Total Maximum Daily Loads for Fecal Pathogens in Buffalo Bayou and Whiteoak Bayou

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FINAL REPORT
REVISION 1

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CHAPTER 1

INTRODUCTION

Portions of Buffalo Bayou (Segments 1013 and 1014) and Whiteoak Bayou (Segment 1017) in Houston, Texas are on the Texas Clean Water Act §303(d) List for pathogen impairments. Water bodies that partially meet or do not meet their designated use are placed on this list. Buffalo and Whiteoak Bayous are among the most fecal-contaminated water bodies in Texas as indicated by the frequency and magnitude of exceedances of the fecal coliform water quality criteria for contact recreation. The purpose of this project is to provide the TCEQ with the information and assistance necessary for the preparation of a Total Maximum Daily Load (TMDL) for the pathogen impairments in Buffalo and Whiteoak Bayous. In addition, the project will result in the preparation of several allocation scenarios, including potential costs and sources of funding that the TCEQ will use to formulate an implementation plan. The TMDL and the implementation plan will be incorporated into a Watershed Action Plan (WAP) that will address violations of water quality criteria for contact recreation in these Houston bayous.

1.1 BACKGROUND

The two bayous that are the subject of this TMDL Study, Buffalo Bayou and Whiteoak Bayous, are designated for contact recreation. Until recently, the water pathogen quality standard for contact recreation was based on the fecal coliform indicator bacteria. For fecal coliform, no sample should exceed 400 colony-forming units (cfu) per 100 mL for contact recreation. In addition,

the geometric mean should be less than 200 cfu/100 mL to meet contact recreation criteria. However, the State of Texas adopted new standards based upon *Escherichia coli* (*E. coli* or EC) rather than the fecal coliform indicator bacteria. For *E. coli*, no sample should exceed 394 cfu/ 100 mL and the geometric mean should be less than 126 cfu/100 mL (30 Texas Administrative Code 307.7(b)(A)). Both bayous have frequently exceeded the fecal coliform standard in the past. The first work order for this study (University of Houston and PBS&J, 2001) demonstrated the regularity and magnitude of these violations and evaluated the trends in the FC historical data. In both bayous, Work Order 1 also identified the data gaps in available FC information and evaluated data needs for model development.

1.2 SCOPE OF THE PROJECT

Work Order #2 included identification and quantification of the sources in the watershed and the development of two HSPF models to predict the fate and transport of bacteria in water and sediment. Work Order 5 is intended to supply information and assistance to the TCEQ TMDL team necessary to complete a TMDL, supply the information and assistance necessary to develop an Implementation Plan to reduce the levels of bacterial indicators of fecal pathogens in Buffalo Bayou and Whiteoak Bayou, and prepare a Bacteria Source Tracking study to determine the proportion of the *E. coli* in the water and sediment of the bayous that is of human origin.

1.3 DESCRIPTION OF THE REPORT

This document constitutes the final report of the TMDL Bacteria Project for Work Order No.

582-0-80121-05. The report summarizes the activities undertaken by the University of Houston and PBS&J during the period September 1, 2002 to August 31, 2003.

Chapter 2 summarizes the support activities conducted by the project team as part of the stakeholder involvement. Presentations given by members of the team at stakeholder meetings are included in the Appendix. A review of the current literature on bacteria and sediment as well as data from Buffalo and Whiteoak Bayous are presented in Chapter 3. A summary of special issues relevant to the TMDL are discussed in Chapter 4. Bacteria loads in the two watersheds were estimated and the results are presented in Chapter 5. An examination of what constitutes low flow conditions is presented in Chapter 6. The HSPF models that were developed under Work Order No. 2 were updated and the model results are presented in Chapter 7. Chapter 8 presents the results of the load allocations. A draft bacteria source tracking plan is described in Chapter 9. Chapter 10 presents a summary on best management practices (BMPs). Finally, Chapter 11 presents the conclusions from this work order.

CHAPTER 2

STAKEHOLDER/PUBLIC EDUCATION AND INVOLVEMENT

2.1 SUMMARY OF SUPPORT ACTIVITIES

The project team supported the stakeholder process facilitated by the Houston Galveston Area Council (HGAC) and Mary Jane Naquin of Environmental Institute of Houston (EIH). The following support tasks were undertaken:

- Development of informational materials summarizing the technical aspects of the project for electronic and hard copy distribution at stakeholder meetings including documents, maps, and quarterly reports;
- Preparation of web based project informational briefs;
- Participation in three stakeholder meetings (February 19, 2003, April 16, 2003 and May 14, 2003);
- Participation in a technical meeting with TCEQ TMDL Program personnel and TCEQ Region 12 personnel on December 10, 2002 to address needs from the local TCEQ Office regarding solids releases and bypasses
- Attending a Bacteria Source Tracking Workshop organized by Texas A & M in Austin (May 6, 2003)
- Meeting with Trent Martin, Harris County Pollution Control District (HCPCD) regarding their proposed BST work in Houston (June 20, 2003)

- Preparation and presentation of technical information at the stakeholder meetings;
- Preparation of responses to questions and information requests from stakeholders and providing rationale for whether or not certain requests by stakeholders for refinement in technical analysis can or cannot be achieved; and
- Providing technical expertise on issues related to microbiological, public health, urban wastewater infrastructure and water quality.

2.2 TECHNICAL PRESENTATIONS AT STAKEHOLDER MEETINGS

Copies of the technical presentations given at the stakeholder meetings are included in Appendix A. Other informational materials prepared by the project team can be found at http://www.hgac.cog.tx/intro/introtmdl.html.

2.3 TECHNICAL PRESENTATIONS AT OTHER MEETINGS

The following list details presentations that have been given by the project team:

- The Water Environment Federation National TMDL Science and Policy 2002 at Phoenix, AZ on November 16, 2002
- The Sixth Biennial State of the Bay Symposium at League City, TX on January 14, 2003
- Texas Water 2003 at Corpus Christi, TX on April 2, 2003 (two presentations: one by Tina Petersen, one by Yu-Chun Su)

CHAPTER 3

BACTERIA IN SEDIMENT

Sediment particles originate from a variety of sources in an urban watershed. Sources include erosion of unstable stream banks, construction sites, agricultural activities, and urban runoff. Sediments are also formed within the water body itself as a result of the growth, metabolism, and death of plants and animals. Sediment enters a water body from runoff and can either be transported downstream or, if the stream energy is low, can settle out. Therefore, there are two different sediment compartments in a stream: the suspended sediment and the bed sediment.

The impacts of both suspended and bed sediment on a water body can be great. Sediment serves as a catalyst, storing and transporting other forms of pollution (ASCE 1975). Sediment can impact the aquatic life in a stream, impair survival and growth of fish and reduce aquatic habitat. In waters designated for drinking water uses, sediment can contribute to taste and odor problems as well as fouling of the intake system. Finally, sediments impair contact recreational uses by reducing water clarity and negatively impacting aesthetics.

The main water quality parameter used to identify the amount of sediment in water is TSS (total suspended solids). TSS can include a wide variety of material, such as silt, decaying plant and animal matter, industrial wastes, and sewage. To measure TSS, a water sample is collected and

filtered through a pre-weighed glass fiber filter and the residue on the filter is dried in an oven. The increase in the weight of the filter represents the total suspended solids.

Bacteria concentrations in water have been strongly correlated by some researchers to sediment concentrations. Additionally, bacteria have been known to be found in high concentrations along stream banks and in bed sediments and are known to resuspend from bed sediment during runoff events. Therefore, sediments are a potential source of bacteria and can play a large role in the maintenance of high bacteria concentrations. This section provides a brief discussion on sediment in addition to a summary of the literature associated with sediment. Measured TSS data in BB and WOB and in the Addicks and Barker Reservoirs are also presented.

3.1 REVIEW OF SEDIMENT LITERATURE

Sediment has been a topic of many studies. Below is a brief literature review on sediment and its relationship with bacteria in various media.

3.1.1 SURVIVAL OF BACTERIA IN SEDIMENT

Studies on the survival of bacteria indicate that sediments present an environment favorable for growth. Fecal bacteria have been shown to survive and, to a certain extent, even to grow in sediments. Sediment has been shown to provide nutrients and organic material for EC as well as protection from predators due to anaerobic regions in the sediment (Enzinger and Cooper, 1976).

Additionally, the sediment protects the organisms from ultraviolet light, which causes bacterial inactivation. Ashbolt *et al.* (1993), Van Donsel and Geldreich (1971) and Buckley *et al.* (1998), for example, suggested that sediments may contain 100 to 1,000 times the number of fecal indicator bacteria contained in the overlying water. Hood and Ness (1982) reported on the survival of *Vibro cholerae* and *Escherichia coli* in sediments and work by Gerba and McLeod (1976) and LaLiberte and Grimes (1982) showed evidence of survival and growth of *E. coli* in sediments.

Gerba and McLeod (1976) studied EC survival in seawater obtained from Galveston and West Bays, specifically to examine the effects of sediment. Samples from the overlying water and sediment in the two bays showed that higher numbers of bacteria were present in sediment than in the seawater. The researchers found that *E. coli* could survive for longer periods of time in unsterile natural seawater when sediment material was present than in seawater alone, and at least on one occasion growth was observed to occur. These findings indicated that EC are capable of using the nutrients in the sediment (even as suspended sediment). The presence of sediment always positively affected the survival of EC, in most cases allowing the organisms to survive 10-15 days longer than they would have when no sediment was present. The researchers did note that the autoclaved sediment they used in their experiments increased the release of nutrients to the organisms, and organisms in natural systems may only experience increased survival by several (3-5) days. The longer survival of *E. coli* in the sediment is attributed to the greater content of organic matter present

in the sediment than is present in seawater.

Burton *et al.* (1987) tested four human-associated bacteria (*Pseudomonas aeruginosa, Salmonella newport, E. coli* and *Klebsiella pneumaniae*) for survival in five freshwater sediments. Continuous flow chambers were designed to mimic in-situ conditions, with sediment collected from several field sites covering the chamber bottom at depths of 8 cm. After 1 week, the chambers were inoculated with 10^7 to 10^9 cfu/mL of bacteria and gently mixed. The upper layer of sediment in the chamber was also resuspended during the bacteria inoculation. Results showed that the bacteria had extended survival in the sediment, when compared with the overlying waters. Relationships between sediment characteristics and bacteria survivability were examined; organic mater did not show any relation, while particle size did. *P. aeruginosa* showed the best survivability, while *S. newport* tended to die off the fastest. This study suggested that the sediment reservoir may permit survival of enteric and pathogenic bacteria for several months.

Davies *et al.* (1995) studied the survival of fecal coliforms (FC), fecal streptococci (FS), and *Clostridium perfringens* spores in freshwater and marine sediments from sites near sewage outfalls. They observed that, in the absence of predators, fecal coliforms may grow in both freshwater and marine sediments, while under natural conditions (presence of predators) a net die-off occurs. The authors also studied viable but nonculturable (VNC) formation of *E. coli* in aquatic sediments associated with sewage outfalls. Throughout the 68-day duration of the experiment, the same

proportion of *E. Coli* organisms remained culturable, which suggested that sediment provide a favorable environment for bacterial growth. This finding supports other researchers' efforts in documented that sediments allow an extended survival of bacteria in comparison with water environments (Goyal and Adams, 1984; Hendricks, 1971; LaBelle *et al,*. 1980; Van Donsel and Geldreich, 1971).

Baudart *et al.* (2000) compared *Salmonella* and fecal coliform loads to coastal water from a river and a wastewater treatment plant (WWTP) outfall. They found that bacterial loads from the river were higher than those from the outfall and were associated with small clay particles (< 2：m) originating from different reservoirs. The bacteria trapped in the particles-sediment accumulated in the downstream part of the river during the lowest water levels and were resuspended during storm events.

Results from laboratory experiments conducted by Howell *et al.* (1996) to measure FC and FS mortality rates at three different temperatures and in three feces amended sediments with different particle size showed that rates declined as sediment particle size decrease and as temperature decreased. However, they found no interaction between these two factors and fecal bacteria persistence. The study concluded that the FC/FS ratio was influenced by temperature, the presence of sediment, and sediment particle size.

3.1.2 SEDIMENTATION

Sedimentation is the gravitational deposition of particles on matrix surfaces. It occurs when the density of a particle is greater than that of the liquid and flow velocities are low (Maier *et al.* 2000).

Bergstein-Ben Dan and Stone (1991) examined the partitioning of fecal indicator bacteria between surface waters, bottom waters, and sediments in lakes and found that sediment "disappearance rates" are smaller in magnitude than those for bottom and surface waters. There is relatively high survival in bottom water and sediment. This shows that sedimentation is an important factor in distributing the bacteria vertically in a water body. Also, the authors state that each bacterial species has its own specific survival rate and response characteristics that determine its distribution over depth and time.

Pommepuy *et al.* (1992) documented the accumulation of indicator bacteria and viruses in sediments and associated it with the sorption of the microorganisms to particles suspended in water, which then sediment out. Furthermore, because light penetration is prevented by suspended matter, survival in sediments may be longer.

Analysis of sediment samples from recreational waters in the UK by Obiri-Danso and Jones (2000) showed no obvious seasonal trend in FC numbers. Fecal indicators were found predominantly in surface layers and numbers decreased with depth. Results of experiments to study the *in situ*

deposition of bacteria onto clean surfaces from the water column during tidal cover showed a deposition rate of 0.1% of the total population of FC. Results indicated that sediments act as a reservoir for fecal indicators.

Work by Erkenbrecher (1981) in an urban shell fishing sub-estuary also confirmed that sediments act as reservoirs of microorganisms in aquatic environments. Furthermore, Grimes (1975 and 1980) stated that sediments act as reservoirs of FC in aquatic environments and with turbulence they resuspend and increase water concentrations.

Marino and Gannon (1991) studied sediments in storm drains and noted that balance between predation and growth could be reached and afterwards the bacteria levels would persist at fairly constant levels. They concluded that storm drain sediments serve as reservoirs of high concentrations of FC and FS during warm, dry weather periods.

3.1.3 RESUSPENSION OF BACTERIA

Resuspension is the result of fluid shear exerted on unconsolidated bottom sediments. Once resuspended, the transport of the sediment is dependent on the "competence" of the flow, or the relationship between the shear velocity and the particle settling velocity (Wotton 1994).

Resuspension of water sediments can occur through various anthropogenic and natural disturbances. Some natural disturbances are caused by increased river discharge, waves, tides, wind turbulence and normal activities of aquatic macro-organisms. Anthropogenic disturbances of water

sediments could occur from dredging, motor boats swimming, walking, and wading. The magnitude of sediment resuspension will vary with the intensity of the resuspension mechanisms and the water depth to the sediment (Matson, Horner et al. 1978).

Crabill *et al.* (1999) analyzed FC in water and sediment samples from Oak Creek, AZ. Correlations were noted between visitation to the creek for recreational purposes and increases in exceedances of the contact recreational standard for FC. The correlation between visitation and standard exceedance was much higher when the sediment was also found to have high concentrations, presumably due to the sediment being resuspended during recreational activities, such as wading. Sediment concentrations were found to increase during the summer months (August to November). Additionally, impaired water quality was also noted following storm events. They found sediment samples with up to 2,200 times the FC counts of the water column. Results showed that resuspension of sediments due to agitation by recreational activities and storm events during the summer season negatively impacted the water quality.

E. coli, FC, and total coliform were monitored between September 1999 and October 2001 in five marinas at Lake Texoma. The study showed that E. coli levels increased with depth, and the bottom water samples had higher concentrations of *E. coli* mainly due to their association with particles. A direct relationship was found between the amount of gasoline sold for recreational boating activities and the resuspension of *E. coli* which indicated that the recreational boating activity

in the lake may have resuspended bottom sediments bound with *E. coli.* Also, the presence of *E. coli* in marinas was not an indication of recent fecal contamination. The highest concentrations of *E. coli* were found at the boat dock points, the gasoline filling station, and marina entrance (An *et al*. 2002).

Stephenson and Rychert (1982) evaluated stream bottom sediments as a possible reservoir of bacterial pollutants available to overlying surface waters via resuspension. The results of their study show *E. coli* concentrations of bottom stream sediments to be 2 to 760 times greater than those of the overlying water. Data obtained from disturbance simulations and from a rainstorm event indicated that *E. coli* in bottom sediments are resuspended and could substantially add to pollution of the overlying waters. They also suggested that microbiological analysis of stream bottom sediments should probably be considered a part of stream water-quality evaluations. Minor disturbances of the organic bottom mass, at the stream-sediment interface, can cause resuspension of the *E. coli* or other indicators, which increases the possibility of pollution of the overlying water body.

Pettibone *et al.* (1996) noted that ship traffic resuspends contaminated bottom river sediments, which may impact water quality. They observed increases in FC, heterotrophic plate count (HPC) and total suspended solids (TSS) immediately after the ship passed with the largest increases at the mid-channel sites. The authors determined that FC levels were strongly correlated with TSS in the water column suggesting re-entrainment of particle-bound bacteria. They called attention to the fact that

since flocculation affects the hydrodynamic properties of particles and their transport, the characteristics of flocculated sediment should be considered in water quality modeling.

Matson *et al.* (1978) conducted a 3-year study of indicator and other bacterial yeasts. Subsurface water samples were taken upstream and downstream of a wastewater treatment plant. Higher concentrations were noted in sediments than in subsurface waters. The authors found that gradual downstream decreases in indicator densities in water were inversely related to river discharge as water borne indicators settled into the sediments or were resuspended into the water column.

In summary, the literature supports the hypothesis that sediments acts as reservoirs for EC and FC. Regrowth and die-off occur within the sediment as well as resuspension due to natural and anthropogenic turbulence. These complex processes, while studied on numerous occasions in laboratory settings, are poorly understood at the watershed scale especially given the dynamic nature of flow regimes in natural systems. It appears clear that sediments harbor high levels of indicator bacteria and that resuspension of sediments can introduce bacteria into the water.

3.2 TSS DATA IN BUFFALO AND WHITEOAK BAYOUS

USGS daily stream flow gage data were obtained for White Oak and Buffalo Bayou for the period of July 1976 to September 2000. These data, along with TSS data from the TCEQ SWQM database, were plotted in Figure 3.1 to show the relationship between flow and TSS.

Overall, TSS concentrations were not strongly correlated with flow. Some stations, though, did exhibit a relationship between TSS and flow that was somewhat significant. These stations include 11360 (Buffalo Bayou at West Belt), 11351 (Buffalo Bayou at Shepherd), and 11387 (Whiteoak Bayou at Heights).

TSS data were collected from the TCEQ SWQM database between 1972 and 2002 were then plotted for various stations along White Oak and Buffalo Bayou (Figures 3.2 and 3.3). Stations were chosen to be plotted based on quantity of TSS data, the widest range of dates and location of the station along the bayou.

Buffalo Bayou TSS data are presented in Figure 3.2. The data are rather sparse at times, possibly indicating changes in the sampling regime for TSS. From the data, it appears that TSS spanned a wider range of values in the 1970's than those measured in the late 1990's. The data ranged from 10 mg/L to 100 mg/L, with the concentrations spanning a narrower range at the most downstream stations on the bayou.

The TSS data for Whiteoak Bayou are shown in Figure 3.3. Stations 11390 and 11398 along White Oak Bayou had fewer data during the 1980's and early 90's. TSS concentrations in Whiteoak Bayou are slightly lower than those seen in Buffalo Bayou, ranging from around 5 mg/L to around 60 mg/L. One reason for these lower TSS concentrations may be the concrete lined channel in the

lower reaches of the bayou, which prevents the accumulation of sediment and thus prevents the scour and resuspension of sediment in WOB.

A factor that needs to be recognized when viewing these TSS data is that most of the monitoring activity tends to avoid bad weather when higher flows, as well as higher TSS and bacteria, tend to occur. This small number of sampling events at higher flows impacts the relationship that is seen in the data.

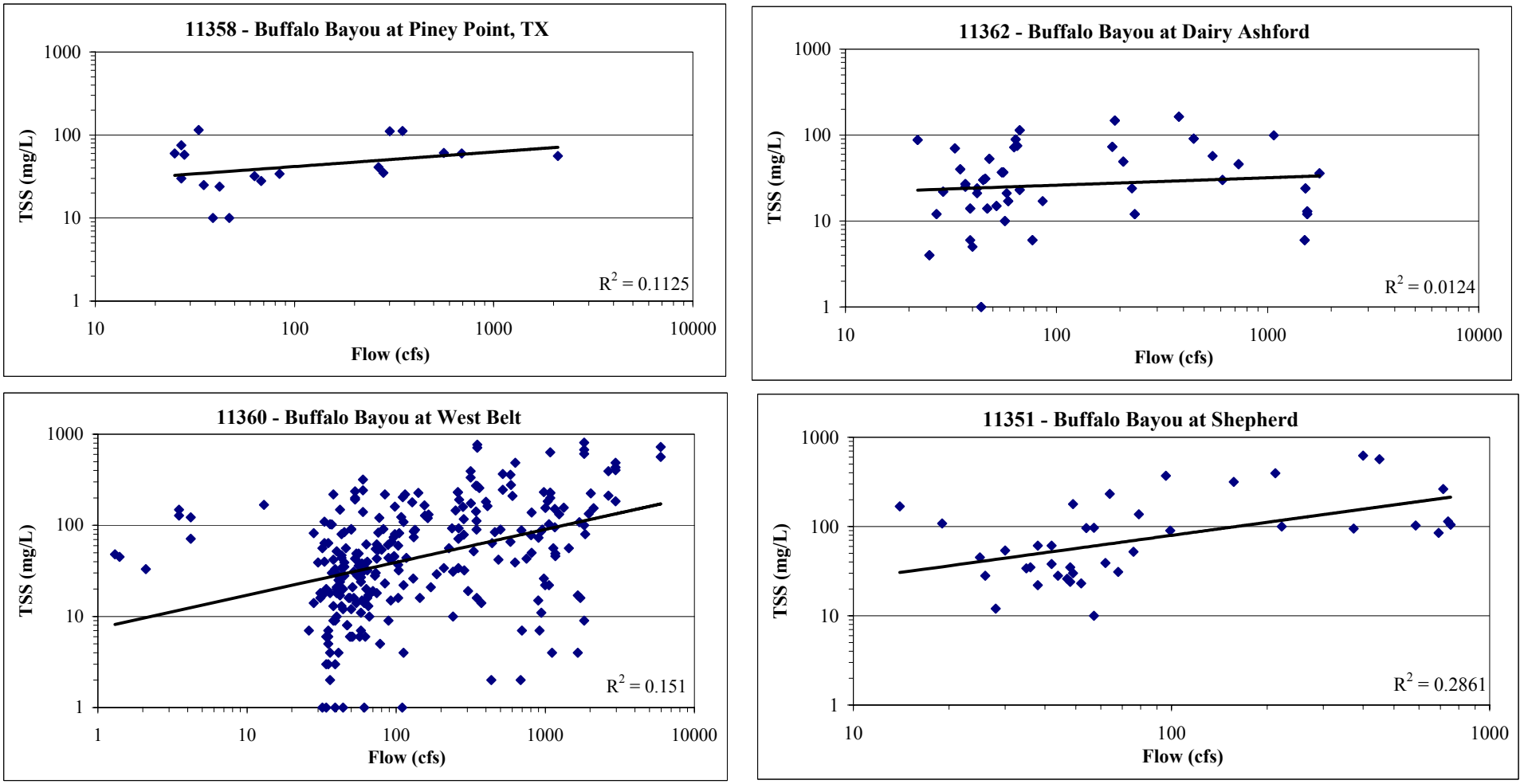
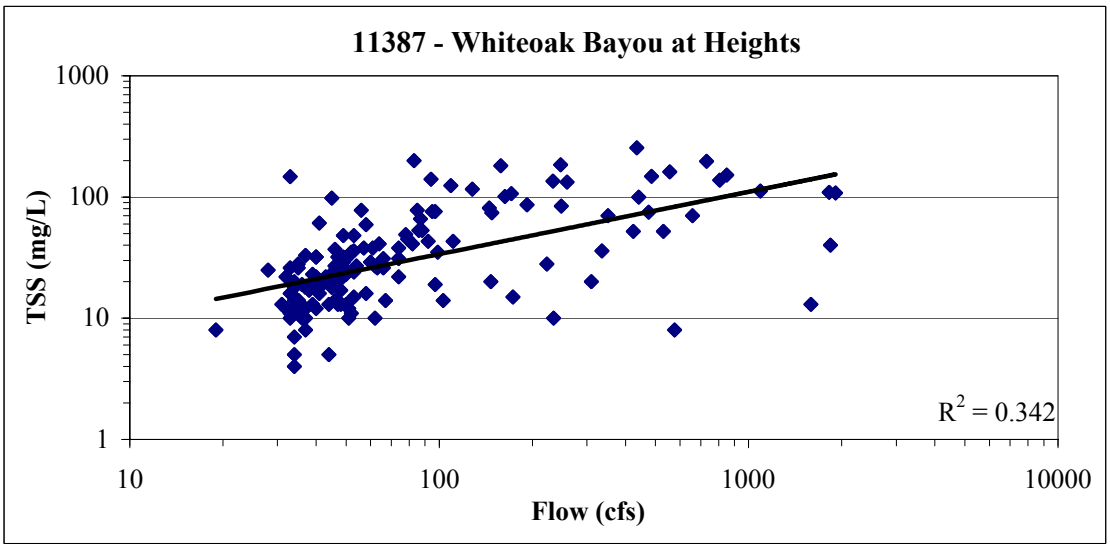


Figure 3.1(A) Relationship between TSS and Flow



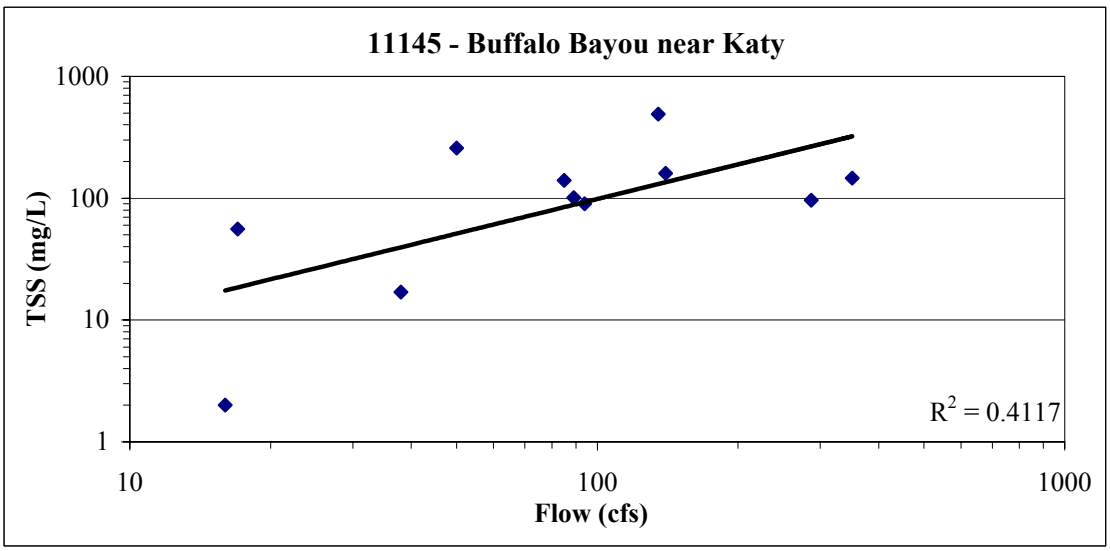


Figure 3.1(B) Relationship between TSS and Flow

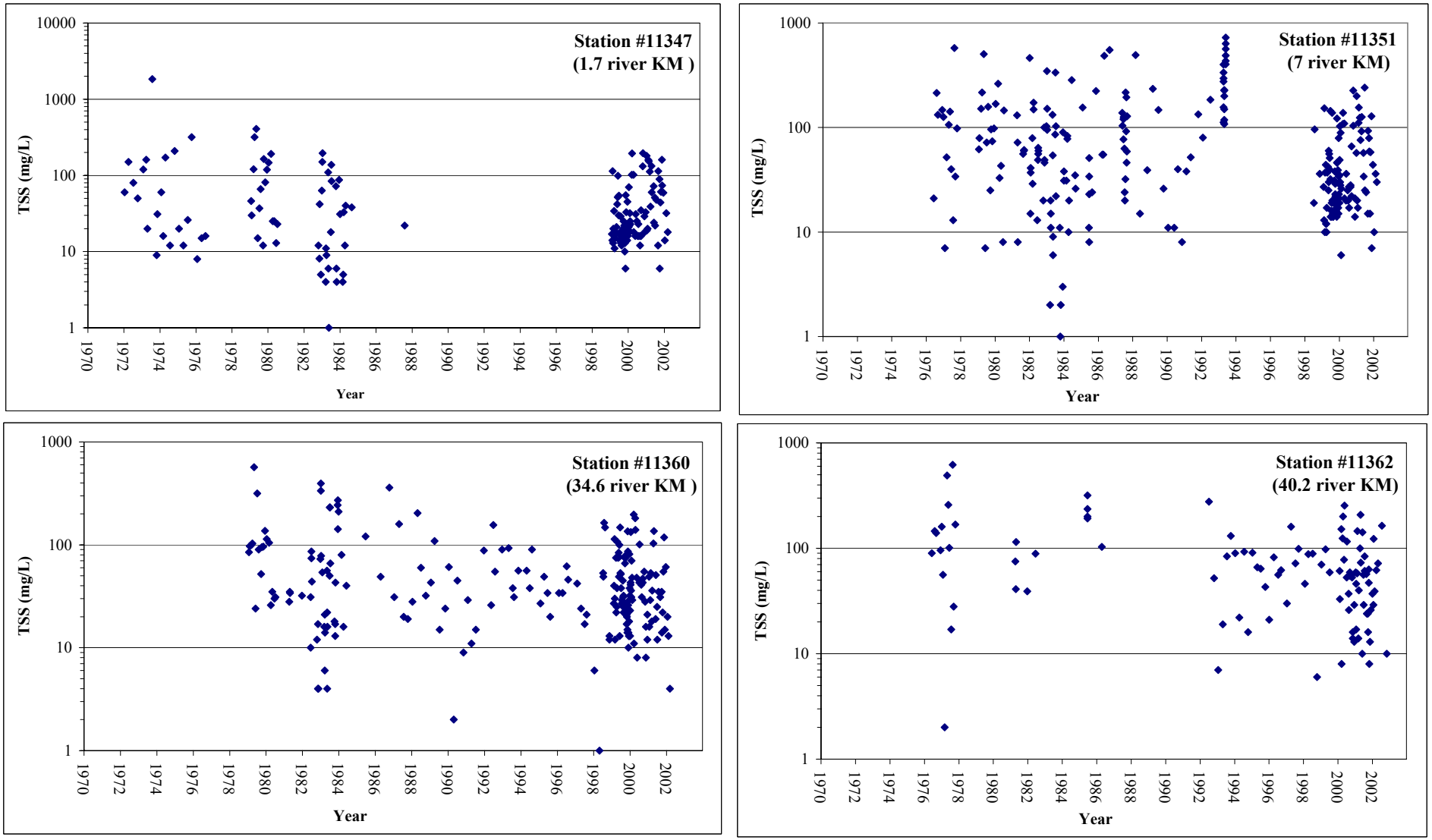


Figure 3.2(A) TSS data for Buffalo Bayou

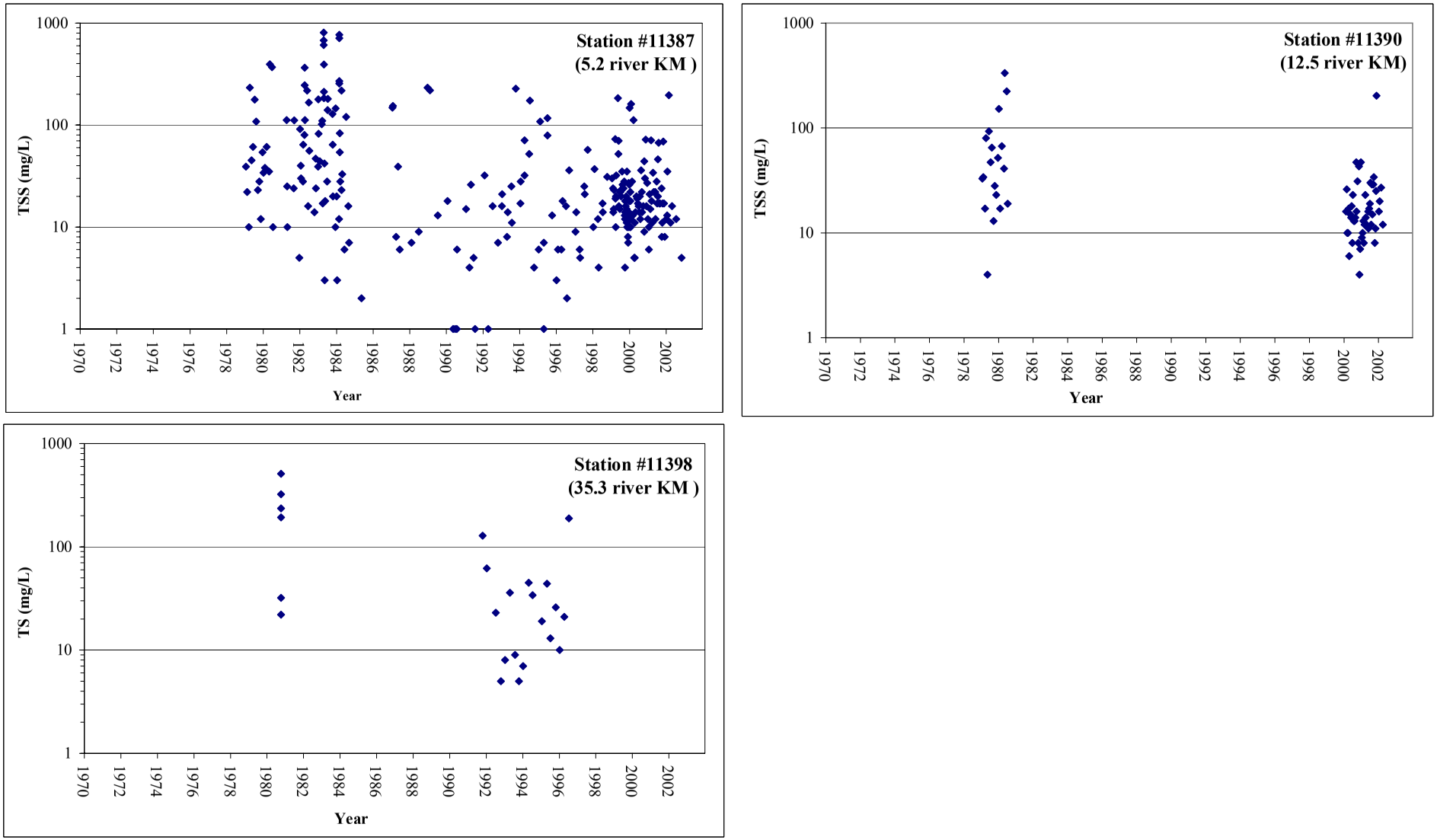


Figure 3.2(B) TSS data for Whiteoak Bayou

3.3 ADDICKS/BARKER SEDIMENT DATA

A water quality study on Barker and Addicks reservoirs was performed by the USGS in the late 1970's and early 1980's (Liscum *et al*, 1987). In the study, the USGS took detailed water quality samples from tributaries to the reservoirs, water in the reservoir and reservoir discharge. Table 3.1 presents a summary of the sediment data. In Barker Reservoir, it is clear that the reservoir is attenuating sediment concentrations, as the tributaries discharging into the reservoir have a mean suspended concentration of 240 mg/L and the discharge from the reservoir is reduced to 119 mg/L. The turbidity data also support this conclusion. In Addicks Reservoir, the relationship is not as clear. The discharge sediment concentration is somewhat higher than the reservoir water. Looking at the turbidity data for Addicks Reservoir, however, there is clearly a reduction in turbidity from inflow to outflow. The conclusion that the sediment concentrations are being attenuated by the two reservoirs is supported by statistical analyses that the USGS performed in the aforementioned study, namely that the inflow and outflow sediment concentrations were significantly different at the 95% confidence level.

Table 3.1 Summary of USGS Reservoir Data

	Barker Reservoir		Addicks Reservoir	
	Mean Suspended Sediment (mg/L)	Mean Turbidity (NTU)	Mean Suspended Sediment (mg/L)	Mean Turbidity (NTU)
Inflow to Reservoir	239.61	112.59	a: 149.94	a: 147.91
			b: 203.95	b: 132.62
Detained water in Reservoir	118.27	95.79	133.03	101.67
Reservoir Discharge	119.14	84.99	157.73	89.82

Notes:
1. Stations used for Barker: 08072300 (inflow), 08072500 (reservoir), 08072501 (outflow)
2. Stations used for Addicks: 08072730 (inflow a), 08072760 (inflow b), 08073000 (reservoir), 08073001 (outflow)
3. Data from Liscum, et al study.
4. NTU stands for nephelometric turbidity units

3.4 TSS FROM NPS FOR WHITE OAK AND BUFFALO BAYOU

The Galveston Bay National Estuary Program (GBNEP) conducted a study that assembled event mean concentration (EMC) values for a variety of parameters (Newell, Rifai et al. 1992). The EMC is a value used to represent the flow weighted average concentration of a given parameter during a storm event. The EMC is calculated by dividing the total constituent mass by the total runoff volume. Table 3.2 presents the EMC values for TSS used in the GBNEP analysis.

Table 3.2 EMC TSS Values for Various Land Uses

Land Use Category	**TSS EMC (mg/L)**
High Density Urban	166
Residential	100
Agricultural	201
Open/Pasture	70
Forest	39
Wetlands	39
Water	0
Barren	220

Source: Newell et al., 1992

TSS loading rates were then determined for an average annual rainfall as shown in Table 3.3. These TSS loads represent a source of EC to the two bayous, however, the interaction mechanisms between the TSS load and EC in the water column are poorly understood.

Table 3.3 TSS Load Data for an Average Annual Rainfall

	Runoff Volume (thousand acre-ft)	**TSS (million kg)**
Buffalo Bayou	116	22
White Oak Bayou	128	24

Source: Newell et al., 1992

CHAPTER 4

EMERGING BACTERIA ISSUES

4.1 RELATIONSHIP BETWEEN EC AND FC

The TCEQ recently published a comparison of FC (using the membrane filtration method) and EC (using the IDEXX method) on field samples collected from Houston Region 12. Results from this study showed that EC concentrations were often higher than FC, despite EC being a subgroup of FC. This phenomenon has been reported in the literature (Davies et al, 1994, Yakub et a., 2002, Gannon and Bussee, 1989) and one possible explanation is that type I and II errors are confounding the results. Some researchers have shown that there are mechanisms for false positives/negatives to occur in the Colilert test. Although these studies provide some insight into the reasons behind the EC:FC ratios, the explanations are still inconclusive.

4.2 BACTERIA SOURCE TRACKING

Bacteria source tracking (BST) is a promising new technology that is used to differentiate between human and non-human sources of fecal indicator bacteria. There are two types of BST techniques, those that rely on molecular methods and those that rely on biochemical methods. Molecular techniques include ribotyping, repetitive PCR (rep-PCR), amplified fragment length polymorphisms (AFLP) and pulsed field gel electrophoresis (PFGE). Biochemical techniques include antibiotic resistance analysis (ARA), carbon utilization profiles and fecal sterol analysis. The following section discusses recent studies using the most promising of the molecular methods (ribotyping, PFGE, AFLP) as well as the phenotypic method, ARA.

4.1.1 RIBOTYPING

Ribotyping (also known as restriction fragment length polymorphisms or RFLP analysis) is conducted primarily on EC bacteria in source tracking methods. This method involves 16sDNA, which is a sequence of genes present in all bacteria that codes for ribosomal RNA. There are portions of this 16sDNA that are highly conserved, meaning that some sequences of genes are present in all bacteria in the same order. Other parts of the 16sDNA are unique to each organism. The 16sDNA is cleaved using restriction enzyme of the highly conserved portions of the gene and primers are applied to amplify the 16sDNA. The polymerase chain reaction technique (PCR) is then used to amplify the portions of the rDNA that have primers (Maier et al 2000). The amplified DNA is analyzed using Southern blotting and Southern hybridization. The Southern blot is a means of permanently fixing single-stranded nucleic acids to a solid support. The DNA is separated by fragment size classes by agarose gel electrophoresis. After the Southern blotting, the DNA is detected by using a radioactive probe, a procedure called Souther hybridization. The hydbridization results in a pattern being produced out of four to twelve bands. Often times, restriction enzymes are used to increase the discriminatory power of the ribotyping technique. The resulting patterns are analyzed using discriminant analysis and a library of source material is used for source identification (Simpson et al 2002).

A recent study conducted by Carson et al. (2001) assessed the applicability of ribotyping to EC strains in humans, cattle, pigs, horses, chickens, turkeys, migratory geese and dogs. A total of 287 samples were analyzed from the source organisms to develop riboprints. The rate of correct classification was determined for the various sources. The method provided accurate results for discriminating between human and non-human riboprints, with an average rate of correct

classification (ARCC) at 97% when the sources were grouped. When each source was analyzed separately, the highest rate of correct classification (RCC) was for chickens, followed by humans. The lowest RCC was for horse, which was often misclassified as turkey or pig. This study provides evidence that typical enteric populations of EC within the studied host species are specific enough to be identified using ribotyping.

Parveen et al. (1999) studied ribotype profiles of 238 EC isolates from human and nonhuman sources. This study found much less diversity in human sources of EC when compared to nonhuman sources and that discriminant analysis can be used to differentiate between the two sources, with an ARCC of 82%. Discriminant analysis identified 97% of nonhuman and 67% of human isolates correctly. The authors of this study used the same isolates to perform antibiotic resistance (see Parveen et al , 1997) and found that ARA identified 82% of human and 68% of nonhuman isolates correctly. Therefore, the authors concluded that ribotyping provided a stronger method for differentiating human and nonhuman sources of fecal pollution.

4.1.2 PFGE

Pulse field gel electrophoresis (PFGE) is another molecular technique that can detect polymorphisms using restriction enzymes, similar to ribotyping. In PFGE, pure culture bacterial cells are digested using restriction enzymes (Maier et al 2000). The digested DNA is then imbedded into specialized electrophoresis gels and pulsed with alternating currents from different directions to separate the DNA. The gel is then stained to produce a fingerprint (Simpson et al, 2002).

The application of this technique to bacteria source tracking has not been well published, but there are numerous reports of this technique being used to identify isolates from disease outbreaks (Popovic et al, 2001; Pestel-Caron, et al., 1999; Mitsuda, et al., 1998' Avery et al., 2002; Tamplin, et al., 1996; Johnson, et al., 1995; Preston et al., 2000). Some investigators, however, have published findings with regard to BST. The differences between EC in stools from children and chickens was explored by Kariuki, et al. (1999). This study compared both the antibiotic resistance profiles and the PFGE clusters from the two sources in Nairobi, Kenya. A total of 24 EC isolates were collected from chickens across 12 farms, while 36 isolates were obtained from children less than 2 years old. Both ARA and PFGE indicated that there are distinct differences between the bacterial flora from stools of children and chickens. The EC isolates were resistant to multiple drugs, while the EC isolates from chicken were only resistant to tetracycline. The PFGE analysis produced a total of 14 different clusters, with 5 distinct clusters among isolates from children and 7 distinct clusters from chickens. Only 1 cluster was found in both chickens and children.

Another study examined the differences between human and nonhuman sources of EC (Parveen et al., 2001). In this study PFGE was used in conjunction with fatty acid methyl ester analysis. A total of 32 EC isolates were selected from a library that was developed for a previous study and analyzed. The researchers found no relationship between the PFGE clusters and the source of the isolate. Thus, the researchers concluded that PFGE may not be an appropriate technology for source tracking. It should be noted that this study acknowledged that other researchers, such as Herbein et al. (1996) had reported differences in clustering between different sources of bacteria.

4.1.3 ARA

Antibiotic resistance can be used to differentiate sources of bacteria. The premise of this method is that human fecal bacteria would be more resistant to antibiotics than nonhuman sources. Domesticated animals can also be differentiated, since they are generally prescribed different antibiotics than humans. In this method, fecal indicator bacteria (fecal streptococci, enterococci, EC and FC have all been studied) are grown on microtiter trays and then transferred onto a series of agar plates, with each plate having been treated with a single antibiotic at a specific concentration. The trays are incubated and the isolate is scored for growth or no growth. The scores for each antibiotic are tabulated for the individual isolates and a pattern of antibiotic resistance emerges that can be used for source differentiation in conjunction with a source library (Simpson et al., 2002).

Fecal streptococci antibiotic resistance profiles were used in conjunction with discriminant analysis by Wiggins (1996) to demonstrate that differences between the sources of indicator bacteria in the environment exist. Wiggins used five different antibiotics: chlorotetracycline hydrochloride (CTC), halofuginone hydrobromide (HAL), salinomycin sodium (SAL), oxytetracycline hydrochloride (OTC) and streptomycin sulfate (STR). Concentrations of antibiotics used in the study were 20, 40, 60, and 80 μg/L of CTC, OTC and STR while concentration of 1, 5, 10 and 15 μg/L were used for SAL and 20, 40, 70, and 100 μg/L were used for HAL. A total of 17 source samples from beef cattle, dairy cattle, turkey, chicken, sewage influence and pristine stream water were collected and from those samples, 1,435 isolates were obtained. The ARCC was 72% when all six sources were analyzed, with the rate of correct classification for human isolates at 92%. When the ARCC was calculated for discrimination between human and nonhuman sources (i.e. all other sources

grouped together), the ARCC increased to 95%. The results presented in the study provide evidence that ARA can be used to differentiate bacterial sources in a watershed.

Parveen et al (1997) conducted a study on Apalachicola Bay, an estuary system in Florida using EC. Their study was intended to demonstrate that different multiple-antibiotic resistance (MAR) profiles exist for point and nonpoint sources of fecal bacteria. Source samples were collected from surface water (from an area where no known point sources exist), animal feces in the surrounding the bay, municipal wastewater influent as well as human volunteers. A total of 765 isolates were cultured, with 82% resistant to one or more antibiotic. EC isolates from point sources showed significantly greater antibiotic resistance than those from nonpoint sources. The results of this study showed that MAR may be used to differentiate sources of EC.

One of the first studies using ARA to differentiate sources in a watershed was performed by Hagedorn et al (1999). The study watershed is located in an agricultural area in Virginia, with potential indicator bacteria sources being waterfowl, domestic livestock, wildlife and malfunctioning septic systems. A library for source identification was developed from 147 samples of fecal streptococci collected from beef cattle, dairy cattle, chickens, deer, humans and waterfowl (geese and ducks) to culture a total of 7,058 isolates. Thirteen antibiotics were used for the analysis: chlorotetracycline hydrochloride, halofuginone hydrobromide, salinomycin sodium, oxytetracycline hydrochloride and streptomycin sulfate, amoxicillin, ampicillin, chloramphenicol, erthromycin, neomycin sulfate, rifampin, tetracycline, and vancomycin hydrohloride. The ACCR using discriminant analysis ranged from 85% for the chicken to 93% for the human isolates. When sources in the Page Brook watershed were pooled into human or nonhuman sources, the ARCC was 96% for

human isolates and 98% for nonhuman isolates. In the source identification part of the study, water quality samples were collected from Page Brook on a monthly basis for over 2 years to yield a total of 4,615 unknown source isolates. Discriminant analysis was used to identify the sources of the isolates based upon the previously developed source library. No human sources were identified using ARA, while the primary source of indicator bacteria was found to be beef cattle.

Wiggins et al (1999) expanded the study conducted by Wiggins (1996) to include more isolates and increased the number of antibiotic concentrations. A total of 236 source samples were collected from beef and dairy cattle, turkey and chicken (poultry), domestic sewage influent and septage (human) and pristine stream water (wild). Antibiotics used in the analysis included amoxicillin, ampicillin, sodium salt, chlorotetracycline hydrochloride, erythromycin, gentamicin, oxytetracycline hydrochloride, salinomycin, streptomycin, tetracycline, and vancomycin. Vancomycin is only used for humans and salinomycin is used only in chickens. Four large sets of fecal strep isolates (from 2,635 to 5,990 isolates per set) were obtained from the source samples. The isolates were tested for antibiotic resistance and analyzed using discriminant analysis. The study examined both isolate-level and sample-level resistance patterns and found that sample-level resistance patterns exhibited much higher ARCCs than the isolate-level patterns. The data in the study confirm that ARA can be used to classify and identify sources of fecal pollution.

Another recent study conducted by Harwood et al (2000) demonstrated that ARA can be applied to determine sources of fecal pollution. This study examined both fecal streptococci and fecal coliform resistance patterns to nine antibiotics (vancomycin, ampicillin, amoxicillin, cephalothin, tetracycline, erythromycin, chlorotetracycline, oxytetracycline, and streptomycin) at four

concentrations. Source samples were collected from wastewater influent (human sources), chicken, cattle (dairy and beef), dog, rabbit, birds and racoons. Due to the difficulty collecting wild animal scat, the number of isolates were relatively small ranging from 83 FC isolates from rabbits to 274 FC isolates from birds. The classification accuracy of the two indicator bacteria database (FC and FS) were first assessed by calculating the ARCC. When the isolates were pooled into human and nonhuman sources, the ARCC for human FS was 75.5% and for nonhuman it was 72.4%. For human FC, the ARCC was 69.3%, while animal isolates were classified correctly 78.4% of the time. Surface waters with known sources were collected and used to test the databases. The first sample was collected from a malfunctioning septic system; the isolates from the sample were classified as primarily human. A sample was collected from the same location once the septic system had been repaired, and this time the dominant sources were cattle and dog. Differences in source identification for this sample were noted between the FC and FS database. This study demonstrated that ARA may be a useful tool for assessing sources of fecal contamination.

4.2 EROSION AND SEDIMENT CONTROLS ON HCFCD CHANNELS

Soils and stream sediments have been shown to support rich populations of bacteria (see Chapter 3 for detailed literature review). Erosion and sediment control in drainage channels handled by the Harris County Flood Control District (HCFCD). Dr. Sherri Dunlap with the HCFCD described the following steps involved in sediment control (Dunlap, 2003):

- HCFCD has an Infrastructure Division that conducts routine inspection and maintenance of the channels;

- The inspection is generally conducted along with mowing operations;
- When minor erosion is found, the Infrastructure Division conducts repair using its own staff and equipment;
- When significant erosion problems are found, the bid process is initiated and a contractor would be selected to conduct the repair. For example, there were 15 bids awarded for channel repair and maintenance in the spring of 2002, including one for BB; and
- The latest channel repair was issued for bids on June 20, 2003. However, it did not include BB or WOB.

In addition, the flood control district provided the following information:

- HCFCD conducted a sediment bacteria sampling effort in 2001. Forty-eight sediment samples were collected from 15 channels, including four samples from W142-00, a tributary channel of BB;
- As documented in a HCFCD (2003), the sampling results were compared against those obtained from Greens Bayou, which was considered by HCFCD as having the least human impacts. The comparison of the sampling results indicated significant bacteria levels in the collected sediments, with fecal coliform levels ranging from 92 to 1,942,768 cfu/g dry weight with a mean of 298,203 cfu/g. This is much higher than the TCEQ standard of 1,000 cfu/g for class A sewage sludge (30 TAC §312.82(a)(1)(C)) ;

- The study also found Salmonella, Streptococcus, and Enterococcus in 32, 47, and 47 of the 48 sediment samples, respectively;
- The high levels of bacteria raise health risk concerns to HCFCD field personnel as well as the public; and
- At present, HCFCD is investigating methods to handle removed channel sediments. Currently the material is taken to a landfill. One possible method being considered is composting. A pilot study may be initiated to study the pros and cons of the composting approach.

4.3 ON-SITE SEWAGE FACILITIES

Existing On-Site Sewage Facilities (OSSF) within the BB and WOB watersheds were checked in this work order. According to Darla Branch of TCEQ[1], no new OSSF permits in the BB or WOB watersheds within the City Limits were issued since June of 1996.

Don Hundle of City of Houston Plan Review[2] recalled having reviewed/inspected about 2.5 septic systems per month for the entire city and there were 2-3 other individuals performing similar work, totaling about 7-8 systems per month or about 100 systems per year prior to 1996. Mr. Hundle started his career with the City in 1985 and the number of septic system inspections remained fairly consistent during his tenure. Based on this information, there are undoubtedly some residences in the

[1]Phone number is 713-267-3232

[2]Phone number is 713-535-7537

watersheds using OSSFs today. However, the number is likely to be very small because the City of Houston or a Municipal Utility District serve most areas of BB and WOB.

According to Debbie Hymer of the Harris County Public Infrastructure-Permit Section[3], 14,578 OSSF permits were issued between 1978 and 1991, and 14,207 permits between 1991 and 2003. As of March 2003, 2,934 facilities were found to be not in compliance. Given that the permits are not renewable, the numbers of permits mentioned above should reflect OSSF permit applications for different facilities. However, the total number of actual facilities is likely to be smaller because: 1) the number does not reflect facilities that were not installed after submitting the applications; 2) re-applications are tracked as new applications; and 3) the number does not reflect the number of facilities no longer in use. Harris County conducts inspections only with the initial application and as a result of citizen complaints. As a result of this information, on-site sewage facilities do exist within the two watersheds and may warrant further investigation.

[3] Phone number is 713-956-3000

CHAPTER 5

BACTERIA LOADS FROM VARIOUS SOURCES

In the first work order, potential sources of bacteria were identified for the Buffalo and Whiteoak Bayou watersheds. These sources included: wastewater treatment effluent, dry weather storm sewer discharges, nonpoint sources of bacteria (water and sediment runoff from the watershed), bacteria from the reservoirs (in Buffalo Bayou only), and in-stream sediments. Two additional sources of bacteria were identified based upon local TCEQ input. These include solids releases from wastewater treatment plants and WWTP overflows and bypasses.

This chapter describes the estimated loads from the various sources of EC in the watershed. Data from TCEQ files were gathered for solids releases and overflows/bypasses. Loads were calculated using Summer 2001 data collected at WWTP and storm sewers discharging under dry weather. NPS loads were estimated using event mean concentrations (EMCs). These loads are compared with the observed loads seen in the bayous.

5.1 TCEQ SOLIDS RELEASES

Solids releases occur at a wastewater treatment plant when there is inadequate residence time, or the plant is experiencing an upset and the sludge does not settle properly. These washouts may occur because there are difficulties in managing the plant correctly or the plant is subject to a high amount of influent during rainfall events.

Based upon local TCEQ input, reports of observed solids releases into the bayou were evaluated to determine their impact on in-stream water quality. Within the examined inspection reports, the following violations were recorded: dissolved oxygen violations, unauthorized discharges to waters of the State (both solids/sludge and wastewater), failure to report unauthorized discharges, evidence of washout, inaccurate flow measurement, ammonia violations, high solids in the aeration basin, and high TSS. The majority of the examined data were not for plants within the Buffalo and Whiteoak Bayou watersheds, but were throughout TCEQ Region 12.

There were several documented solids washouts where fecal coliform data were collected, although none were located in the Buffalo and Whiteoak Bayou watersheds. High FC and TSS values in the receiving streams were generally associated with the plant washouts, but the values in the studied reports ranged from 460 cfu/dL (at TCEQ ID 11720-001, 3/17/99) to 252,000 cfu/dL (TCEQ ID 11200-001, 12/7/01). One of the confounding factors in these data are the upstream concentrations of FC that are sometimes high, making it difficult to discern the impact of the washouts. When measurements at the outfall were taken during washouts, the FC concentrations ranged from 1,800 cfu/dL (TCEQ 10436-001, 4/20/99) to 153,000 cfu/dL (TCEQ ID 13765-001, 5/17/01). Only one of the reports actually reported a discharged volume of 24,000 gallons of sludge that was removed from the stream (TCEQ ID 11200-001, 12/7/00).

The impact of these solids washouts is difficult to quantify for several reasons. One primary reason is that the volume of the sludge that has been discharged to the receiving stream is rarely reported. Additionally, the flux of bacteria into the water column from sludge has not been studied, and the change in in-stream bacteria concentrations cannot be calculated. Finally, washouts generally

do not occur continuously and their transient nature makes it difficult to estimate their load and impact.

5.2 SELF-REPORTING OVERFLOWS AND BYPASSES

Self-reporting data were supplied by the local TCEQ office and used to calculate EC loads to Buffalo and Whiteoak Bayous. The database contains information primarily regarding the City of Houston plants in these two subwatershed. These data contain the date of the discharge and an estimated volume of the discharge. To estimate annual FC loads from untreated sewage, an estimate of FC concentration of 500,000 cfu/dL was used. This assumption was based on the rationale that this flow is primarily storm water mixed with some smaller proportion of sanitary sewage; the exact proportion will vary considerably but will probably be at least five parts storm water to one part sewage (Jensen and Su, 1992). The calculated loads are presented in Table 5.1. The self-reported loads to Buffalo Bayou were one order of magnitude higher than those to Whiteoak Bayou.

Table 5.1 Loads from Self-reporting Overflows and By-passes

	EC Load (MPN/year)	Reporting Period
Buffalo Bayou	1.9×10^{12}	October 1997 through December 2002
Whiteoak Bayou	6.1×10^{11}	December 2000 through December 2002
Total	1.5×10^{12}	

Notes/Abbreviations:
1. EC converted from FC using ratio of standards (126/200)
2. MPN: most probable number

In Work Order 1, data for overflows and bypasses were collected from the City of Houston Public Works and Engineering Department, the local TCEQ files and the City of Houston Health and Human Services Department (See Final Report for Work Order 1). Table 5.2 presents a summary of these data for 1998 through 2000. The discharge was assumed to be raw sewage with an FC concentration of 500,000 cfu/dL. The loads calculated in Table 5.2 are one order of magnitude higher than those presented in Table 5.1. This may be because the data in Table 5.1 were primarily from large City of Houston plants, while the data in Table 5.2 encompass additional bypasses and overflows reported to the complaint system. The main conclusion that can be drawn from these data is that Buffalo Bayou does exhibit a higher load from bypasses than does Whiteoak Bayou, and the annual load to the bayous is generally on the order of 10^{12} or 10^{13}.

Table 5.2 EC Load from Self-Reporting Data from 1998 through 2000

	EC Load (MPN/yr)
Buffalo Bayou	1.135E+13
Whiteoak Bayou	7.97E+12
Total	1.93E+13

Notes/Abbreviations:
1. Table prepared using data from Table 3.6 presented in Final Report for Work Order 1
2. EC converted from FC using ratio of standards (126/200)
3. Loads averaged over 3 year period from 1998 through 2000
4. MPN: most probable number

5.3 POINT SOURCE LOADS

Wastewater treatment plants and dry weather storm sewer flows were sampled during the summer of 2001. EC and flow measurements were collected at each plant in the early morning and

again at mid-morning. Flow weighted geometric mean concentrations were developed for plants that were not sampled; a concentration of 6.14 MPN/dL was used for Whiteoak Bayou and a concentration 5.47 MPN/dL was used for Buffalo Bayou. Because the collected flow data were instantaneous measurements, a 5-year average flow was developed using self-reported monthly data instead. These flows and the measured concentration data (or flow weighted geometric mean) were used to develop the loads presented in Table 5.3

Also presented in Table 5.3 are two additional load calculations. The Baseline Load is the load calculated using the measured concentrations from Summer 2001 (except when they were greater than the ambient water quality criteria, then the long-term geometric mean concentration was employed) and flow. For wastewater treatment plants, the permitted flow was used while for DWSS discharges, the flow was the sampled flow. This Baseline Load should be representative of the greatest load from WWTP and DWSS dischargers using the measured data (except when it exceeds the ambient criteria) so that all discharges do not cause the bayou to exceed ambient water quality criteria. As seen in Table 5.3, the use of permitted flow causes a 2-order of magnitude increase over the Measured Load. The Standard Load is the load calculated when it is assumed that **all** discharges from WWTP and DWSS are discharging at the long-term geometric mean ambient bacteria water quality standard, regardless of what was measured in the Summer 2001 sampling event. This load also uses the permitted flows for WWTP dischargers rather than the sampled or modeled flows. The Standard Load is indicative of the maximum load that could be discharged from WWTP and DWSS discharges that would not cause an exceedance of ambient water quality standard.

Table 5.3. Point Source Loads

Sub watershed	Watershed	WWTP (flow acre-ft/hr, load cfu/hr)					DWSS (flow ac-ft/hr, ld cfu/hr)			
		Modeled Flow	Permitted Flow	Measured Load	Baseline Load	Standard Load	Measured Flow	Measured Load	Baseline Load	Standard Load
33	BB	1.18E+00	3.38E+00	7.99E+07	5.26E+09	5.26E+09				
34	BB						4.18E-03	8.57E+07	8.63E+07	6.52E+06
35	BB						3.79E-03	2.35E+04	5.92E+06	5.92E+06
39	BB						2.17E-02	3.23E+06	3.67E+07	3.38E+07
44	BB	9.59E-05	6.39E-04	6.49E+03	9.97E+05	9.97E+05	3.08E-05	2.41E+04	4.81E+04	4.81E+04
45	BB						4.16E-03	5.50E+08	5.50E+08	6.48E+06
47	BB						5.45E-05	4.92E+05	4.92E+05	8.50E+04
50	BB						4.83E-04	6.45E+06	6.53E+06	7.54E+05
52	BB						8.24E-03	1.82E+09	1.82E+09	1.28E+07
53	BB	2.88E-01	3.90E-01	1.95E+07	6.08E+08	6.08E+08	7.82E-04	1.77E+07	1.78E+07	1.22E+06
54	BB						3.70E-03	5.38E+09	5.39E+09	5.76E+06
55	BB	4.52E-01	1.53E+00	3.06E+07	2.39E+09	2.39E+09	5.25E-03	3.25E+04	8.19E+06	8.19E+06
56	BB	1.20E-04	1.41E-03	8.11E+03	2.19E+06	2.19E+06				
	Total	1.92E+00	5.30E+00	1.30E+08	8.27E+09	8.27E+09	5.23E-02	7.86E+09	7.92E+09	8.16E+07
1	WO	5.02E-02	6.39E-03	3.11E+05	9.97E+06	9.97E+06				
2	WO	1.16E+00	2.85E+00	5.53E+08	6.35E+09	4.45E+09				
4	WO	3.78E-01	1.97E+00	8.70E+07	3.19E+09	3.07E+09	3.78E-04	4.49E+05	6.16E+05	5.90E+05
7	WO	1.79E-01	5.12E-01	1.36E+07	7.98E+08	7.98E+08	1.36E-03	8.77E+04	2.12E+06	2.12E+06
9	WO	1.92E-01	4.27E-01	1.35E+07	6.66E+08	6.66E+08				
10	WO	1.26E-01	4.22E-01	1.57E+07	6.58E+08	6.58E+08	2.50E-03	4.45E+07	4.68E+07	3.91E+06
11	WO	1.27E-01	3.79E-01	4.33E+07	6.28E+08	5.91E+08	1.30E-03	6.13E+05	2.02E+06	2.02E+06
13	WO	2.18E-01	4.52E-01	1.35E+07	7.05E+08	7.05E+08	1.09E-03	7.60E+04	1.69E+06	1.69E+06
17	WO	1.57E-02	3.58E-02	2.53E+05	5.58E+07	5.58E+07				
40	WO	4.82E-03	7.54E-03	2.98E+04	1.18E+07	1.18E+07	1.44E-02	1.52E+07	3.28E+07	2.25E+07
41	WO						6.02E-03	9.45E+07	9.95E+07	9.38E+06
42	WO	3.52E-03	1.92E-02	2.37E+06	2.99E+07	2.99E+07	1.78E-02	8.40E+08	8.58E+08	2.78E+07
43	WO						3.22E-02	7.26E+09	7.28E+09	5.03E+07
	Total	2.46E+00	7.08E+00	7.42E+08	1.31E+10	1.10E+10	7.71E-02	8.25E+09	8.32E+09	1.20E+08

Notes:
Modeled flow is the average of the monthly self-reported flows from 1995 to 2000
Measured load is the product of modeled flow and the measured concentration
Permitted load is the product of the permitted flow and the measured concentration
Standard Load is the product of the permitted flow and the long-term water quality standard, 126 MPN/dL
Baseline Load is the product of the permitted flow and the measured concentration, if greater than 126 MPN/dL, or the water quality standard, 126 MPN/dL

5.4 RUNOFF LOADS CALCULATED FROM EMCS

Event mean concentration (EMCs) are flow-weighted averages of a water quality constituent and have been developed for various land uses. Generally, EMCs are developed on a watershed specific basis, but the values can be used interchangeably to some extent if the watersheds are similar in nature. EMCs can be translated into watershed loads through PLOAD, a model developed by the US EPA (US EPA 2001), or similar tools.

PLOAD is a simple, GIS-based tool that estimates pollutant loads on an annual basis for urbanized areas within a watershed. Input data required for the model to run include land use, EMCs for the pollutant based upon land use categories, percent of land use that is impervious, and the percentage of rainfall that results in runoff from the watershed. The PLOAD method of using EMCs and the volume of runoff to determine the NPS load can also be implemented in a spreadsheet, rather than a GIS environment. The spreadsheet approach was used for the calculations presented below.

For the purposes of this analysis, land use data from the 1987 USGS National Land Cover Dataset were used (1987). The data use the Anderson Land Use Classification System. Input EMCs were obtained from two sources: a study conducted on Galveston Bay in the early 1990's (Newell et al. 1992) and the MS4 permit data for Houston (Storm Water Management Joint Task Force 2002). The Galveston Bay study EMCs were calculated using a combination of National Urban Runoff Program data and site-specific runoff data, while the MS4 permit data were calculated using sampling events conducted in the BB and WOB watersheds. Table 5.4 presents a summary of the fecal coliform EMCs that were used to develop the annual loads for the Buffalo and Whiteoak Bayou watershed.

Table 5.4 Fecal Coliform EMCs

Land Use Description	FC EMCs (MPN/dL)	Source
Low Intensity Residential	40,052	Storm Water Management Joint Task Force 2002
High Intensity Residential	40,052	Storm Water Management Joint Task Force 2002
Commercial/Industrial/ Transportation	72,617	Storm Water Management Joint Task Force 2002
Mixed Forest	34,865	Storm Water Management Joint Task Force 2002
Shrubland	2,500	Newell et al, 1992
Grasslands/Herbaceous	2,500	Newell et al, 1992
Pasture/Hay	2,500	Newell et al, 1992
Row Crops	2,500	Newell et al 1992
Urban/Recreational Grasses	2,500	Newell et al 1992
Woody Wetlands	34,965	Storm Water Management Joint Task Force 2002
Emergent Herbaceous Wetlands	34,965	Storm Water Management Joint Task Force 2002

Note: Storm Water Management Joint Task Force data are presented as average of 3 seasons

The SCS runoff curve number method (Natural Resource Conservation Service 1986) was used for runoff depth calculations rather than the runoff coefficient approach used in PLOAD. The runoff depth was calculated for the entire year using the average rainfall over the past 30 years (50.31 inches per year as reported by NOAA (2001). This volume was multiplied by the EC EMC for each land use type to obtain a bacterial load for each land use. The land use categorizations for the watershed did not exactly correspond to the categorizations for the EMCs. Therefore, EMCs for residential land uses were used for both low and high intensity residential land use and EMCs for commercial land use were applied to the USGS National Land Cover Dataset category of commercial/industrial/transportation.

The resulting yearly runoff loads, normalized by subwatershed area and converted to *E. coli*, are shown in Figure 5.1 for Buffalo Bayou and Whiteoak Bayou. The calculated loads range from 6.27×10^{10} to 2.24×10^{12} MPN/acre/year. The total load of NPS to Buffalo Bayou is 4.32×10^{16} MPN/year for the entire watershed, including the Addicks and Barker Reservoir watersheds. For Whiteoak Bayou, the total load is 1.43 x 10^{17} MPN/year.

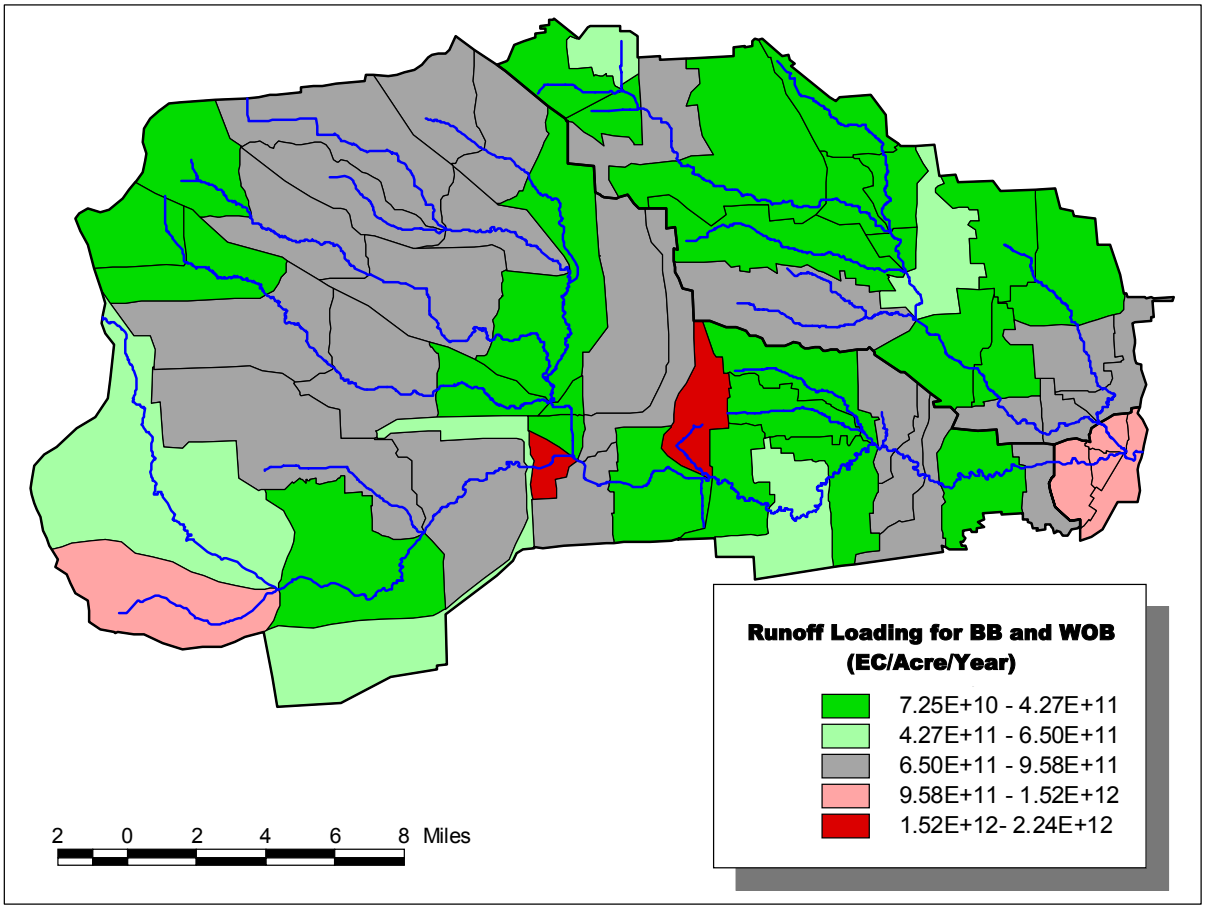


Figure 5.1. Runoff Loading to Buffalo and Whiteoak Bayous

5.5 COMPARISON OF LOADS

Table 5.5 summarizes the calculated loads to Buffalo and Whiteoak Bayous from each of the identified sources: wastewater treatment effluent, dry weather pipe discharges, the Addicks and Barker drainage areas (Buffalo Bayou only), runoff sources, by-passes and overflows, and potential solids releases. Also included in the table is the dry weather load for each bayou. The load for Barker Reservoir was calculated by taking observed concentrations at the dam during the model simulation period (April 1, 1999 through September 30, 2001) and assuming them to be constant until the next sample was taken (creating a step function-like graph). The concentration was multiplied by the daily reservoir flow and a conversion factor to obtain the yearly load. Water quality data have not been collected since the Liscum study (1987). Therefore, a mean of the USGS data was assumed to be constant to calculate the load from Addicks Reservoir.

The runoff loads in Table 5.5 are the highest bacteria loads for both Buffalo and Whiteoak Bayous, with the reservoirs (including runoff from half the Buffalo Bayou watershed). Most of the bacteria sources in the two watersheds are low-flow sources, with the exception of runoff. Due to the frequent and small rain events in Houston, however, runoff may be an influencing factor at lower flow as well. Unlike the other low-flow sources, though, runoff is not a constant low flow source.

The WWTPs, DWSS discharges and by-passes/overflows are a small percentage of the dry weather load in each bayou. The dry weather load is, in turn, about one-thousandth of the runoff load. The challenge is understanding the source of the dry weather load.

Table 5.5 Relative Annual Loads from Point and Non-point Sources

	Buffalo Bayou (MPN/year)	**Whiteoak Bayou (MPN/year)**
WWTP Effluent[1]	1.1×10^{12}	6.5×10^{12}
Dry-weather Pipe Discharges[2]	7.5×10^{13}	7.2×10^{13}
Addicks and Barker Drainage Area	1.2×10^{15}	Not applicable
Runoff	1.2×10^{18}	6.7×10^{17}
By-passes and Overflows[3]	1.9×10^{12}	6.1×10^{12}
Potential Solids Releases	Cannot be Calculated	Cannot be Calculated
Dry Weather Load[4]	1.9×10^{15}	1.2×10^{15}

1. See Table 5.3, column labeled WWTP - Standard Load
2. See Table 5.3, column labeled DWSS - Measured Load
3. See Table 5.1
4. From Table 6.4, at Shepherd and Heights

CHAPTER 6

DETERMINING A LOW FLOW CONDITION

One essential step in preparing a TMDL is determining the critical flow conditions. Both Buffalo and Whiteoak Bayous are designated for contact recreation. At the same time, these water bodies have had modifications to the natural channel and flow regime to accommodate flood control structures. On Buffalo Bayou, the upstream reservoirs impound runoff and incoming streams under high flow conditions. On Whiteoak Bayou, the channel has been modified and in the lower part of the watershed, concrete lined. These modifications may make contact recreation at higher flows dangerous. Additionally, the water quality standards were developed to protect human health during full-body contact recreation (Cabelli, 1983). Thus, an examination into what constitutes a low flow condition was needed.

Typically "low flows" in streams occur during the summer months and in the absence of rainfall. Dry weather flows for streams that receive effluent, such as WOB and BB, are mostly a reflection of the effluent discharge. However, Houston receives around 48 inches of rainfall annually distributed throughout the year and some rainfall occurs even during "dry weather" conditions. Hence, two possible criteria come to mind when defining a "low flow" condition for BB and WOB: (1) flow-based using the 7Q2/7Q10 or the median flow as a measure; or (2) Flow/Rainfall based upon the 7Q2/7Q10/median flow and less than "x" inches of rainfall in "y" days. Both of these criteria have been evaluated for the two watersheds as will be seen later in the chapter.

The City of Austin conducted a detailed study on runoff, which included bacteria data. The study documents several important pieces of information. The data document that high concentrations in runoff do originate from undeveloped areas. Also, the study shows that development increases the volume of runoff. Finally, the City of Austin experiences high concentrations of EC in their streams even without the presence of WWTP contributions on the streams.

Previous studies, such as one conducted in the City of Austin, have also documented the relationship between flow and bacteria concentrations based upon intensive monitoring of both large and small streams. The Austin data suggest that a higher impervious cover and more efficient drainage systems cause more rapid runoff and higher runoff volume that scours the creek beds and produces higher constituent concentrations in the creeks. Accordingly, it is essential that any definition of a suitable condition for the application of the contact recreation standard consider low or dry weather flows and also have some mechanism to isolate conditions affected by recent rain events. Before examining flow and rainfall relationships, historical low flow and wastewater treatment plant effluent data will be presented to clarify some observations regarding the two bayous.

6.1 HISTORICAL LOW FLOWS IN BB AND WOB

The long term flow records from USGS stream gages were analyzed to investigate the historical low flows in both WOB and BB. The Heights gage (08074500) was employed for the analysis on WOB, while the Dairy-Ashford (08073500) and West Belt (08073600) gages were studied on BB. Flows at the West Belt and Piney Point gages on BB have similar flows, so Piney

Point was not included in the analysis. The flow record at Shepherd is incomplete, as it is a flood-hydrograph partial-record station, and therefore this station was not included in the low-flow analysis either. Figure 6.1 shows the historical flows for Heights Blvd and includes the yearly average, yearly median, lowest 7-day average, and lowest daily flow for each year during the period from 1937 to 2001. It can be seen that the period from 1950 to 1985 shows a steady increase in the low flow values, due in part to increases in wastewater discharges. A much smaller change in the average flows is seen in the data, as the average flows are more influenced by differences in rainfall rather than WWTP flows. In Whiteoak Bayou, the period from 1985 to 2001 appears to have a relatively consistent amount of wastewater effluent discharged to the bayou. The average 7-day minimum for the same period at Heights is 29.6 cfs, which is 63% of the median (Table 6.1).

Figures 6.2 and 6.3 present the historical flows for Dairy Ashford and West Belt in BB. Although the general increasing trend seen in the flow data are similar to those seen in Whiteoak Bayou, the there are some significant differences between the two bayous. The ratio of minimum 7-day flow to the median flow in Buffalo Bayou is different from that seen in Whiteoak Bayou. The average 7-day minimum flow during the period from 1985 to 2001 BB at Dairy Ashford is 22.8 cfs, while the median flow is 127.9 cfs, with the 7-day minimum making up 18% of the median flow (Table 6.1). Additionally, the minimum 7-day flow is BB is lower than that in WOB (22.8 cfs at Dairy Ashford compared to 29.6 cfs in WOB).

FIGURE 6.1
08074500 White Oak Bayou at Heights Blvd

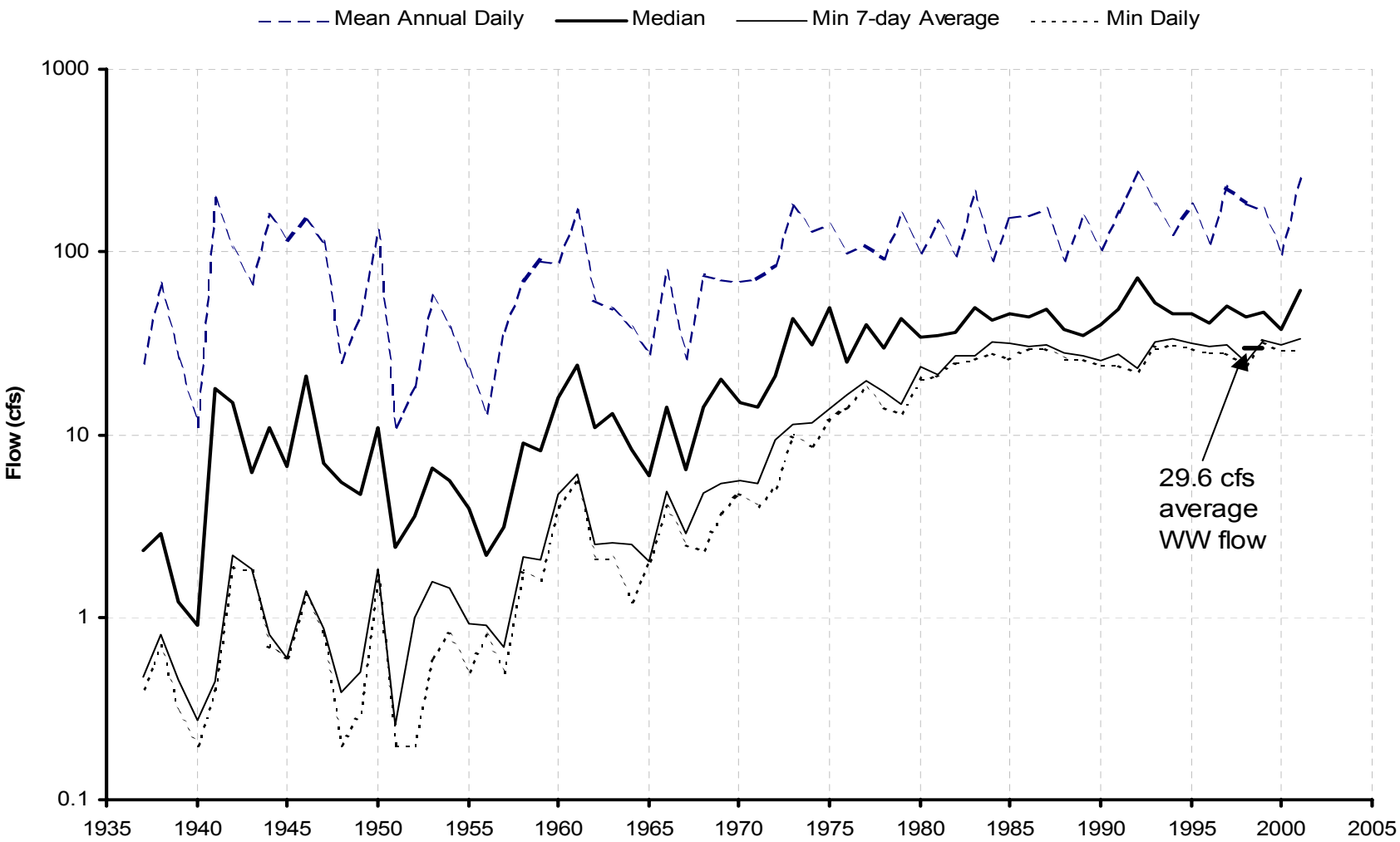


FIGURE 6.2
08073500 Buffalo Bayou at Dairy Ashford Road

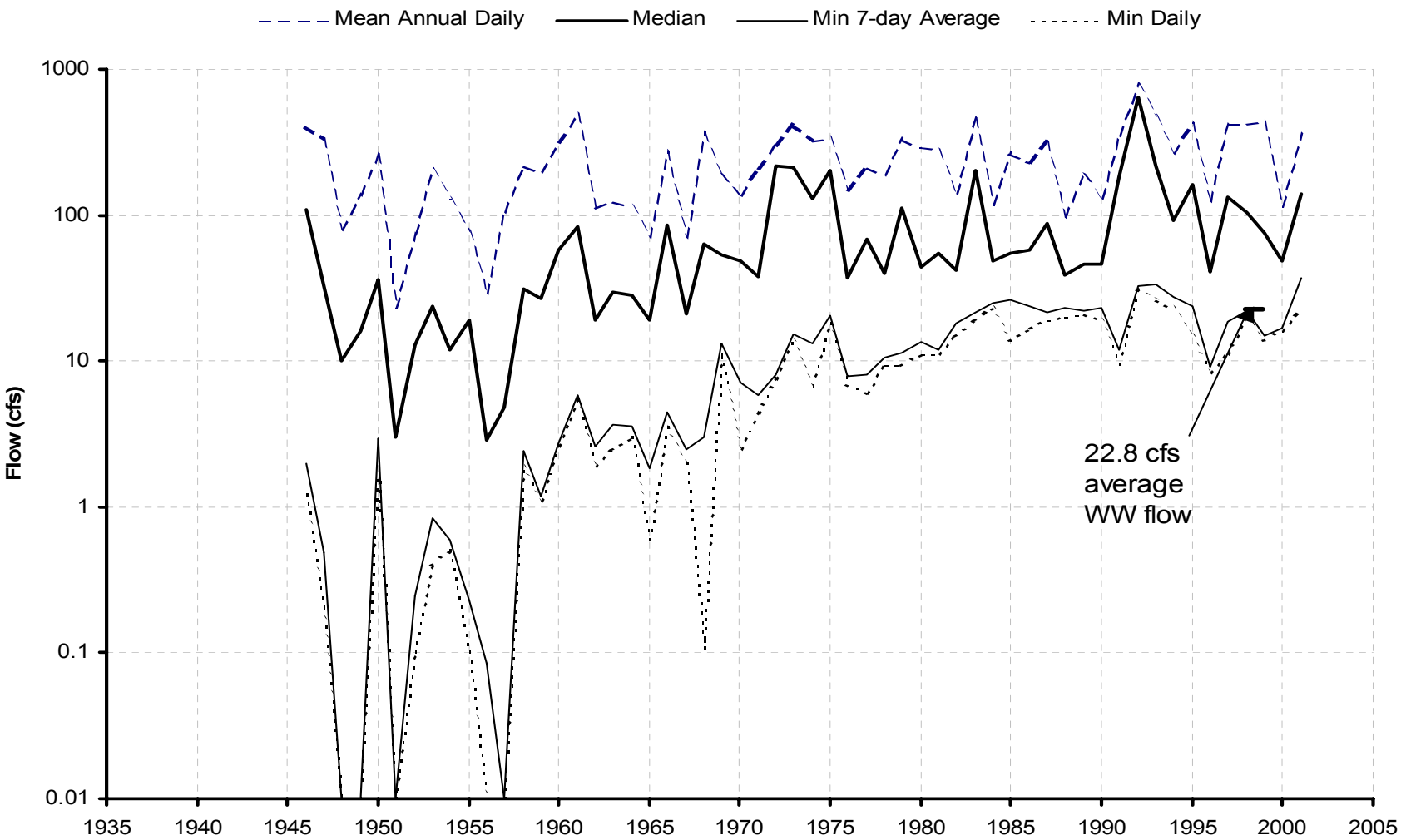


FIGURE 6.3
08073600 Buffalo Bayou at West Belt Drive

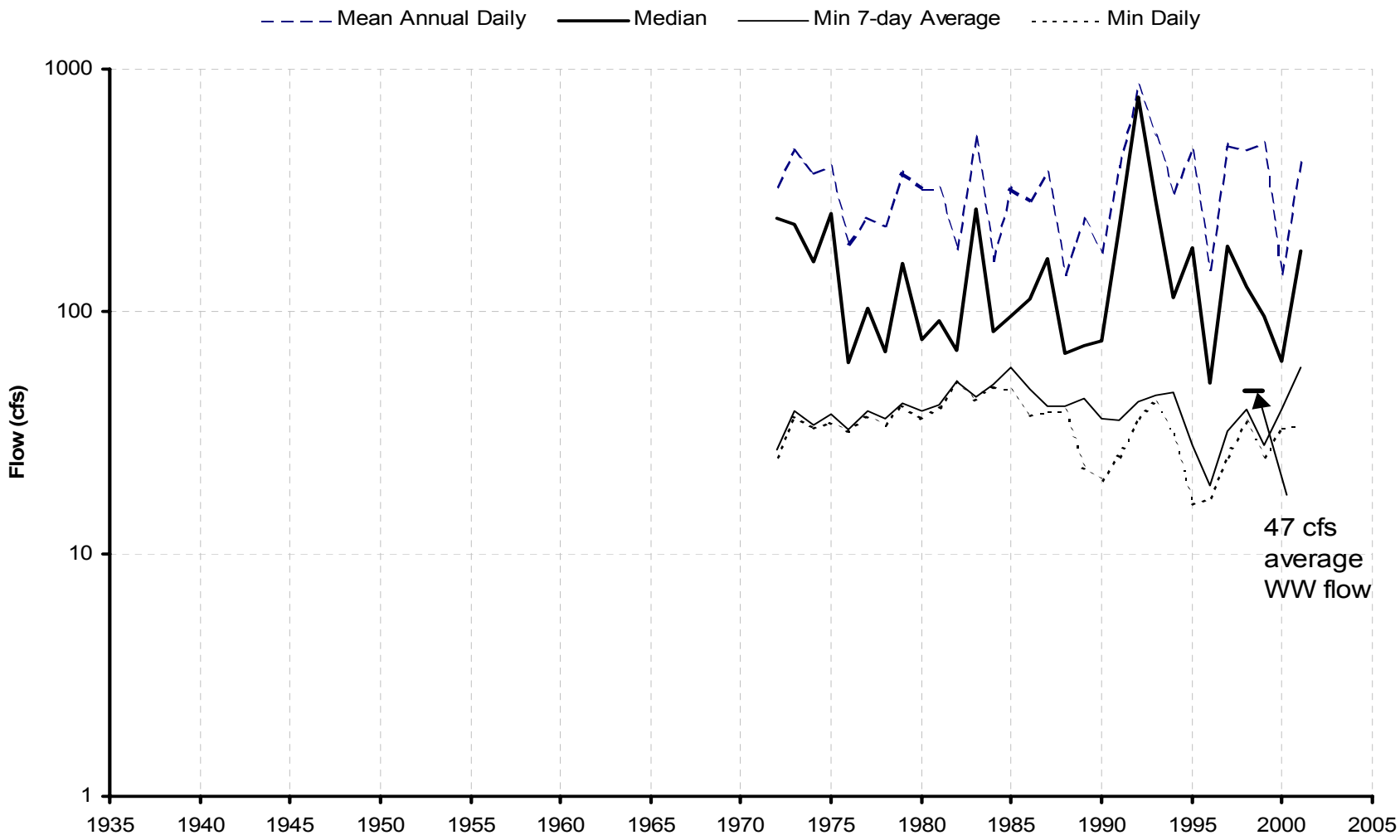


Table 6.1 Comparison of Average Flows (cfs) for 1985-2001

Gage	Cumulative WWTP Effluent Flow (cfs)[1]	7-Day Minimum Flow	Median Flow
Dairy Ashford, BB	33	22.8	127.9
West Belt, BB	47	40.2	132.4
Heights, WOB	29.4	29.6	47.1

Note:
[1] Sum of all average WWTP effluent flow that originates above each USGS flow gage

These differences observed between the ratios of the 7-day minimum flow to the median flow in the two bayous may be attributed to the location of the wastewater dischargers in the watershed. Most of the wastewater sources to the Dairy Ashford USGS gage are located upstream of the Barker and Addicks reservoirs. Additional sources of WWTP effluent are present between Dairy Ashford and West Belt, with an increase in WWTP effluent of 14 cfs seen between the two gages. Thus, there is an increase in the 7-day minimum average flow at West Belt, although the 7-day minimum flow to West Belt is still lower than the average WWTP flow, but not to the same degree as Dairy Ashford. This suggests that during dry periods, the water in the bayou may seep into the stream bed during its long passage along BB. Whiteoak Bayou, on the other hand, has a shorter flow distance and a channel that is concrete lined over much of the reach, which minimizes the possibility of seepage. Thus the 7-day minimum flow and WWTP effluent are more in agreement in Whiteoak Bayou. Clearly, the role of wastewater discharges in BB is more variable than it is in WOB. However, without wastewater discharges, the dry weather or low flow condition for either bayou is near zero.

In conclusion, very low flows, such as the 7-day minimum flows, in the bayous have been shown to consist almost entirely of wastewater discharges. The amount of such discharges has been increasing steadily in both bayous particularly during the period from 1950 to 1985. The amount of wastewater that is lost to bank seepage appears to be greater in Buffalo Bayou, especially above the Dairy Ashford gage. The impact of wastewater discharges in Whiteoak Bayou also appears to be stronger than in Buffalo Bayou, based upon the strong relationship between wastewater effluent and the minimum 7-day flows.

6.2 RAIN, FLOW AND BACTERIA RELATIONSHIPS

To analyze the effects of runoff on the routine monitoring data, a set of daily rain data for several rain gages in the two watersheds was obtained for the period 1992 to 2001. The great majority of the available bacterial data are from Health and Human Services, collected from 1998 to 2001 at a typical rate of two samples per month. These samples are collected on a routine basis, but periods of rainfall are skipped for safety reasons. Some of the stations had a small number of TCEQ observations dating back to 1992. None of the City of Houston Public Works & Engineering data are included in the data set. All of the data are reported as EC levels, with FC observations reduced by the ratio from the Standards of 126/200. The locations of the rain gages and bayou stations where flow and bacteria were measured as shown in Figure 6.4.

Bacteria monitoring data are collected much less frequently than rain data. To assess the relation, the collection dates for major stations were selected and the rain data from selected rain gages was associated with sampling data. The total amounts of rain on the day of sampling, along

with the day before and 5 days before, were tabulated. The first analysis tested the correlation between the amount of antecedent rain and the bacteria concentration.

Correlation coefficients for flow and several time periods using two different rain gages in each watershed are shown in Table 6.2. The correlation between daily average flow and EC is positive, but small, at the WOB gage, and virtually non-existent for the BB gages possibly due to the attenuation of EC in the Barker and Addicks flood detention reservoirs (see Section 5.1.5.3 in University of Houston and PBS&J, 2003 for additional discussion). The correlation with rain amount on the day of collection is much stronger than that with flow, and stronger on BB than on WOB. Interestingly, the correlation with rain on the day before bacteria sample collection was less strong than on the day of collection, and the 5-day total had a still smaller correlation.

The data in Table 6.3 show the results of a multiple regression analysis with EC and two different variables, either flow or daily rainfall. For Whiteoak Bayou, the best result was obtained using a combination of flow and same-day rain, but the regression still only explains about 13% of the observed variance. The upstream and nearby precipitation data were the best predictors for Buffalo Bayou, with an R^2 value greater than 0.4 for the Dairy Ashford and West Belt stations. At the Shepherd station, the rain results explained about 20% of the variance, less than the other BB stations but more than the WOB station.

FIGURE 6.4
LOCATIONS OF SAMPLING STATIONS AND RAIN GAGES

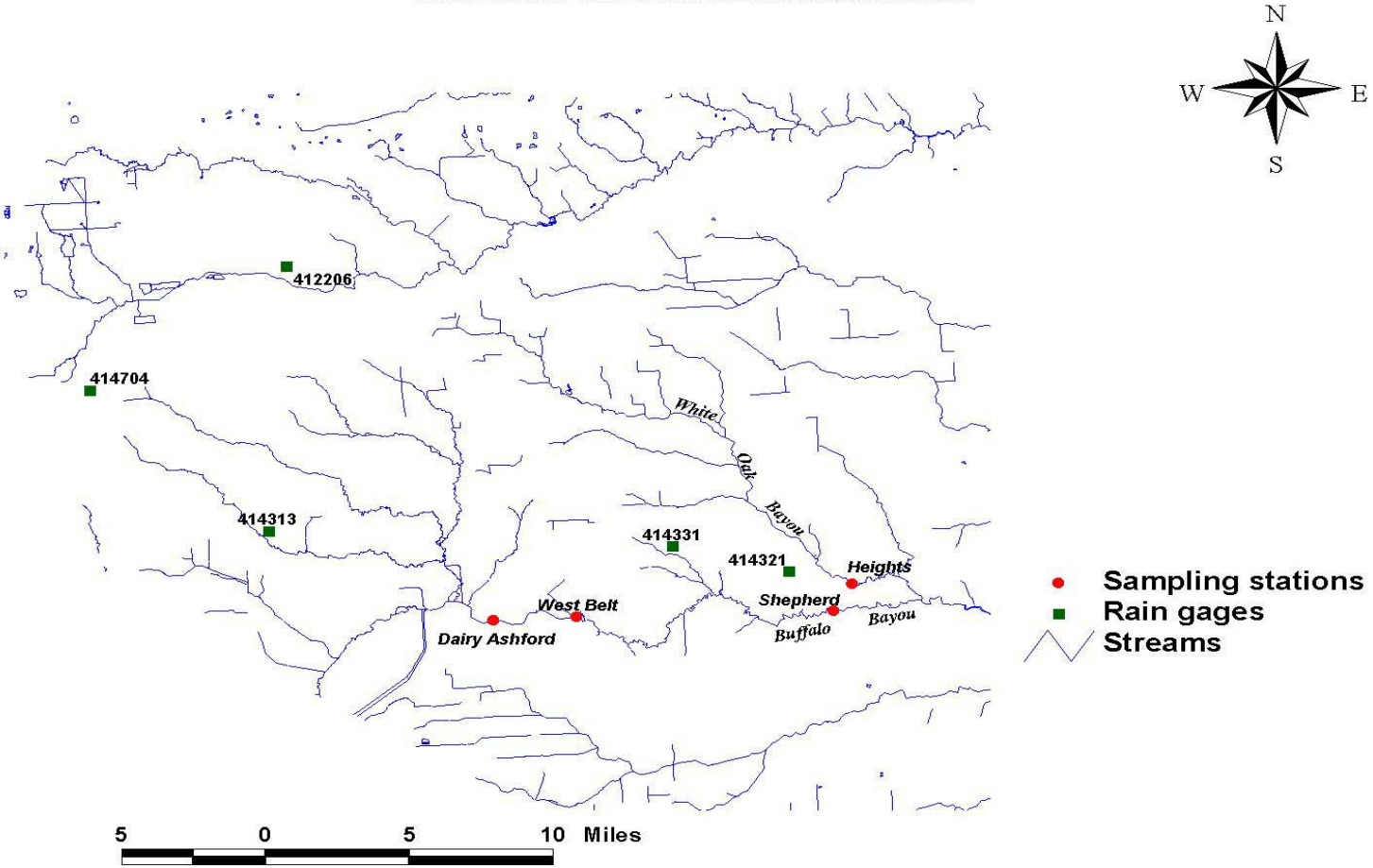


TABLE 6-2
CORRELATION COEFFICIENT BETWEEN DEPENDENT VARIABLE, EC, AND INDEPENDENT VARIABLES

SITE		Flow, cfs	Upstream rain, in			Nearby rain,in		
			Rain on Day of Sample	Rain on Day Before Samp.	Total Rain Days -1 to -5	Rain on Day of Sample	Rain on Day Before Samp.	Total Rain Days -1 to -5
White Oak-Heights		0.250	0.322	0.303	0.205	0.204	0.179	0.149
Buffalo-Dairy Ashford		0.040	0.626	0.028	-0.012	0.589	0.141	-0.048
Buffalo-West Belt		0.097	0.653	0.147	-0.013	0.469	0.215	0.028
Buffalo - Shepherd		0.082	0.392	0.048	-0.032	0.415	0.015	-0.022

Table 6-3

Best Regression Equation between Dependent Variable, EC, and Independent Variables								
SITE	Intercept	Number Ind variables	Variable 1		Variable 2		Multiple R	R-square
			Name	Coefficient	Name	Coefficient		
White Oak-Heights	6218.1	2	Daily Flow	4.4852	Same Day Rain US	7379.2	0.364	0.133
Buffalo-Dairy Ashford	2104.7	2	Same Day Rain NB	8732.4	Same Day Rain DS	6619.3	0.655	0.429
Buffalo-West Belt	2272.9	2	Same Day Rain NB	15295.5	Same Day Rain DS	2028.3	0.656	0.431
Buffalo - Shepherd	5087.9	2	Same Day Rain NB	9808.8	Same Day Rain DS	13588.6	0.450	0.202

NB- Near by
DS- Downstream
US- Upstream

Having established that rainfall explains a small part of the observed bacteria data variability, the next step in the analysis was to examine the data set with different rainfall amounts excluded. Table 6.4 shows EC, daily flow, and the number of observations when screening is done using different rain periods and amounts. At Heights in WOB, if only the data with no rain on the day of collection are considered, the number of observations drops from 124 to 101, the average flow drops from 70 cfs to 57 cfs, and the geometric mean EC level drops from 3,109 to 2,573 cfu/dL. Eliminating events where there was any rain on the day before sample collection removes more observations but has minimal effect on the resulting geometric mean EC level. This is somewhat surprising since bacteria samples are usually collected in the morning, and it would be expected that at least half of the rain on the day of collection occurred after the samples were collected, thus not influencing the bacteria data. Going further and eliminating events with rain in the previous 5 days reduces the number of observations even more, and again has minimal effect on the EC geometric mean concentrations. Apparently, the largest effect of rain on bacteria levels is associated with very recent runoff.

While the effect of eliminating days with any rain appears to be small, the effect of only considering days with significant rain is large. Considering only bacteria collection days where there was a half inch of rain or more, geometric mean EC levels were in the range of 15,000 cfu/dL, much higher than routine observations. Although these data are not collected to characterize runoff events, it appears that the impact of precipitation is evident in the data. It should be noted that there are very few data available for use in this analysis.

These conclusions are confirmed when examining FC data for a much longer period of record, from 1970 through 2001, and at multiple stations. Figure 6.5 presents the relationship in BB and WO between FC and the number of dry weather days. A very small downward trend is evident in the data, indicating that the concentrations of bacteria do decline a slight amount when there is no rainfall. However, this figure also confirms that both bayous frequently exceed water quality standards, even after long periods without rain, with FC geometric means of 2,274 cfu/dL for BB and 1,953 for WOB.

Using the same data set from 1970 through 2001, the relationship between FC and the amount of rainfall that fell the day of sample collection was examined, as shown in Figure 6.6. These data confirm that the concentrations of bacteria are substantially higher under rainfall conditions, with geometric means of 3,467 cfu/dL for BB and 11,817 cfu/dL for WOB. The plots show a large amount of scatter in the concentrations when precipitation on the day of sampling was minimal, while the concentrations become more stable with larger amounts of rainfall. Again, these data confirm that rainfall does play a role in maintaining the high concentrations of indicator bacteria seen in BB and WOB.

TABLE 6.4
EC RESULTS USING UPSTREAM GAGE

Geometric Mean of EC Data (cfu/dL)

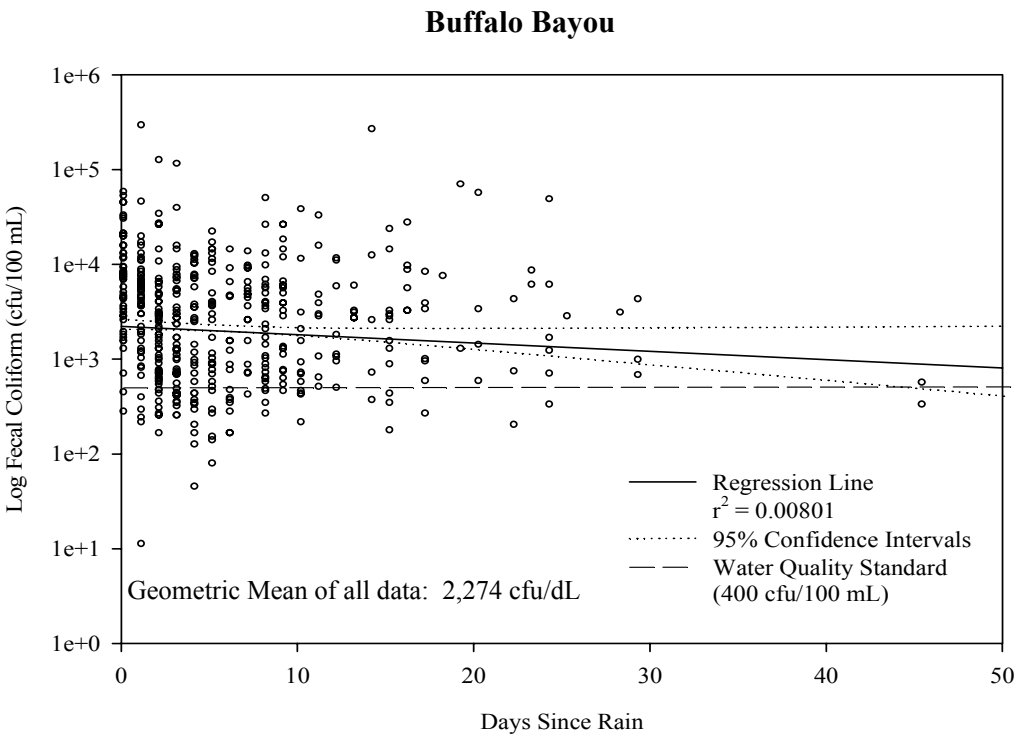
	All Data	No Rain on Day of Sample	No Rain on Day Before Sample	No Rain Days -1 to -5	Rain > 0.5 in on Day of Sample	Rain > 0.5 in on Day Before Sample
White Oak - Heights	3,109	2,573	2,448	2,733	15,846	12,232
Buffalo - Dairy Ashford	826	548	685	661	14,502	2,409
Buffalo - West Belt	1,295	867	1,009	946	15,202	3,906
Buffalo - Shepherd	2,600	2,046	2,317	2,622	15,363	6,443

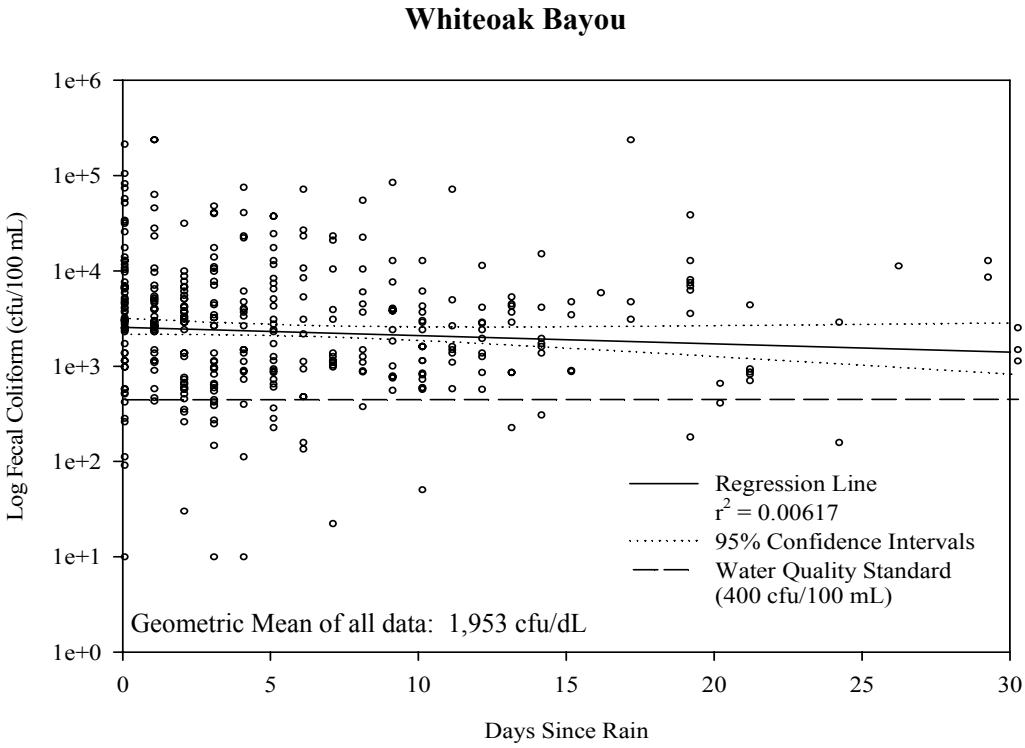
Geometric Mean of Flow Data (cfs)

	All Data	No Rain on Day of Sample	No Rain on Day Before Sample	No Rain Days -1 to -5	Rain > 0.5 in on Day of Sample	Rain > 0.5 in on Day Before Sample
White Oak - Heights	70	57	52	50	475	419
Buffalo - Dairy Ashford	129	111	98	67	317	420
Buffalo - West Belt	115	97	94	81	313	283

Number of Observations

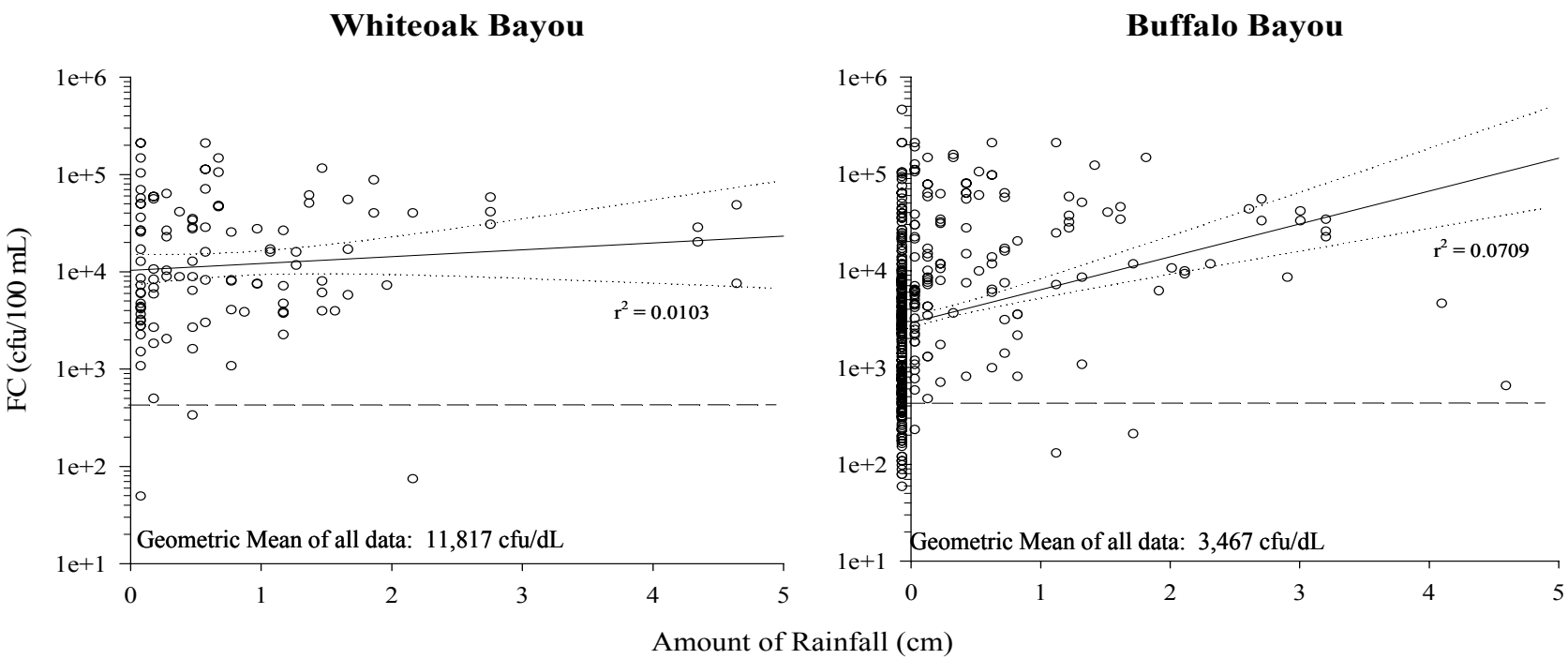
	All Data	No Rain on Day of Sample	No Rain on Day Before Sample	No Rain Days -1 to -5	Rain > 0.5 in on Day of Sample	Rain > 0.5 in on Day Before Sample
White Oak - Heights	124	101	93	54	8	11
Buffalo - Dairy Ashford	89	75	69	35	8	11
Buffalo - West Belt	125	102	96	55	13	15
Buffalo - Shepherd	137	116	110	57	14	14





Note: Data from all stations beween 1993 - 2001 were used to develop these plots

Figure 6.5
Relationship between FC and Dry Weather



Note: Data from all stations beween 1993 - 2001 were used to develop these plots

Figure 6.6
Relationship between FC and Rainfall

6.3 RELATIONSHIP BETWEEN MEDIAN FLOW AND RAINFALL

The median flow has been suggested as one possible definition of low flow in the bayous, and therefore, the relationship between median flows and rainfall was examined in Whiteoak Bayou. Buffalo Bayou is not currently included in this analysis. Both the Heights and Cole Creek gages on Whiteoak Bayou were initially examined, but because of the incomplete data at Cole Creek, only the Heights data could be analyzed. Flow data from 1990-2000 were analyzed to determine the median flows as well as the number of days that the daily average stream flow exceeded the median flow. Rainfall data from the Harris County Office of Emergency Management were also compiled for that same time period at three gages, Heights (Gage 520), Brickhouse Gully at Costa Rica (580), and Buffalo Bayou at Milam (2220). These gages were selected because of their location and also because they have an adequate period of record for the analysis. The Brickhouse Gully site represents an upstream location in Whiteoak Bayou, while the Buffalo Bayou at Milam site represents the locations in the lower part of the Whiteoak Bayou watershed.

The median over the past 10 years was calculated to be approximately 50 cfs, with fluctuations in median flows ranging from 40 cfs in 1990 to 68 cfs in 1992 (Table 6.5). Additionally, the number of days that exceed 50 cfs were also tabulated and are presented in Table 6.5. These data demonstrate that the yearly median vary substantially (anywhere from 32% to 67% of the year.

In order to determine if the median flows are significantly impacted by rainfall, the daily rainfall and the 3-day moving average rainfall that occurs when the daily flow at Heights is less than the median were compiled for three different locations in Whiteoak Bayou. It should be noted that at median flow (Q=50 cfs at Heights), the travel time in WOB is 3 days. Thus, three days is a

reasonable window to examine. The results are presented in Table 6.6 and Table 6.7. From the data, it appears that very little rainfall occurs on days when the flow in WOB is less than 50 cfs, with an average rainfall in the upstream part of the watershed at 0.002 inches and a three-day moving average of 0.01 inches of precipitation. Rainfalls as large as 0.2 inches can occur above or near the gage while the flows are below 50 cfs, although the maximum rainfall in the watershed below the gage was much higher. This analysis indicates that minimal rainfall occurs on days when the flow is less than 50 cfs, and thus the approximate median flow might be an adequate definition of a "dry weather" condition.

Table 6.5
Median Flows and Days Exceeding 50 cfs over past 10 years

Year	Median	# Days > 50 cfs	% of Year
1990	40	239	65%
1991	52	180	49%
1992	68	118	32%
1993	53	165	45%
1994	47	205	56%
1995	44	220	60%
1996	42	219	60%
1997	57	157	43%
1998	46	218	60%
1999	42	245	67%
		Max:	67%
		Min:	32%

Table 6.6
Rainfall (in) when flow in Whiteoak Bayou is less than 50 cfs

	At the Gage (Heights)	Upper Watershed (Brickhouse Gully)	Lower Watershed (BB @ Milam)
Min	0	0	0
Max	0.2362	0.1181	4.5670
Avg	0.0035	0.0019	0.0533
Median	0	0	0

Table 6.7
3-Day Moving Average of Rainfall (in) when flow is less than 50 cfs

	At the Gage (Heights)	Upper Watershed (Brickhouse Gully)	Lower Watershed (BB @ Milam)
Min	0	0	0
Max	0.9055	0.6431	1.5223
Avg	0.0163	0.0110	0.0592
Median	0	0	0

6.4 PROPOSED DRY WEATHER CONDITION

The existing water quality criteria were developed from epidemiological data for swimming at public beaches during good weather conditions. The primary measures of swimming related illness were gastroenteritis and eye and ear infections, all associated with full body contact and water ingestion.

The two watersheds in question behave quite differently. The flow in Buffalo Bayou is strongly influenced by the upstream Addicks and Barker Reservoirs. Buffalo Bayou is also unchannelized. Whiteoak Bayou, on the other hand, is channelized all along the length of the main stem and is concrete lined in the lower half of the watershed. This channelization causes water to move quickly through the system.

Based upon the analyses presented, there appears to be two possible methods of selecting "dry weather" or "low flow" conditions, either based upon the flow in the bayou or precipitation in the watershed. It is possible that a flow-based criteria cannot be a valid measure of the absence of runoff introducted bacteria, simply because localized rain events can introduce substantial bacterial levels without increasing the flow above the selected level. Some of the analyses in this chapter suggest that a lack of significant rainfall in the upstream watershed is a workable approximation of a dry weather condition. At the same time, other analyses suggest that the median flow or a similar measure is an appropriate condition because only very small rainfall events (less than 0.1 in) typically occur while the median flow is maintained in the stream. Possibly, the best dry weather condition is a combination of both lower flow and no rainfall.

The models developed in this TMDL are currently being used to evaluate standard possible attainment strategies for "low flow" conditions. However, it is noted that there is the fundamental issue of whether a swimming-based criterion is appropriate for an urban bayou comprised primarily of treated wastewater. The level of wastewater treatment today is high and for most parameters, the quality of effluent is better than that of the receiving stream.

There is a strong move in more arid parts of the state to promote the beneficial reuse of wastewater for irrigation in part due to this high level of wastewater treatment. However, to date, no one has seriously proposed the use of treated wastewater for filling swimming pools or other types of direct contact recreation. It is very doubtful that a use attainability analysis, as recommended by the National Research Council (2001) in its review of the TMDL program, would find that the waters of BB and WOB suitable for the contact recreation without significant decreases in the bacteria concentrations. The bayou waters, however, may be suitable for boating and other activities that involve incidental contact and a criterion could be established for this type of use. There is precedent for such a criterion but the epidemiological data to support the criteria development have not been collected thus far. The precedent is for a "non-contact" recreation standard that has been historically set at ten times the contact or swimming criterion.

CHAPTER 7

HSPF MODELING

Two models were developed in the previous work order for Buffalo and Whiteoak Bayou. These models were developed for the period from April 1, 1999 through September 30, 2001 and were calibrated using observed data from this period. This chapter provides an overview of the bacteria models and details some adjustments that were made to the models to better reflect observed conditions.

This chapter also details the results of sensitivity analysis for the sediment and nonpoint source parameters in the model. These data provide insight into the important processes in the model that cause the greatest impact on model results.

7.1 WHITEOAK BAYOU MODELING

Calibration efforts continued for the Whiteoak Bayou model during Work Order 5, with an emphasis being placed on matching observed concentrations rather than observed loads. The concentrations were determined to be the primary calibration parameter as the target criteria for concentration. Loads are secondary because concentration data were available in more locations throughout the watershed while loads could only be calculated at locations where a flow gage is available. The WO5 bacteria calibration results are presented in Table 7.1. The model calibration

is improved with respect to the concentrations, but the loads are not matched as well relative to the WO2 results.

A longitudinal plot of geometric mean concentrations over the entire model simulation period is presented in Figure 7.1. The observed concentrations for the two-and-one-half year model simulation period are also presented on this figure with error bars representing the 95% confidence interval for each geometric mean. As can be seen in this figure, the modeled data fit the observed concentrations relatively well, with the calibrated line falling within the 95% confidence interval for almost all observed points. As with the Work Order 2 calibrated model, the elimination of the bacteria associated with wastewater treatment plants and the dry weather storm sewer flows has very little effect on the concentrations observed in the bayou over the two and a half year model period. Measurements of these sources indicated they were minor. The elimination of non-point source loads used to calibrate the model brings the simulated concentrations very close to the water quality standard.

Table 7.1 Water Quality Summary and Model Performance for Whiteoak Bayou.

Comparison of Hourly Bacteria Loading[1]						
	Heights			Cole Creek		
	Modeled	Observed	Error	Modeled	Observed	Error
Overall Load	3.95E+15	2.98E+14	1225%	7.80E+12	9.71E+12	-20%
High Flow Load [2]	3.44E+15	2.32E+14	1382%	7.34E+12	1.03E+13	-28%
Low Flow Load [3]	3.33E+13	2.08E+13	60%	1.76E+11	2.16E+11	-19%
AUC - Total Loading [4]	7.42E+19	5.72E+18	1197%	1.58E+14	1.98E+14	-21%

Comparison of Geomean Concentrations[1]						
	West 43rd			Little Whiteoak		
	Modeled	Observed	Error	Modeled	Observed	Error
Overall GM	1231.14	757.26	63%	2507.21	4042.04	-38%
High Flow GM [2]	14022.90	914.91	1433%	75264.15	40197.91	87%
Low Flow GM [3]	390.84	409.81	-5%	483.00	2639.53	-82%
AUC - of log data	1393.17	1302.40	7%	4723.73	5025.05	-6%
	Heights			Cole Creek		
	Modeled	Observed	Error	Modeled	Observed	Error
Overall GM	2785.49	2955.78	-6%	146.91	1846.02	-92%
High Flow GM [2]	138362.48	17450.43	693%	7467.83	22988.61	-68%
Low Flow GM [3]	397.21	1733.99	-77%	50.51	773.08	-93%
AUC - of log data	2844.73	3051.41	-7%	2123.24	2945.28	-28%

[1] Modeled values calculated only when an observed data point available.

[2] High flow was considered to be greater than approximately the 80th percentile of the modeled data.

[3] Low flow was considered to be less than approximately the median of the modeled data.

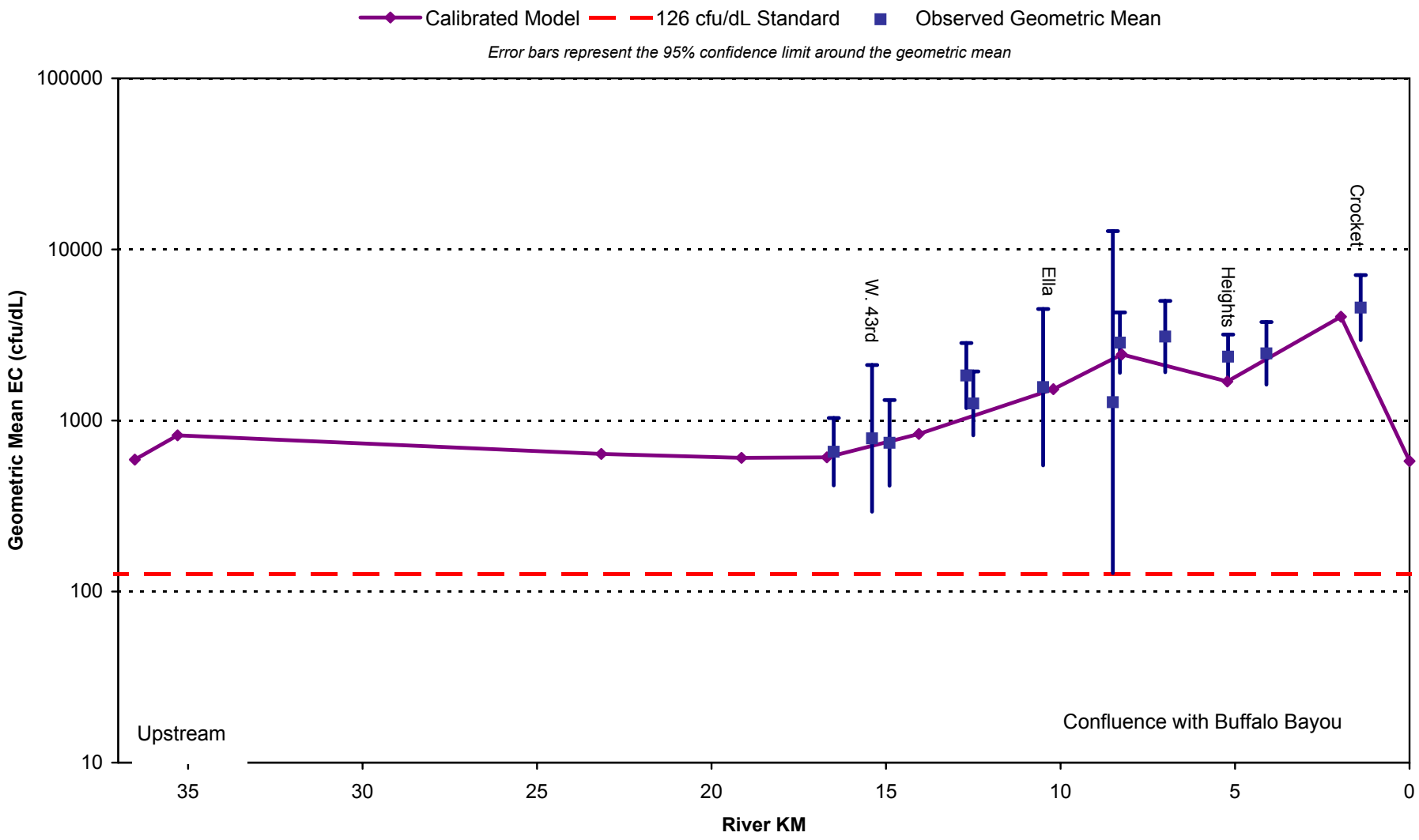


Figure 7.1 Model Output presented Longitudinally Along Whiteoak Bayou

7.2 BUFFALO BAYOU MODELING

The HSPF model presented in Work Order 2 for Buffalo Bayou was also modified during Work Order 5. The Buffalo Bayou model was refined to use the two upstream reservoirs as upstream boundary conditions. Reservoir flows were included in the model as a point source. This refinement was completed to better characterize the impact of the reservoirs on the EC concentrations in Buffalo Bayou and to better represent bacteria sources between the reservoirs and Dairy Ashford. The two models for Buffalo and Whiteoak Bayou were also examined to ensure that physical parameter values were consistent between the two watersheds, when appropriate. This analysis resulted in some modifications to the density of sediment in the model as well to the settling velocities, which are a function of sediment density.

To build the EC input time-series for the Barker Reservoir, two different approaches were undertaken. The first approach was to correlate the historical flows at Dairy Ashford with FC data from Highway 6. This approach, however, was not used due to the low correlation coefficient (see Figure 7.2).

The second approach undertaken was to correlate FC data at Barker Reservoir with the FC concentrations at Highway 6 to obtain a linear regression as shown in Figure 7.3. Three outliers were identified and removed from the data set to obtain a linear equation. As there were no data from the Barker Reservoir for the model simulation period, the regression could be used to obtain FC concentrations using the Highway 6 data available during the simulation period. The resultant FC concentrations were transformed to EC concentrations by multiplying by 0.63 (126/200). The final

model input used the concentrations calculated using this approach and assuming the time-series followed a step function (Figure 7.4).

Other methods were also investigated for use in the calibration, including performing linear regression between the data points predicted by the regression equation developed in the second approach described above as well as assuming a constant value for the entire series equal to the geometric mean of the historical data at Barker reservoir. However, the step function method presented in Figure 7.4 was used because it provided the best calibration fit. For the Addicks Reservoir, the outflow EC concentration was assumed constant and equal to the mean concentration from historical data (transformed to EC using the factor 126/200). This value was 465 MPN/dL.

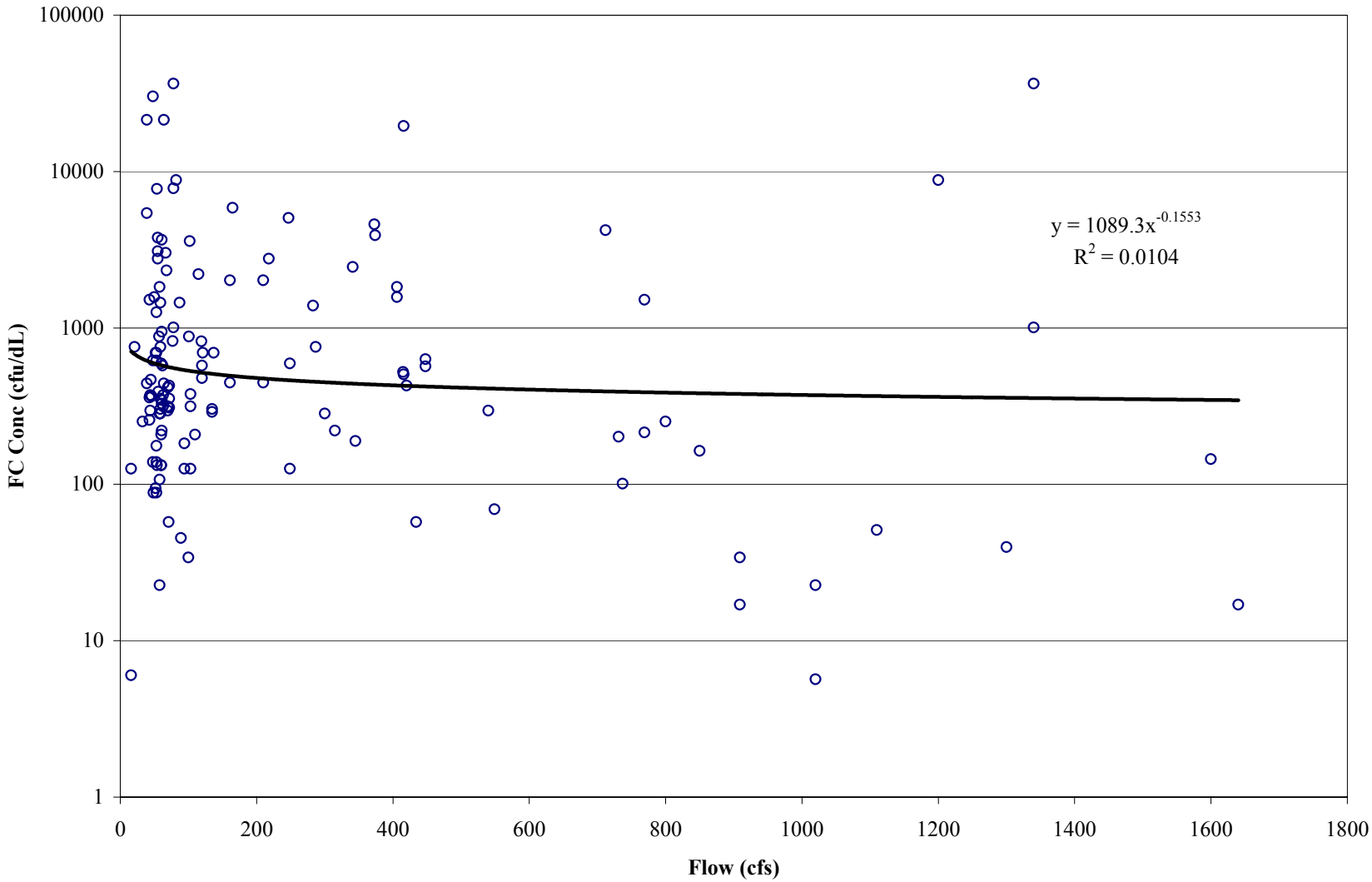


Figure 7.2 Relationship between Dairy Ashford Flow and FC at Highway 6

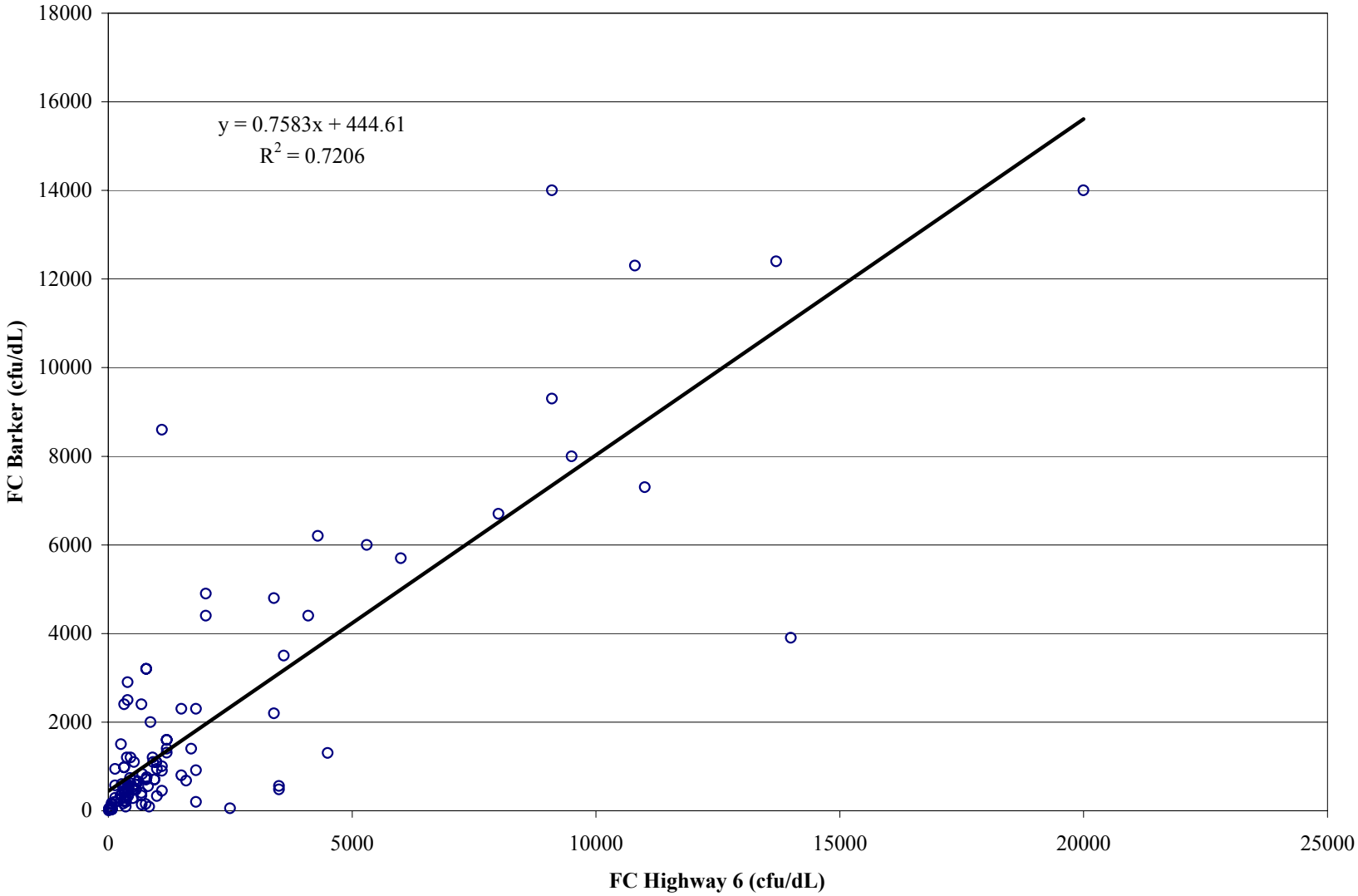


Figure 7.3. Relationship between FC at Highway 6 and Barker.

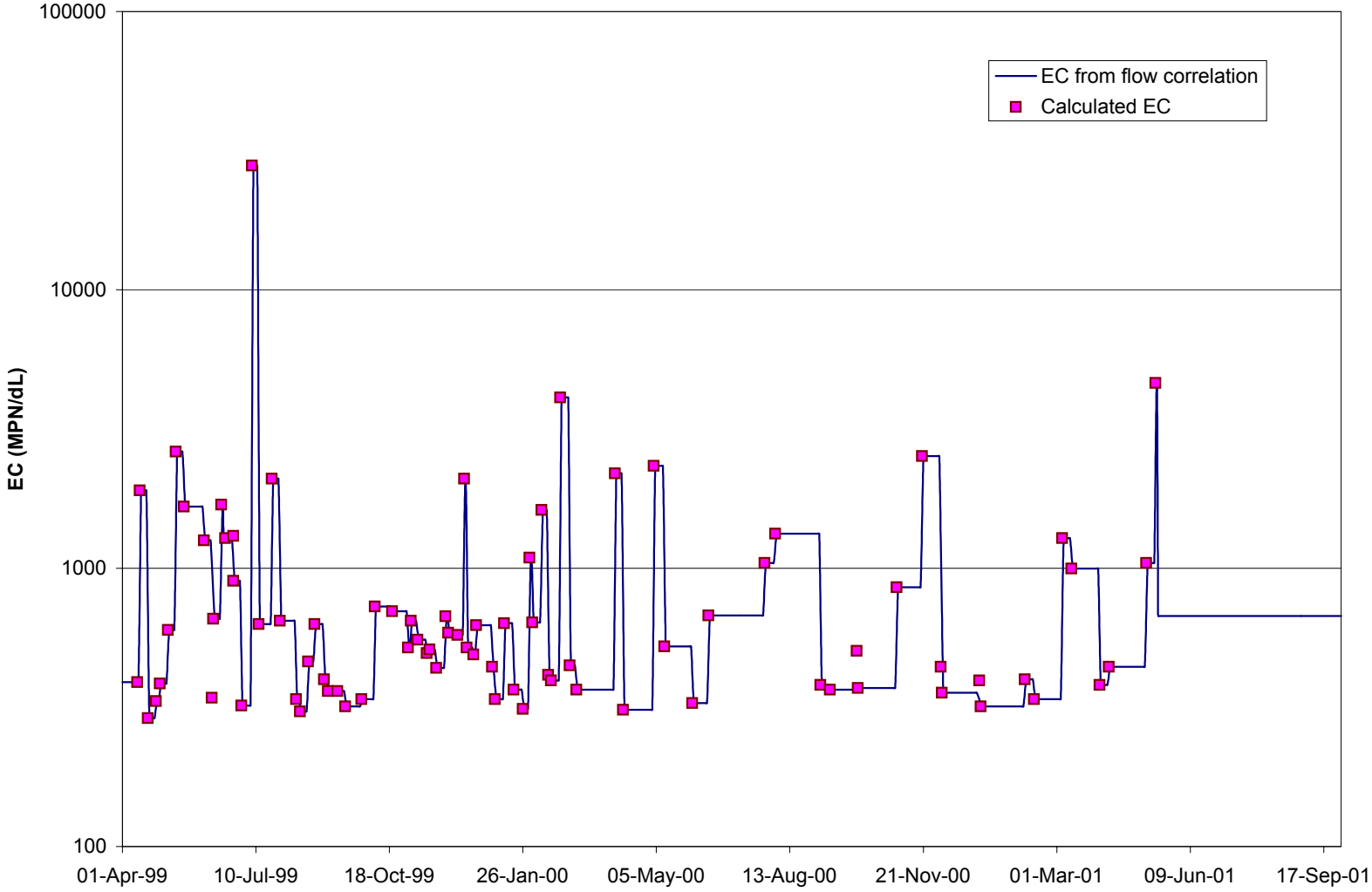


Figure 7.4 Barker Reservoir EC Input

A summary and assessment of model performance for Buffalo Bayou hydrology is presented in Table 7.2. It is clear from this table that the model fit is quite good, although the observed flows at the Shepherd gage appear to be somewhat underestimated. The West Belt gage site shows the overall best fit, followed by the Piney Point gage. The model is over predicting the lowest flows at all sites except Shepherd. The fit of the modeled storm volumes to the observed storm volumes are also quite good, with the largest error of 20% occurring at Shepherd. One reason why the Shepherd gage may demonstrate larger errors than the other three gages is that it only records flow values around 100 cfs or higher, thus the observed flow data are discontinuous and are heavily weighted toward storm events. Therefore, although the Shepherd gage has the poorest fit for flow, the results are considered acceptable for the purposes of this model.

Table 7.2. Hydrology Summary and Model Performance for Buffalo Bayou

Data Source	Location	Total Volume	90th Percentile Flow	10th Percentile Flow	Storm Volume[2]	Summer Volume
Observed	Dairy Ashford	3.96E+05	58.8	2.7	7.74E+04	9.45E+04
	West Belt	4.84E+05	72.6	3.8	9.79E+04	1.19E+05
	Piney Point	5.19E+05	75.4	4.8	1.05E+05	1.32E+05
	Shepherd[4]	4.69E+05	207.6	93.4	1.08E+05	1.15E+05
Modeled	Dairy Ashford	4.53E+05	57.0	4.3	8.73E+04	1.09E+05
	West Belt	4.84E+05	61.8	4.7	9.34E+04	1.17E+05
	Piney Point	5.52E+05	73.7	6.0	1.06E+05	1.35E+05
	Shepherd[4]	3.62E+05	172.0	55.8	8.64E+04	1.68E+05
Error[3]	Dairy Ashford	14%	-3%	59%	13%	15%
	West Belt	0%	-15%	24%	-5%	-2%
	Piney Point	6%	-2%	24%	1%	2%
	Shepherd[4]	-23%	-17%	-40%	-20%	46%

Notes:

[1] Volumes are in acre-ft/simulation period

[2] Storm values calculated as total flow following the storms (from the first precipitation to when the flow returns to pre-stor conditions):

07/17/1999 12/08/1999 01/08/2000 01/27/2000 02/07/2000 04/02/2000 07/23/2000

09/12/2000 11/05/2000 12/12/2000 03/14/2001 04/16/2001 05/26/2001 07/26/2001 08/06/2001

[3] Error percentage calculated as (Model Value - USGS Value) / USGS Value, 0% indicated perfect match

[4] Flow statistics compiled for Shepherd gage only when observed flow available

Several different plots were prepared to assess the fit of the modeled flows to the observed flows. The cumulative probability distribution function for flow is presented for all four Buffalo Bayou calibration sites in Figure 7.5. The graphs in Figure 7.5 show that overall, the model is over predicting during low flows at the Dairy Ashford and Piney Point locations, while underestimating at the West Belt and Shepherd locations. The flows above the 80th percentile, however, are matched very well at Dairy Ashford and Piney Point.

Figure 7.6 presents a plot of the simulated flow versus the observed flow for all four calibration sites in Buffalo Bayou. Overall, the fits are very good with the R^2 at Dairy Ashford, West Belt and Piney Point being greater than 0.8 and the slopes of the regression equation being quite close to that of the line of equality. The plot for Shepherd only contains values from the model where an observed value was also available. The R^2 at Shepherd is lower, only 0.557, but this is still considered a good fit since some of the observed values at lower flows are estimated and not measured.

A plot of the model output at each of the four flow calibration gages in Buffalo Bayou is shown in Figure 7.7 for the entire period of the model simulation. As previously mentioned, the flows at the Shepherd station below 100 cfs are estimated and therefore the data in the figure are quite sparse. The plots demonstrate that overall the modeled flows match the observed flows quite well with some model overestimation during very low flow events.

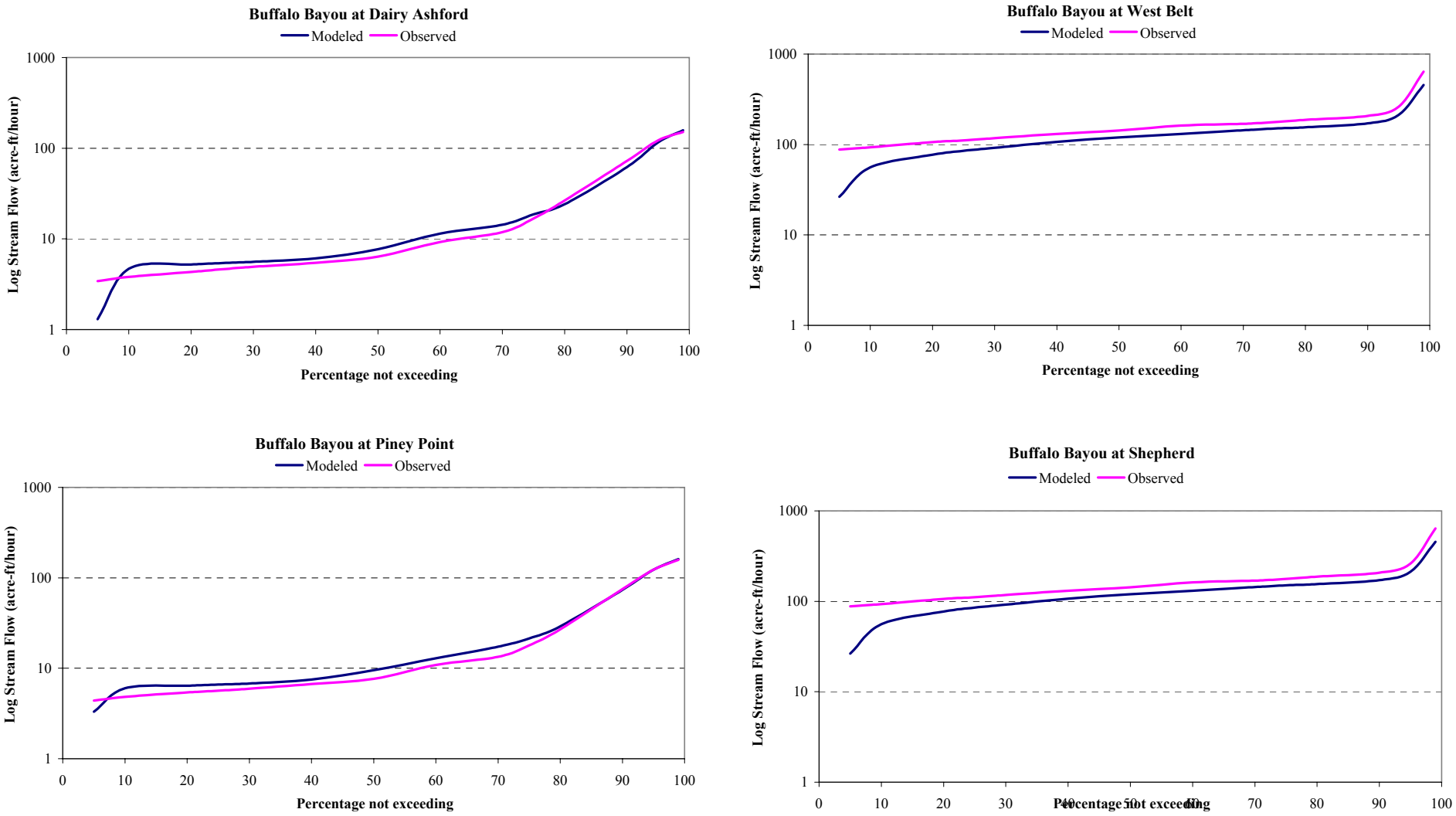


Figure 7.5 Cumulative flow frequency curves for simulated and observed flows in Buffalo Bayou

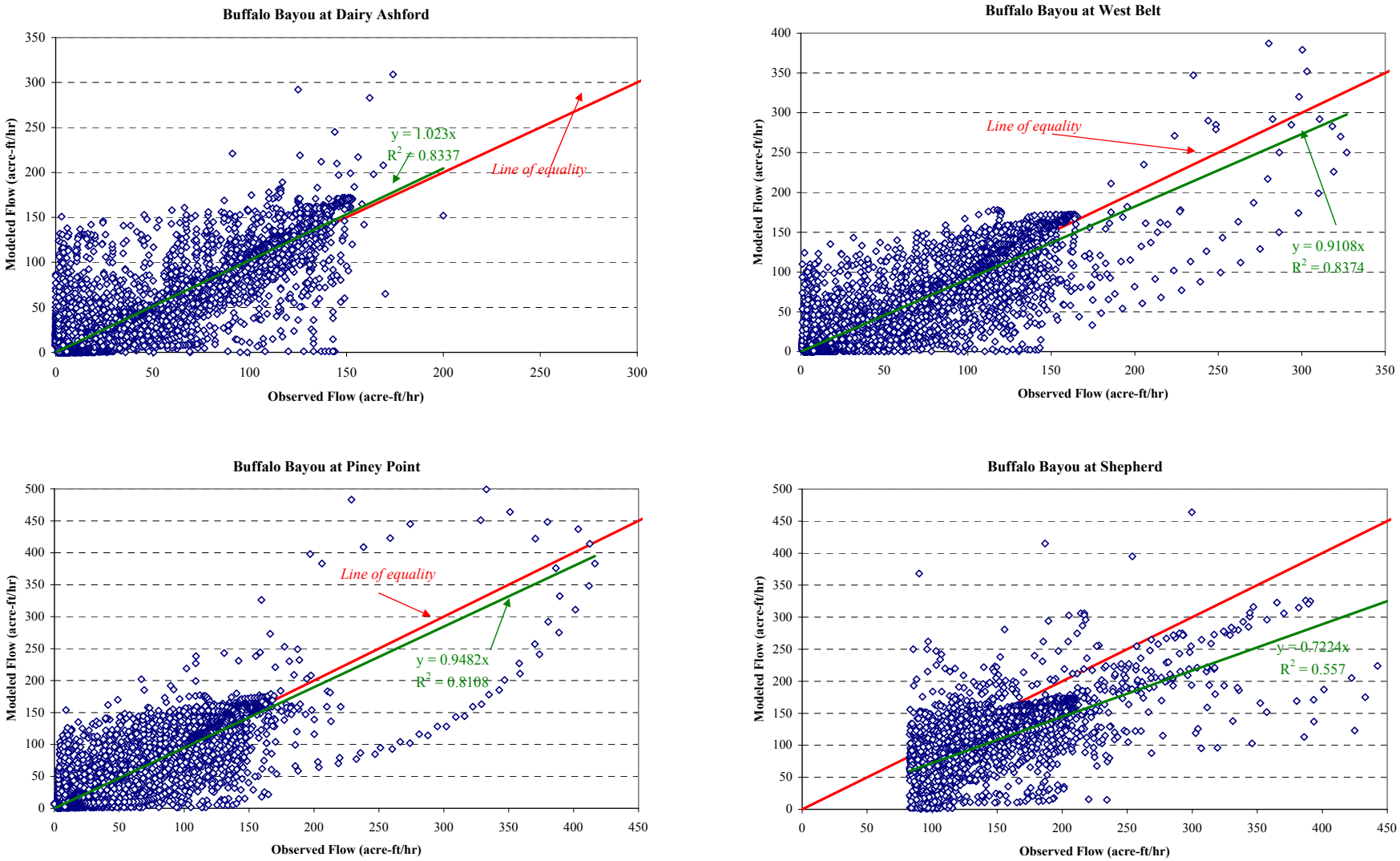


Figure 7.6 Comparison of observed and Simulated flows in Buffalo Bayou

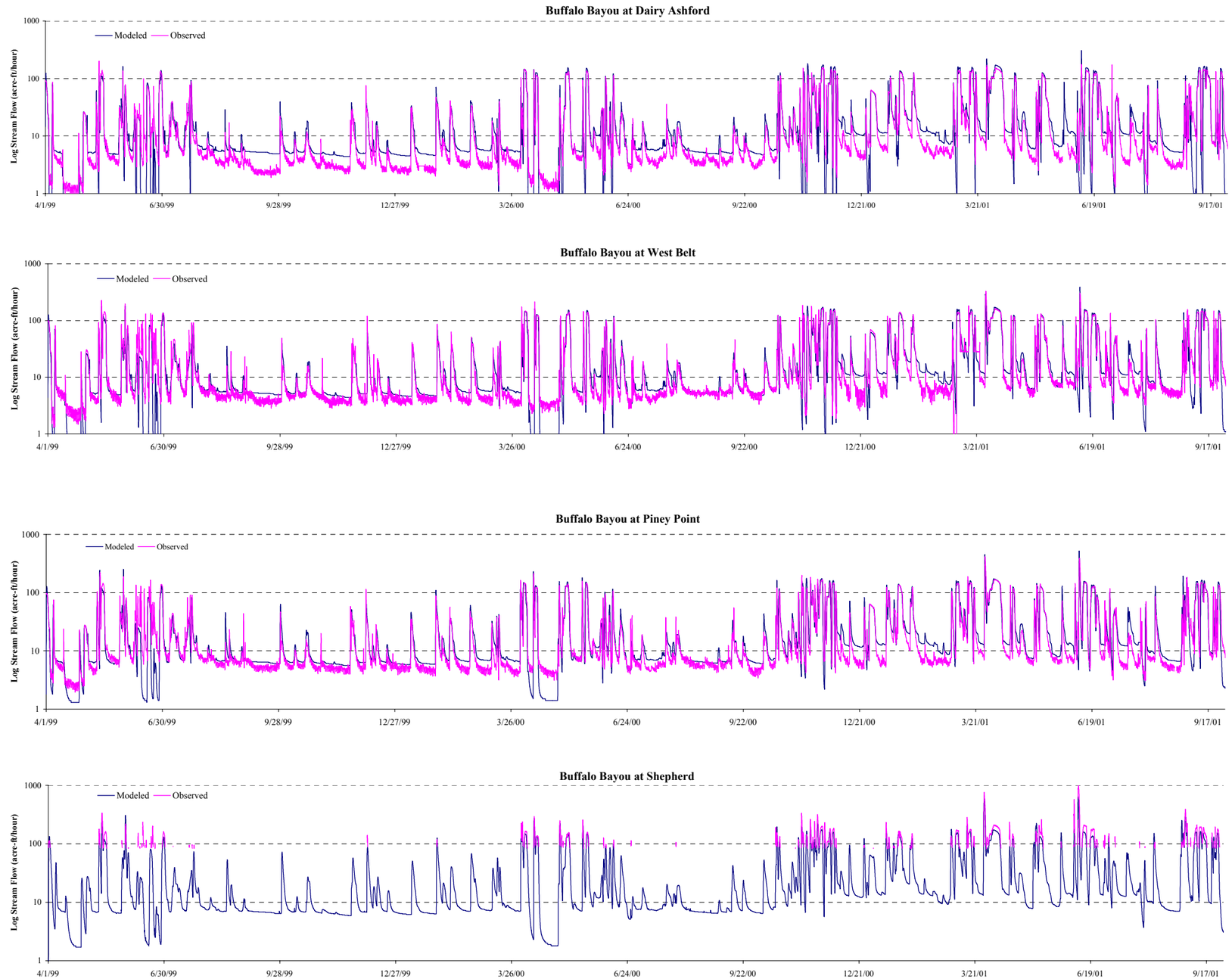


Figure 7.7 Model and Simulated Flows at Buffalo Bayou Hydrology Calibration Locations.

The bacteria data for Buffalo Bayou were also simulated. Table 7.3 presents the modeled results for EC at eight different calibration gages along Buffalo Bayou. These calibration sites include Highway 6, Eldridge, Dairy Ashford, West Belt, Briar Forest, Voss, Chimney Rock, and Shepherd. The model overall geometric mean at seven of the stations fit the observed data well; the only possible exception occurring at Voss with the model underestimating the observed geometric mean by 42%. The concentrations of EC during high flow conditions are generally over predicted by the model. The low flow (flows less than or equal to the 20th percentile) geometric mean concentrations predicted by the model are underestimating the observed geometric means at West Belt, Voss and Shepherd and overestimating the observed geometric means at all other calibration locations.

Figures 7.8(A) and 7.8(B) present the observed EC versus simulated EC in Buffalo Bayou at the eight stations. The data points are distributed fairly evenly around the line of equality, therefore indicating that no clear overestimation or underestimation of observed data occurring at these locations.

Figures 7.9(A) through 7.9(D) show observed EC along with model output for all eight locations in Buffalo Bayou for the entire model simulation period. The plot for Highway 6 in Figure 7.9(A) demonstrates that the model is matching the observed data very well. There are some occasions when the model is over predicting the observed EC data, such as at Dairy Ashford in April 2001. Generally, though, the model is matching the extremes of the data well.

Table 7.3. Water Quality Summary and Model Performance for Buffalo Bayou

	Highway 6			Eldridge			Dairy Ashford			West Belt		
	Observed	**Modeled**	**Error**	**Observed**	**Modeled**	**Error**	**Observed**	**Modeled**	**Error**	**Observed**	**Modeled**	**Error**
Overall GM	369.13	363.95	-1%	567.54	555.90	-2%	685.09	594.09	-13%	1178.37	756.65	-36%
High Flow GM [2]	987.29	1552.90	57%	977.54	1429.50	46%	1192.33	684.56	-43%	2708.21	2659.50	-2%
Low Flow GM [3]	341.81	12.80	-96%	270.63	543.92	101%	521.73	397.40	-24%	869.46	860.48	-1%
Flow > median GM	628.06	1029.60	64%	1328.24	851.23	-36%	1562.25	1137.68	-27%	1994.51	1245.97	-38%
Flow < median GM	226.99	137.68	-39%	264.03	378.83	43%	412.52	398.30	-3%	786.66	515.90	-34%
Load[4]							9.166E+12	1.958E+13	114%	2.009E+13	4.293E+13	114%

	Briar Forest			Voss			Chimney Rock			Shepherd		
	Observed	**Modeled**	**Error**	**Observed**	**Modeled**	**Error**	**Observed**	**Modeled**	**Error**	**Observed**	**Modeled**	**Error**
Overall GM	746.69	629.14	-16%	1186.39	726.61	-39%	1062.08	1160.64	9%	2355.19	2247.53	-5%
High Flow GM [2]	965.05	1192.36	24%	2059.09	7880.86	283%	1699.38	3231.26	90%	2700.24	7351.07	172%
Low Flow GM [3]	261.29	317.35	21%	925.73	203.81	-78%	224.05	440.85	97%	2563.62	1023.04	-60%
Flow > median GM	1307.99	982.27	-25%	1676.86	2419.38	44%	2483.77	3480.05	40%	2682.90	6867.78	156%
Flow < median GM	547.58	476.83	-13%	846.16	224.42	-73%	454.15	387.09	-15%	2139.62	986.86	-54%
Load[4]	2.510E+13	4.911E+12	-80%							4.725E+13	2.185E+14	362%

[1] Concentrations are geomean of all concentrations where an observed data point is available.

[2] High flow was considered to be greater than approximately the 80th percentile of the modeled data.

[3] Low flow was considered to be less than approximately the 20th percentile of the modeled data.

[4] Loads were calculated only for the stations with observed flow data

Error percentage calculated as (Modeled - Observed) / Observed, 0% indicates perfect match

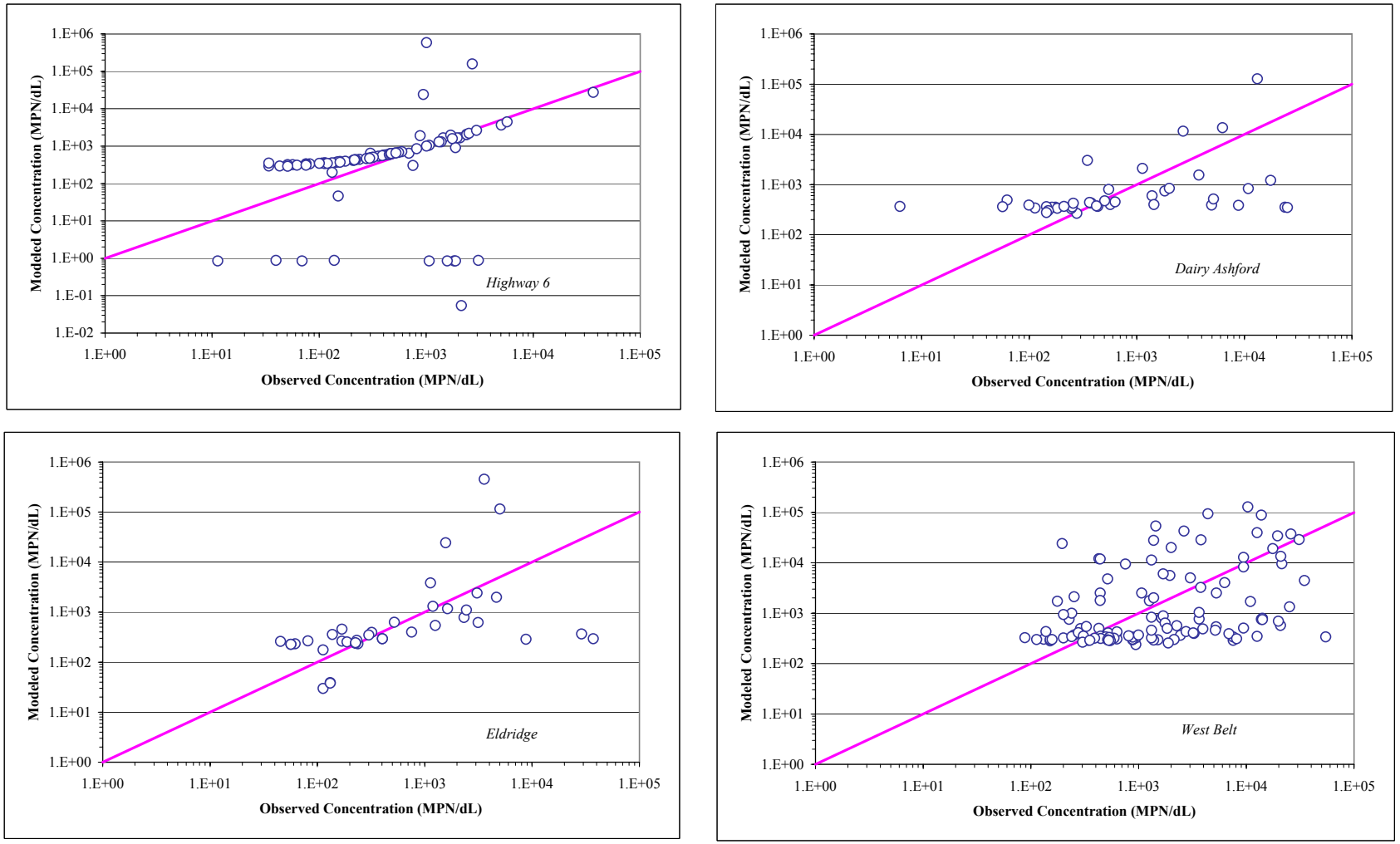


Figure 7.8(A) Model versus Observed EC Concentrations in Buffalo Bayou.

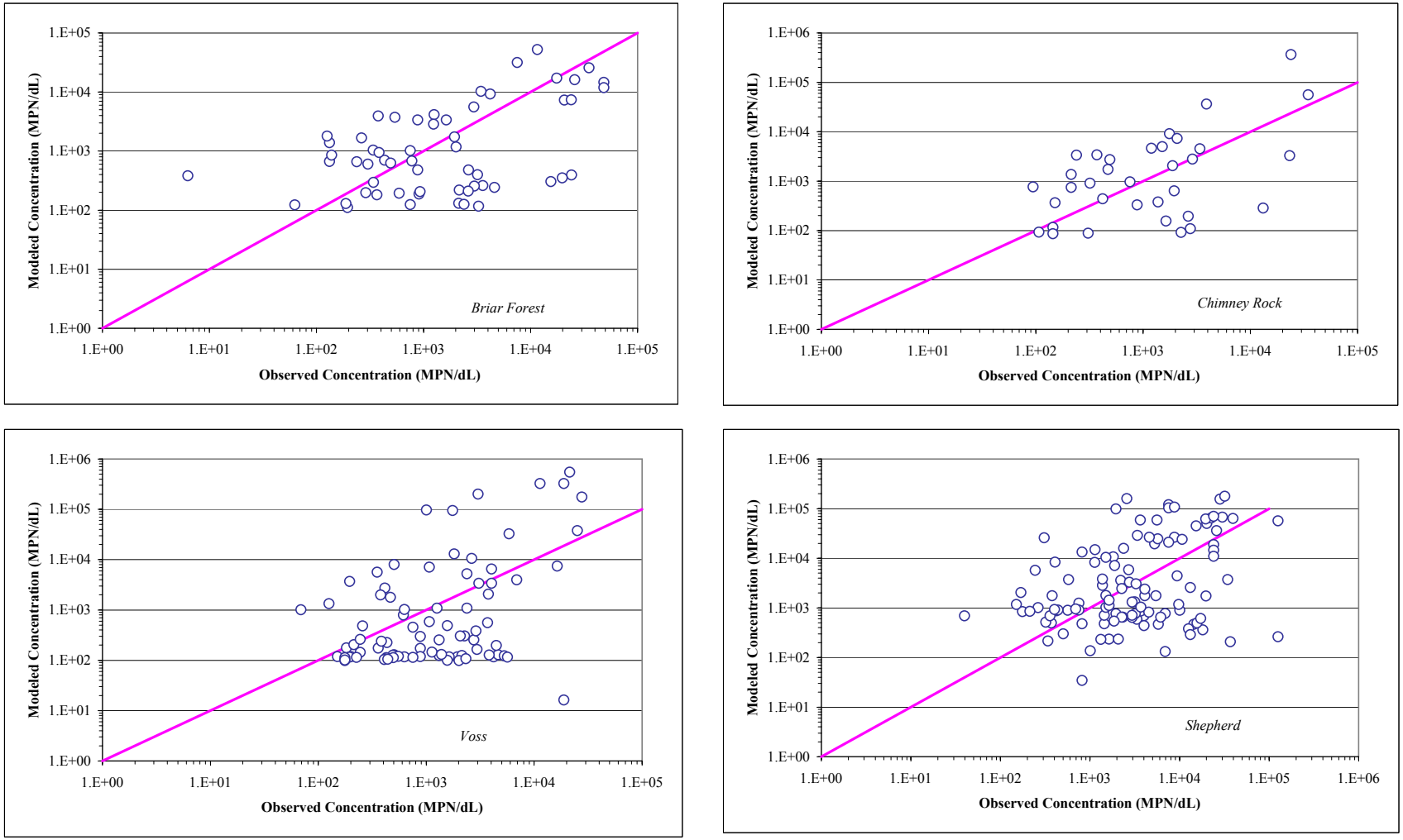
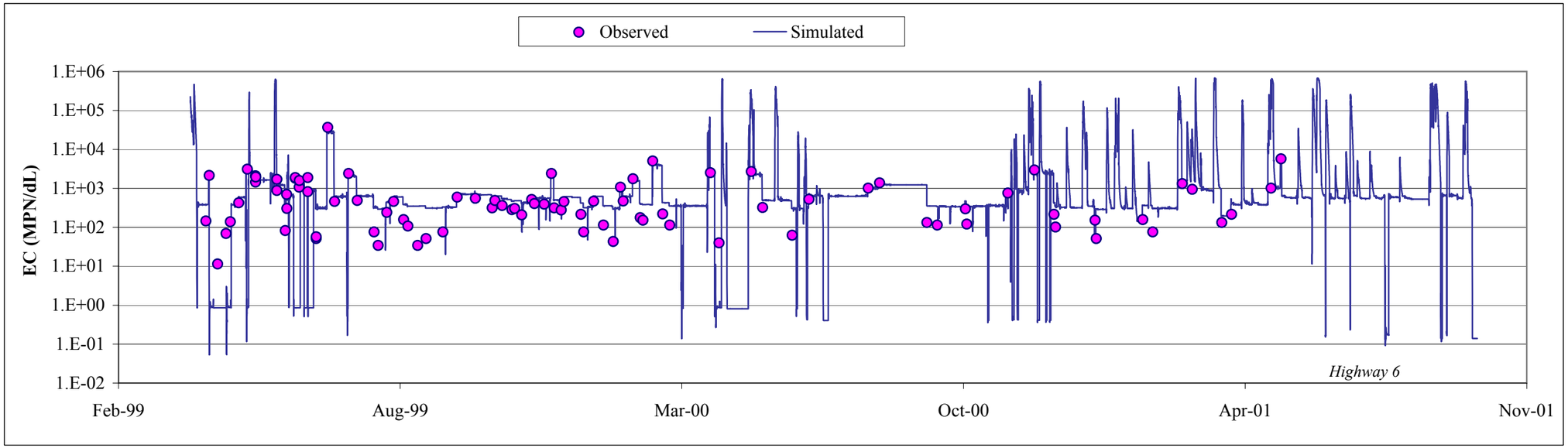


Figure 7.8(B) Model versus Observed EC Concentrations in Buffalo Bayou.



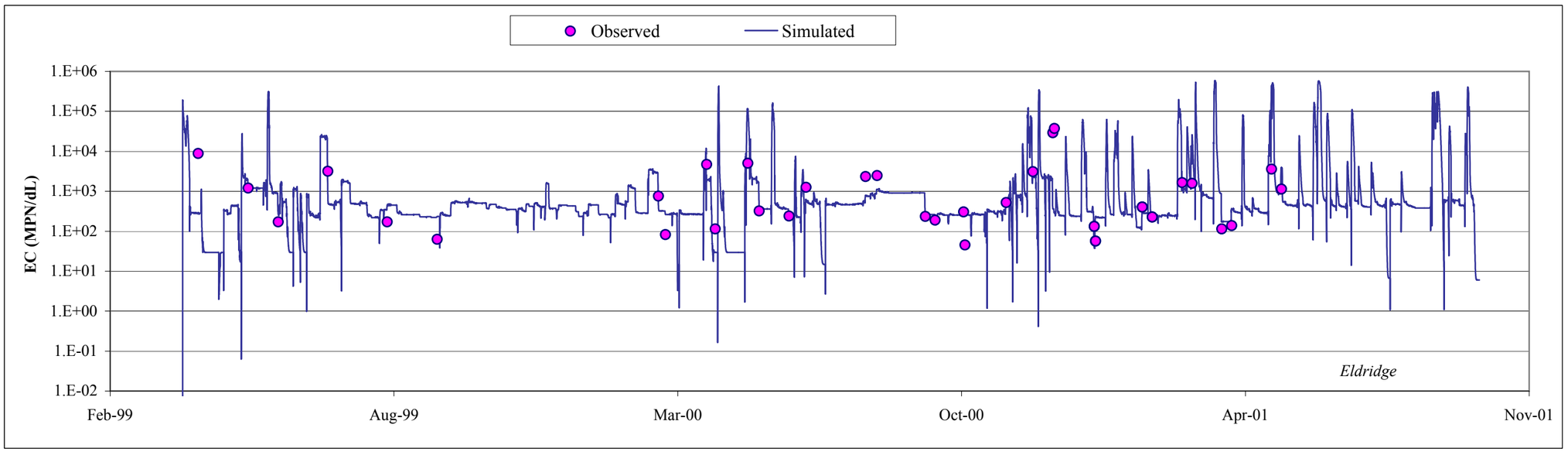
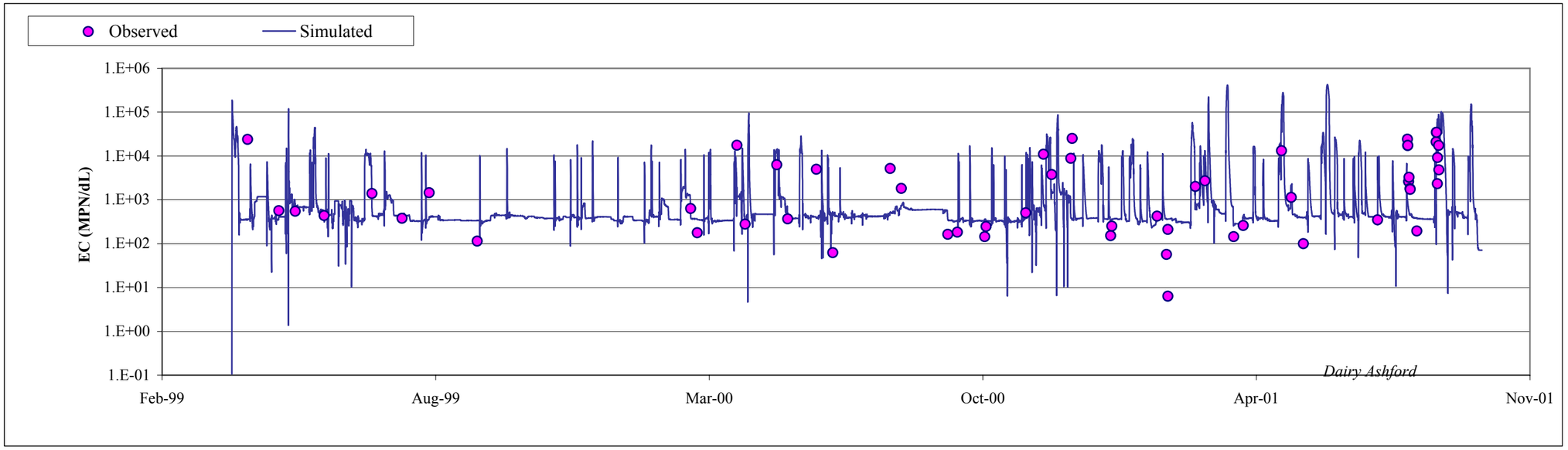


Figure 7.9(A). Model and Observed EC concentrations over Entire Simulation Period.



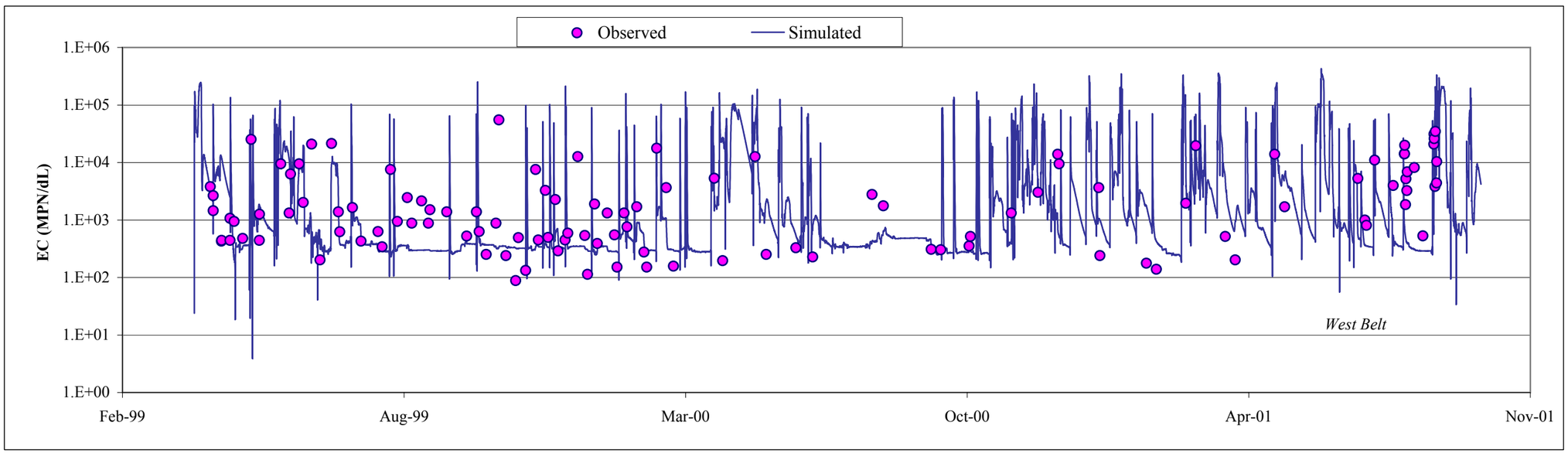
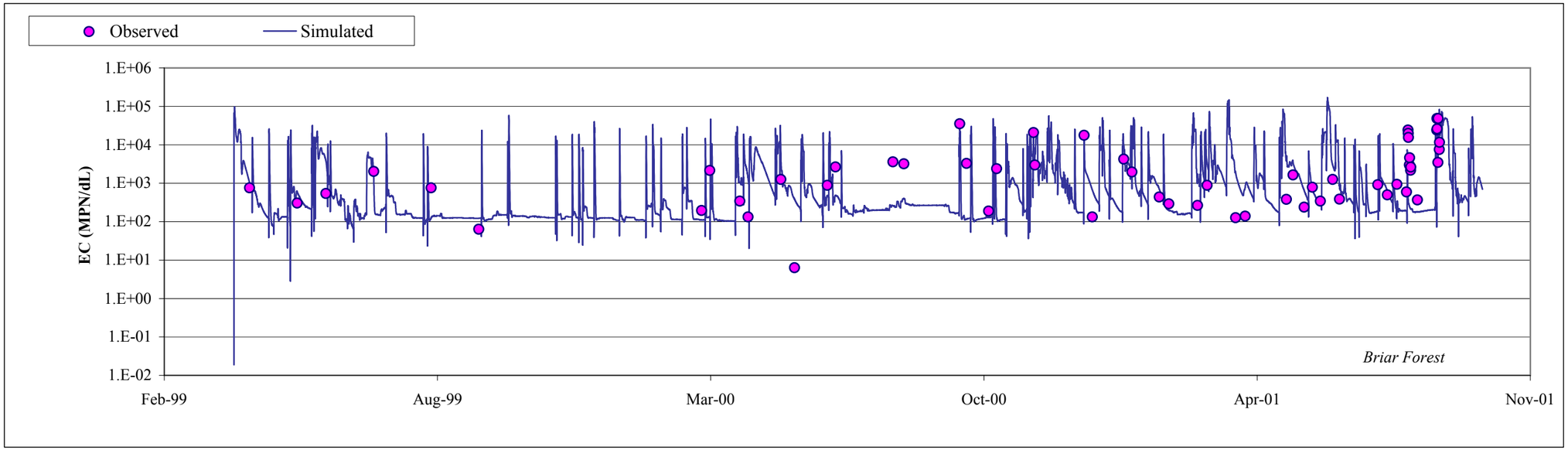


Figure 7.9(B). Model and Observed EC concentrations over Entire Simulation Period.



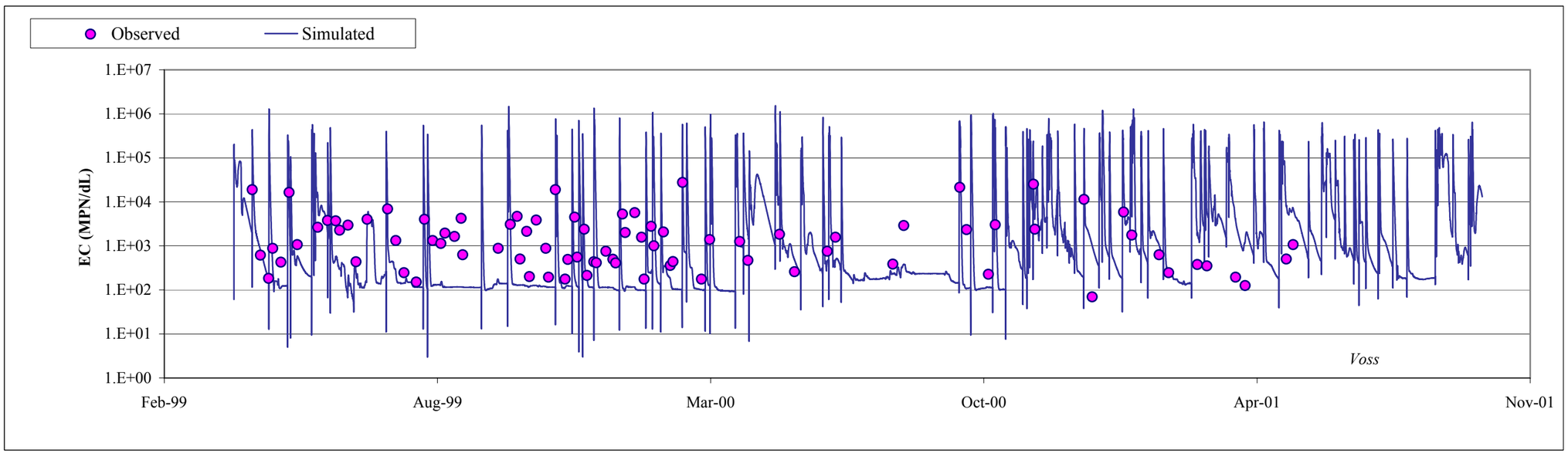


Figure 7.9(C). Model and Observed EC concentrations over Entire Simulation Period.

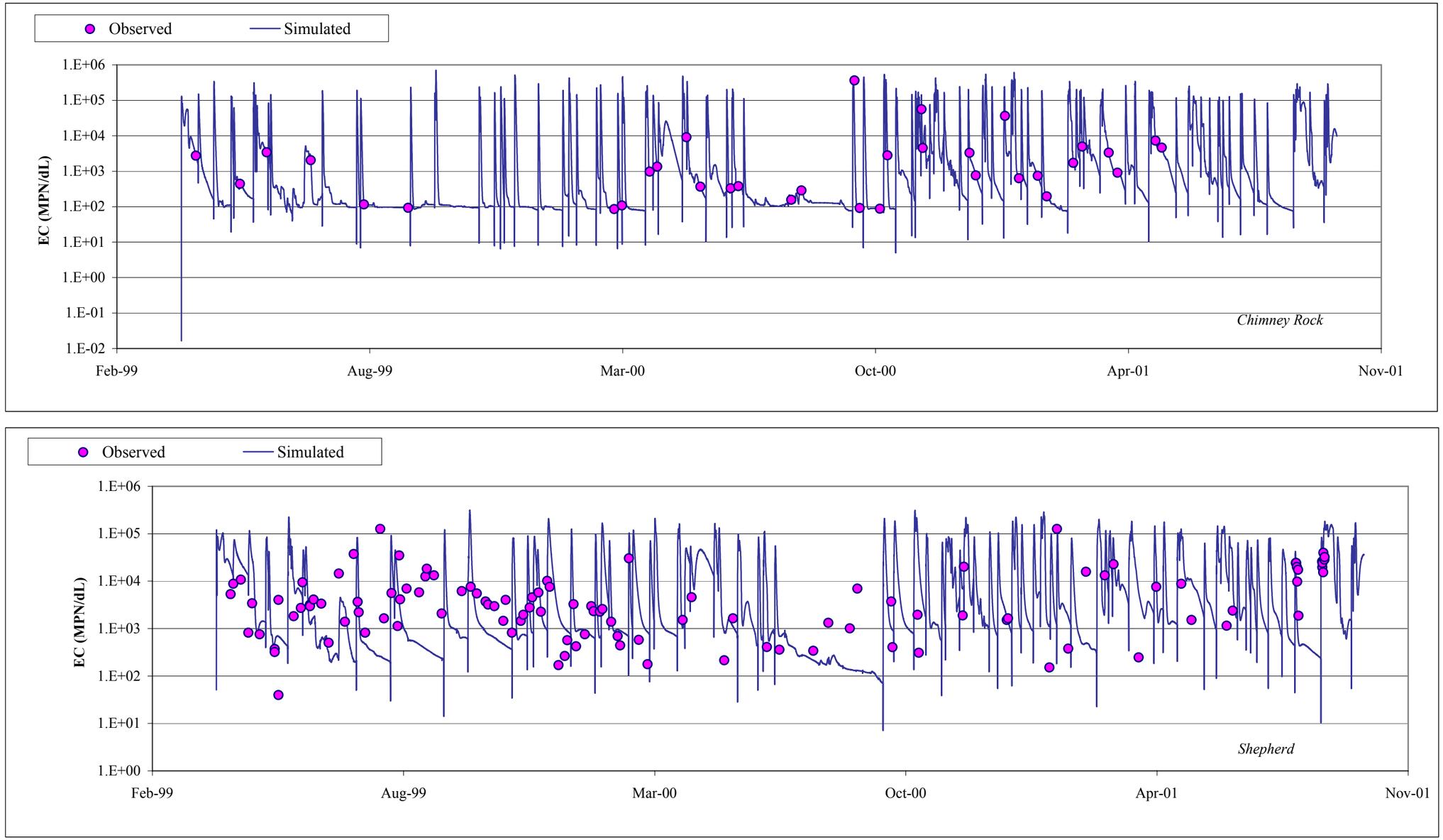
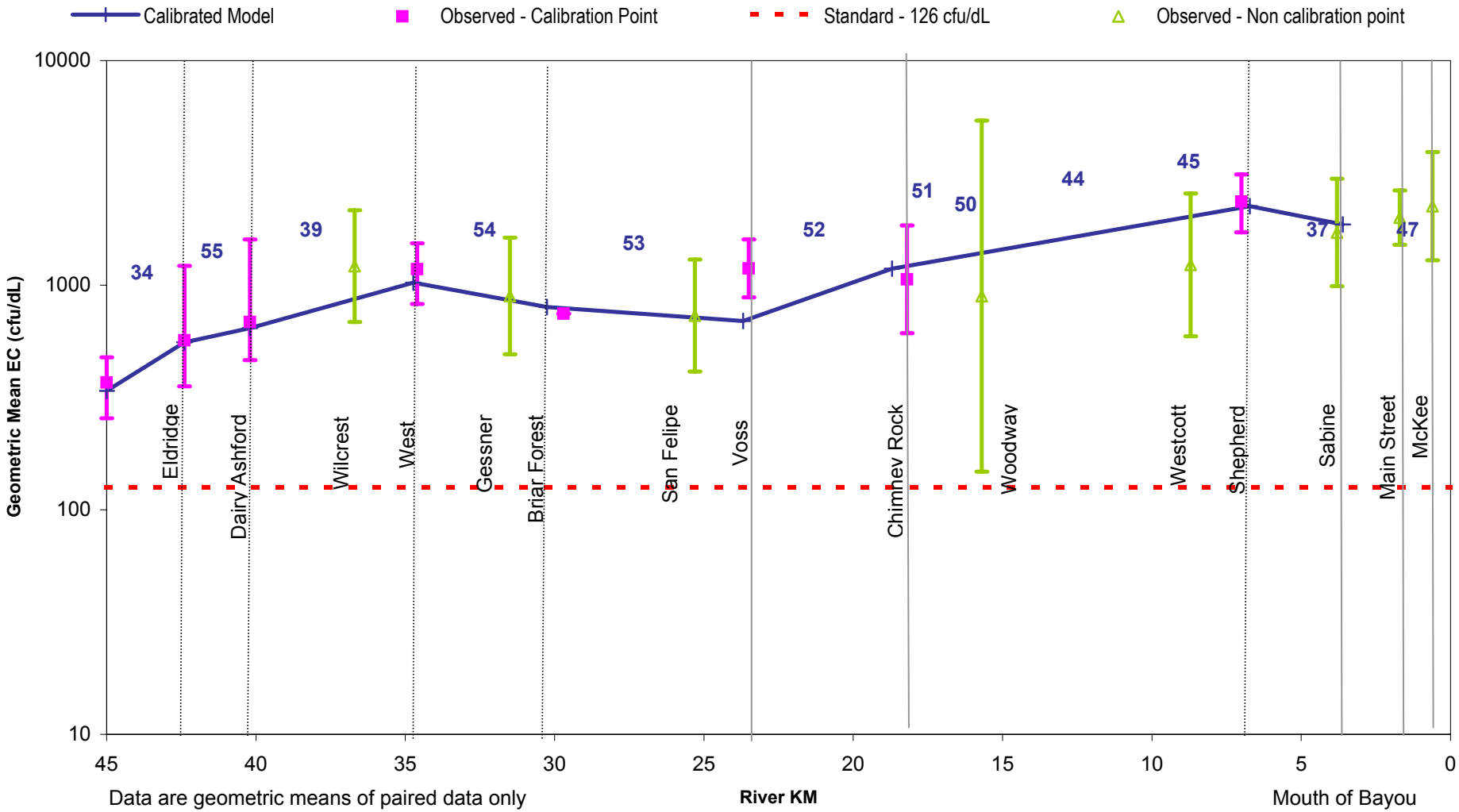


Figure 7.9(D). Model and Observed EC concentrations over Entire Simulation Period.

The fit of the model longitudinally along the bayou is presented in Figure 7.10. The model matches the spatial variation along the bayou that is present in the observed data quite well. Some points, indicated as "Observed-Non Calibration" on the figure, were not used for calibration. There are two primary reasons for this. At several stations, there were very few observed data points and thus the level of certainty associated with the data was deemed inadequate for model calibration. Another reason was that some sites were located in the middle of a subwatershed, and model results are obtained at subwatershed outlets only.

Figure 7.10 Model Calibration presented Longitudinally Along Buffalo Bayou



7.3 SEDIMENT SENSITIVITY ANALYSIS

Model sensitivity to changes in sediment parameters was assessed by multiplying and dividing the parameters by a set value of 10. The value of 10 was chosen arbitrarily and may cause some parameters to extend outside the range of acceptable values, but the results still provide an indication of the impact of such parameter changes.

The sensitivity analysis for Whiteoak Bayou (Table 7.4) demonstrated that the bacteria results were sensitive to changes in the first order decay rate for sediment as well as the transport of solids and the detached sediment wash off. Changes in the first order decay rates for bed and suspended sediment showed large changes in model bacteria concentrations at Heights and Little Whiteoak Bayou, with increases up to 53%. At West 43rd, the model showed the greatest amount of change when the exponent in the solids transport equation was increased by 10. The sediment concentrations in the bayou were most sensitive to detached sediment wash off and solids transport, with the Heights location showing the most response to parameter change.

A similar sensitivity analysis was completed for Buffalo Bayou as shown in Table 7.5. Buffalo Bayou showed much more sensitivity to changes in sediment parameters, with the most change in model results stemming from changes to parameters in the sediment transport equations.

Table 7.4 Sediment Sensitivity in Whiteoak Bayou

	% Change in EC Concentration															% Change in TSS Concentrations														
	Overall					LF Geomean					HF Geomean					Overall					LF Geomean					HF Geomean				
Model Parameter	**CC**	**Heights**	**Ella**	**W 43rd**	**LWOB**	**CC**	**Heights**	**Ella**	**W 43rd**	**LWOB**	**CC**	**Heights**	**Ella**	**W 43rd**	**LWOB**	**CC**	**Heights**	**Ella**	**W 43rd**	**LWOB**	**CC**	**Heights**	**Ella**	**W 43rd**	**LWOB**	**CC**	**Heights**	**Ella**	**W 43rd**	**LWOB**
KRER*10	0%	0%	0%	0%	0%	0%	0%	-1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
KRER/10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
JRER*10	0%	0%	0%	1%	-2%	0%	0%	-3%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	-1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
JRER/10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
AFFIX*10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
AFFIX/10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
KSER*10	-4%	-3%	-1%	-5%	-6%	0%	-11%	-12%	0%	-1%	-21%	-7%	0%	0%	-1%	0%	-7%	-4%	-3%	-4%	0%	0%	0%	-3%	-1%	0%	0%	0%	-2%	-1%
KSER/10	0%	1%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
JSER*10	-4%	-3%	-1%	-5%	-6%	0%	-10%	-12%	0%	-1%	-20%	No data	0%	0%	-1%	0%	-7%	-4%	No data	-4%	0%	0%	0%	-3%	No data	0%	0%	0%	-2%	-1%
JSER/10	-24%	-5%	-3%	**-10%**	-5%	-1%	**-22%**	0%	-1%	**-1%**	**-33%**	**-16%**	-3%	0%	0%	0%	**-10%**	**-7%**	**-6%**	0%	-1%	0%	0%	**-4%**	**-2%**	0%	**0%**	0%	**-3%**	0%
KGER*10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
KGER/10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
JGER*10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
JGER/10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
KEIM*10	-2%	0%	0%	0%	-14%	0%	-1%	0%	0%	0%	-3%	-1%	0%	0%	-1%	0%	-1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
KEIM/10	2%	4%	1%	4%	13%	0%	1%	0%	0%	0%	3%	1%	0%	0%	1%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
JEIM*10	**5%**	11%	5%	**17%**	27%	0%	**2%**	0%	1%	**2%**	**4%**	**1%**	**1%**	1%	3%	0%	**2%**	**1%**	**0%**	0%	**0%**	0%	1%	**1%**	**0%**	0%	**1%**	0%	**0%**	0%
JEIM/10	**-29%**	-2%	-1%	-2%	**-49%**	**-26%**	-3%	**-28%**	0%	0%	-9%	-1%	**-4%**	0%	**-4%**	**-9%**	-4%	-1%	-1%	**-9%**	**-1%**	0%	**-1%**	-1%	0%	0%	0%	**-4%**	-1%	**-3%**
ACCSDP*10	-1%	-1%	0%	-1%	-1%	0%	-6%	-2%	0%	0%	-9%	-4%	0%	0%	0%	0%	-3%	-2%	-1%	-1%	0%	0%	0%	-1%	-1%	0%	0%	0%	-1%	0%
ACCSDP/10	1%	3%	1%	4%	2%	**0%**	2%	**0%**	0%	1%	4%	1%	0%	0%	0%	**0%**	2%	1%	0%	**0%**	0%	0%	0%	1%	0%	0%	0%	**0%**	0%	**0%**
REMSDP*10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
REMSDP/10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
TAUCD*10-silt	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
TAUCD/10-silt	0%	0%	0%	0%	-6%	0%	0%	0%	0%	0%	0%	0%	0%	0%	-1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
TAUCS*10-silt	-2%	0%	-1%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
TAUCS-0-silt	-2%	0%	-1%	0%	1%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
M*10-silt	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
M/10-silt	-4%	0%	-1%	-1%	0%	-1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
TAUCD*10-clay	0%	0%	0%	1%	7%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
TAUCD/10-clay	0%	0%	0%	0%	-14%	0%	0%	0%	0%	0%	0%	0%	0%	0%	-1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
TAUCS*10-clay	-12%	-4%	-8%	-2%	2%	0%	0%	0%	0%	0%	0%	0%	-2%	-1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
TAUCS10-clay	-12%	-4%	-9%	-4%	-1%	0%	1%	0%	0%	0%	1%	0%	-2%	-1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
M*10-clay	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
M/10-clay	-5%	-3%	-5%	-1%	0%	-1%	0%	0%	0%	0%	0%	0%	-1%	-1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
KSUSP*10	1%	**52%**	**27%**	12%	**51%**	0%	0%	0%	**8%**	1%	0%	0%	0%	**3%**	**7%**	0%	0%	0%	0%	0%	0%	**1%**	**2%**	0%	0%	**2%**	0%	0%	0%	0%
KSUSP/10	0%	**-53%**	**-13%**	-2%	-36%	0%	0%	0%	**-4%**	0%	0%	0%	0%	**-1%**	-3%	0%	0%	0%	0%	0%	0%	**0%**	-1%	0%	0%	**-1%**	0%	0%	0%	0%
KBED*10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
KBED/10	0%	**-53%**	**-13%**	-2%	-36%	0%	0%	0%	**-4%**	0%	0%	0%	0%	**-1%**	-3%	0%	0%	0%	0%	0%	0%	**0%**	-1%	0%	0%	**-1%**	0%	0%	0%	0%

Note: Please see Appendix XXXXX for descriptions of model parameters

Table 7.5 Sediment Sensitivity in Buffalo Bayou

	% Change in EC Concentration															% Change in TSS Concentrations															
	Overall					LF Geomean					HF Geomean					Overall					LF Geomean					HF Geomean				
Model Parameter	**DA**	**WB**	**CR**	**BB@610**	**SHEP**	**DA**	**WB**	**CR**	**BB@610**	**SHEP**	**DA**	**WB**	**CR**	**BB@610**	**SHEP**	**DA**	**WB**	**CR**	**BB@610**	**SHEP**	**DA**	**WB**	**CR**	**BB@610**	**SHEP**	**DA**	**WB**	**CR**	**BB@610**	**SHEP**
KRER*10	0%	-2%	-1%	-17%	-15%	-6%	-3%	-16%	0%	-2%	-1%	-7%	0%	0%	-2%	-2%	0%	-1%	-2%	-4%	0%	0%	0%	0%	-1%	0%	0%	-1%	0%	-1%
KRER/10	6%	1%	0%	15%	17%	7%	1%	15%	0%	2%	0%	7%	1%	0%	2%	2%	0%	0%	2%	4%	0%	0%	0%	0%	1%	0%	0%	1%	0%	1%
JRER*10	3%	1%	0%	3%	4%	3%	0%	5%	0%	0%	0%	3%	0%	0%	0%	1%	0%	0%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
JRER/10	0%	-2%	-1%	-18%	-16%	-6%	-3%	-17%	0%	-2%	-1%	-7%	0%	0%	-2%	-2%	0%	-1%	-2%	-4%	0%	0%	0%	0%	-1%	0%	0%	-1%	0%	-1%
AFFIX*10	0%	0%	0%	1%	1%	0%	0%	1%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
AFFIX/10	0%	0%	0%	-4%	-4%	-1%	0%	-3%	0%	0%	0%	-1%	0%	0%	0%	0%	0%	0%	0%	-1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
KSER*10	-4%	0%	0%	-5%	-8%	-3%	0%	-6%	0%	0%	0%	-3%	0%	0%	-1%	-1%	0%	0%	-1%	-1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
KSER/10	8%	1%	0%	17%	20%	9%	1%	17%	0%	2%	0%	9%	1%	0%	2%	3%	0%	0%	3%	4%	0%	0%	1%	0%	1%	0%	1%	1%	0%	2%
JSER*10	8%	1%	0%	17%	20%	9%	1%	17%	0%	2%	0%	9%	1%	0%	2%	3%	0%	0%	3%	4%	0%	0%	1%	0%	1%	0%	1%	1%	0%	2%
JSER/10	21%	-418%	64%	-240%	-1280%	-7268%	-4470%	-311422%	-12%	-6%	-3426%	-6664%	25%	34%	-18%	-77%	-76%	-76%	-78%	-162%	11%	14%	-4%	-20%	-20%	-3%	-1%	-19%	-20%	-33%
KGER*10	-31%	-13%	-21%	-250%	-253%	-88%	-26%	-255%	-1%	-13%	-14%	-104%	-2%	-2%	-13%	-19%	-4%	-6%	-23%	-32%	0%	0%	-3%	-2%	-8%	0%	-3%	-7%	-2%	-10%
KGER/10	8%	7%	15%	42%	42%	17%	10%	39%	1%	6%	4%	18%	1%	2%	6%	6%	1%	3%	6%	12%	0%	0%	2%	1%	3%	0%	2%	2%	1%	5%
JGER*10	8%	7%	15%	42%	42%	17%	10%	39%	1%	6%	4%	18%	1%	2%	6%	6%	1%	3%	6%	12%	0%	0%	2%	1%	3%	0%	2%	2%	1%	5%
JGER/10	-1%	0%	-1%	-1%	-1%	-5%	-11%	-6%	0%	0%	-10%	-4%	0%	0%	0%	-1%	-3%	-3%	-1%	-1%	0%	0%	0%	-1%	0%	0%	0%	-1%	-1%	0%
KEIM*10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
KEIM/10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
JEIM*10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
JEIM/10	-590%	-26%	-23%	-2088%	-1577%	-185%	-108%	-510%	-3%	-33%	-10%	-183%	-24%	-2%	-29%	-38%	-3%	-27%	-37%	-48%	-6%	-1%	-7%	-1%	-13%	-1%	-8%	-13%	-10%	-14%
ACCSDP*10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
ACCSDP/10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
REMSDP*10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
REMSDP/10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
TAUCD*10-silt	1%	0%	0%	0%	1%	1%	0%	8%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%
TAUCD/10-silt	0%	0%	0%	0%	0%	-1%	-1%	-2%	0%	0%	0%	-1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
TAUCS*10-silt	-1%	0%	0%	0%	1%	8%	4%	16%	0%	0%	6%	6%	0%	0%	0%	3%	2%	2%	2%	5%	0%	0%	0%	1%	1%	0%	0%	1%	1%	2%
TAUCS-0-silt	-3%	0%	0%	-1%	0%	0%	0%	5%	0%	0%	1%	-1%	0%	0%	0%	1%	1%	0%	0%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%
M*10-silt	-2%	0%	0%	-1%	0%	4%	2%	9%	0%	0%	2%	2%	0%	0%	0%	2%	1%	1%	1%	3%	0%	0%	0%	0%	0%	0%	0%	1%	0%	1%
M/10-silt	2%	0%	0%	1%	0%	-2%	3%	-17%	0%	0%	4%	-5%	0%	0%	0%	-1%	1%	1%	-2%	-5%	0%	0%	0%	1%	-1%	0%	0%	-1%	1%	-2%
TAUCD*10-clay	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
TAUCD/10-clay	0%	0%	0%	0%	0%	0%	0%	-1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
TAUCS*10-clay	9%	0%	2%	4%	4%	0%	0%	-2%	0%	1%	0%	1%	1%	0%	0%	0%	0%	0%	0%	-1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
TAUCS10-clay	Model would not run when this parameter lowered																													
M*10-clay	-1%	0%	0%	0%	0%	1%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
M/10-clay	5%	0%	1%	3%	2%	-1%	0%	-1%	0%	0%	0%	-1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
KSUSP*10	76%	1%	28%	79%	78%	0%	0%	0%	0%	17%	0%	0%	18%	3%	17%	0%	0%	0%	0%	0%	5%	1%	5%	0%	0%	0%	5%	0%	0%	0%
KSUSP/10	-96%	-1%	-8%	-63%	-56%	0%	0%	0%	0%	-5%	0%	0%	-8%	-1%	-5%	0%	0%	0%	0%	0%	-2%	0%	-1%	0%	0%	0%	-1%	0%	0%	0%
KBED*10	4%	0%	1%	2%	2%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
KBED/10	-1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Note: Please see Appendix C for descriptions of model parameters
DA- Dairy Ashford, WB - West Belt, CR - Chimney Rock, BB@610- Buffalo Bayou at 610, SHEP- Shepherd

CHAPTER 8

LOAD ALLOCATION

A total maximum daily load (TMDL) is the maximum amount of a pollutant that a water body can assimilate and still meet water quality standards. When a water body exceeds water quality standards, the allowable loads are allocated to the point and nonpoint sources in the watershed. These allocations are determined through the equation

$$LC = WLA + LA + MOS,$$

where loading capacity (LC) is the maximum amount of a pollutant a stream can receive without violating water quality standards, the wasteload allocation (WLA) is the portion of the loading capacity allocated to point sources, the load allocation (LA) is the portion of the loading capacity allocated to nonpoint sources, and the margin of safety (MOS) accounts for uncertainty in the calculated loading capacity.

This chapter discusses the approach taken to develop the TMDL. The approach included an analysis of the end points and the margin of safety for the TMDL, an examination of the seasonal and flow conditions, the development of baseline conditions using the calibrated HSPF models and finally development of scenarios and allocations to point and nonpoint sources.

8.1 TMDL END POINT AND MARGIN OF SAFETY

The end point of the TMDL represents the in-stream water quality target. For the purposes of the BB and WOB TMDLs, there are two end points. The endpoints are the instantaneous water

quality standard for EC of 394 MPN/dL and the geometric mean standard of 126 MPN/dL. The model outputs hourly values, and therefore outputs 24-hourly concentrations per day. These concentrations were averaged together on a daily basis to come up with a daily concentration. These daily concentrations were used to assess the TMDL endpoints because this value would generally be more conservative than using the hourly values, averaging out the highs and lows. Additionally, the 30-day geometric mean standard of 126 MPN/dL was calculated only when there were 10 or more points available to calculate the geometric mean, per the TCEQ Guidance for Assessing Texas Surface and Finished Drinking Water Quality Data (2002).

An explicit 5% margin of safety was incorporated into the two end points, making the endpoints 374 MPN/dL and 120 MPN/dL. There is also implicit margin of safety incorporated into the calibrated HSPF models because conservative assumptions were made throughout the modeling process.

8.2 CRITICAL CONDITIONS AND SEASONAL VARIATION

Flooding is a problem in the Houston area and both bayous have been modified to some extent to minimize flooding along their reaches. Whiteoak Bayou has been channelized and concrete lined to move water quickly down the bayou and out of the watershed. Buffalo Bayou has two flood reservoirs located in the upper watershed that close when the possibility of flooding in the lower reaches materializes. The flood water is detained until the storm subsides. Therefore, storm events cause both channels to experience high rates of flow that make them unsafe for contact recreation. Additionally, the two previous Work Orders have documented frequent exceedances of the water

quality standard under both high and low flow conditions. Consequently, low flow conditions (i.e. those that exclude storm events) would be an appropriate critical condition for these two bayous. Low flow conditions were examined in Chapter 6 and the median flow and a no-rain condition were found to be the most appropriate method of discriminating between low and high flows. Thus, for a preliminary analyses, flows less than the median are considered to be the critical condition for the TMDL. This critical condition was implemented in the context of the TMDL by excluding all hourly concentrations with hourly flows greater than the median to eliminate all but the low flow conditions for the two bayous.

Seasonality is another important consideration for TMDLs. The Houston area experiences weather that is considered coastal temperate weather conditions, characterized by three seasons (spring, summer and fall) and frequent rainfall events. The differences in FC concentrations were examined on a seasonal basis in Work Order 1. The analysis found that some stations did exhibit differences between winter and summer months. The HSPF model was calibrated to represent conditions during all seasons, both winter and summer. Therefore, the model inherently accounts for seasonal differences in the hydrology and source loading.

8.3 BASELINE CONDITIONS

The models were used to assess the baseline conditions in the two watersheds. The two models were calibrated for the period from April 1, 1999 to September 30, 2001. The models were calibrated to observed flow and water quality at several locations throughout the bayous. WWTP flows in the calibrated models incorporated the 5-year average self-reported flow from all WWTP

in the watersheds and the measured concentrations at each plant. As an example of a possble baseline scenario, the WWTP loads were modified to include the permitted flow and the geometric mean standard was assumed for plants where measured concentrations were lower than 126 MPN/dL.

The change from 5-year average flow to permitted flow resulted in dramatic changes in the flow regime in Whiteoak Bayou, with the median flow almost doubling from 50 cfs to 118.2 cfs at the Heights gage. In Buffalo Bayou, the difference in flow was not as dramatic because there are fewer WWTP in the modeled portion of the watershed,. Median flows in Buffalo Bayou changed from 151 cfs to 192 cfs at the Shepherd gage, demonstrating that the bayou flow was minimally affected by the change to permitted WWTP flows.

A comparison of flow and EC output for the calibrated and baseline models is presented in Figure 8.1 for Heights. The flow is clearly impacted by changing to permitted WWTP flows rather than the 5-year average flows, as shown in the upper graph. The low flows are maintained around 8 acre-ft/hour rather than the 2 acre-ft/hour in the calibrated model. The storm events, however, are not noticeably affected as these flows are much larger. The difference in the EC concentrations between the two models is presented in the lower figure. The figure shows that the very low concentrations are maintained around 120 MPN/dL in the Baseline Model, as opposed to being around 70 MPN/dL in the Calibrated Model. The higher concentrations for EC, however, are not affected.

An analysis of the maximum instantaneous and maximum 30-day geometric mean concentration under low flow conditions was also performed along the bayous, as shown in Figures 8.2 and 8.3. The preliminary baseline conditions show lower maximum 30-day geometric mean and

maximum daily concentrations than the calibrated model for Whiteoak Bayou (Figure 8.2). This may be due to the additional flow in the bayou from WWTP that minimizes the impact of NPS from small rain events on the receiving streams. In Buffalo Bayou, there were very small differences between the calibrated and baseline models (Figure 8.3). The differences are minor, so they are not apparent on the figure except in Figure 8.3b at the lower end of the bayou in Subwatershed 37. Buffalo Bayou has only 6 WWTP in the portion of the watershed simulated using HSPF, compared to the 47 in Whiteoak Bayou and therefore the change from 5-year average flow to permitted flow is not that significant.

Using permitted flows for the bacterial TMDL allocations raises important issues that need to be addressed:

i. The use of permitted flows for all dischargers during dry weather periods is the traditional means of wasteload allocation modeling for dissolved oxygen. This tends to produce a very conservative result and is thus accepted by the regulatory standpoint. With indicator bacteria the situation is more complex, as the flow itself can affect modeled bacteria levels.

ii. Domestic wastewater facilities treat flows that are conveyed in underground sanitary sewers. These are typically free of leaks when initially constructed but develop leaks over time. During rain periods the groundwater level is high and some water enters the sanitary sewers. This results in an increase in the flow at the treatment plants. The design and permitting system recognizes this, and permits are typically written for a flow that will not be exceeded during a wet month. The permit limits also incorporate capacity for anticipated growth. As a result, permit limits are typically 2 to 4 times larger than would be discharged during a dry

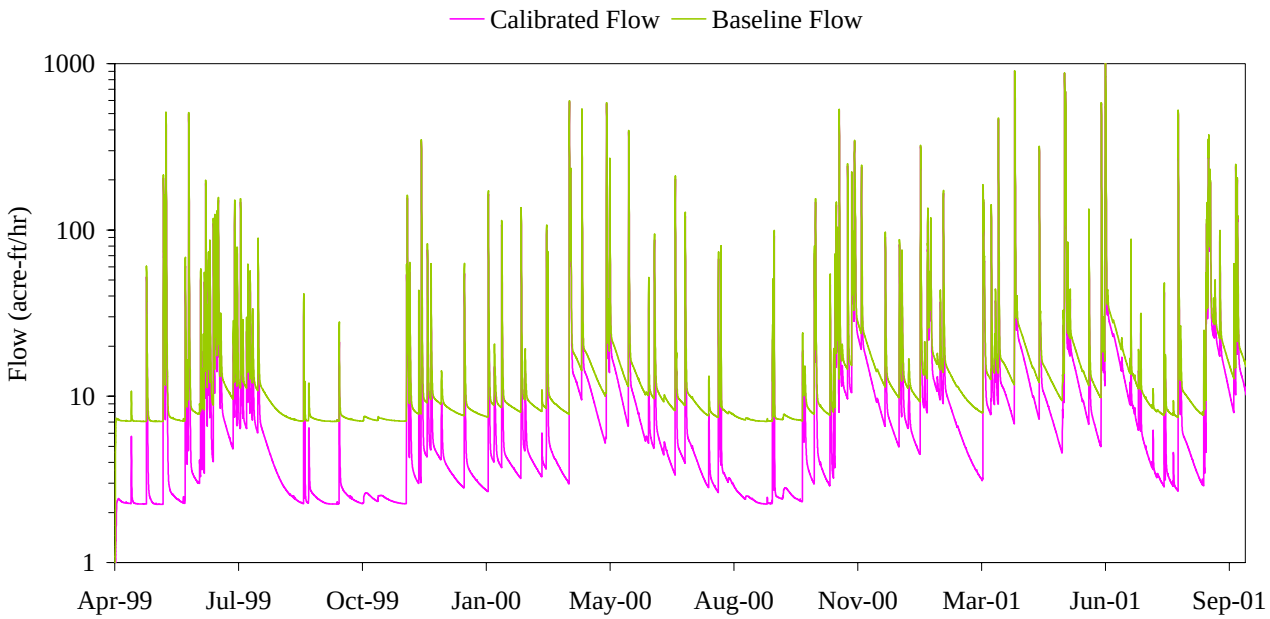
period.

iii. WWTPs do not discharge at their permit level in dry weather, and not be in violation of its permit in wet weather.

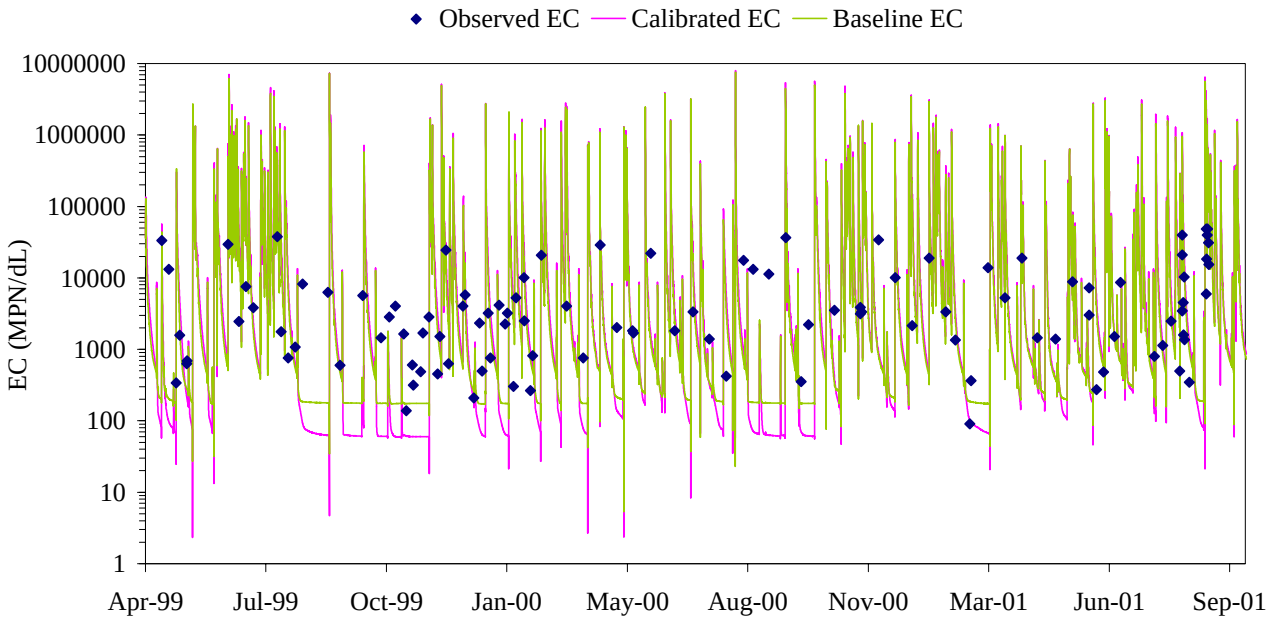
iv. There are a large number (approximately 170) of WWTPs in the watersheds. It is unlikely that all plants would discharge at the permitted flow at the same time.

v. WWTPs that treat domestic waste are required to disinfect prior to discharge. The typical permit calls for meeting a chlorine residual of 1 mg/L for a 20 minute detention time at the full permitted flow. In dry weather the detention time is considerably larger. This permit requirement ensures inactivation of fecal coliform in the effluent.

vi. While using permitted flows and an EC concentration of 126 MPN/dL may be appropriate for waste load modeling, it may not be appropriate for TMDL load allocations in dry weather conditions because of the large discrepancy between dry weather flows and permitted flows. The HSPF model runs presented in the remainder of the chapter while using permitted flows are intended to illustrate the sensitivity of the model to these issues.



Flow Comparison



EC Comparison

Figure 8.1 Comparison of Calibrated and Baseline Models at Heights

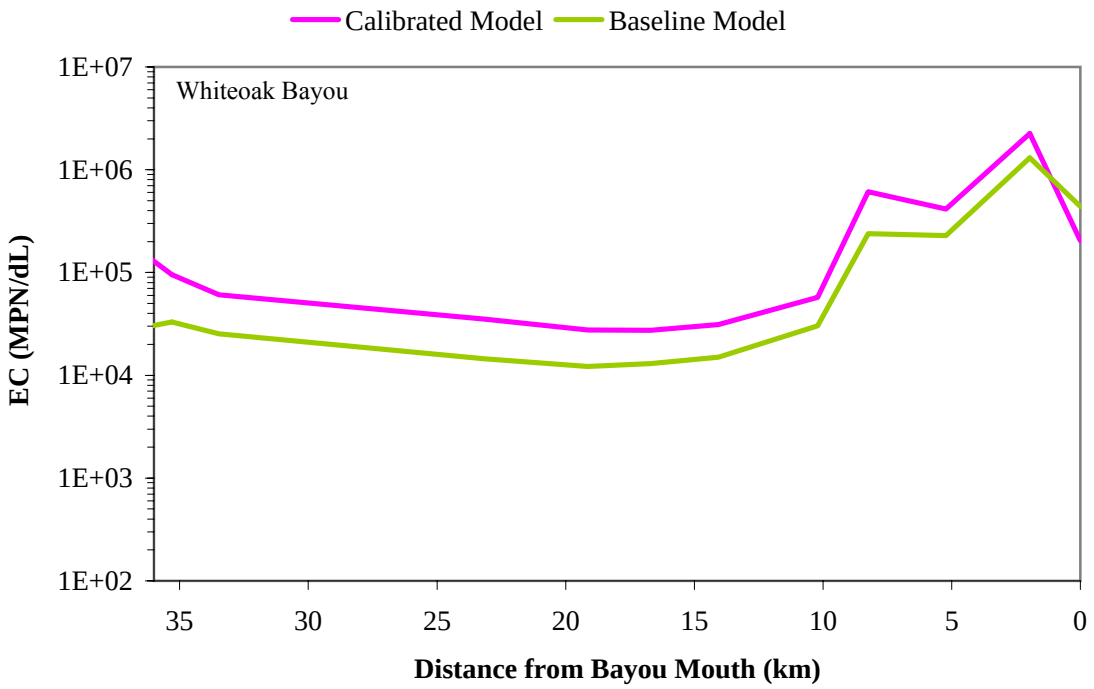


Figure 8.2a Maximum 30-day Geometric Mean Under Low Flow Conditions

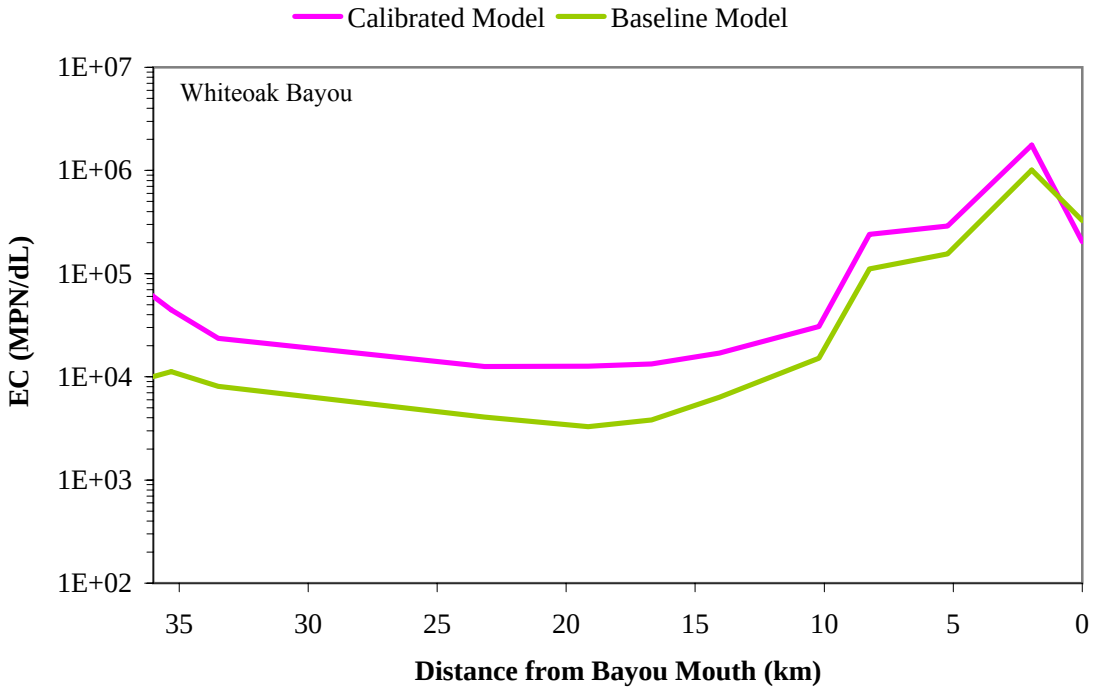


Figure 8.2b Maximum Daily Concentration Under Low Flow Conditions

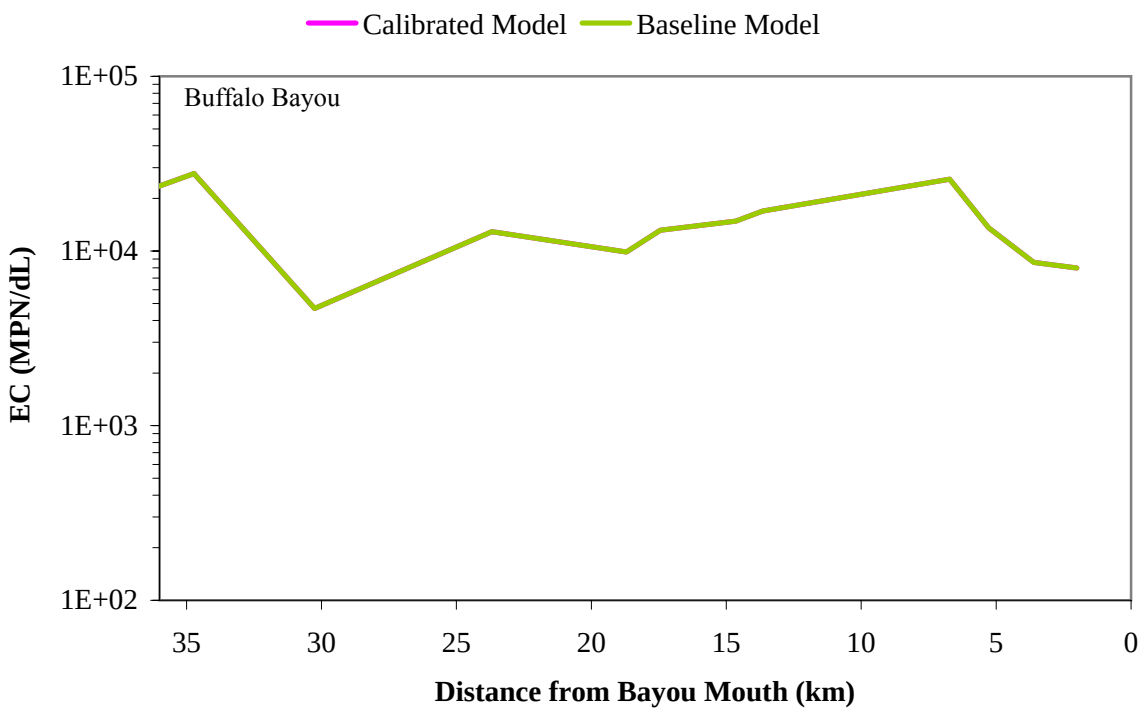


Figure 8.3a Maximum 30-day Geometric Mean Under Low Flow Conditions

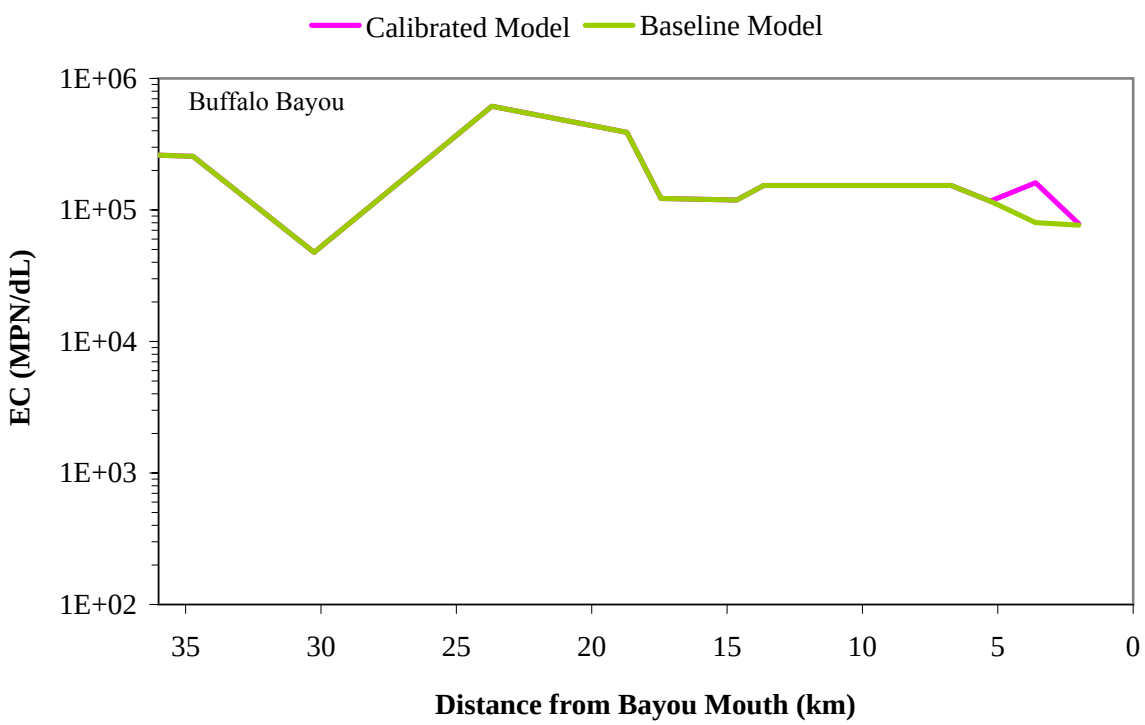


Figure 8.3b Maximum Daily Concentration Under Low Flow Conditions

8.4 SOURCE ASSESSMENT

The sources to the bayous were analyzed by running the model while eliminating each source individually. These assessments provided an indication as to the magnitude of improvement resulting from eliminating a particular source. The sources of bacteria include both point and nonpoint sources. The loading from point sources is from both WWTP effluent and DWSS flows, while nonpoint sources include any bacteria that enters the bayous from the watershed, such as that from animal feces deposited in a park or bacteria associated with sediment in a street. Reservoirs are also an issue in the Buffalo Bayou watershed. The impact of these loads on the bayou were determined by eliminating each source and then running the model.

The impact of the sources were also assessed under different flow conditions. The overall flow condition represents source assessment scenarios for the entire simulation period (April 1, 1999 - September 30, 2001). The low flow condition was defined as less than the median flow. This scenario was assessed by selecting only the hourly concentrations that met the low flow criteria (less than the median). The high flow scenario was assessed in a similar fashion; the high flows (defined as greater than the median) and their associated EC concentrations were identified and geometric means were calculated.

The following two sections present the results of the source assessment for Whiteoak and Buffalo Bayous. The figures are presented longitudinally along the bayous from upstream to downstream, which allows the visualization of the spatial variation in the source impacts.

8.4.1 WHITEOAK BAYOU

Figure 8.4a presents the overall loads to Whiteoak Bayou. As seen in the figure, the bayou is minimally affected by the elimination of wastewater treatment effluent. The elimination of dry weather sources of EC from WWTP and DWSS discharges (WWTP and DWSS) results in limited improvement in the water quality in the lower reaches of the bayou. When NPS accumulation of EC is eliminated, there is significant improvement over the base case (all sources are active), although the standard is not achieved.

The load allocation scenarios under low flow are examined in Figure 8.4b. This scenario is particularly important as contact recreation could be expected to occur under these conditions. The low flow base case concentrations are about 20% lower than concentrations found in the entire simulation period. When the EC associated with WWTP and DWSS discharges are eliminated, the upstream portion of the bayou fluctuates about the water quality standard of 126 MPN/dL, ranging from 124 to 188 MPN/dL. The EC concentrations in the lower reaches begin to increase once the bayou becomes concrete lined, probably due to increased NPS EC loads. NPS elimination results in most reaches of the bayou meeting the contact recreation standard. NPS loads still impact the EC levels in the bayou under low flow conditions because the analysis takes into account antecedent conditions.

Figure 8.4c presents the sources of EC to the bayou under high flow conditions. Similar to the low flow analysis, the high flows and their associated EC concentrations were isolated from the entire simulation period and geometric means of the EC data were calculated. EC levels under high flow conditions are over 600% higher than concentrations seen over the entire simulation period.

Under high flow conditions, WWTP and DWSS flows have almost no impact on the concentrations observed in the bayou. The elimination of NPS pollution does result in some improvement in EC concentrations, but does not lower the concentration below the standard.

8.4.2 BUFFALO BAYOU

The overall allocation scenario results for Buffalo Bayou are shown in Figure 8.5a. In Buffalo Bayou, the identified sources were point sources (WWTP and DWSS flows), NPS and upstream sources (the reservoirs). The removal of EC associated with point sources has little impact on the geometric means over the entire simulation period. The is reasonable since most wastewater treatment plants in the Buffalo Bayou watershed are located above the reservoirs, and only 6 plants are found below the reservoirs. Nonpoint sources of EC are rather significant in the overall model, as there is a dramatic effect on model results when this source is eliminated. Finally, the elimination of EC input from the Barker and Addicks Reservoirs appears to have some effect on the upstream sections of the Buffalo Bayou watershed, but the impact of this source becomes negligible around Chimney Rock.

Under low flow conditions, the concentrations of EC in the bayou are much lower than the overall simulation (Figure 8.5b). The point sources also begin to play a larger role in the model, with the middle portion of the watershed beginning to approach the water quality standard when the associated EC is eliminated. Nonpoint sources of EC are not as significant under low flow conditions as they were when examined over the entire simulation period. However, the elimination of NPS does result in the standard being met in the lower portion of the bayou. The reservoirs appear to have a similar impact on the bacteria levels in Buffalo Bayou, with their influence again extending to

Chimney Rock.

Finally, under high flow conditions the EC concentrations are much higher, with upstream concentrations just below 1,000 MPN/dL as shown in Figure 8.5c. There is a very strong increasing trend in EC concentrations moving downstream along the bayou which was not present in the other scenarios. Additionally, only the elimination of NPS and the reservoirs appear to have an impact on the concentrations in the bayou. The elimination of NPS will achieve the standard in the majority of the bayou. The elimination of EC associated with the Barker and Addicks Reservoirs does have an impact on the high flow concentrations, with the entire watershed being affected, although minimally in the lower watershed.

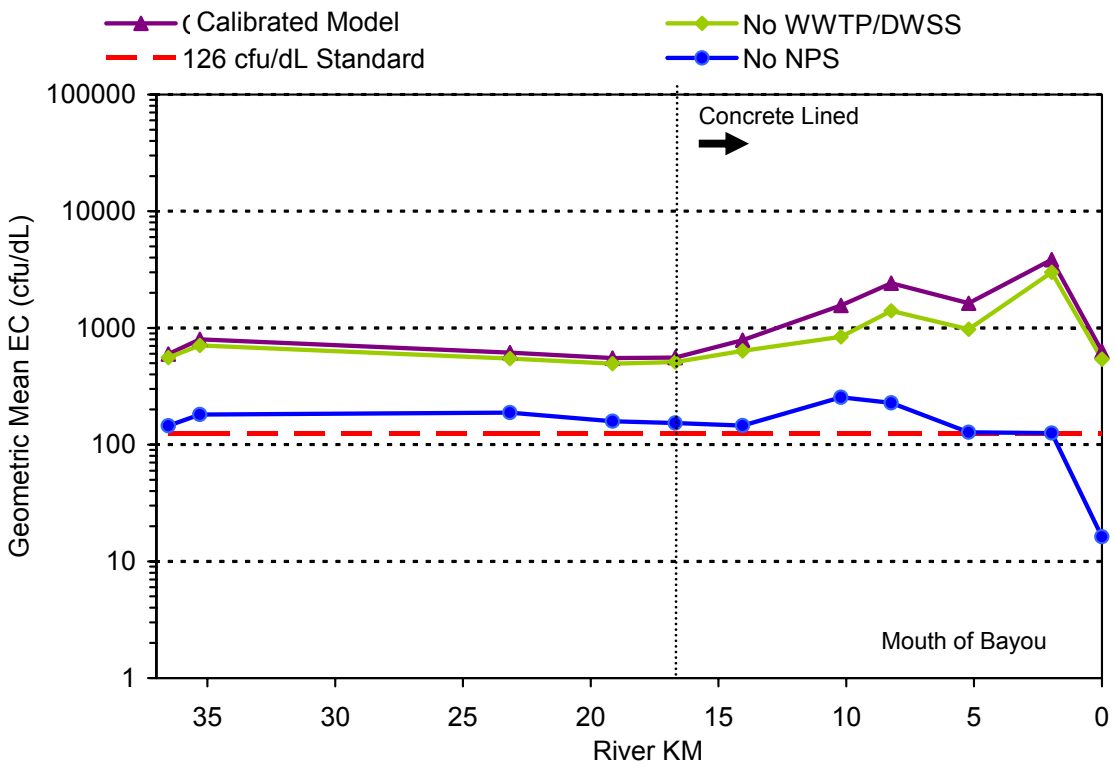


Figure 8.4a Whiteaok Bayou Source Asessement Scenario - All Flows

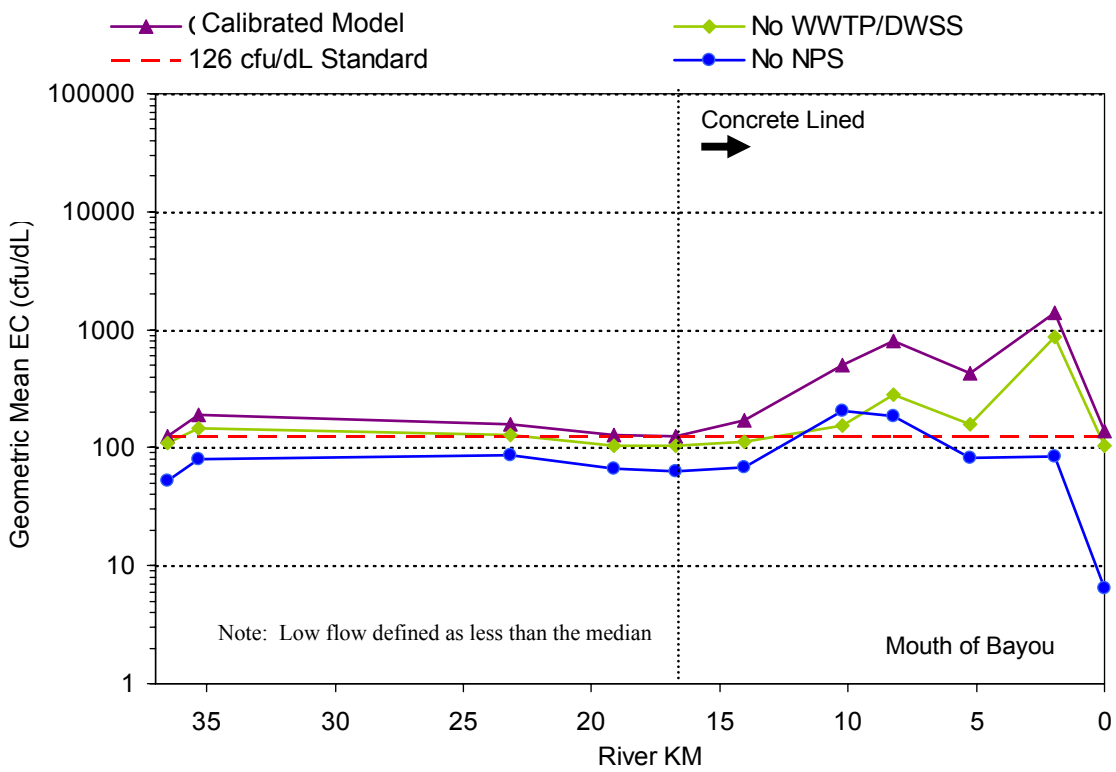


Figure 8.4b Whiteoak Bayou Source Asessement Scenario - Low Flow

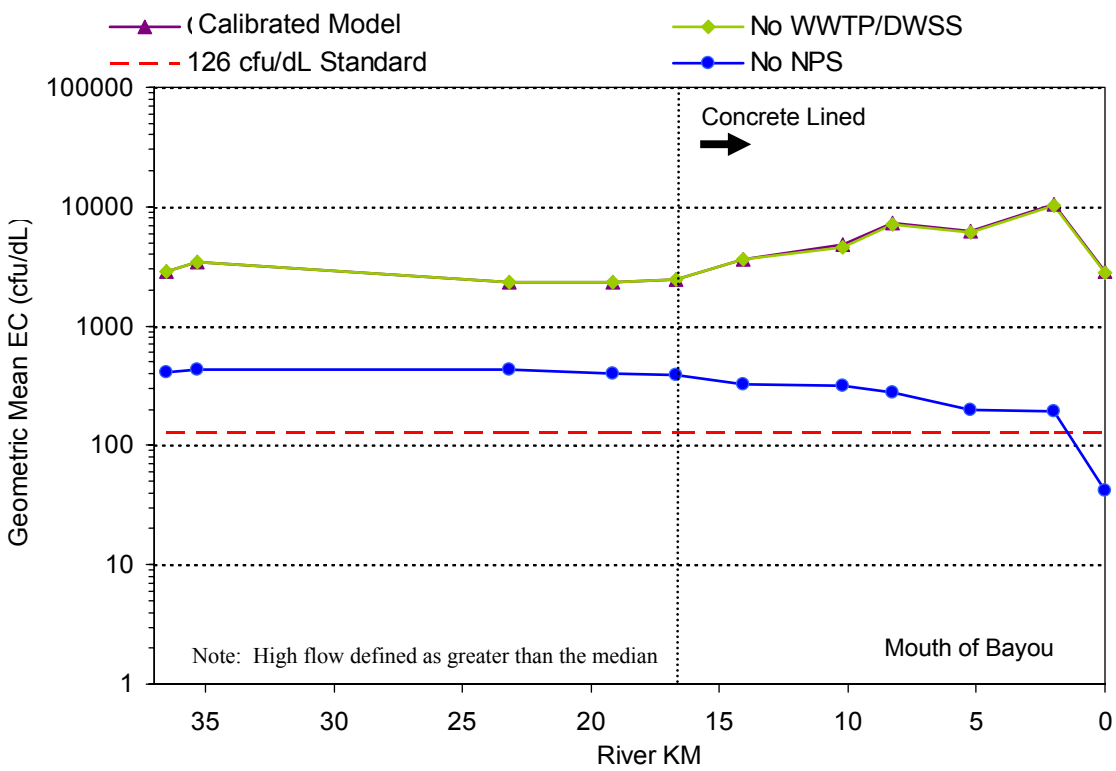


Figure 8.4c Whiteoak Bayou Source Asessement Scenario - High Flow

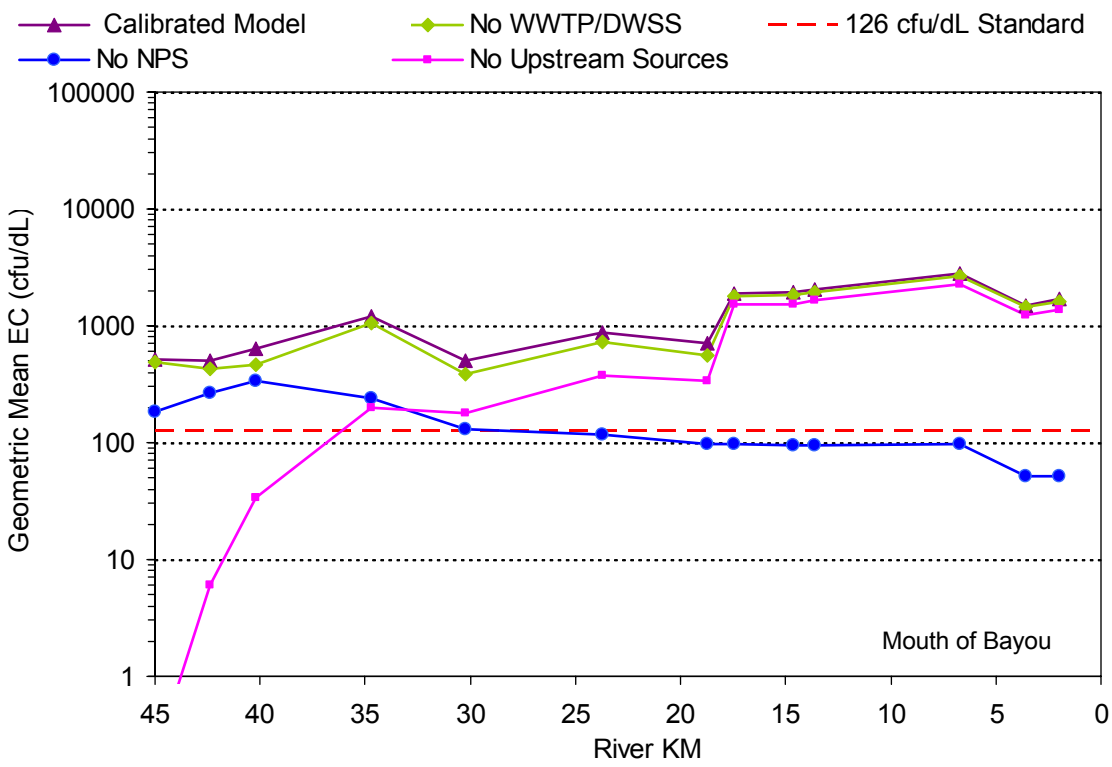


Figure 8.5a Buffalo Bayou Source Asessement Scenario - All Flows

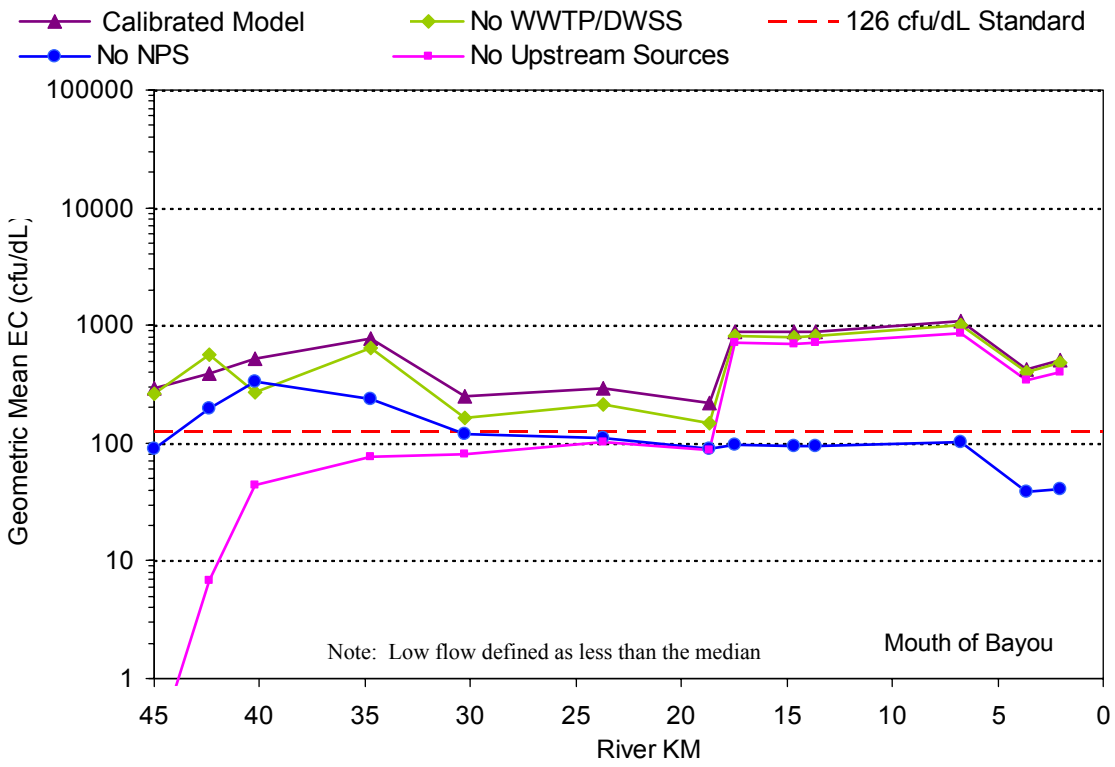


Figure 8.5b Buffalo Bayou Source Asessement Scenario - Low Flow

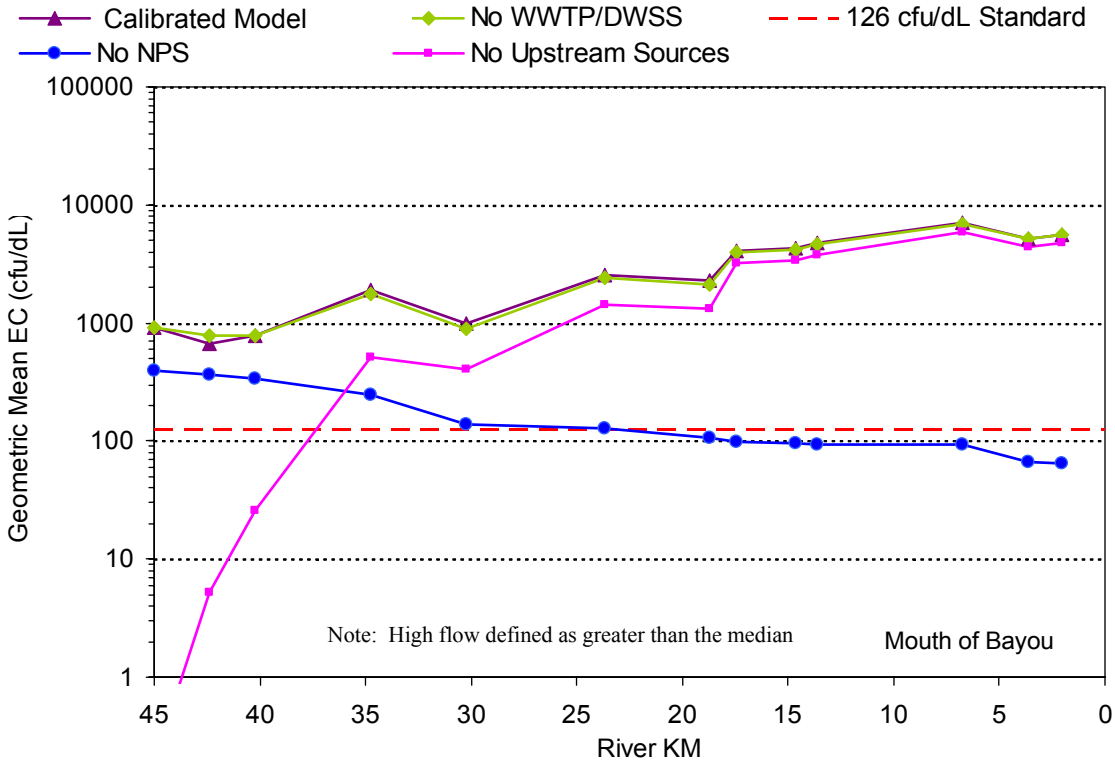


Figure 8.5c Buffalo Bayou Source Asessement Scenario - High Flow

8.5 ALLOCATIONS

The allocations for Buffalo and Whiteoak Bayou were completed using a iterative top-down approach. The allocation process began at the headwaters of each bayou (subwatershed 13 for Whiteoak Bayou and subwatersheds 28 and 34 for Buffalo Bayou). The loadings in the subwatersheds were adjusted until the output concentration from the subwatershed met the water quality criteria. The subwatershed immediately downstream of the headwater subwatersheds was adjusted next, and so on.

The primary sources of bacteria loading in the calibrated and baseline models are point sources (WWTP and DWSS flows), nonpoint sources and the reservoirs in Buffalo Bayou. The point sources were assumed to meet the long-term geometric mean of 126 MPN/dL, and thus the load that corresponded to this concentration in conjunction with the permitted flow was entered for each WWTP and DWSS flow. Although it was found during the Summer 2001 sampling that most WWTPs and some DWSS flows discharged much lower concentrations than the 126 MPN/dL, the maximum concentration associated with point sources was the long-term geometric mean. This assumption provides aa better estimate of the allowable load for the WWTPs and DWSS discharges. The WWTP and DWSS flows may discharge up to the long-term geometric mean and thus this value was assumed to provide conservative estimates of load reductions. Nonpoint source loads were determined through a trial and error process. The NPS load to the subwatershed was reduced until the concentration at each subbasin outlet met the water quality standards. The Addicks and Barker reservoirs were treated similarly to point sources; they were assumed to discharge the 126 MPN/dL standard throughout the simulation period.

An important point to keep in mind is that these allocations represent only one possible load reduction strategy. Other strategies may also result in the achievement of the water quality targets and will be further explored in this TMDL. The allocations for the two bayous are presented in Table 8.1. The baseline conditions, discussed in Section 8.3, use the permitted flow rather than the 5-year average flow for WWTP effluent discharge flows. It should be noted that the nonpoint source bacteria pollution is divided into three categories in this table: the nonpoint source loads, which represent the direct surface loading of bacteria, the sediment load, which represents the amount of bacteria associated with surface sediment, and the interflow load, which represents a concentration of bacteria in the shallow groundwater following a rain event. If NPS was reduced in a subwatershed, the reduction occurred equally in all three categories.

The allocations in Table 8.1 represent a wide range of reductions, from 0% to 99.99%. The WWTP in Buffalo Bayou have no required reductions since no sampling occurred that documented any exceedances in the plants in the lower watershed. In Whiteoak Bayou, reductions are needed in three watersheds, 2, 4, and 11. NPS load allocations required the largest reductions, which is consistent with the source analysis that showed it was the primary source of bacteria to the bayous.

Figure 8.6 present the baseline concentrations in the bayous compared to the final concentration after the recommended reductions. These figures demonstrate that the allocations that have been recommended result in both bayous meeting the two TMDL endpoints, the instantaneous endpoint and the long-term geometric mean endpoint. It is noted that significant reductions in loads are needed to meet the standards at low flow, in excess of 90% reduction of point and nonpoint sources for more than 70% of the subwatersheds. This may not be realistic or achievable with existing abatement technologies.

Table 8.1. Comparison of Baseline and Allocation Loads.

Bayou	Sub watershed	Baseline						Allocation						Reduction					
		NPS Load *MPN/acre/day*	Sediment Load *MPN/ton sed*	Interflow Load *MPN/ft^3*	Reservoir Load *MPN/day*	WWTP Load *MPN/hr*	DWSS Load *MPN/hr*	NPS Load *MPN/acre/day*	Sediment Load *MPN/ton sed*	Interflow Load *MPN/ft^3*	Reservoir Load *MPN/day*	WWTP Load *MPN/hr*	DWSS Load *MPN/hr*	NPS Load	Sediment Load	Interflow Load	Reservoir Load	WWTP Load	DWSS Load
Whiteaok Bayou	1	9.12E+11	1.00E+07	1.00E+03		9.97E+06		1.43E+08	1.01E+03	1.00E+00		9.97E+06		99.984%	99.990%	99.90%			
	2	5.80E+12	1.74E+01	1.00E+03		4.45E+09		5.80E+11	1.22E+00	1.00E+02		6.35E+09		90%	93%	90%		-43%	
	3	8.10E+11	3.00E+07	1.00E+03				8.44E+08	2.10E+05	1.00E+02				99.896%	99.3%	90%			
	4	1.81E+06	2.00E+07	1.00E+03		3.07E+09	6.16E+05	1.81E+06	2.00E+07	1.00E+03		3.19E+09	5.90E+05	0%	0%	0%		-4%	4%
	5	2.05E+11	2.00E+07	1.00E+00				2.75E+08	1.10E+05	1.00E-02				99.87%	99.4%	99%			
	6	1.80E+11	2.00E+07	1.00E+00				2.50E+08	1.10E+05	1.00E-02				99.86%	99.4%	99%			
	7	9.31E+10	2.00E+07	1.00E+03		7.98E+08	2.12E+06	9.31E+10	2.00E+07	1.00E+03		7.98E+08	2.12E+06	0%	0%	0%		0%	0%
	8	1.22E+11	2.00E+07	1.00E+03				1.22E+11	2.00E+07	1.00E+03				0%	0%	0%			
	9	8.97E+10	2.00E+07	1.00E+03		6.66E+08		7.63E+09	1.01E+07	1.00E+03		6.66E+08	0.00E+00	91%	50%	0%		0%	
	10	6.80E+08	1.00E+07	1.00E+03		6.58E+08	4.68E+07	6.80E+08	1.00E+07	1.00E+03		6.58E+08	3.91E+06	0%	0%	0%		0%	92%
	11	2.03E+11	2.00E+07	1.00E+03		5.91E+08	2.02E+06	2.03E+09	2.00E+05	1.00E+01		6.28E+08	2.02E+06	99.0%	99.0%	99.0%		-6%	0%
	12	2.36E+11	2.00E+07	1.00E+03				8.48E+08	1.10E+05	1.00E+01				99.6%	99.4%	99.0%			
	13	1.78E+11	2.00E+07	1.00E+03		7.05E+08	1.69E+06	7.90E+09	1.10E+06	1.00E+02		7.05E+08	1.69E+06	96%	94%	90%		0%	0%
	17	3.94E+09	2.00E+07	1.00E+03		5.58E+07		3.94E+09	2.00E+07	1.00E+03		5.58E+07		0%	0%	0%		0%	
	40	1.88E+13	3.00E+07	1.00E+00		1.18E+07	3.28E+07	1.07E+10	2.01E+04	1.00E-03		1.18E+07	2.25E+07	99.94%	99.93%	99.90%		0%	32%
	41	4.18E+12	3.00E+09	1.00E+00			9.95E+07	1.82E+10	2.01E+07	1.00E-03			9.38E+06	99.6%	99.3%	99.9%			91%
	42	1.11E+13	3.00E+07	1.00E+00		2.99E+07	8.58E+08	9.93E+09	2.10E+04	1.00E-03		2.99E+07	2.78E+07	99.91%	99.93%	99.90%		0%	97%
	43	1.98E+12	2.00E+09	1.00E+00			7.28E+09	1.98E+10	2.00E+07	1.00E-02			5.03E+07	99%	99.0%	99.0%			99.3%
	46	3.80E+12	3.00E+07	1.00E+00				5.63E+09	2.00E+04	1.00E+00				99.85%	99.93%	0%			
	48	3.98E+10	3.00E+07	1.00E+00				3.99E+08	2.01E+05	1.00E-02				99.0%	99.3%	99.0%			
	49	9.63E+11	3.00E+07	1.00E+00				7.80E+11	2.00E+07	1.00E+00				19%	33%	0%			
Buffalo Bayou	26	2.00E+06	8.76E+11	1.00E+08				1.01E+04	7.31E+09	1.00E+04				99.5%	99.2%	99.990%			
	27	2.00E+06	8.76E+11	1.00E+08				1.01E+05	7.31E+10	1.00E+05				95.0%	91.7%	99.90%			
	28	1.00E+06	8.76E+11	1.00E+08				1.00E+03	8.76E+08	1.00E+05				99.90%	99.900%	99.90%			
	33	2.00E+04	2.19E+07	1.00E+08		5.26E+09		2.00E+04	2.19E+07	1.00E+08		5.26E+09		0%	0%	0%		0%	
	34	2.00E+04	7.41E+08	1.00E+08			8.63E+07	1.10E+03	8.41E+05	1.00E+06			6.52E+06	94.5%	99.887%	99.00%			92%
	35	2.00E+04	7.41E+08	1.00E+08			5.92E+06	1.01E+03	7.30E+07	1.00E+05			5.92E+06	95.0%	90.1%	99.90%			0%
	37	2.00E+02	2.19E+09	1.00E+08				2.00E+02	2.19E+09	1.00E+08				0%	0%	0%			
	39	2.00E+02	7.45E+10	1.00E+08			3.67E+07	1.10E+00	8.76E+06	1.00E+05			3.38E+07	99.5%	99.988%	99.90%			8%
	44	2.00E+06	2.19E+11	1.00E+08		9.97E+05	4.81E+04	1.01E+05	7.45E+09	1.00E+05		9.97E+05	4.81E+04	95.0%	96.6%	99.90%		0%	0%
	45	2.00E+06	2.19E+11	1.00E+08			5.50E+08	1.01E+05	7.31E+10	1.00E+05			6.48E+06	95.0%	66.6%	99.90%			99%
	47	2.00E+06	2.19E+11	1.00E+08			4.92E+05	2.00E+06	2.19E+11	1.00E+08			8.50E+04	0%	0%	0%			83%
	50	2.00E+06	2.19E+11	1.00E+08			6.53E+06	1.10E+04	8.76E+08	1.00E+05			7.54E+05	99.5%	99.6%	99.9%			88%
	51	2.00E+06	2.19E+11	1.00E+08				1.10E+05	8.76E+09	1.00E+06				94.5%	96.0%	99.0%			
	52	2.00E+04	2.19E+07	1.00E+08			1.82E+09	1.01E+04	7.45E+06	1.00E+06			1.28E+07	49.5%	66.0%	99.0%			99%
	53	1.00E+06	2.19E+11	1.00E+08		6.08E+08	1.78E+07	1.00E+03	8.76E+08	1.00E+05		6.08E+08	1.22E+06	99.9%	99.6%	99.9%		0%	93%
	54	2.00E+04	2.19E+07	1.00E+08			5.39E+09	2.00E+04	2.19E+07	1.00E+08			5.76E+06	0%	0%	0%			100%
	55	2.00E+04	1.84E+09	1.00E+08		2.39E+09	8.19E+06	1.10E+02	8.41E+06	1.00E+06		2.39E+09	8.19E+06	99.5%	99.5%	99.00%		0%	0%
	56	2.00E+04	2.19E+09	1.00E+08		2.19E+06		1.01E+04	7.45E+08	1.00E+06		2.19E+06		50%	66%	99%		0%	
	Addicks				6.23E+10						1.54E+10						75.3%		
	Barker				1.17E+11						1.37E+10						88%		

Notes:
Loads are in bacteria/acre/day except interflow which is bacteria/ft3 and sediment load which is in bacteria/ton of sediment
% Reductions calculated as: (Baseline - Allocation)/Baseline
Baseline WWTP and DWSS Loads are presented in Table 5.3 as "Baseline Model"
Allocation WWTP and DWSS Loads are presented in Table 5.3 as "Standard Load"

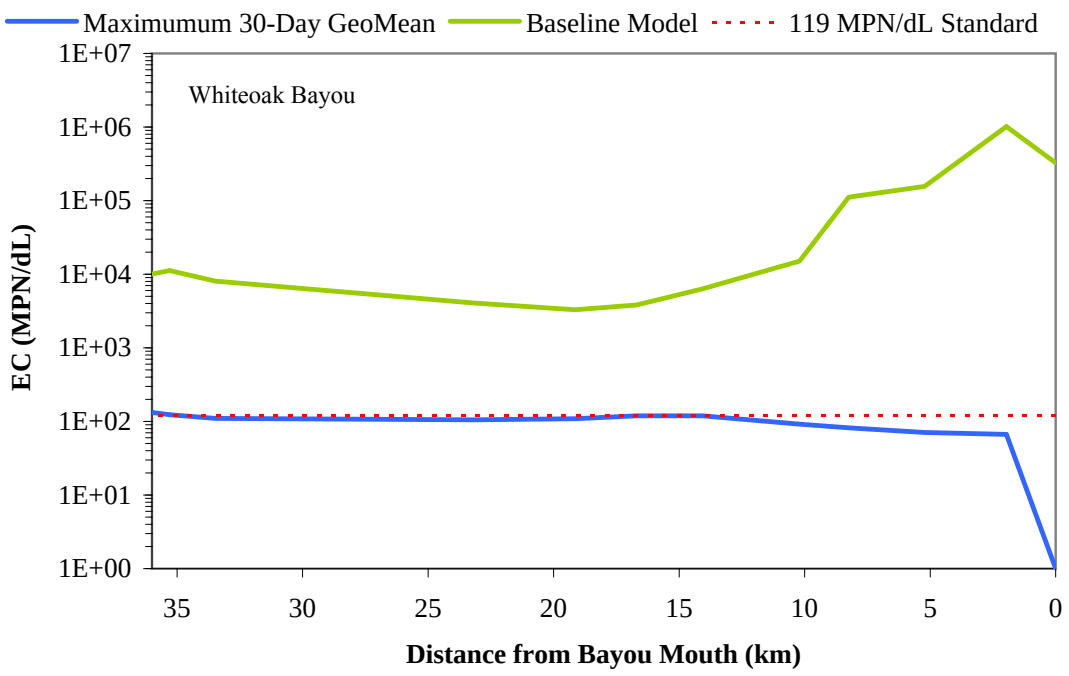


Figure 8.6a Maximum 30-day Geometric Mean Under Low Flow Conditions After Reductions

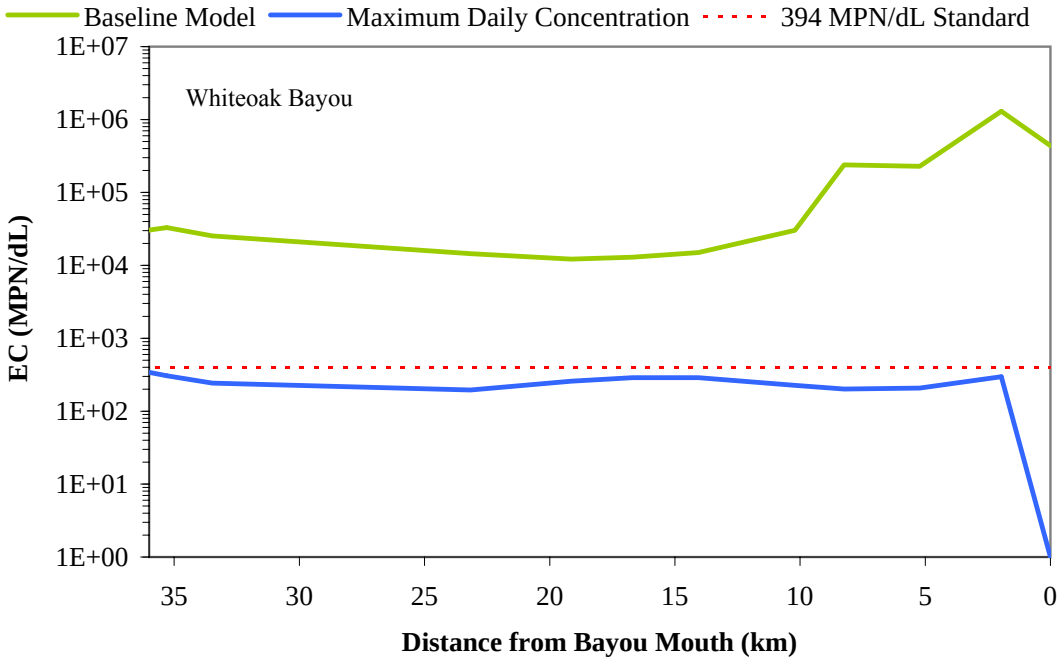


Figure 8.6b Maximum Daily Concentration Under Low Flow Conditions After Reductions

Note: 30-day Geometric mean calculated with a minimum of 10 daily concentrations

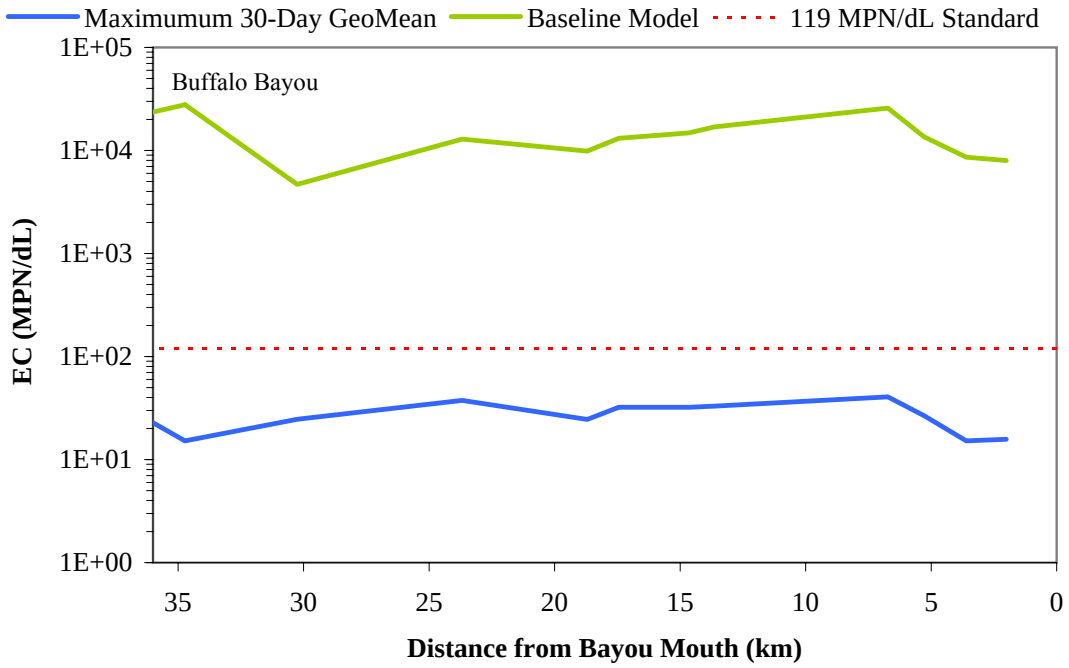


Figure 8.7a Maximum 30-day Geometric Mean Under Low Flow Conditions after Reductions

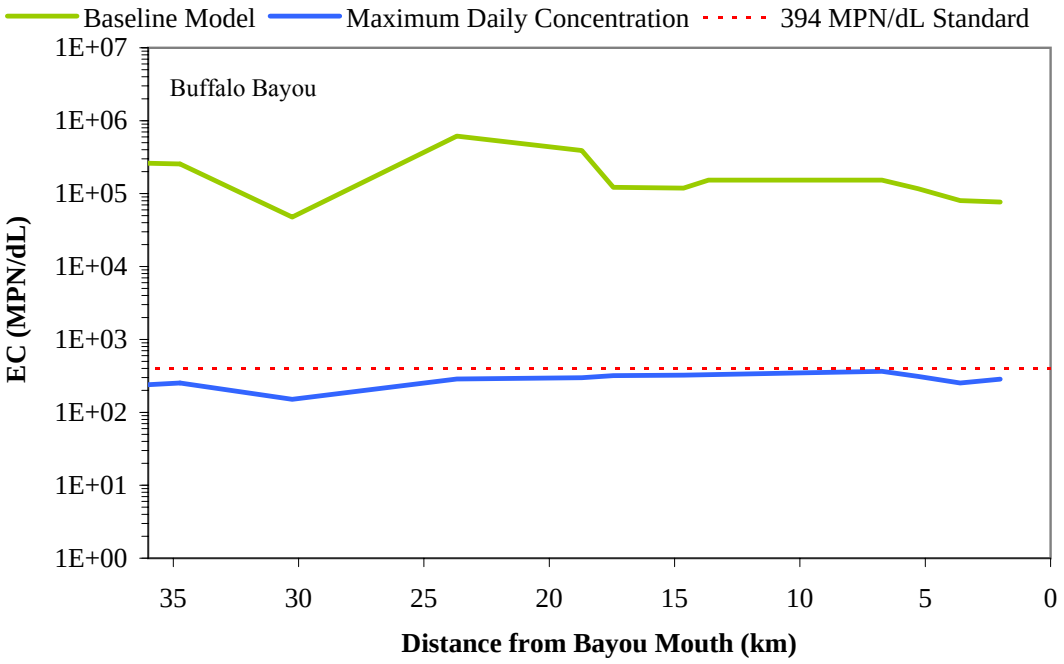


Figure 8.7b Maximum Daily Concentration Under Low Flow Conditions after Reductions

Note: 30-day Geometric mean calculated with a minimum of 10 daily concentrations

CHAPTER 9

BEST MANAGEMENT PRACTICES

Indicator bacteria concentrations in Buffalo Bayou (BB) and White Oak Bayou (WOB) average well above the criteria for contact recreation during dry weather, and greatly exceed the criteria during wet weather. During dry weather, the bulk of the flow in the bayous is from permitted wastewater treatment plants (WWTP). During dry weather there are also contributions from smaller water flows. During wet weather the bulk of the flow is runoff. Since wet weather is fairly common in the Houston area, measures to reduce indicator bacteria concentrations during runoff conditions need to be considered.

The term best management practice (BMP) is normally associated with storm water and non-point sources, not with point sources such as WWTPs. In the remainder of this chapter, the terms point and non-point are not used to avoid confusion. In regulatory terms, the term "point source" applies to flows at a single location that are permitted through the Texas Pollutant Discharge Elimination System (TPDES). This includes wastewater discharges (the traditional point sources) and runoff flows in TPDES permitted municipal separate storm sewers (MS4). With this definition (40 CFR 122.2), all runoff flows in the study area, except those from agricultural fields and those that enter without a managed channel, are point sources.

For this analysis of bacterial inputs there are two general categories of best management practices (BMP) that could be considered: operational and structural. Operational BMPs are defined as management practices that reduce or prevent contaminants from being introduced, while structural

BMPs are structures that are designed to reduce nonpoint source pollution.

This section addresses the present situation with regard to BMPs relevant to bacteria levels that exist today and that are to be in place in the near future, including both operational and structural BMPs. Additionally, it presents a current view of BMP practices that are being implemented across the Houston area through the Stormwater Joint Task Force.

9.1 OPERATIONAL BMPS

Structural BMPs are devices that remove contaminants after they have been introduced. Operational BMPs can include the elimination of non - storm water discharges, good housekeeping, spill prevention and response, regular inspections and testing, regular maintenance, inspection and/or sampling of storm water before discharges, and employee training (Zimmerman 1996).

In Buffalo and Whiteoak Bayous, operational BMPs include the full spectrum of operational activities that control inputs including the main sources of water in streams such as spring and bank flows, WWTP effluent, storm water runoff, and sources that shouldn't exist such as unpermitted discharges, sewer leaks, and runoff from improperly managed sites. Of these, the runoff component is clearly the largest by volume and dominates during wet periods. But non-runoff inputs can be important in streams where the only real potential for recreational uses is during non-runoff periods. This section reviews the major sources of bacteria in the study area where operational BMPs are a factor, and recommends additional actions that appear to be appropriate. It does not attempt to cover all operational BMPs.

9.1.1 SEWER LEAKS

The City of Houston operates the wastewater collection and treatment system in the lower part of the study area, and a number of special districts serve that function in the upper reaches of BB and WOB. While sanitary sewers may function well when initially constructed, a combination of aging, corrosion, shifting soils, tree root intrusion, accumulation of grease and debris, inappropriate use, and limited resources for maintenance has generally resulted in periodic blockages and/or leaks. The leaks can be both into and out of the sewer. Chronic leaks out of the sewer in dry conditions may be hard to detect, while leaks into the sewer contribute to overflows in the lower parts of the collection system during wet weather events. A particular problem is property owners inappropriately connecting storm drains into the sanitary sewer, contributing to downstream overflows during runoff events. Sewer blockages can occur from situations such as grease buildup or a collapsed line. Such blockages result in sewage release, usually from a manhole upstream of the blockage. At times the flow goes into a storm drain, making it difficult to detect without going to the outfall of the storm drain in the receiving stream.

In general, such sanitary sewer problems are rare in newer systems but tend to get worse with time and redevelopment. As a consequence, the major problems with collection system maintenance are expected to be within the area served by the City of Houston. Areas served by districts in the upper reaches tend to have fewer problems, primarily because they are newer systems.

The City of Houston maintains the collection system in both a routine operational mode and within a long-term planning process. The operational mode involves responding to reports of problems, documenting failure, and correcting the problem. In some cases the problems may involve

lines that require major upgrade and/or replacement. The main example of this is the Greater Houston Wastewater Program in the early 1990s, where over a billion dollars was invested in upgrades to major lines. Repairs and replacements continue today, but at a more modest pace.

As systems age, it is likely that portions of the sanitary sewer system will be in need of repair and upgrade. This will be a continuous need. Determining the proper balance of resources to invest in this infrastructure component is the topic of an EPA initiative known as CMOM (Capacity Assurance, Management, Operation, and Maintenance). The EPA initiative is under review by the federal Office of Management and Budget. Once enacted, all collection system owners will be required to develop CMOM plans for their system. Satellite systems (those that send their wastewater to a regional authority) will also be required to obtain permits.

The proposed EPA program provides the framework for management, operation and maintenance of all parts of the collection system. Owners will be required to provide a written CMOM plan that details how the owner will provide the necessary funding and resources to ensure that adequate capacity is available to minimize the occurrence of Sanitary Sewer Overflows (SSOs). The initiative further includes provisions on emergency response, record keeping, and reporting.

The CMOM draft regulations contains six primary components addressing: 1) General Standards; 2) Management Program; 3) Overflow Response Plan; 4) System Evaluation and Capacity Assurance Plan; 5) CMOM Program Audits; and 6) Communication. While the specific details of the CMOM program have not been defined and are not yet in effect, some form of the program is likely to be implemented in the near future. When implemented, the EPA CMOM program can be expected to contribute to reducing sanitary sewer leakage, and thus bacterial loads to bayous from this source.

9.1.2 MONITORING AND INSPECTION

A key operational BMP for minimizing bacteria inputs to the bayous is monitoring and inspection. For many years the City of Houston has supported programs to monitor bacteria concentrations in the bayous. This has resulted in the area being one of the most heavily monitored parts of the state.

Monitoring on the main bayous is useful in detecting major collection system leaks. A number of major breaks and line leaks were discovered from the monitoring data (Glanton, 2003). However, the bayou monitoring effort is generally only useful in providing information that a leak exists somewhere between two stations. Finding the specific source typically requires a more detailed inspection.

More detailed inspections along bayous and tributaries are performed sometimes, but are not routinely required at this time. Examples of such studies include the sampling efforts in this TMDL study during the summer of 2001, and the recent Clean Rivers Program effort on Brickhouse Gully (tributary to WOB), Turkey Creek (tributary to BB), Mason Creek (tributary to BB) and Garner's Bayou (tributary to Greens Bayou). These detailed inspections involved trips along the channel, either by small boat or on foot, to find and sample water inputs during dry weather. Generally, both studies documented a number of small inflows with high bacteria concentrations.

It should be noted that such high concentration inputs are not exclusively sewer leaks. In an investigation by the City where a sewer leak was suspected, the actual source turned out to be wash water from a fish packing operation. Once that wash water was conveyed to the sanitary sewer, the

problem was resolved (Glanton, 2003).

Ultimately, if long-term progress is to be made in managing dry weather NPS inputs, a program of periodic inspection and monitoring along the bayous and major tributaries will likely be needed.

9.1.3 OPERATIONAL BMPs FOR WWTPs

Although BMPs generally are applied for NPS pollution, BMPs can be applied to the operation of a WWTP. By almost any standard, operational measures to minimize WWTP outputs are mature, having evolved over more than 30 years. In the case of the City of Houston plants there is a sophisticated and efficient system with automatic monitoring and procedures for the early detection of problems. However, problems still exist due to operator error and equipment failure. Budgets for personnel and maintenance are chronically tight and permits are not always met. Still, there is little indication of a systemic problem with meeting bacteria limits by City of Houston plants, and operational parameters are carefully controlled.

A somewhat different situation exists with the smaller special district plants in the more upstream reaches of the two bayous. Like the City of Houston plants, monitoring of bacteria levels in this study and by Harris County Pollution Control confirms that bacteria levels are generally attained most of the time, but there are occasional exceedances. One problem that has been noted by TCEQ regional personnel is that the sludge management system of the treatment plants is not always appropriate and solids releases occur into bayous. These sludge releases have the potential to contribute to elevated bacteria levels. Accordingly, it is recommended that operational procedures

(permit requirements) be modified to include requirements for record keeping to document that the appropriate amount of sludge was being produced and that it was being disposed of properly.

9.2 STRUCTURAL BMPS

There are many different types of structures designed to improve the quality of runoff flows. Structural BMPs consist of devices to remove contaminants from runoff by methods such as settling, filtration or biological uptake, controls along drainage pathways to reduce erosion and provide treatment, and end of pipe controls on non-storm inputs such as air pollution control for particulates (Zimmerman 1996).

9.2.1. DETENTION SYSTEMS

Detention/Irrigation systems capture and dispose of runoff without direct release to receiving streams. Detention ponds treat incoming storm water runoff by physical, biological, and chemical processes. The physical process removes pollutants by gravitational settling of particulates, organic matter, metals, and bacteria during the residence time in the pond. The biological process removes pollutants via uptake by algae and wetland plants in the permanent pool for nutrients. The chemical process removes contaminants via volatilization and chemical activity that break down and eliminate a number of pollutants.

These types of systems are very good for residential use and they also have a low capital cost and maintenance burden. However, the ponds generally require a minimum of 25 acres to maintain a permanent pool. Thus, high density or urban areas may limit the use and applicability of a detention

pond due to the large land requirement of the pond.

Wet detention ponds can be designed for any size basin and are generally for the removal of sediment, BOD, organic nutrients and trace metals. Removal efficiencies for these basins for suspended sediment removal are estimated to be around 79%, while bacterial removal is estimated to be 70% (Vermont and Georgia Stormwater Management Manuals). Small commercial sites often do not have adequate land area available for a wet pond, since an adequate length to width ratio is needed for the required pond depth (3:1 to 7:1). The basins are good for large watershed with constant hydrology, however, these systems are not advisable for dense urban areas and therefore would not be considered a viable option for the Buffalo and Whiteoak Bayou watersheds.

Wet detention ponds with filtration systems are systems that can be used to remove suspended solids, but not dissolved pollutants. Any small to medium drainage basin can use this design. This system is generally not recommended because of the ineffectiveness of the removal of the pollutants and the high maintenance of the filter. These systems have been shown to have removal efficiencies similar to wet detention ponds without filtration. They have been successfully applied in North Carolina by researchers studying ponds that receive drainage from residential and mixed use watersheds (Mallin et al 2002).

9.2.2 OPEN CHANNELS

Open channels are engineered to collect and treat storm water runoff or a particular drainage area. These channels can be used to convey storm water and remove pollutants by filtration through the grass and infiltration through the soil from a particular drainage area. The swales greatly reduce

the runoff time, thereby not overwhelming the receiving water body.

One type of open channel is the dry swale or grassy swale, which allows the entire volume of runoff to be filtered or infiltrated through the bottom of the swale. Grassy swales can be used as a pretreatment method for other downstream BMPs.

Another common type is the wet swale, wetland channel, or vegetated swale. This type of open channel accepts more intense or concentrated loads than grassy swales and requires a lower velocity flow and lower peak velocities to remain effective. TSS removal efficiencies for grassy swales are reported to be around 68%, and 74% for the vegetated filter strip. Bacteria removal using either swale has been reported to be poor, with bacterial growth, rather than removal, being noted in the filter strips by several researchers (US EPA 2003).

The vegetative filter strip or buffer strip is another commonly employed open channel BMP. These BMPs are flat land areas with low slopes designed to accept runoff as overland sheet flow. These strips can accept more intense or concentrated loads than grassy swales. The strips must receive low velocity flows for them to remain effective.

Researchers have reported that filter strips can be an effective method of bacteria removal. Agricultural applications of these filter strips are prevalent, while urban applications are not frequently reported in the literature. A vegetative filter strip was used to polish effluent from a constructed wetland (Cameron et al, 2003). This filter strip achieved removals of TSS at 22%, FC at 28% and EC at 22%. Lim et al (1997) showed that filter strips were effective in removing FC, with influent concentrations as high as $2x10^7$ cfu/dL from pasture runoff, using filter strips 6 m long. Vegetative filter strips have also been reported to not be effective in all situations. Chaubey et al

(1994) demonstrated that filter strips 3 m and 21 m did not significantly reduce the concentration of FC in the incoming runoff from fields that had been treated with swine manure.

9.2.3 SAND FILTERS

Sand filters or filtration basins are designed to capture and temporarily store storm water runoff and pass it through a filter bed of sand. Most sand filters consist of two chamber structures. The first is a sediment forebay that removes floatable and heavy sediments. The second chamber removes additional pollutants by filtering runoff through a sand bed.

There are three kinds of sand filters, a surface sand filter, a perimeter sand filter, and an underground sand filter. A surface sand filter is a ground level open-air structure that consists of a pretreatment sediment forebay and a filter bed chamber. A perimeter sand filter is an enclosed filter system typically constructed just below grade in a vault along the edge of an impervious area such as a parking lot. An underground sand filter is intended for extremely space limited and high-density areas.

There is a high capital cost and maintenance burden associated with these filters. Frequent back washing must be performed to maintain the design flow and removal rates. Sand filters are frequently used to treat drinking water, but have also been applied for wastewater treatment. In a field application of the sand filter to on-site sewage system, the sand filter exhibited removal rates for FC around 91% (Harrison et al, 2000). Other studies show a removal efficiency for TSS between 79% to 88%, while for bacteria the removal efficiencies are only around 40%.

9.2.4 CONSTRUCTED WETLANDS

Constructed wetlands provide physical, chemical and biological water quality treatment. They are designed to treat both urban storm water and control runoff volumes. Water treatment is achieved through settling and uptake by marsh vegetation. These engineered wetlands require a continuous base flow or a high water table to support the aquatic vegetation. The wetlands are good methods for residential use with a moderate capital cost and maintenance burden. The gravel wetland or pocket wetland is good for residential and high density/ultra urban areas with a moderate capital cost and high maintenance burden.

Various studies report a wide range of removal efficiencies. A study conducted on two wetlands designed for municipal wastewater and stormwater treatment exhibited FC reductions of 97 to 99.9% (Stenstrom and Carlander, 2001). Another study involved the design of a three-cell free surface wetland for treatment of municipal wastewater in a rural setting (Cameron et al, 2003). This wetland demonstrated removals of TSS at 93%, FC at 52% and EC at 58%. Two subsurface flow constructed wetlands that included a sand filter were intended to treat wastewater from a small housing community (Jillson et al, 2001). The removal rate achieved was over 96% in the wetland alone and 98% in the wetland and sand filter together. The other wetland demonstrated removal efficiencies at 99.3%.

9.2.5 ALUM TREATMENT

Alum treatment systems provide a chemical treatment of storm water runoff by injecting liquid alum into storm water lines. Non-toxic precipitates of aluminum hydroxide and aluminum phosphate are formed that combine with pollutants causing the sedimentation of contaminants. The

system is good for providing treatment in high density/ultra-urban areas, but has very high maintenance requirements. No land is required for the system because it is fit onto an existing system. Alum treatment has been shown to provide bacteria removal greater than 99% and TSS removal around 90%.

9.3 CONTROLS UNDER THE STORMWATER JOINT TASK FORCE

Under the NPDES/TPDES Municipal Separate Storm Sewer Systems (MS4) permit program, the City of Houston, Harris County, HCFCD, and the Texas Department of Transportation (TxDOT) have formed a Joint Task Force (JTF) to regulate discharge of storm water runoff. The JTF issued local storm water regulations effective October 1, 2001 that require the use of storm water BMPs for both construction and post construction activities. The post construction or permanent BMPs are required only for areas of new developments or significant redevelopments, the definitions of which are documented in the JTF regulations. In general, New Development is the development of an undeveloped parcel of land that is greater than 5 acres in size, Significant Redevelopment is a change of one acre or more to the impervious surface on a 5-acre or larger developed parcel.

Under the JTF regulations and the TPDES Phase II general permit for construction activities, all construction that will disturb one acre or larger of land surface will be required to develop and implement a Storm Water Pollution Prevention Plan (SWP3) and submit an Notice of Intent (NOI) to the Texas Commission on Environmental Quality (TCEQ). The SWP3 should include a description of the construction site, BMPs to control pollutants including controls, maintenance and inspections, identification of non-storm water discharges, and identification of appropriate pollution

prevention measures. The "Storm Water Management Handbook for Construction Activities" (JTF, 2001) outlines the guidance for controlling pollutants at construction sites and provides aids for the preparation of SWP3s. Typical construction BMPs recommended by JTF include phasing of construction activities, flow diversion, overland flow management, permanent drainage way establishments, inlet protection, sediment trapping, and general source control measures.

For New Developments and Significant Redevelopments, a set of construction plans that include an SWP3 and a Storm Water Quality Management Plan (SWQMP) should be prepared and submitted for approval. The SWQMP should include a description of the site, both structural and non-structural BMPs for storm water quality control, and a long-term maintenance and inspection plan.

The JTF has published "Storm Water Quality Management Guidance Manual" and "Minimum Design Criteria for Implementation of Certain Best Management Practices for Storm Water Runoff Treatment Options" in 2001. The "Storm Water Quality Management Guidance Manual" provides a list of possible BMPs for SWQMP development. Non-structural BMPs are listed in Section 4.1 and structural BMPs are listed in Sections 4.2 - 4.6 of the document. Structural BMPs listed in the document include Dry Basins, Wet Ponds, Constructed Wetlands, Catch Basins, Oil/Grit Separators, Grassed Swales and Vegetated Filter Strips. Non-structural BMPs recommended by JTF include the following:

- Street stenciling
- Inlet stenciling
- Household hazardous materials storage/disposal

- Litter control
- Landscaping practices
- Fueling station practices
- Vehicle/equipment washing and steam cleaning processes
- Liquid loading, unloading, and storage practices

The Minimum Design Criteria document includes design parameters for the following structural BMPs:

- Grass Swales - Grass-lined channels designed for water quality purpose.
- Filter Strips - Vegetative strips intended to treat sheet flow.
- Dry Detention Basins - Dry ponds except following storm events.
- Wet Ponds - Ponds having a permanent wet bottom.
- Wetlands Treatment Systems - Shallow marsh areas for storm water treatment.

While these non-structural and structural BMPs are aimed at improving water quality, they are not specifically developed for bacteria. In fact, most BMPs target sediment as the primary constituent. While not selected for bacteria control, actions that reduce sediment are also effective at reducing bacteria, as both sediment and bacteria are suspended particulate matter. Furthermore, some of the above structural BMPs act to reduce the peak flow rate and the total volume of runoff flow, thus reducing the scour of bacteria from the streambed.

Based on the information from the JTF, the following summarizes the status of BMPs in Harris County.

9.3.1 HARRIS COUNTY - CONSTRUCTION BMPS

Contractors and land developers are required to submit a copy of their NOIs to the jurisdictional authority at the same time they submit the NOI to TCEQ. Currently Harris County does not use the NOIs for any purpose because they are incomplete. Instead, the County looks at a project's acreage when it comes up for permits to determine whether the site should be inspected periodically during construction. The County performs thousands of inspections and re-inspections every year and issues hundreds of violations. Violations are typically issued for failure to install and/or maintain BMPs (silt fences, etc.) but can be for uncontained trash and chemicals, waste paints, etc.

9.3.2 HARRIS COUNTY - POST-CONSTRUCTION BMPS

According to Scott Bean of Harris County Engineering and Plan Review, Harris County reviews construction plans for all projects located in unincorporated areas of Harris County. If the project meets the definition of "new development" or "redevelopment" and is not "grandfathered", then an SWQMP must be prepared including the design of a structural control to "clean-up" the first ½" of runoff from the project area. If everything checks out with the design (calculations and design criteria), Harris County will approve the plans and a storm water quality permit can be issued. Once the project is complete, a Professional Engineer (PE) should submit an as-built certificate to Harris County certifying that the structural control was completed per the approved drawings. Harris County will conduct a final inspection and issue a certificate of compliance if everything checks out.

Harris County has signed-off on plans for approximately 150 projects involving permanent structural BMPs. About 100 are still under construction and 30 are complete. These numbers are for

the unincorporated areas of Harris County, and no watershed-specific numbers are available. The approximate distribution of these structural BMPs is as follows: 70% dry detention basins, 20% hydrodynamic separation facilities (e.g. CDS Technology), 10% all other BMPs (swales, buffers).

The permanent BMPs should be maintained by either the property owner, Municipal Utility Districts (MUD), or Home Owners' Associations (HOA). In some instances, HCFCD might take over the maintenance of the BMPs, but such instances have not been defined yet. Harris County conduct random inspections of the permanent BMPs and renew the permits every year when the permit holder submits PE certifications and annual reports.

Harris County is developing a process to ensure that the permanent BMPs are built and maintained properly. However, in reality, the owners of the BMPs for smaller facilities such as warehouses, mini-storage properties, strip centers, etc., may not maintain the BMPs correctly or follow the clean-up schedule. Harris County expects that it will probably take a few inspections before the BMP owners realize the need to maintain the BMPs properly.

9.3.3 CITY OF HOUSTON

Under the JTF, the City of Houston has a storm water permitting program that is similar to Harris County. According to Zia Mohammadi of the City of Houston, the City performs approximately 130 inspections per year, mostly while BMPs are being constructed. About 60% of the permanent BMPs are hydrodynamic separators, 20% dry ponds, and 20% others (swales, filter strips, etc.). The City also focuses on educating the public and contractors through seminars, brochures and public school programs.

9.3.4 HCFCD - BMP EFFECTIVENESS EVALUATION

HCFCD has a monitoring protocol to evaluate the effectiveness of structural BMPs designed to improve storm water runoff quality. Currently, several site-specific monitoring plans are being developed. Monitoring is expected to begin once the plans have been approved by HCFCD. The monitoring is expected to provide local data for evaluating the effectiveness of BMPs in the Houston area. Such data are very limited or non-existent at the present time.

The draft monitoring plans calls for sampling bacteria where the holding time (6-8 hours) requirement can be met. This will limit the amount of data for bacteria removal that can be obtained.

9.3.5 TCEQ - CONSTRUCTION NOIs

According to Cindy Lee of TCEQ Wastewater Permitting (512-239-4524), TCEQ has just begun the process of entering the NOIs submitted under the TPDES General Permits for Construction Activities into a tracking database. The backlog of NOI data is anticipated to be completely entered by August 2003. The data entry is expected to continue indefinitely.

9.4 CONCLUSIONS

This chapter detailed the various BMP options for the Houston area as well as examples of some BMPs that are being implemented across the BB and WOB watersheds. These BMPs provide a wide range of applicability and options for implementation. The HSPF modeling to determine load and wasteload allocations demonstrates the need for stormwater controls as well as nonpoint source controls.

The load allocations for Buffalo and Whiteoak Bayou demonstrated that reductions in loads are needed for the WWTP, DWSS discharges, NPS loads and the reservoir discharges. Some of the BMPs discussed in this chapter may address these load reductions and are described in the following paragraphs.

Most importantly, NPS load reductions (either at the end of an MS4 pipe or from runoff directly into the bayou) is the largest load reduction required. Many of the BMPs discussed in this chapter may be used for NPS load reductions, including constructed wetlands, alum treatment, detention basins, vegetated buffers and swales. None of these alone can achieve the very high levels of reductions (up to 99.99%) required to meet the TMDL endpoints across the bayou. It may be necessary to implement two of these BMPs in series. Another approach may be to reduce NPS at the source. This would require community involvement to increase citizen awareness as well as practices to reduce nonpoint source pollutants, such as street cleaning.

WWTP load reductions are also required to meet the TMDL endpoints. The operational BMPs described in this chapter should continue to be rigorously implemented at all plants. Work Order 6 will also investigate solids disposal practices at WWTP that may also impact WWTP load reductions.

DWSS discharge controls are required to achieve load reductions. Reductions may be achieved by alum treatment or constructed wetlands. However, practices to control the sources of the leaks should receive the majority of the effort to reduce DWSS loads. This would involve monitoring, inspection and maintenance. Additionally, implementing the EPA initiative termed Capacity Assurance, Management, Operation, and Maintenance (CMOM) is expected to result in

additional load reductions. It should be noted that this initiative is in the review stage at EPA, and therefore this program may not address the needs of this TMDL for several years.

Finally, the two upstream reservoirs on Buffalo Bayou have been shown to discharge high concentrations of bacteria (See Final Report for Work Order 5, January 2003). These concentrations must be reduced in order for Buffalo Bayou to meet the water quality targets for bacteria. There are two options for reducing the loads from the reservoirs: treating the reservoir as a point source or considering the entire reservoir watersheds. Treating the reservoir as a point source would require treating the reservoir discharge using a BMP, such as alum or an in-line detention basin, or managing the reservoir to improve water quality. The necessary load reductions of 75% and 88% for Addicks and Barker reservoirs, respectively, could be met using the two BMPs mentioned.

The other option is considering the entire reservoir watershed, This upper watershed has not been the focus of the TMDL study for Buffalo and Whiteoak Bayou watersheds because the Buffalo Bayou 1013 segment begins at Highway 6. This option would require investigating sources of bacteria within the upper watersheds and expanding the scope of the TMDL to include those areas.

CHAPTER 10

DRAFT BST SAMPLING PLAN

As Chapter 5 demonstrated, there are numerous sources of bacteria in the Buffalo and Whiteoak Bayou watersheds. These sources include WWTP effluent, DWSS discharges, and nonpoint source pollution. Nonpoint sources of pollution are by nature diffuse and diverse. DWSS discharges may have human sources, but may also reflect nonpoint source pollution that is transported through the storm sewer system. The purpose of the bacteria sampling plan is to better identify the exact sources of pollution in the two watersheds to aid in the development of bacteria abatement strategies.

There are currently two methods of bacterial source tracking (BST) that are being considered for application in the watersheds, pulse-field gel electrophoresis (PFGE) and antibiotic resistance analysis (ARA) representing genotypic and phenotypic methods respectively. A description of the two methods and a review of current literature were presented in Chapter 4.

10.1 SOURCE SAMPLING

Both of the proposed methods are library dependent, meaning that source material must be collected and profiled to provide a comparison for the water quality samples. As shown in Table 10.1, there are approximately 28 different mammalian species that are found in the type of habitat typically found in the Buffalo and Whiteoak Bayou watersheds. This list was developed from studies conducted in a nearby watershed and discussions with those familiar with the watershed (Armand

Bayou Nature Center, 2002). In addition, there are numerous species of migratory and nonmigratory birds that are known to be native to the watershed.

Investigations into the population of some sources were undertaken. Domesticated dogs (*Canus familiarus*) are a prevalent species in the watershed, as are cats (*Felis cattus*). From July 2002 to June 2003, there were 51,544 domesticated dogs and cats licensed within the City of Houston. In addition, according to an article on the Houston SPAC, about 48,000 animals were dropped off at the CAP & Special Pals program in 1993. This indicates that a reasonable estimate for the number of dogs and cats within the Houston area is probably somewhere around 100,00 animals. Dogs are generally believed to be a greater potential source of indicator bacteria to surface waters than cats, therefore this species will be included in the source sampling.

Although the Houston area is highly urbanized, there are some areas that can be considered agricultural or where individuals may have livestock their property. The Texas Agricultural Statistics Service (http://www.nass.usda.gov/tx/mcounty.htm) reported the following livestock populations for District 9, which encompasses 13 counties in Southeast Texas, including Harris County as of 1/1/2002:

Cattle: 54,000 (all cattle & calves) with 33,000 of those as beef cattle

Goats: 3,000 (all goats)

Hogs & Pigs: 2,000 (total in District 9)

Poultry: 3,642,000 (total in District 9)

Sheep: 2,500 (total in District 9).

Additionally, there are some known areas of livestock in the Buffalo and Whiteoak Bayou watersheds. In the upper part of Whiteoak Bayou, cattle were observed to be present during field

reconnaissance. Sam Houston Race Park, a facility for horse racing, is also present in the watershed. It is estimated that 500 horses reside at the park, although discussions with the Park's WWTP personnel indicated that all runoff and cleaning water from the stables are routed to the Park's municipal WWTP. Finally, the Houston Polo Club maintains a polo field as well as stables and paddocks near Memorial Park in the Buffalo Bayou watershed. Therefore, cattle and horses are proposed for source sampling.

The Houston area is known to have a large population of bats (around 600,000). Bats prefer to roost under bridges and in trees, both of which are near water in the Houston area. The most common species of bats in the Houston area is the Mexican Free-Tailed Bat, with other less important species described in Table 10.1. Migratory species of bats are present in greatest numbers from April to September. A very rough estimate of numbers of Houston bats is between 500,000 and 1,000,000. Field reconnaissance demonstrated the presence of bats under several bridges within the BB and WOB watersheds, including the bridges over Buffalo Bayou at Waugh and Briar Forest. Bats may be a large contributor, in terms of NPS loading, to the watersheds and are therefore being considered for source sampling.

The Upper Texas Gulf Coast is well known as an excellent location for seeing a variety of birds. According to Brent Ortigo of Texas Parks & Wildlife Department[4], the U.S. Geological Survey (USGS) maintains a database of Breeding Bird Surveys, which are most effective for showing trends of bird populations but not total population numbers. The surveys are conducted

[4] Phone number is 361-576-0022

Table 10.1 Mammalian Sources of EC in BB and WOB Watersheds.

Common Name	Species
Armadillo	*Dasypus novemoinctus*
Big brown bat	*Epesicus fuscus*
Big free-tailed bat	*Nyctinomops macrotis*
Bobcat	*Lynx rufus*
Coyote	*Canis latran*
Eastern cottontail	*Sylvilagus floridanus*
Eastern flying squirrel	*Glaucomys volans*
Eastern gray squirrel	*Sciurus carolinensis*
Eastern Pipistrelle (bat)	*Pipistrellus subflavus*
Eastern red bat	*Lasiurus borealis*
Evening bat	*Nycticeius humeralis*
Fox squirrel	*Sciurus niger*
Hispid cotton rat	*Sigmodon hispidus*
Hoary bat	*Lasiurus cinereus*
Mexican free-tailed bat	*Tadarida brasiliensis*
Norway rat/brown rat	*Rattus norvegicus*
Nutria	*Myocaster coypus*
Opossum	*Didelphis marsupialis*
Raccoon	*Procyon lotor*
Red Fox	*Vulpes fulva*
River Otter	*Lutra canadensis*
Short-tailed shrew	*Blarina brevicauda*
Striped skunk	*Mephitis mehitis*
Swamp rabbit	*Sylvilagus aquaticus*
White-footed mouse	*Peromyscus leucopus*
White-tailed deer	*Odocoileus virginianus*
Domesticated dog	*Canis familiaris*
Domesticated cat	*Felis cattus*
Horse	*Equus equus*
Cow	*Bos taurus*

Sources of data: Armand Bayou Nature Center Natural Resource Management Plan, March 2002
Barbara French of Bat Conservation International
Texas Agricultural Statistics Service

during the summer by making 3-minute bird counts during 50 stops over a 24.5 mile path (all stops were along roadways). Christmas Bird Counts were also conducted during the winter with a different process but the collected data are also for population trend analysis but not total population determination. A total of 132 different species of birds were counted during the Christmas Bird Count in 2003 at a location near Buffalo Bayou (Texas Birds, 2003). Mr. Ortigo does not know of any other database that may contain bird population data in the BB or WOB watersheds. A list of bird species compiled for Armand Bayou, a bayou located in the Houston area, is included in Appendix B. Although birds are not mammals, they have been shown to excrete fecal indicator bacteria and pathogens (Butterfield, Coulson et al. 1983; Kapperud and Rosef 1983; Girdwood, Fricker et al. 1985; Kirkpatrick 1986; Furness and Monaghan 1987; Whelan, Monaghan et al. 1988; Levesque, Brosseau et al. 1993; Grant, Sanders et al. 2001; Haack, Fogarty et al. 2003). Waterfowl may represent a major direct source of bacteria to the bayous and runoff may carry bird feces deposited on pervious and impervious surfaces to the bayous as well. Therefore, birds are considered a major potential source because of the large bird populations and the potential for direct deposition of feces into the bayous.

The population of the City of Houston is over 1.9 million people. Over 50 WWTP are scattered throughout the two watersheds to manage and treat the sewage. Even so, humans represent a major potential source and characterization of human profiles is necessary for a thorough BST project. Influent from WWTP will be collected and profiles to provide data on the human contribution in the watersheds.

Based upon the review of the bacterial sources in the watershed, six groups of organisms were selected for sampling. These groups may comprise several species, or one singular species. The sources that will be profiled using ARA and PFGE will include the following categories of

organisms:

- Bat (includes all 7 species)
- Dog
- Human (WWTP influent)
- Horse
- Cow
- Bird (may include any species native to the watershed, with focus primarily on waterfowl)

Three events of source sampling will take place, once in the fall, spring and summer of 2003-2004. Approximately 10 isolates of EC will be cultured from each source sample, yielding a total of 30 isolates from each source.

It should be noted that although only six sources will be sampled in the watershed, Texas A&M - Corpus Christi has developed an extensive database that comprises numerous species. Studies have shown that BST libraries are not necessarily specific to geographic locations (Gordon, 2001; Wiggins et al, 1999). The portability of the source library will be examined using the six source profiles collected in the BB and WOB. If the data are comparable, the entire source library from Texas A&M - Corpus Christi will be employed for the BST effort.

10.2 BST SAMPLING

There are six proposed sampling locations along the bayous (Figure 10.1). Each location will be sampled twice: once during dry weather (both sediment and water), once during wet weather. If sediment cannot be collected at the Heights location (due to the presence of the concrete lining), the

sediment sample will be collected right before the concrete lined section of the bayou instead. Two wet weather samples will be collected at Site 5, once when the reservoirs are open (a small rain event) and once when the reservoirs are closed (large rain event). Additionally, sampling of one storm sewer discharging under dry weather is also proposed in each watershed.

These proposed sampling locations were chosen to fulfill the goals of the sampling, namely to identify the sources of bacteria to the watershed under different conditions. Wet weather samples will provide data that can be used to identify nonpoint sources of pollution, as will samples collected at sites without any WWTPs upstream. Dry weather samples will be aimed to identify the primary sources of bacteria and will be compared to the wet weather sources. It is anticipated that sediment data will provide insight as to whether it is a source of EC and whether the sediment EC bacteria originate from sources different from those of the EC suspended in the water column.

Land use was a consideration in the selection of the sampling sites. Sites 1 and 4 are located on streams draining small watersheds (< 14 square miles) that are primarily residential and have no wastewater treatment plants on the reach. Site 6 is situated on a small, unnamed tributary that flows through Memorial Park before reaching Buffalo Bayou, so that the majority of the drainage area is considered open land. Sites 3 and 5 are located on the main stem of the two bayous and are intended to characterize the overall sources in the watershed. Finally, site 2 is located downstream of several wastewater treatment plants on Cole Creek. This site will be compared with sites 1 and 4 to observe the impact of WWTPs on the ARA and PFGE profiles.

This plan is a preliminary plan that is subject to revision and constitutes a suggested approach to the sampling. The BST final plan will be presented in the QAPP in Work Order #6 r this TMDL.

Figure 10.1 BST Sampling Locations

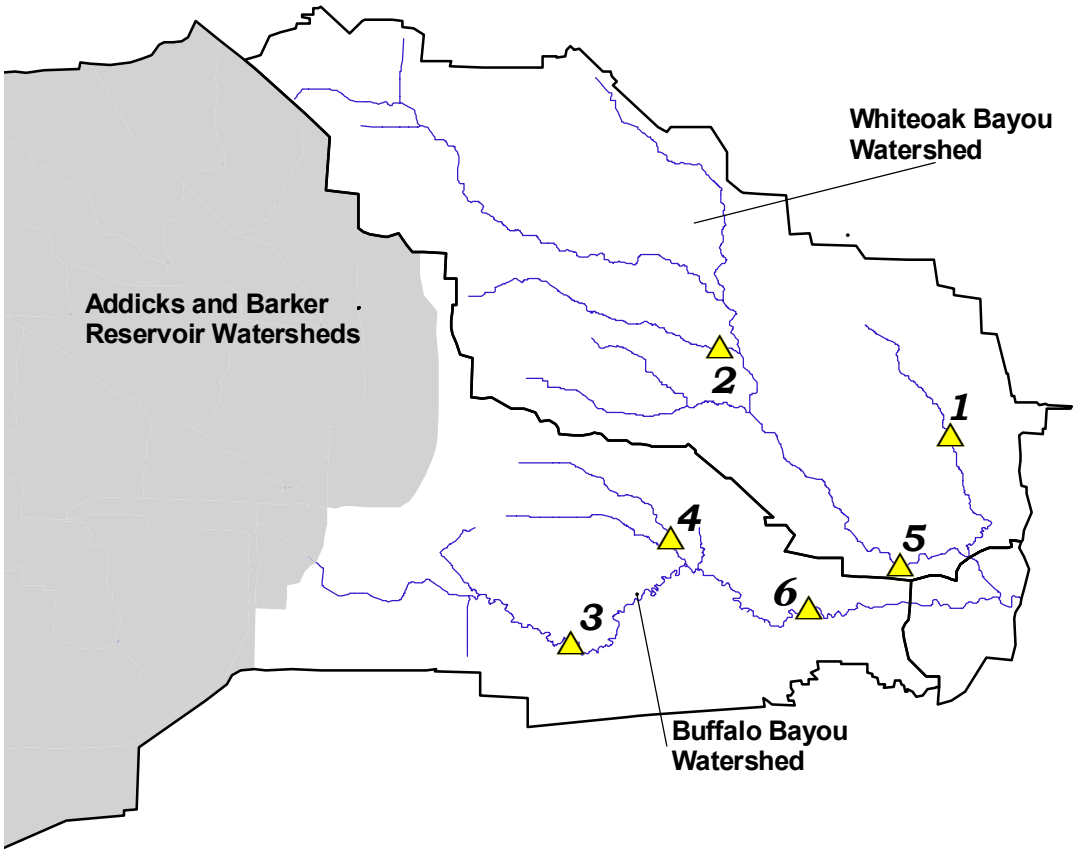


Table 10.2. BST Sampling Location Details

Sampling Station	Watershed	Wet Weather Sample	Dry Weather Sample	Sediment Sample	WWTP on Reach	Flow Gage	TCEQ Station ID	Location
1	WOB	1	1	1			NA	LWOB @ Stokes Rd
2	WOB	1	1	1	X		16593	CC @ Bolivia
3	BB	2[a]	1	1		X	11358	Piney Point
4	BB	1	1	1			16592	Spring Branch @ Wirt Rd
5	WOB	1	1	1		X	11387	Heights
6	BB	1	1	1			NA	Unnamed Trib @ Memorial
SS-WOB	WOB		1					
SS-BB	BB		1					
	Total Samples	7	8	6				

[a] - Samples during wet weather will be collected twice: once when reservoirs are open, once when closed

10.3 ANTIBIOTIC RESISTANCE PROFILING (ARP) MICROBIOLOGICAL ANALYSES DIGITAL DATABASE SETUP

Approximately 300 Escherichia coli isolates stored at Texas A&M University-Corpus Christi from previous research (Price and Mott, 2002) were recharacterized using an expanded panel of antibiotics and the BIO-MIC instantaneous plate reader and NCCLS software to standardize the data. The isolates had been obtained from fecal samples of a range of animals including: dog, fox, cow, goat, laughing gull, coot, brown pelican, cormorant, white ibis, javelina, deer, swine, cat, sheep, white pelican, human, raccoon, coyote, and horse. The samples were collected from the south Texas region.

Antibiotic test plating, using a panel of 20 antibiotics (Table 1), was performed for each isolate following NCCLS M2-A7 (2002) and M31-A2 (2002) methodology and quality controls. Duplicates were included for 20% of the isolates. The quality control strains were Pseudomonas. aeruginosa ATCC 27853, Staphylococcus. aureus ATCC 25923, and E. coli ATCC 25923. Controls were run weekly and for each new lot number of media or antibiotics. BIOMIC was used for an instantaneous reading and interpretation following NCCLS M100 (2002). This system calculates antibiotic minimum inhibitory concentrations (MICs) and records zone diameters automatically from the standard disk diffusion method. BIOMIC also determines whether each isolate is susceptible, intermediate or resistant (S-I-R) based on published NCCLS guidelines. EXPERT software checked quality control, test results and unlikely results. A sample print-out is included in Figure 10.2. This method has proven to improve reading consistency and speed thereby minimizing technologist variation.

The results of this recharacterization yields a completed database stored in the BIOMIC

system with back-ups saved on the hard drive and on CD.

Table 10.3

Antibiotics Used to Establish Antibiotic Resistance Profiles of

E. coli Isolates from South Texas

Antibiotic	**Concentration (ug)**
Amoxicillin-clavulanate	30
Amplicillin	10
Chloramphenicol	30
Ciprofloxacin	5
Enrofloxacin	5
Gentamicin	10
Kanamycin	30
Nalidixic acid	30
Neomycin	30
Tetracycline	30
Cefazolin	30
Cefotaxime	30
Ceftazidime	30
Ceftriaxone	30
Doxycycline	30
Imipenem	10
Spectinomycin	100
Streptmycin	10
Sulfasoxazole	0.25
Trimethoprim-sulfamethoxazole	1.25/23.75

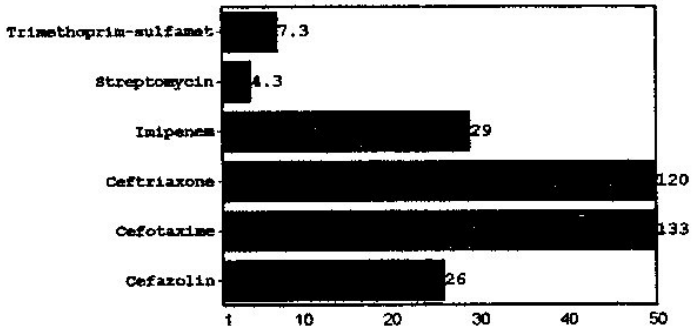
Aug 12, 2003

Specimen Date	29 May, 2003	Initialed	TF /
Specimen Number	Aa1	Isolate Number	1
		Specimen Type	STOOL
Organism	Escherichia coli		

ANTIBIOTICS	CATEGORY	MM	MIC (mcg/ml)	SERUM IQ *
Cefazolin	S	22	4.3	26
Cefotaxime	S	30	0.60	133
Ceftazidime	S	28		
Ceftriaxone	S	30	< 1.0	> 120
Doxycycline	S	17	3.2	0.63
Imipenem	S	28	< 0.56	> 29
Spectinomycin	S	29		
Streptomycin	S	19	3.5	4.3
Sulfasoxazole	S	29		
Trimethoprim-sulfamethoxazole	S	28	< 4.1	> 7.3

RELATIVE ACTIVITY

SERUM IQ *



* IQ, Inhibitory Quotient = Tissue Concentration at lowest usual dosage / MIC.

Figure 10.2. Sample BIOMIC Print-Out

CHAPTER 11

CONCLUSIONS

The indicator bacteria problem in the Buffalo and Whiteoak Bayous is a complex problem, emanating from several diverse sources. These sources have been identified through examination of monitoring data, sampling in the two watersheds, and modeling. One potential source that has been the subject of much investigation for this TMDL is sediment. Sediment has been discussed as a potential source of indicator bacteria since the 1970's. The literature has documented that bacteria can thrive on suspended as well as bed sediments for extended periods of time. Stream banks have also been identified as a potential bacteria source.

Loads of indicator bacteria from the various sources in the two watersheds were calculated based upon available monitoring data. The loads were estimated from point sources, self-reporting overflows and bypasses, and nonpoint sources. Loads could not be calculated from solids release data. Loads from nonpoint sources in both watersheds were found to be the largest source of indicator bacteria, followed by the Addicks and Barker reservoirs in Buffalo Bayou. In Whiteoak Bayou, the second largest source was DWSS flows. WWTP effluent and by-passes and overflows contributed the smallest loads.

Low flow conditions were also examined in this report. The findings of this analysis indicate that there is a difference between low and high flow concentrations in the bayou. Several different analyses were conducted to determine if a single value could be found that would represent low flow conditions in both bayous. Based upon the analyses, it was determined that flows less than the

median in the bayous represented a typical low flow condition.

The calibrated HSPF models were presented in the document. Several adjustments have been made in the past work order, with the most significant being the update of the Buffalo Bayou model to use the Addicks and Barker Reservoirs as an upstream boundary condition. The updated models were used to determine load and wasteload allocations for both bayous. The calibrated models were modified to include permitted, rather than 5-year average, flows from WWTPs and also assumed that WWTPs discharging concentrations less than the long-term geometric mean standard were discharging 126 MPN/dL. These "baseline" models were used for load allocations. The final allocations for both bayous showed that major reductions are required in NPS loads, with up to 99.99% reductions being required in some subbasins. Reductions in WWTP effluent loads and DWSS loads are also required, as is a reduction in the load from the two reservoirs in Buffalo Bayou.

BMPs in use across the country and in the Houston area were summarized in this report. It appears, based upon literature data, that the BMPs discussed in this chapter would provide adequate load reductions to meet the TMDL endpoints. Implementing a single BMP for NPS reduction may not be adequate to meet some of the higher reductions, and therefore BMPs could be installed in series or programs to reduce NPS deposition could be implemented. WWTP load reductions might be achieved through stringent enforcement of the operational BMPs and maintenance of the plants. DWSS loads could be reduced through increased monitoring, inspection and maintenance. If those efforts are inadequate, a treatment system may be implemented for the storm sewer pipes. Finally, load reductions from the reservoirs may be achieved through treating the reservoir discharge or identifying the sources of indicator bacteria in the reservoir watersheds.

Bacteria source tracking is an emerging technology that has the potential to determine the sources of bacteria for a watershed. There are several source tracking methods that have been used, including ribotying, pulse-field gel electrophoresis (PFGE), and antibiotic resistance analysis (ARA). Two of these technologies, PFGE and ARA, have been proposed for implementation on Buffalo and Whiteoak Bayous. A sampling plan has been proposed, which includes source sampling of six sources: cattle, horses, bats, humans, birds, and dog. A total of 6 sampling locations have been identified as potential sites for runoff, dry weather and sediment sampling. The sampling plan will be finalized in the Quality Assurance and Procedures Plan (QAPP) for the upcoming Work Order.

In conclusion, the Buffalo and Whiteoak Bayou watersheds have many diverse sources of indicator bacteria. The TMDL targets, the instantaneous standard and the long-term geometric mean standard at low flow, may both be met through load reductions in these two watersheds. The bacterial sources must be managed through BMPs in order to meet these TMDL targets. The BMPs discussed in this document are potential solutions. More detailed investigation into the appropriate BMPs and their costs are required before a specific solution for the two watersheds can be selected.

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APPENDIX A

STAKEHOLDER PRESENTATIONS

APPENDIX B

BIRD SPECIES OF ARMAND BAYOU NATURE CENTER

(excerpted from the Armand Bayou Nature Center Natural Resource Management Report, 2002.

Obtained from http://www.abnc.org/Preservation.htm)

Birds

COMMON NAME		GENUS/SPECIES		FAMILY
Acadian Flycatcher		*Empidonax virescens*		Tyrannidae
American Bittern		*Botaurus lentiginosus*		Ardeidae
American Coot		*Fulica americana*		Rallidae
American Crow		*Corvus brachyrhynchos*		Corvidae
American Goldfinch		*Carduelis tristis*		Fringillidae
American Kestrel		*Falco spaverius*		Falconidae
American Pipit		*Anthus rubescens*		Motacillidae
American Redstart		*Setophaga ruticilla*		Parulidae
American Robin		*Turdus migratorius*		Turdidae
American White Pelican		*Pelecanus erythrorhynchos*		Pelecanidae
American Woodcock		*Scolopax minor*		Scolopacidae
Anhinga		*Anhinga anhinga*		Anhingidae
Baltimore Oriole		*Icterus galbula*		Icteridae
Barn Owl		*Tyto alba*		Tytonidae
Barn Swallow		*Hirundo rustica*		Hirundinidae
Barred Owl		*Strix varia*		Strigidae
Bay-breasted Warbler		*Dendroica castanea*		Parulidae
Belted Kingfisher		*Ceryle alcyon*		Alcedinidae
Black Vulture		*Coragyps atratus*		Cathartidae
Black-and-white Warbler		*Mniotilta varia*		Parulidae
Black-bellied Whistling Duck		*Dendrocynga autumnalis*		Anatidae
Black-billed Cuckoo		*Coccyzus erythropthalmus*		Cuculidae
Blackburnian Warbler		*Dendroica fusca*		Parulidae
Black-chinned Hummingbird		*Archilochus alexandri*		Trochilidae
Black-crowned Night-heron		*Nycticorax nycticorax*		Ardeidae
Black-necked Stilt		*Himantropus mexicanus*		Recurvirostridae
Blackpoll Warbler		*Dendroica striata*		Parulidae
Black-throated Gray Warbler		*Dendroica nigrescens*		Parulidae
Black-throated Green Warbler		*Dendroica virens*		Parulidae
Blue Grosbeak		*Guiraca caerulea*		Cardinalidae
Blue Jay		*Cynocitta cristata*		Corvidae
Blue-gray Gnatcatcher		*Polioptila caerulea*		Sylviidae
Blue-headed Vireo		*Vireo solitarius*		Vireonidae
Blue-winged Teal		*Anas discors*		Anatidae
Blue-winged Warbler		*Vermivora pinus*		Parulidae
Bobolink		*Dolichonyx oryzivorus*		Icteridae
Brewer's Blackbird		*Euphagus cyanocephalus*		Icteridae
Broad-winged hawk		*Buteo platypterus*		Accipitridae
Brown Creeper		*Certhia americana*		Certhiidae
Brown Pelican		*Pelecanus occidentalis*		Pelecanidae
Brown Thrasher		*Toxostoma rufum*		Mimidae
Brown-headed Cowbird		*Molothrus ater*		Icteridae
Canada Goose		*Branta canadensis*		Anatidae
Canada Warbler		*Wilsonia canadensis*		Parulidae
Carolina Chickadee		*Poecile carolinensis*		Paridae
Carolina Wren		*Thryothorus ludocicianus*		Troglodytidae
Caspian Tern		*Sterna caspia*		Laridae
Cattle Egret		*Bubulcus ibis*		Ardeidae
Cedar Waxwing		*Bombycilla cedrorum*		Bombycillidae

COMMON NAME		GENUS/SPECIES		FAMILY
Cerulean Warbler		*Dendroica cerulea*		Parulidae
Chestnut-sided Warbler		*Dendroica pensylvanica*		Parulidae
Chimney Swift		*Chaetura pelagica*		Apodidae
Chipping Sparrow		*Spizella passerina*		Emberizidae
Chuck-will's-widow		*Caprimulgus carolinesis*		Caprimulgidae
Cliff Swallow		*Petrochelidon pyrrhonota*		Hirundinidae
Common Goldeneye		*Bucephala clangula*		Anatidae
Common Grackle		*Quiscalus quiscula*		Icteridae
Common Moorhen		*Gallinula chloropus*		Rallidae
Common Nighthawk		*Chordeiles minor*		Caprimulgidae
Common Snipe		*Gallinago gallinago*		Scolopacidae
Common Yellowthroat		*Geothlypis trichas*		Parulidae
Cooper's Hawk		*Accipiter cooperi*		Accipitridae
Crested Caracara		*Caracara plancus*		Accipitridae
Dark-eyed Junco		*Junco hyemalis*		Emberizidae
Dickcissel		*Spiza americana*		Cardinalidae
Double-crested Cormorant		*Phalacrocorax auritus*		Phalacrocoracidae
Downy Woodpecker		*Picoides pubescen*		Picidae
Eastern Bluebird		*Sialia sialis*		Turdidae
Eastern Kingbird		*Tryannus tryannus*		Tyrannidae
Eastern Meadowlark		*Sturnella magna*		Icteridae
Eastern Phoebe		*Sayornis phoebe*		Tyrannidae
Eastern Screech-Owl		*Otus asio*		Strigidae
Eastern Towhee		*Pipilo erythrophthalmus*		Emberizidae
Eastern Wild Turkey		*Meleagis gallopavo silvertris*		Phasianidae
Eastern Wood-Pewee		*Contopus virens*		Tyrannidae
European Starling		*Sturnus vulgaris*		Sturnidae
Field Sparrow		*Spizella pusilla*		Emberizidae
Forester's Tern		*Sterna foresteri*		Laridae
Fox Sparrow		*Passerella iliaca*		Emberizidae
Golden-crowned Kinglet		*Regulus satrapa*		Regulidae
Golden-winged Warbler		*Vermivora chrysoptera*		Parulidae
Grasshopper Sparrow		*Ammodramus savannarum*		Emberizidae
Gray Catbird		*Dumetella carolinensis*		Mimidae
Great Blue Heron		*Ardea herodias*		Ardeidae
Great Crested Flycatcher		*Myiarchus crinitus*		Tyrannidae
Great Egret		*Ardea alba*		Ardeidae
Great Horned Owl		*Bubo virginianus*		Strigidae
Greater White-fronted Goose		*Anser albifrons*		Anatidae
Greater Yellowlegs		*Tringa melanoleuca*		Scolopacidae
Great-tailed Grackle		*Quiscalus mexicanus*		Icteridae
Green Heron		*Butorides virenscens*		Ardeidae
Green-winged Teal		*Anas crecca*		Anatidae
Groove-billed Ani		*Crotophaga sulcirostris*		Cuculidae
Hairy Woodpecker		*Picoides villosus*		Picidae
Harris Sparrow		*Zonotrichia querula*		Emberizidae
Hermit Thrush		*Catharus guttatus*		Turdidae
Herring Gull		*Larus argentatus*		Laridae
Hooded Merganser		*Lophodytes cucullatus*		Anatidae
Hooded Warbler		*Wilsonia citrina*		Parulidae
House Sparrow		*Passer domesticus*		Passeridae
House Wren		*Troglodytes aedon*		Troglodytidae

COMMON NAME		GENUS/SPECIES		FAMILY
Inca Dove		*Columbina inca*		Columbidae
Indigo Bunting		*Passerina cyanea*		Cardinalidae
Kentucky Warbler		*Oporornis formosus*		Parulidae
Killdeer		*Charadrius vociferus*		Charadriiae
Lark Bunting		*Calamospiza melanocorys*		Emberizidae
Laughing Gull		*Larus atricilla*		Laridae
Least Bittern		*Ixobrychus exilis*		Ardeidae
Least Flycatcher		*Empidonax minimus*		Tyrannidae
Least Sandpiper		*Calidris minutilla*		Scolopacidae
Least Tern		*Sterna antillarum*		Laridae
LeConte's Sparrow		*Ammodramus leconteii*		Emberizidae
Lesser Scaup		*Aythya affinis*		Anatidae
Lesser Yellowlegs		*Tringa flavipes*		Scolopacidae
Lincoln's Sparrow		*Melospiza lincolnii*		Emberizidae
Little Blue Heron		*Egretta caerulea*		Ardeidae
Loggerhead Shrike		*Lanius ludovicianus*		Laniidae
Long-billed Dowitcher		*Limnodromus griseus*		Scolopacidae
Louisiana Waterthush		*Seiurus motacilla*		Parulidae
Magnificant Frigatebird		*Fregata magnificens*		Fregatidae
Magnolia Warbler		*Dendroica magnolia*		Parulidae
Mallard		*Anas platyrhynchos*		Anatidae
Marsh Wren		*Cistothorus palustris*		Troglodytidae
Merlin		*Falco columbarius*		Falconidae
Mississippi Kite		*Ictinia mississippiensis*		Accipitridae
Mottled Duck		*Anas fulvigula*		Anatidae
Mourning Dove		*Zenaida macroura*		Columbidae
Mourning Warbler		*Oporornis philadelphia*		Parulidae
Nashville Warbler		*Vermivora ruficapilla*		Parulidae
Neotropic Cormorant		*Phalacrocorax brasilianus*		Phalacrocoracidae
Northern Bobwhite		*Colinus virginianus*		Odontophoridae
Northern Cardinal		*Cardinalis cardinalis*		Cardinalidae
Northern Flicker		*Colaptes auratus*		Picidae
Northern Harrier		*Circus cyaneus*		Accipitridae
Northern Mockingbird		*Mimus polyglottos*		Mimidae
Northern Parula		*Parula americana*		Parulidae
Northern Pintail		*Anas acuta*		Anatidae
Northern Rough-winged Swallow		*Stelgidopteryx serripennis*		Hirundinidae
Nothern Waterthrush		*Seiurus noveboracensis*		Parulidae
Orange-crowned Warbler		*Vermivora celata*		Parulidae
Orchard Oriole		*Icterus spurius*		Icteridae
Osprey		*Pandion haliaetus*		Accipitridae
Ovenbird		*Seiurus aurocapillus*		Parulidae
Painted Bunting		*Passerina ciris*		Cardinalidae
Palm Warbler		*Dendroica palmarum*		Parulidae
Peregrine Falcon		*Falco peregrinus*		Falconidae
Pied-billed Grebe		*Podilymbus podiceps*		Podiciedidae
Pileated Woodpecker		*Dryocopus pileatus*		Picidae
Pine Siskin		*Carduelis pinus*		Fringillidae
Pine Warbler		*Dendroica pinus*		Parulidae
Prothonotary Warbler		*Protonaria citrea*		Parulidae
Purple Finch		*Carpodacus purpureus*		Fringillidae
Purple Gallinule		*Porphyrula martinica*		Rallidae

COMMON NAME		GENUS/SPECIES		FAMILY
Purple Martin		*Progne subis*		Hirundinidae
Red-bellied Woodpecker		*Melanerpes carolinus*		Picidae
Red-breasted Nuthatch		*Sitta canadensis*		Sittidae
Red-eyed Vireo		*Vireo oivaceus*		Vireonidae
Red-headed Woodpecker		*Melanerpes erythrocephalus*		Picidae
Red-shouldered Hawk		*Buteo lineatus*		Accipitridae
Red-tailed Hawk		*Buteo jamaicensis*		Accipitridae
Red-winged Blackbird		*Agelaius phoeniceus*		Icteridae
Ring-billed Gull		*Larus delawarensis*		Laridae
Rock Dove		*Columba livia*		Columbidae
Roseate Spoonbill		*Ajaia ajaja*		Threskiornithidae
Rose-breasted Grosbeak		*Pheucticus ludovicianus*		Cardinalidae
Royal Tern		*Sterna maxima*		Laridae
Ruby-crowned Kinglet		*Regulus calendula*		Regulidae
Ruby-throated Hummingbird		*Archilochus colubris*		Trochilidae
Rufous Hummingbird		*Selasphorus rufus*		Trochilidae
Sandhill Crane		*Grus canadensis*		Gruidae
Savannah Sparrow		*Passerculus sandwichensis*		Emberizidae
Scarlet Tanager		*Piranga olivacea*		Thraupidae
Scissor-tailed flycatcher		*Tryannus forticatus*		Tyrannidae
Sedge Wren		*Cistothorus platensis*		Troglodytidae
Sharp-shinned hawk		*Accipiter striatus*		Accipitridae
Snow Goose		*Chen caerulescens*		Anatidae
Snowy Egret		*Egretta thula*		Ardeidae
Solitary Sandpiper		*Tringa solitaria*		Scolopacidae
Song Sparrow		*Melospiza melodia*		Emberizidae
Sora		*Porzana carolina*		Rallidae
Spotted Sandpiper		*Actitus macularia*		Scolopacidae
Sprague's Pipit		*Anthus spragueii*		Motacillidae
Summer Tanager		*Piranga rubra*		Thraupidae
Swainson's Hawk		*Buteo swainsoni*		Accipitridae
Swainson's Thrush		*Catharus ustulatus*		Turdidae
Swainson's Warbler		*Limnothlypis swainsonii*		Parulidae
Swallow-tailed Kite		*Elanoides forficatus*		Accipitridae
Swamp Sparrow		*Melospiza georgiana*		Emberizidae
Tennessee Warbler		*Vermivora peregrina*		Parulidae
Tree Swallow		*Tachycineta bicolor*		Hirundinidae
Tricolored Heron		*Egretta tricolor*		Ardeidae
Tufted Titmouse		*Baeolophus griseus*		Paridae
Turkey Vulture		*Cathartes aura*		Cathartidae
Veery		*Catharus fuscescens*		Turdidae
Vermillion Flycatcher		*Pyrocephalus rubinus*		Tyrannidae
Vesper Sparrow		*Pooecetes gramineus*		Emberizidae
Virginia Rail		*Rallus limicola*		Rallidae
Warbling Vireo		*Vireo gilvus*		Vireonidae
Western Sandpiper		*Calidris mauri*		Scolopacidae
Whip-poor-will		*Caprimulgus vociferus*		Caprimulgidae
White Ibis		*Eudocimus albus*		Threskiornithidae
White-crowned Sparrow		*Zonotrichia leucophrys*		Emberizidae
White-eyed vireo		*Vireo griseus*		Vireonidae
White-faced Ibis		*Plegadis chihi*		Threskiornithidae
White-tailed Hawk		*Buteo albicaudatus*		Accipitridae

COMMON NAME		GENUS/SPECIES		FAMILY
White-tailed Kite		*Elanus leucurus*		Accipitridae
White-throated Sparrow		*Zonotrichia albicollis*		Emberizidae
Wilson's Warbler		*Wilsonia pusilla*		Parulidae
Winter Wren		*Troglodytes troglodytes*		Troglodytidae
Wood Duck		*Aix sponsa*		Anatidae
Wood Stork		*Mycteria americana*		Ciconiidae
Wood Thrush		*Hylocichla mustelina*		Turdidae
Worm-eating Warbler		*Helmitheros vermivorus*		Parulidae
Yellow Warbler		*Dendroica petechia*		Parulidae
Yellow-bellied Sapsucker		*Sphyrapicus varius*		Picidae
Yellow-billed Cuckoo		*Coccyzus americanus*		Cuculidae
Yellow-breasted Chat		*Icteria virens*		Parulidae
Yellow-crowned Night-heron		*Nyctanassa violacea*		Ardeidae
Yellow-rumped Warbler		*Dendroica coronata*		Parulidae
Yellow-throated Vireo		*Vireo flavifrons*		Vireonidae
Yellow-throated Warbler		*Dendroica dominica*		Parulidae

APPENDIX C

MODEL PARAMETER DESCRIPTIONS

TABLE B-1. HSPF INPUT PARAMETERS

Parameter	Units	Model Type		Description
PWAT-PARM2				**Second Group of PWATER Parameters**
FOREST	none	Hydrology	Pervious	the fraction of the PLS which is covered by forest, and which will therefore continue to transpire in winter. This is only relevant if snow is being considered (i.e., CSNOFG = 1)
LZSN	inches	Hydrology	Pervious	the lower zone nominal storage
INFILT	inches/hour	Hydrology	Pervious	an index to the infiltration capacity of the soil
LSUR	feet	Hydrology	Pervious	length of the assumed overland flow plane
SLSUR		Hydrology	Pervious	slope of the overland flow plane
KVARY	1/inches	Hydrology	Pervious	parameter which affects the behavior of groundwater recession flow, enabling it to be non-exponential in its decay with time
AGWRC	1/day	Hydrology	Pervious	basic groundwater recession rate if KVARY is zero and there is no inflow to groundwater; AGWRC is defined as the rate of flow today divided by the rate of flow yesterday
PWAT-PARM3				**Third Group of PWATER Parameters**
PETMAX	deg F	Hydrology	Pervious	air temperate below which E-T will arbitrarily be reduced below the value obtained from the input time series
PETMIN	deg F	Hydrology	Pervious	temperature below which E-T will be zero regardless of the value in the input time series
INFEXP	none	Hydrology	Pervious	exponent in the infiltration equation
INFILD	none	Hydrology	Pervious	ratio between the maximum and mean infiltration capacities over the PLS
DEEPFR	none	Hydrology	Pervious	fraction of groundwater inflow which will enter deep (inactive) groundwater, and, thus, be lost from the system as it is defined in HSPF
BASETP	none	Hydrology	Pervious	fraction of remaining potential E-T which can be satisfied from baseflow (groundwater outflow), if enough is available
AGWETP	none	Hydrology	Pervious	fraction of remaining potential E-T which can be satisfied from active groundwater storage if enough is available
PWAT-PARM4				**Fourth Group of PWATER Parameters**
CEPSC	inches	Hydrology	Pervious	interception storage capacity
UZSN	inches	Hydrology	Pervious	upper zone nominal storage
NSUR	complex	Hydrology	Pervious	Manning's n for the assumed overland flow plane
INTFW	none	Hydrology	Pervious	interflow inflow parameter
IRC	1/day	Hydrology	Pervious	interflow recession parameter. Under zero inflow, this is the ratio of today's interflow outflow rate to yesterday's rate.
LZETP	none	Hydrology	Pervious	lower zone E-T parameter. It is an index to the density of deep-rooted vegetatior

TABLE B-1. HSPF INPUT PARAMETERS

Parameter	Units	Model Type		Description
PWAT-PARM5				**Fifth Group of PWATER Parameters**
FZG	/inches	Hydrology	Pervious	parameter that adjusts for the effect of ice in the snow pack on infiltration when IFFCFG is 1. It is not used if IFFCFG is 2.
FZGL	none	Hydrology	Pervious	lower limit of INFFAC as adjusted by ice in the snow pack when IFFCFG is 1. If IFFCFG is 2, FZGL is the value of INFFAC when the lower layer temperature is at or below freezing
PWAT-STATE1				**PWATER Initial State Variables**
CEPS	inches	Hydrology	Pervious	initial interception storage
SURS	inches	Hydrology	Pervious	initial surface (overland flow) storage
UZS	inches	Hydrology	Pervious	initial upper zone storage
IFWS	inches	Hydrology	Pervious	initial interflow storage
LZS	inches	Hydrology	Pervious	initial lower zone storage
AGWS	inches	Hydrology	Pervious	initial active groundwater storage
GWVS	inches	Hydrology	Pervious	initial index to groundwater slope; it is a measure of antecedent active groundwater flow
SED-PARM1		Sediment	Pervious	**First Group of SEDMNT Parameters**
CRV/CRVFG		Sediment	Pervious	if CRVFG is 1, erosion-related cover may vary throughout the year. Values are supplied in Table-type MON-COVER
VSIV/VSIVFG		Sediment	Pervious	if VSIVFG is 1, the rate of net vertical sediment input may vary throughout the year. If VSIVFG is 2, the vertical sediment input is added to the detached sediment storage only on days when no rainfall occurred during the previous day. Values are supplied in Table type MON-NVSI
SDOP/SDOPFG		Sediment	Pervious	flag that determines the algorithm used to simulate removal of sediment from the land surface. If SDOPFG is 1, sediment removal will be simulated with the algorithm used in the predecessor models, ARM and NPS. If is is 0, a different algorithm will be used (see the Functional Description for details)

TABLE B-1. HSPF INPUT PARAMETERS

Parameter	Units	Model Type		Description
SED-PARM2				**Second Group of SEDMNT Parameters**
SMPF	none	Sediment	Pervious	"supporting management practice factor." It is used to simulate the reduction in erosion achieved by use of erosion control practices
KRER	complex	Sediment	Pervious	coefficient in the soil detachment equation
JRER	complex	Sediment	Pervious	exponent in the soil detachment equation
AFFIX	/day	Sediment	Pervious	fraction by which detached sediment storage decreases each day as a result of soil compaction
COVER	none	Sediment	Pervious	fraction of land surface which is shielded from rainfall erosion (not considering snow cover, which is handled by the program)
NVSI	pounds/acre/day	Sediment	Pervious	rate at which sediment enters detached storage from the atmosphere. A negative value can be supplied, for example, to simulate removal by human activity or wind.
SED-PARM3				**Third Group of SEDMNT Parameters**
KSER	complex	Sediment	Pervious	coefficient in the detached sediment washoff equation
JSER	complex	Sediment	Pervious	exponent in the detached sediment washoff equatior
KGER	complex	Sediment	Pervious	coefficient in the matrix soil scour equation, which simulated gully erosion
JGER	complex	Sediment	Pervious	exponent in the matrix soil scour equation, which simulates gully erosior
SED-STOR				**Initial Storage of Detached Sediment**
DETS	tons/acre	Sediment	Pervious	initial storage of detached sediment
QUAL-INPUT				**Nonseasonal PQUAL Parameters**
SQO	quantity/acre	Bacteria	Pervious	initial storage of QUALOF on the surface of the PLS
POTFW	quantity/ton	Bacteria	Pervious	the washoff potency factor
POTFS	quantity/ton	Bacteria	Pervious	the scour potency factor
ACQOP	quantity/acre/day	Bacteria	Pervious	rate of accumulation of QUALOF
SQOLIM	quantity/acre	Bacteria	Pervious	maximum storage of QUALOF
WSQOP	inches/hour	Bacteria	Pervious	rate of surface runoff which will remove 90 percent of stored QUALOF per hour
IOQC	quantity/feet^3	Bacteria	Pervious	concentration of the constituent in interflow outflow; it is meaningful only if this QUAL is a QUALIF
AOQC	quantity/feet^3	Bacteria	Pervious	concentration of the constituent in active groundwater outflow; it is meaningful only if this QUAL is QUALGW
IWAT-PARM2				**Second Group of IWATER Parameters**
LSUR	feet	Hydrology	Impervious	length of the assumed overland flow plane
SLSUR	none	Hydrology	Impervious	slope of the overland flow plane
NSUR		Hydrology	Impervious	Manning's n for the assumed overland flow plane
RETSC	feet	Hydrology	Impervious	retention (interception) storage capacity of the surface

TABLE B-1. HSPF INPUT PARAMETERS

Parameter	Units	Model Type		Description
IWAT-PARM3				**Third Group of IWATER Parameters**
PETMAX	deg F	Hydrology	Impervious	air temperature below which E-T will arbitrarily be reduced below the value obtained from the input time series
PETMIN	deg F	Hydrology	Impervious	temperature below which E-T will be zero regardless of the value in the input time series. These values are only used if snow is being considered (i.e., CSNOFG = 1 in Table-type IWAT-PARM1)
IWAT-STATE1				**IWATER Initial State Variables**
RETS	inches	Hydrology	Impervious	initial retention storage
SURS	inches	Hydrology	Impervious	initial surface (overland flow) storage
SLD-PARM2				**Second Group of SOLIDS Parameters**
KEIM	complex	Sediment	Impervious	coefficient in the solids washoff equation
JEIM	complex	Sediment	Impervious	exponent in the solids washoff equation
ACCSDP	tons/acre/day	Sediment	Impervious	rate at which solids accumulate on the land surface
REMSDP	/day	Sediment	Impervious	fraction of solids storage which is removed each day when there is no runoff, for example, because of street sweeping
SLD-STOR				**Initial Solids Storage**
SLDS	tons/acre	Sediment	Impervious	initial storage of solids on the impervious surface
QUAL-INPUT				**Surface Storage of qual and Nonseasonal Parameters**
SQO	quantity/acre	Bacteria	Impervious	initial storage of QUALOF on the surface of the ILS
POTFW	quantity/ton	Bacteria	Impervious	washoff potency factor
ACQOP	quantity/acre/day	Bacteria	Impervious	rate of accumulation of QUALOF on the surface
SQOLIM	quantity/acre	Bacteria	Impervious	maximum storage of QUALOF on the surface
WSQOP	inches/hour	Bacteria	Impervious	rate of surface runoff that will remove 90 percent of stored QUALOF per hour
HYDR-PARM2				**Parameters for HYDR Section**
LEN	miles	Hydrology	Reaches	length of the RCHRES
DELTH	feet	Hydrology	Reaches	drop in water elevation from the upstream to the downstream extremities of the RCHRES. (It is used if section OXRX is active and reaeration is being computed using the Tsivoglou-Wallace equation; or if section SEDTRN is active and sandload transport capacity is being computed using either the Toffaleti or Colby method)
STCOR	feet	Hydrology	Reaches	correction to the RCHRES depth to calculate stage
KS	none	Hydrology	Reaches	weighting factor for hydraulic routing
DB15/DB50	inches	Hydrology	Reaches	median diameter of the bed sediment (assumed constant throughout the run)

TABLE B-1. HSPF INPUT PARAMETERS

Parameter	Units	Model Type		Description
SED-GENPARM				
BEDWID	feet	Sediment	Reaches	width of the cross-section over which HSPF will assume bed sediment is deposited (regardless of stage, top-width, etc); BEDWID is constant. It is used to estimate the depth of bed sediment
BEDWRN	feet	Sediment	Reaches	bed depth which, if exceeded (e.g., through deposition) will cause a warning message to be printed in the echo file (MESSU)
POR	none	Sediment	Reaches	porosity of the bed (volume voids/total volume). It is used to estimate bed depth
SAND-PM				**General Sediment Related Paramters**
D	inches	Sediment	Reaches	effective diameter of the transported sand particles
W	inches/second	Sediment	Reaches	fall velocity in still water for D sand particles
RHO	grams/centimeter^3	Sediment	Reaches	density of the sand particles
KSAND	complex	Sediment	Reaches	coefficient in the sandload power function formula
EXPSND	complex	Sediment	Reaches	exponent in the sandload power function formula
SILT-CLAY-PM				**Parameters for Silt or Clay**
D	inches	Sediment	Reaches	effective diameter of the transported particles
W	inches/second	Sediment	Reaches	fall velocity in still water for D particles
RHO	grams/centimeter^3	Sediment	Reaches	density of the particles
TAUCD	pounds/feet^2	Sediment	Reaches	critical bed shear stress for deposition. Above this stress, there will be no deposition; as the stress drops below this value to zero, deposition will gradually increase to the value implied by the fall velocity instill water
TAUCS	pounds/feet^2	Sediment	Reaches	critical bed shear stress for scour. Below this value, there will be no scour; above it, scour will steadily increase
SSED-INIT				**Initial Concentration of Suspended Sediment**
Sand	milligrams/liter	Sediment	Reaches	initial concentration of suspended sand
Silt	milligrams/liter	Sediment	Reaches	initial concentration of silt
Clay	milligrams/liter	Sediment	Reaches	initial concentration of clay
BED-INIT				**Initial Content of Bed Sediment**
BEDDEP	feet	Sediment	Reaches	initial total depth (thickness) of the bed
GQ-GENDECAY				**Parameters for "General" Decay of qual**
FSTDEC	/day	Bacteria	Reaches	first-order decay rate for qual
THFST	none	Bacteria	Reaches	temperature correction coefficient for first-order decay of qual

TABLE B-1. HSPF INPUT PARAMETERS

Parameter	Units	Model Type		Description
GQ-SEDDECAY				**Parameters for Decay of Contaminant Adsorbed to Sediment**
KSUSP		Bacteria	Reaches	decay rate for contaminant adsorbed to suspended sediment
THSUSP		Bacteria	Reaches	temperature correction coefficient for contaminant adsorbed to suspended sediment
KBED		Bacteria	Reaches	decay rate for contaminant adsorbed to bed sediment
THBED		Bacteria	Reaches	temperature correction coefficient for contaminant adsorbed to bed sediment
GQ-KD				**Adsorption Coefficients of qual**
ADPM1	liters/milligram	Bacteria	Reaches	distribution coefficient for qual with suspended sand
ADPM2	liters/milligram	Bacteria	Reaches	distribution coefficient for qual with suspended silt
ADPM3	liters/milligram	Bacteria	Reaches	distribution coefficient for qual with suspended clay
ADPM4	liters/milligram	Bacteria	Reaches	distribution coefficient for qual with bed sand
ADPM5	liters/milligram	Bacteria	Reaches	distribution coefficient for qual with bed silt
ADPM6	liters/milligram	Bacteria	Reaches	distribution coefficient for qual with bed clay
GQ-ADRATE				**Adsorption/Desorption Rate Parameters**
ADPM1	/day	Bacteria	Reaches	Transfer rates between adsorbed and desorbed state of qual with suspended sand
ADPM2	/day	Bacteria	Reaches	Transfer rates between adsorbed and desorbed state of qual with suspended silt
ADPM3	/day	Bacteria	Reaches	Transfer rates between adsorbed and desorbed state of qual with suspended clay
ADPM4	/day	Bacteria	Reaches	Transfer rates between adsorbed and desorbed state of qual with bed sand
ADPM5	/day	Bacteria	Reaches	Transfer rates between adsorbed and desorbed state of qual with bed silt
ADPM6	/day	Bacteria	Reaches	Transfer rates between adsorbed and desorbed state of qual with bed clay