	100	0	3	0.2
Rch 7	0.4	10	1	100	0	3.5	0.2
Oxbow 11	0.1	3	1	300	0	3.5	0.2
Oxbow 12	0.1	3	1	50	0	3.5	0.2
Lateral #2	0.2	1	1	50	100	2	0.2
Rch 8	0.4	1	1	300	0	4.1	0.2
Rch 9	0.4	1	1	300	0	3.8	0.2
Rch 10	0.4	1	1	300	0	3.5	0.2
Rch 11	0.4	1	1	300	0	3.3	0.2
Lateral #4b	0.4	1	1	300	0	2	0.2
Rch 12	0.6	1	1	300	0	3.1	0.2
Rch 13	0.5	1	1	200	0	3	0.2
Rch 14	0.5	1	1	0	0	2.8	0.2
Rch 15	0.5	1	1	-100	0	2.5	0.2
Hudson Gully	0.4	1	1	-3000	0	2	0.2
Rch 16	0.5	1	1	0	0	2.2	0.2
Rch 17	0.5	1	1	0	0	2	0.2
Rch 18	0.5	1	1	-100	0	2	0.2
Rch 19	0.5	1	1	-300	0	1.9	0.2
Rch 20	0.5	1	1	-300	0	1.9	0.2
Rch 21	0.5	1	1	-600	0	1.8	0.2
Rch 22	0.7	1	1	-500	0	1.5	0.2
Rch 23	0.8	1	1	-500	0	1	0.2
Rch 24	0.8	1	1	-500	0	1	0.2
Rch 25	0.5	2	1	-500	-100	1	0.2
Gum Gully	0.01	1	5	-500	0	2	0.2
Lateral #8	0.6	1	1	-500	0	1	0.2

Table 9. Reach-specific parameters for the Cow Bayou dissolved oxygen model

Reach Name	Scale factor for wind	Light Extinction	cBOD Decay Rate Scale Factor	Benthic Ammonium Flux mg/m^2/day	Benthic Phosphate Flux mg/m^2/day	Sediment Oxygen Demand g/m^2/day	Zooplankton Population
Rch 1	1	2	0.9	-200	0	1	0.3
Oxbow 1	1	2	0.9	-200	0	1	0.3
Rch 2	1	2	0.9	-200	0	1	0.2
Rch 3	1	2	0.9	-200	0	1	0.3
Rch 4	1	2	1	-200	0	1.2	0.1
Oxbow 2A	1	0.2	1	300	0	12	0.01
Rch 5	1	2	1	0	0	1.2	0.2
Oxbow 2B	1	2	1	0	0	1	0.2
Rch 6	1	2	1	0	0	1.6	0.2
Oxbow 3	0.9	2	1	300	0	15	0.2
Coon Bayou	0.1	100	1.3	100	0	7	0.01
Rch 7	1	0.7	1	0	0	2.5	0.1
Rch 8	1	0.7	1	-200	0	2.7	0.01
Rch 9	1	0.7	1	-200	0	2.7	0.01
Rch 10	1	0.7	1	-200	0	2.7	0.01
Rch 11	1	0.7	1	-200	0	2.6	0.01
Rch 12	0.8	0.7	1	-200	0	2.6	0.01
Rch 13	0.7	0.5	0.5	-200	-300	2.6	0.01
Sandy Creek	0.3	0.5	0.5	-200	0	2	0.01
Rch 14	0.1	100	0.5	300	0	5	0.01
CClower	0.1	0.5	0.5	100	0	1.5	0.1
CCupper	0.7	3	0.5	-200	0	0.5	0.2
Rch 15	0.5	2	1	-100	0	1.5	0.1
Terry Gully	0.9	3	0.7	-300	0	0.5	0.1
Rch 16	0.3	100	1.3	-100	-90	3	0.4
Rch 17	0.5	2	1.3	-100	0	3	0.1

Table 10. Reach-specific parameters for the Adams Bayou E. coli model

Reach Name	E. coli decay rate day-1	Benthic E. coli Flux‡ #/m^2/day
Rch 1	0.56	0
Rch 2	0.56	0
Oxbow #1	0.56	0
Rch 3	0.56	0
Rch 4	0.56	0
Rch 5	0.56	0
Lateral #1	2.88	-200000
Rch 6	0.56	0
Rch 7	0.56	0
Oxbow 11	0.56	200000
Oxbow 12	0.56	200000
Lateral #2	2.88	-2000000
Rch 8	0.56	200000
Rch 9	0.56	200000
Rch 10	0.56	200000
Rch 11	0.56	200000
Lateral #4b	2.4	0
Rch 12	0.56	200000
Rch 13	0.56	200000
Rch 14	0.56	200000
Rch 15	0.56	200000
Hudson Gully	2.88	-2000000
Rch 16	0.56	200000
Rch 17	0.56	200000
Rch 18	0.56	200000
Rch 19	2.4	200000
Rch 20	2.4	200000
Rch 21	2.4	200000
Rch 22	2.69	0
Rch 23	2.88	-4000000
Rch 24	2.88	0
Rch 25	2.88	0
Gum Gully	2.88	-1500000
Lateral #8	2.88	0

‡ negative values represent deposition to sediments, while positive values reflect fluxes from sediments to water

Table 11. Reach-specific parameters for the Cow Bayou E. coli model

Reach Name	E. coli decay rate day-1	Benthic E. coli Flux‡ #/m^2/day
Rch 1	0.35	0
Oxbow 1	0.35	0
Rch 2	0.35	0
Rch 3	0.35	0
Rch 4	0.23	0
Oxbow 2A	0.09	100000
Rch 5	0.09	100000
Oxbow 2B	0.09	100000
Rch 6	0.09	100000
Oxbow 3	0.09	100000
Coon Bayou	0.14	100000
Rch 7	0.14	100000
Rch 8	0.23	0
Rch 9	0.23	0
Rch 10	0.14	0
Rch 11	0.14	0
Rch 12	0.14	0
Rch 13	0.14	0
Sandy Creek	0.14	0
Rch 14	0.23	-20000
CClower	0.50	0
CCupper	0.58	-10000
Rch 15	0.50	0
Terry Gully	0.58	-30000
Rch 16	0.58	0
Rch 17	0.58	-80000

‡ negative values represent deposition to sediments, while positive values reflect fluxes from sediments to water

Calibration and Verification Results

Dissolved Oxygen Model

The results of model calibration for dissolved oxygen are displayed in figures 22 and 23 for Adams and Cow Bayou, respectively. While there is some tendency in the model to overestimate the lowest DO observations and underestimate the highest observed DO levels, the models do a good job overall of simulating the range and spatial patterns of DO in the bayous. Both models make more accurate predictions of daily average DO concentrations than daily minimum concentrations. The average r-squared values were 0.902 for daily average DO and 0.859 for daily minimum DO in Adams Bayou, and very few values were more than 1 mg/l different from measured values.

Tables 12 and 13 compile for Adams and Cow Bayous the station-by-station error statistics, comparing dissolved oxygen and other simulated parameters of the dissolved oxygen model with individual point measurements (not daily average or minima). The statistic shown here is the RMSE as a percentage of the measured value, for both calibration and verification periods. More model error statistics are provided in Appendix A. For dissolved oxygen at all Adams Bayou stations, the average RMSE was 0.91 mg/l, 51% of the measured values. The RMSE % was particularly high at some sites due to the very low DO concentrations observed. For the Cow Bayou system, the average RMSE was 0.75 mg/l, 20% of the measured values.

The Adams Bayou model also did a fairly good job of simulating all parameters. The Cow Bayou model did a fairly good job of simulating all parameters except ChlA. The model was not able to accurately simulate an algal bloom and dieoff during the first intensive survey, when ChlA concentrations in middle reaches of Cow Bayou ranged from 50 to 84 µg/l, then declined rapidly to 10-20 µg/l in the same day.

E. coli Model

The results of model calibration for E. coli are displayed in figures 24 and 25 for Adams and Cow Bayou, respectively. While there is significant scatter in the data, there are clear relationships between observed and predicted levels of E. coli. For the Adams Bayou model, the correlation r^2 value was 0.604, but only 0.344 for the Cow Bayou model. This is largely due to the fact that the range of measured E. coli in the Adams Bayou system (16 – 6,130 MPN/100 ml) was an order of magnitude greater than that in the Cow Bayou system (2 – 461 MPN/100 ml). E. coli model performance plots for each monitoring site are included in Figures 26 and 27. Bacteria are difficult to model in part because they are living organisms that can multiply very rapidly. They are also difficult to measure reproducibly, with two water samples taken simultaneously from the same volume of water sometimes yielding quite different results. Most statistics on bacteria concentration, including the primary water quality criterion for E. coli (geometric mean of 200/100 ml of water) are based on log-transformed data. The $\log_{10}$ RMSE of model predictions for the Adams Bayou EC model was 0.33 log units for the calibration period and 0.45 for the verification period. In the Cow Bayou model, the $\log_{10}$ RMSE was 0.30 log units for the calibration period and 0.39 for the verification period.

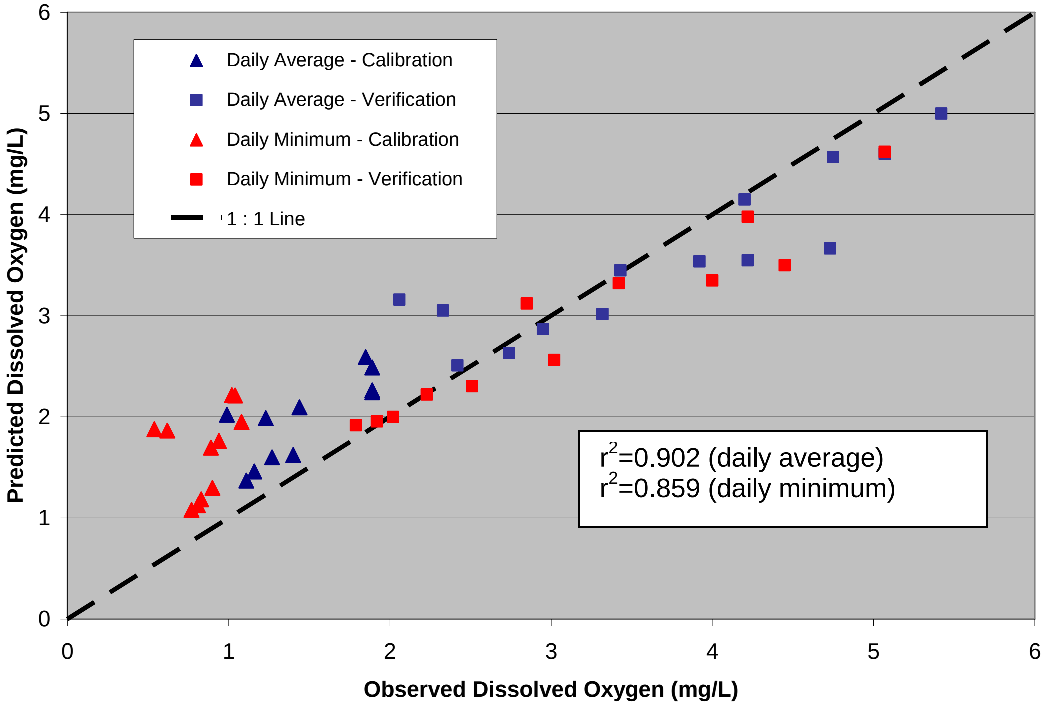


Figure 22. Adams Bayou dissolved oxygen model calibration performance

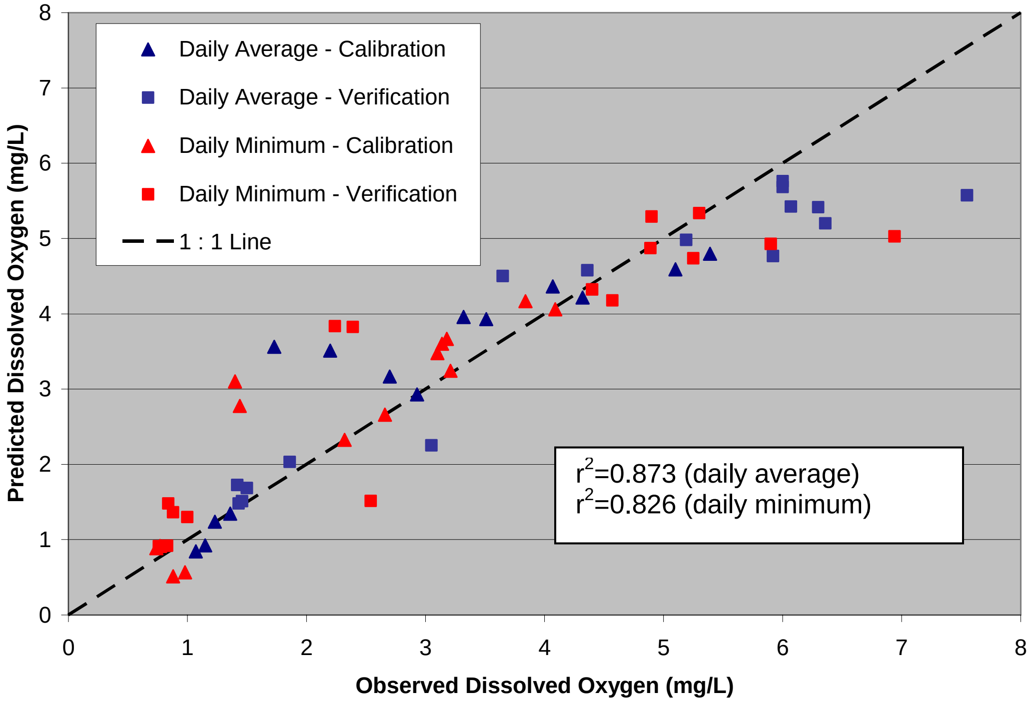


Figure 23. Cow Bayou dissolved oxygen model calibration performance

Table 12. Average RMSE as a percentage of measured values of several simulated water quality parameters in the Adams Bayou model

Station ID	DO	cBOD	NH3N	TKN	NO3N	PO4P	TSS	VSS	ChlA
AB2	53%	29%	71%	23%	36%	19%	51%	24%	42%
AB3	41%	20%	56%	32%	55%	28%	28%	29%	54%
AB4	26%	13%	37%	28%	54%	39%	26%	38%	79%
AB5	44%	11%	28%	22%	33%	19%	67%	65%	65%
AB6	25%	13%	65%	28%	21%	46%	28%	50%	69%
AB7	44%	15%	57%	27%	11%	36%	59%	60%	63%
AB8	17%	23%	14%	25%	7%	10%	35%	27%	96%
AL1	106%	28%	75%	28%	29%	38%	94%	23%	61%
AO11	67%	24%	29%	18%	32%	65%	57%	25%	41%
AO12	143%	62%	46%	44%	53%	51%	118%	26%	47%
AL2	84%	32%	33%	32%	56%	26%	41%	0%	0%
HG	28%	18%	184%	32%	45%	50%	90%	22%	55%
GG	15%	20%	28%	34%	8%	60%	53%	51%	43%
AL8	18%	17%	20%	36%	9%	39%	29%	23%	27%
Average	51%	23%	53%	29%	32%	38%	55%	33%	53%

Table 13. Average RMSE as a percentage of measured values of several simulated water quality parameters in the Cow Bayou model

Station ID	DO	cBOD	NH3N	TKN	NO3N	PO4P	TSS	VSS	ChlA
CB0.5	11%	27%	76%	39%	42%	65%	49%	65%	89%
CB1	23%	40%	47%	35%	42%	70%	93%	60%	49%
CB2	28%	47%	56%	31%	45%	69%	28%	38%	160%
CB2.5	22%	32%	71%	28%	60%	52%	29%	31%	73%
CB3	20%	45%	51%	27%	79%	64%	34%	38%	133%
CB3.5	32%	80%	28%	41%	45%	50%	48%	69%	160%
CB4	31%	38%	29%	19%	63%	81%	67%	59%	78%
CB5	4%	64%	6%	19%	35%	8%	20%	65%	13%
CO2	21%	35%	72%	27%	37%	63%	41%	33%	37%
CO3	23%	43%	60%	29%	56%	67%	38%	44%	58%
CNB	25%	19%	20%	22%	24%	57%	28%	47%	67%
CC	13%	48%	17%	20%	4%	5%	70%	52%	28%
TG2	9%	12%	21%	55%	32%	32%	36%	42%	27%
Average	20%	41%	43%	30%	43%	53%	45%	49%	75%

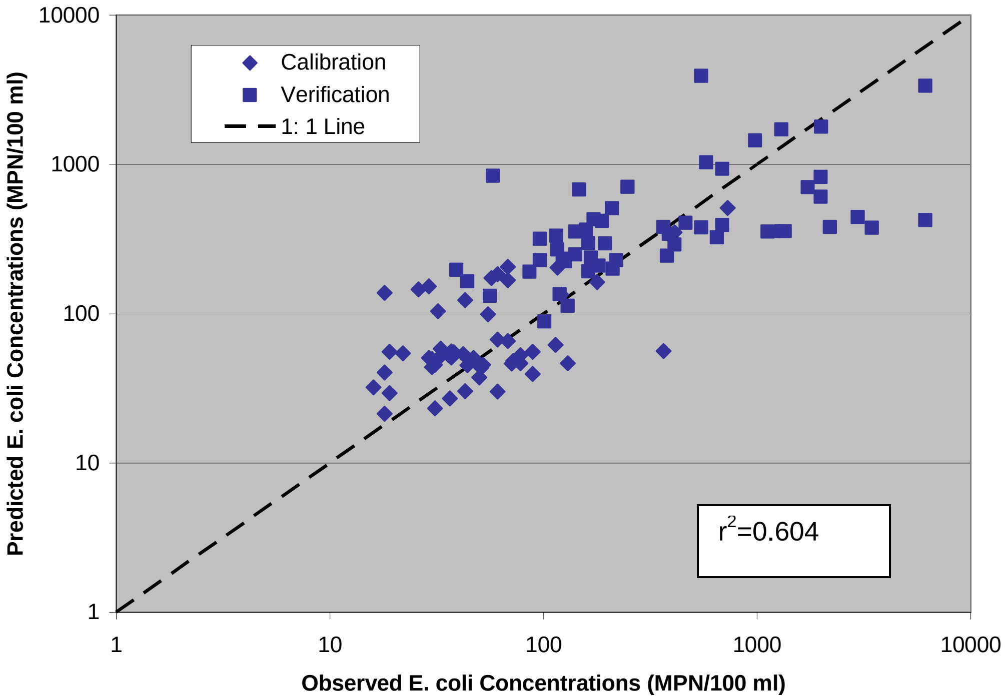


Figure 24. Adams Bayou E. coli model calibration performance – all sites

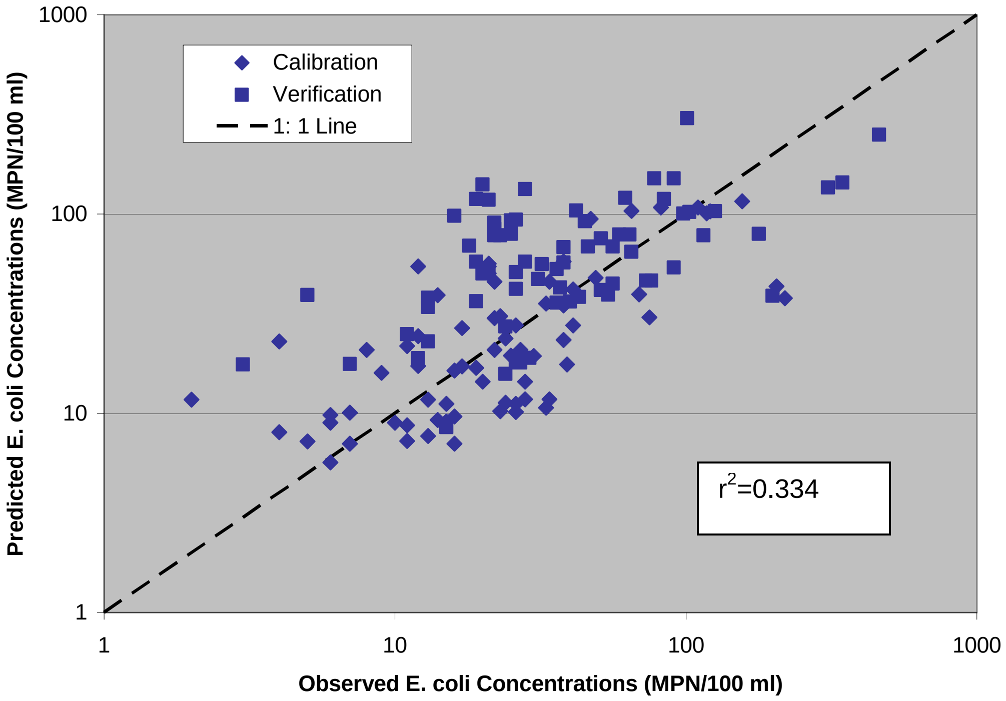


Figure 25. Cow Bayou E. coli model calibration performance – all sites

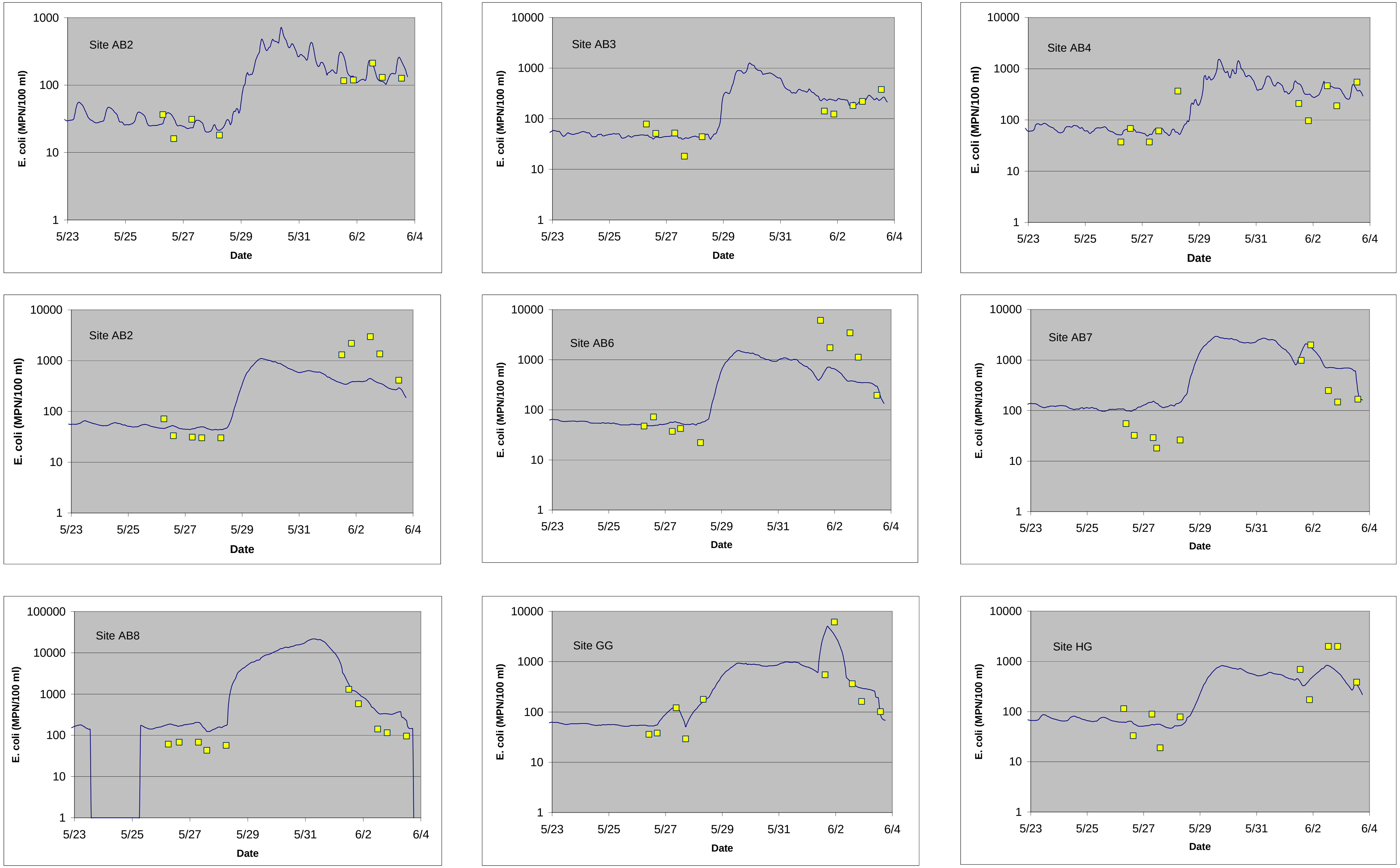


Figure 26. E. coli calibration in Adams Bayou sites. Note that the results from the verification period (June 29 – July 1) were simply appended to those from the calibration period (May 26-28) in these figures, for concise display, so the dates for the verification period are falsely shown as June 1 – 3.

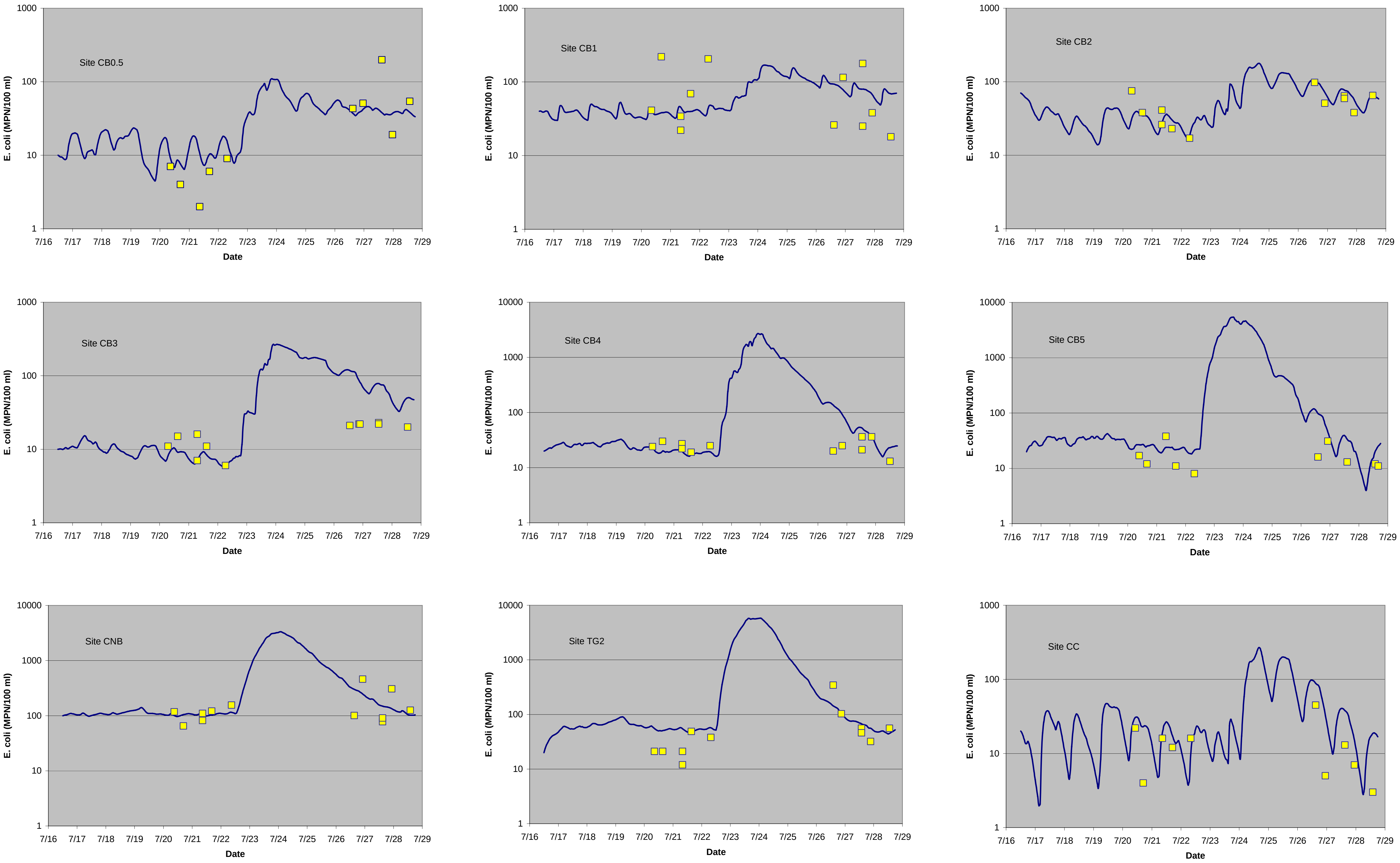


Figure 27. E. coli calibration at Cow Bayou sites. Note that the results from the verification period (August 24 – 26) were simply appended to those from the calibration period (July 20-22) in these figures, for concise display, so the dates for the verification period are falsely shown as July 27 – 29.

Model Results

Following calibration and verification of the RMA2 and WASP models with 7-day simulations, longer-term simulations were performed to evaluate the reach-specific status with respect to existing impairments of water quality criteria. Additional simulations were performed with reduced pollutant loadings (e.g, 10%, 20%, .. 100% reductions) to identify the level of reductions required to meet water quality standards. The long-term period simulated was from January 1, 2002 to March 26, 2005. For the Cow Bayou model, this simulation was performed as a single model run. For the Adams Bayou model, the simulation period was broken into multiple model runs because the hydrodynamic model "crashed" on a few dates in Gum Gully.

Load reductions were applied uniformly to all existing loads, as the objective was not to evaluate specific pollutant sources but to calculate the TMDL, or the maximum amount of loading the waterbody could assimilate while still meeting water quality standards. EC load reductions were applied only to EC loads. For the dissolved oxygen models, however, load reductions were applied to cBOD and nutrient (NH3N, NO3N, OrgN, PO4P, OrgP) loads. All of these parameters affect instream dissolved oxygen levels, and most pollutant sources contribute both cBOD and nutrients so that a reduction in cBOD loading could not be done without a similar reduction in nutrient loading. SOD levels were also reduced by the same fraction. Because the source of SOD is water column cBOD and ammonia that have settled to the sediment bed, a reduction of cBOD and nutrient loading is expected to yield a similar reduction in SOD, albeit with some time lag. However, dissolved oxygen levels were most sensitive to cBOD loadings, and TMDLs for dissolved oxygen should be based on that parameter.

Water Quality Targets

The water quality standards for E. coli state that the geometric mean of E. coli should not exceed 126 colonies/100 ml, and single samples should not exceed 394 colonies/100 ml. Note that contact recreation criteria also exist for other indicator bacteria (enterococcus and fecal coliform), the EC criterion was selected because the water bodies addressed are primarily comprised of fresh water and fecal coliform are no longer a recommended indicator species. For the geometric mean criterion, the geometric mean of all water quality samples at each site is directly compared to the criterion to determine whether water quality standards are supported. For the single sample criterion, it is the practice of TCEQ that the standards are considered attained if less than 25% of ambient water samples from a site exceed the single sample criterion. Failure to meet either the single-sample or geometric mean criteria is sufficient for a determination that water quality standards are not supported.

The water quality standards for DO require that daily average DO concentrations at any site in Cow Bayou tidal or Adams Bayou tidal must be at least 4 mg/l, and daily minimum DO concentrations must be above 3 mg/l. These same criteria also apply to Coon Bayou and Cole Creek in the Cow Bayou system, and to Hudson Gully in the Adams Bayou system. In Adams Bayou above tidal, Cow Bayou above tidal, and Gum Gully, the criteria are 3 mg/l and 2 mg/l for daily average and daily minimum DO concentrations, respectively. Terry Gully must meet a daily average DO criterion of 5 mg/l and a daily minimum DO criterion of 3 mg/l. In order for water quality standards to be judged as fully supported, no more than 10% of measurements can fall below these criteria. Failure to meet either the daily average or daily minimum criterion is sufficient for a determination that water quality standards are not supported.

Load Reductions and TMDLs

Existing pollutant loads were provided in the watershed modeling report (Parsons 2006). Table 14 summarizes these existing loads for the key pollutants most closely related to water quality impairments. Nonpoint sources exceed point sources except for NH3N in Adams Bayou tidal. Point sources also contribute a significant part of the total loads of cBOD in Adams Bayou tidal and Cow Bayou tidal.

Table 14. Existing loads of key pollutants to Adams and Cow Bayou segments

Waterbody	cBOD (lbs/day)			NH3N (lbs/day)			EC (colonies/day)		
	Point	Non-point	Total	Point	Non-point	Total	Point	Non-point	Total
Adams Bayou above tidal	0	137	137	0	20	20	0	3.5E+11	3.5E+11
Gum Gully	0	42	42	0	5.5	5.5	0	1.2E+11	1.2E+11
Hudson Gully	0	14	14	0	1.8	1.8	0	4.1E+10	4.1E+10
Adams Bayou tidal†	72	85	157	35	8.6	43.6	3.8E+09	2.2E+11	2.2E+11
Cow Bayou above tidal	20	723	743	2	75	77	2.2e+09	1.1E+12	1.1E+12
Cole Creek	0	217	217	0	30	30	0	4.3E+11	4.3E+11
Terry Gully	0	660	660	0	104	104	6.6E+08	1.4E+12	1.4E+12
Coon Bayou	3	114	117	0.3	18	19	0	3.0E+11	3.0E+11
Cow Bayou tidal†	420	734	1,154	22	131	153	9.4E+09	1.9E+12	1.9E+12

†Note that loads to tributaries are not included in the loads of the main tidal segment, i.e. they are not double-counted, although they also could be considered as loads to the downstream segment

The load reductions required to meet contact recreation standards in the Adams Bayou water quality impaired segments are illustrated in figures 28 and 29. The reductions required to meet the geometric mean criterion are in all cases greater than those required to meet the single sample criterion. The required load reductions were calculated at each ambient monitoring site, and the load reductions for the segment are those from the site requiring the greatest load reductions. Required load reductions ranged from 15% in Hudson Gully to 83% in Gum Gully (Table 15).

The load reductions required to meet contact recreation standards in the Cow Bayou water quality impaired segments are illustrated in figures 30 and 31. Cow Bayou tidal and Cole Creek are projected to currently meet water quality standards for contact recreation without load reductions. Terry Gully requires a 20% reduction in EC loading to meet water quality standards, and Coon Bayou will require an 83% load reduction to meet water quality standards.

Load reductions required to meet dissolved oxygen criteria were similar throughout the Adams Bayou system (Figure 32), ranging between 51% in Adams Bayou above tidal and 60% in Adams Bayou tidal. In the Cow Bayou system (Figure 33), Coon Bayou and Cole Creek require 27% and 28% load reductions, respectively, to meet dissolved oxygen criteria. Terry Gully is predicted to require a 65% load reduction to meet DO criteria. Cow Bayou tidal is predicted to require a 69% load reduction to meet DO criteria.

Cow Bayou above tidal is an interesting case. The HSPF model, used to simulate water quality in the above tidal reaches of Cow Bayou, predicts that DO criteria are not met 36% of the time. These violations of DO criteria were predicted by the model to occur when there was no flow but perennial pools in the bayou. This is known to occur somewhat frequently. Reducing cBOD loads in the model, even up to 100%, did not predict that DO levels would improve. It is not known how well the model predicts re-aeration under these no flow conditions. Additional field monitoring under no-flow conditions would be required to confirm these model predictions. Since load reductions could not be shown to lead to attainment of water quality standards, a TMDL cannot be established for this segment.

Maximum allowable loads of cBOD, NH3N, and EC that are predicted to allow water quality standards to be met are provided in Table 16. These are calculated based on average percent reductions from total existing loading to the waterbody. The water quality impairments are not uniformly distributed throughout the larger waterbodies such as Cow Bayou tidal, Adams Bayou tidal, and Cow Bayou above tidal. Neither are the pollutant loads mixed throughout the waterbodies, and assimilative capacity may vary greatly with distance from the Sabine River. The load reductions described apply only to the case where a single uniform load reduction percentage is applied to all pollutant sources to the waterbody. The actual load reductions required to allow water quality standards to be met will vary with the pollutant source, and reducing some specific loads may not result in improved water quality. The model may be used to evaluate the impact of varying load reductions on a source-specific basis.

Table 15. Summary of load reductions required to meet water quality standards for DO and EC

Waterbody	cBOD, nutrients	EC
Adams Bayou above tidal	51%	77%
Gum Gully	58%	83%
Hudson Gully	55%	15%
Adams Bayou tidal†	60%	73%
Cow Bayou above tidal	?	0%
Cole Creek	28%	0%
Terry Gully	65%	20%
Coon Bayou	27%	83%
Cow Bayou tidal†	69%	0%

Table 16. Maximum Allowable Loads

Waterbody	cBOD (lbs/day)	NH3N (lbs/day)	EC (colonies/day)
	Total	Total	Total
Adams Bayou above tidal	67	9.8	8.1E+10
Gum Gully	18	2.3	2.0E+10
Hudson Gully	6.3	1.8	3.5E+10
Adams Bayou tidal†	63	17	5.9E+10
Cow Bayou above tidal	?	?	1.1E+12
Cole Creek	156	22	4.3E+11
Terry Gully	231	36	1.1E+12
Coon Bayou	85	14	5.1E+10
Cow Bayou tidal†	358	47	1.9E+12

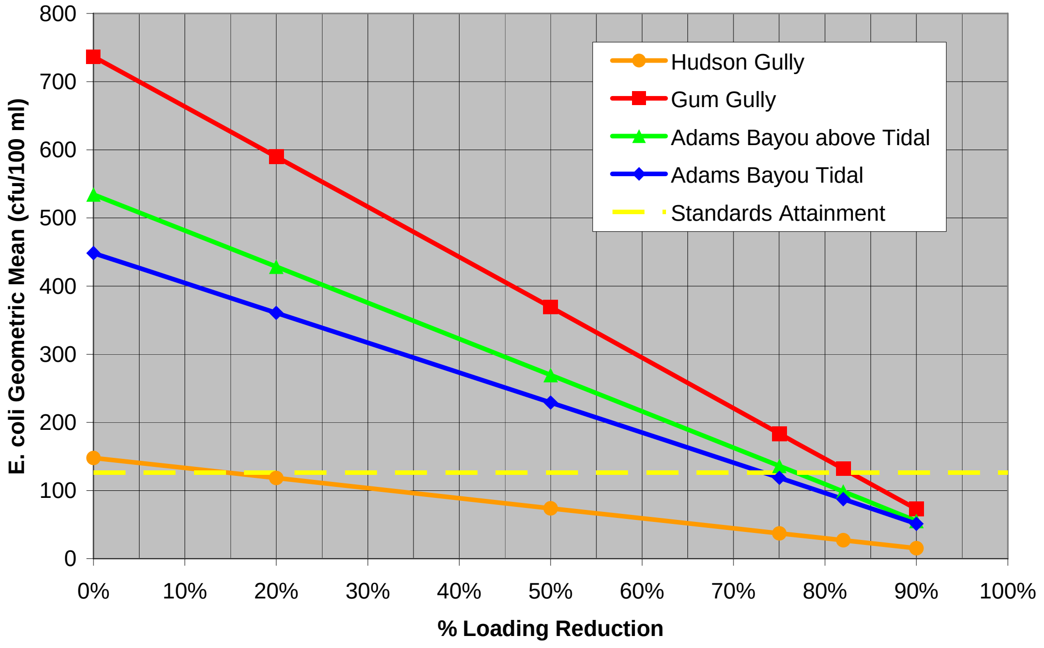


Figure 28. Adams Bayou system contact recreation standards attainment – geometric mean criterion

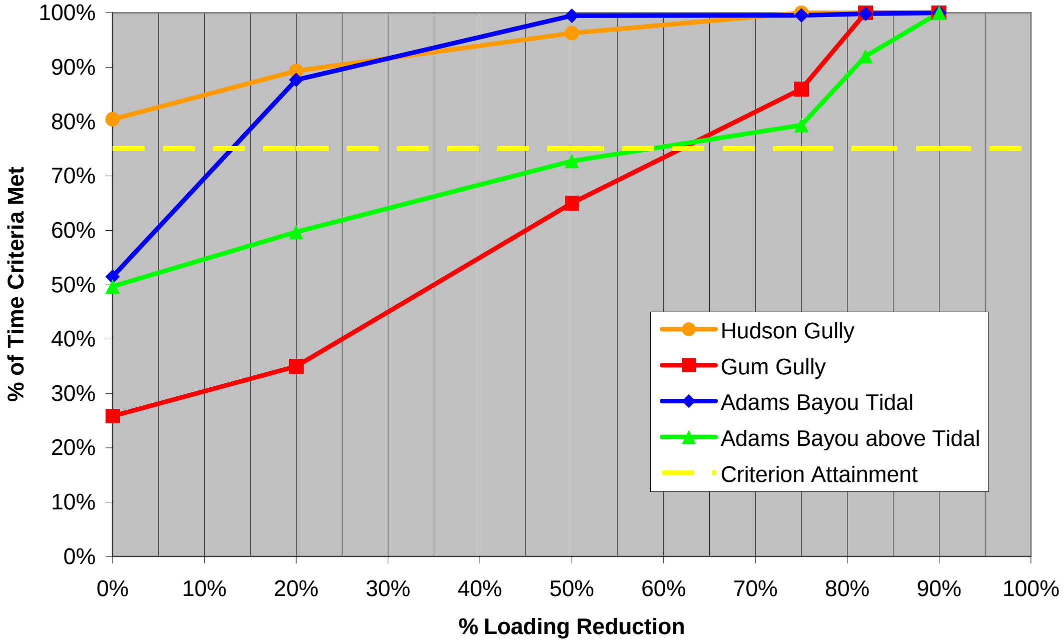


Figure 29. Adams Bayou system contact recreation standards attainment – single sample criterion

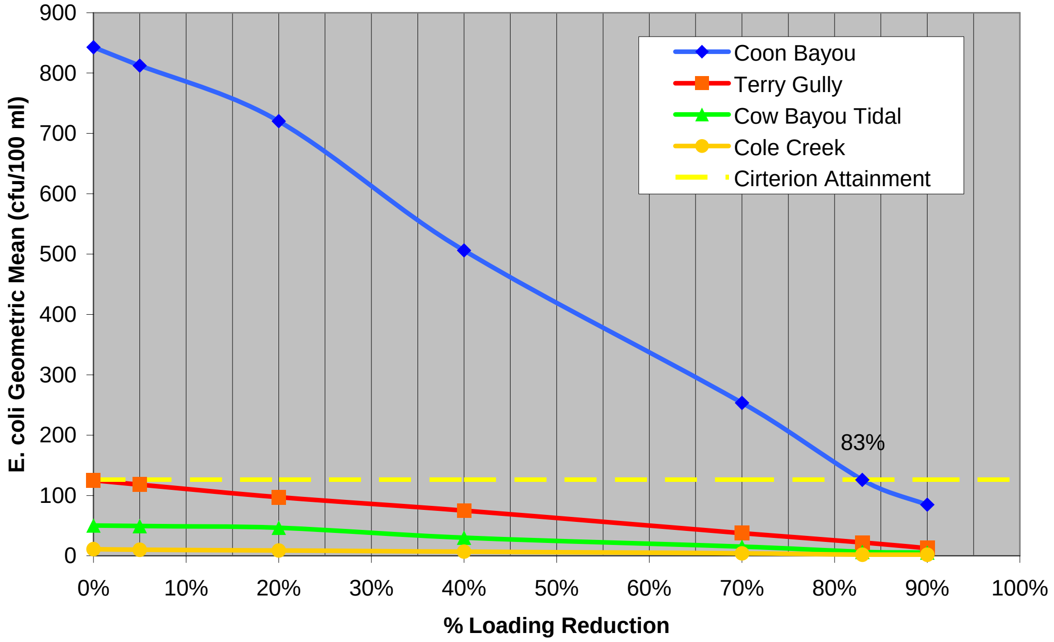


Figure 30. Cow Bayou system contact recreation standards attainment – geometric mean criterion

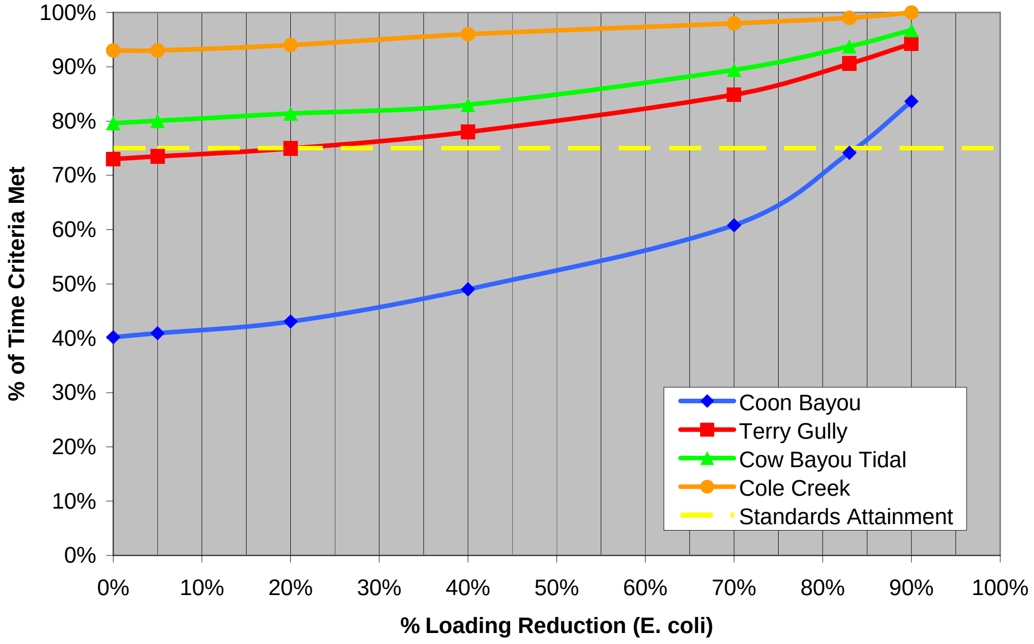


Figure 31. Cow Bayou system contact recreation standards attainment – single sample criterion

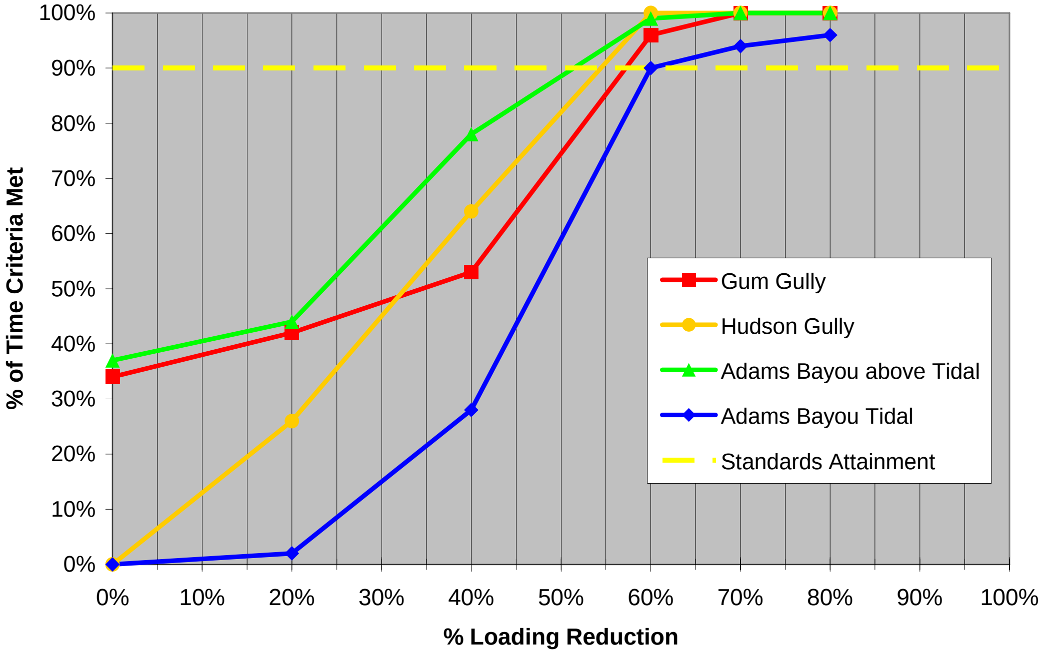


Figure 32. Adams Bayou system dissolved oxygen standards attainment

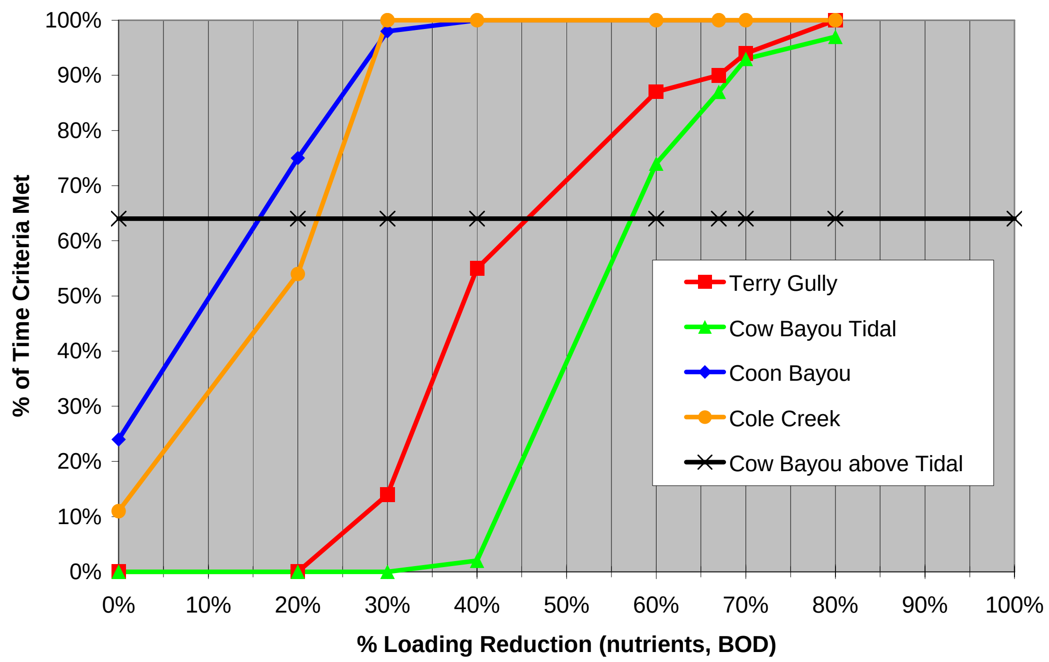


Figure 33. Cow Bayou system dissolved oxygen standards attainment

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Appendix A. Error Statistics

Table A1. Error statistics for the Adams Bayou dissolved oxygen model

	Average	AB2	AL1	AO11	AO12	AL2	AB3	AB4	HG	AB5	AB6	AB7	AB8	GG	AL8
Root Mean Square Error															
NH3N	0.06	0.10	0.07	0.05	0.06	0.04	0.11	0.08	0.12	0.04	0.06	0.05	0.01	0.03	0.02
TKN	0.32	0.25	0.30	0.20	0.48	0.37	0.38	0.36	0.32	0.27	0.31	0.32	0.29	0.36	0.37
NO3N	0.02	0.02	0.01	0.02	0.02	0.02	0.04	0.03	0.03	0.01	0.01	0.00	0.00	0.00	0.00
PO4P	0.10	0.08	0.19	0.30	0.22	0.23	0.14	0.17	0.10	0.04	0.06	0.04	0.01	0.07	0.07
TSS	6.89	5.38	8.58	5.33	10.69	4.61	3.32	3.94	8.94	17.32	6.89	17.75	5.34	8.71	5.08
VSS	1.03	0.88	0.91	0.87	0.97	0.00	1.10	1.72	0.92	3.83	3.00	3.22	1.03	2.31	0.90
ChlA	6.51	3.20	11.50	4.35	5.64	0.00	6.51	8.13	14.77	6.66	11.43	5.02	8.43	2.59	2.43
UCBOD	1.59	1.97	2.42	1.60	4.52	3.11	1.52	1.03	1.60	0.88	1.07	1.16	1.59	1.26	1.21
DO	0.91	0.99	1.71	0.83	1.78	1.55	0.78	0.67	0.91	0.98	0.76	1.68	0.30	0.23	0.77
Mean Error															
NH3N	0.01	0.01	0.04	-0.01	0.01	0.02	-0.07	-0.04	0.09	0.01	0.04	0.01	0.01	0.01	0.00
TKN	0.13	0.02	0.13	0.12	0.05	0.09	-0.21	-0.15	0.28	0.13	0.25	0.19	0.26	0.31	0.33
NO3N	0.00	0.00	0.00	0.00	0.00	0.01	-0.04	-0.01	-0.01	0.01	0.00	0.00	0.00	0.00	0.00
PO4P	0.00	0.01	-0.05	0.26	0.11	-0.18	-0.08	-0.14	0.03	0.00	0.04	0.01	0.01	-0.02	-0.04
TSS	2.04	5.04	6.51	5.05	6.86	2.65	2.74	0.57	6.99	-4.97	-1.83	-9.32	3.76	2.22	2.37
VSS	-0.89	-0.30	-0.38	0.03	-0.26	-1.82	-0.44	-0.89	-0.16	-2.15	-2.39	-1.96	-0.16	-1.34	-0.27
ChlA	-1.44	1.02	-8.87	-0.74	-4.54	-0.41	-4.33	3.61	-10.16	3.35	-4.36	1.79	3.43	0.05	0.03
UCBOD	-0.09	0.73	-0.52	0.73	-0.03	-2.75	-0.88	-0.48	-0.45	0.31	0.16	-0.02	0.40	0.60	0.93
DO	0.24	0.71	1.34	0.54	1.05	-0.06	0.41	0.09	-0.31	0.58	-0.16	-0.74	0.25	0.21	-0.56
Mean Absolute Error															
NH3N	0.05	0.08	0.05	0.04	0.05	0.03	0.09	0.06	0.09	0.03	0.05	0.04	0.01	0.02	0.01
TKN	0.27	0.19	0.23	0.16	0.34	0.31	0.32	0.29	0.29	0.22	0.25	0.27	0.27	0.31	0.33
NO3N	0.01	0.01	0.01	0.01	0.02	0.02	0.04	0.03	0.02	0.01	0.01	0.00	0.00	0.00	0.00
PO4P	0.10	0.07	0.18	0.26	0.19	0.18	0.12	0.14	0.09	0.03	0.05	0.03	0.01	0.04	0.04
TSS	5.70	5.04	6.53	5.05	7.50	3.25	2.74	3.22	6.99	8.50	4.49	11.14	4.39	6.66	4.30
VSS	1.29	0.72	0.63	0.86	0.78	1.82	0.95	1.30	0.80	2.43	2.50	2.23	0.83	1.57	0.70
ChlA	4.88	2.66	8.87	4.02	4.54	0.85	5.01	7.26	10.16	4.05	7.63	3.55	5.35	2.32	2.06
UCBOD	1.43	1.68	2.12	1.40	3.23	2.75	1.32	0.83	1.30	0.71	0.85	0.79	1.19	0.89	1.01
DO	0.78	0.76	1.34	0.62	1.22	1.12	0.68	0.50	0.73	0.84	0.66	1.22	0.28	0.22	0.69

Table A2. Error statistics for the Cow Bayou dissolved oxygen model

	Average	CB0.5	CO2	CB1	CO3	CNB	CB2	CB2.5	CB3	CB3.5	CC	TG2	CB4	CB5
Root Mean Square Error														
NH3N	0.14	0.09	0.13	0.09	0.18	0.08	0.09	0.10	0.09	0.10	0.09	0.34	0.20	0.29
TKN	0.24	0.18	0.17	0.22	0.24	0.25	0.27	0.25	0.26	0.44	0.12	0.43	0.18	0.14
NO3N	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.02	0.00	0.01	0.05	0.03
PO4P	0.02	0.02	0.02	0.05	0.04	0.04	0.04	0.03	0.02	0.02	0.00	0.02	0.02	0.00
TSS	3.69	3.45	2.59	8.19	3.11	3.74	3.21	2.85	3.54	5.01	2.20	4.31	4.47	1.26
VSS	1.63	1.39	0.86	1.70	1.37	2.69	1.75	1.32	1.82	2.86	0.91	1.77	1.32	1.48
ChlA	12.47	10.13	2.78	6.48	4.15	15.98	28.58	13.52	29.39	32.12	2.78	5.27	9.64	1.25
UCBOD	2.48	1.22	1.75	2.13	2.05	1.82	3.37	2.37	3.96	6.39	1.90	0.94	1.89	2.41
DO	0.75	0.63	0.94	1.28	0.94	0.91	1.18	0.99	1.01	0.61	0.55	0.21	0.40	0.06
Mean Error														
NH3N	0.01	0.03	-0.09	-0.08	-0.16	-0.05	-0.08	-0.04	0.05	0.01	0.01	0.21	0.09	0.18
TKN	0.02	0.11	-0.05	0.05	-0.17	-0.05	0.03	-0.05	-0.03	-0.19	0.11	0.43	-0.04	0.13
NO3N	-0.01	0.00	-0.01	0.00	-0.01	0.00	0.00	0.01	0.01	-0.01	0.00	0.00	-0.04	-0.03
PO4P	-0.01	0.00	0.00	-0.03	-0.02	-0.02	-0.02	0.00	0.01	0.00	0.00	0.01	0.00	0.00
TSS	1.42	1.32	2.05	0.63	1.34	-0.08	0.09	1.59	1.72	-0.79	2.05	4.18	3.38	1.03
VSS	-0.60	-0.73	-0.68	-0.73	-0.98	-1.66	-0.44	-0.55	-0.22	-0.41	-0.55	0.13	0.00	-1.03
ChlA	-3.28	3.69	-1.16	2.87	2.04	-11.03	-10.73	0.48	-16.94	-15.48	0.48	0.49	3.05	-0.45
UCBOD	-0.67	0.58	-0.25	0.10	0.60	-0.70	-1.65	-1.87	-2.96	-2.55	-0.83	0.10	0.14	0.56
DO	0.06	-0.39	0.77	-0.71	0.83	0.70	0.42	0.08	-0.47	-0.17	-0.41	0.13	0.01	0.01
Mean Absolute Error														
NH3N	0.12	0.08	0.11	0.08	0.16	0.06	0.08	0.08	0.07	0.09	0.08	0.26	0.17	0.22
TKN	0.21	0.15	0.15	0.16	0.17	0.22	0.23	0.21	0.24	0.34	0.11	0.43	0.15	0.13
NO3N	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.04	0.03
PO4P	0.02	0.02	0.01	0.04	0.03	0.03	0.03	0.02	0.02	0.01	0.00	0.02	0.02	0.00
TSS	3.16	3.18	2.31	5.42	2.65	3.07	2.95	2.35	3.06	4.59	2.05	4.18	4.06	1.23
VSS	1.25	0.80	0.80	1.33	1.14	2.14	1.19	1.00	1.49	2.13	0.55	1.59	1.06	1.04
ChlA	9.74	9.41	2.41	5.04	3.65	11.04	18.82	10.75	24.93	24.02	2.38	4.20	9.21	0.77
UCBOD	1.90	0.93	1.56	1.76	1.64	1.30	2.46	1.87	3.14	4.05	1.49	0.59	1.62	2.25
DO	0.63	0.51	0.81	0.95	0.84	0.79	1.07	0.87	0.85	0.51	0.43	0.19	0.34	0.04