Brazos River Basin and Bay Expert Science Team Environmental Flow Regime Recommendations Report

Final Submission to the
Brazos River Basin and Bay Area Stakeholder Committee,
Environmental Flows Advisory Group,
and the Texas Commission on Environmental Quality

March 1, 2012

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Dear Members of the Texas Environmental Flows Advisory Group:

For your consideration, the Brazos River Basin and Bay Expert Science Team (Brazos BBEST) hereby submits its final report pursuant to its charge under Senate Bill 3 (80th R, 2007), including environmental flow recommendations with rationales. The Brazos BBEST members have reached consensus on the presentation of the recommendations submitted in this document.

Respectfully submitted,

Tom Gooch, Chair

Executive Summary

The Brazos Basin Expert Science Team (Brazos BBEST) was appointed by the Brazos Basin Area Stakeholders Committee (Brazos BBASC) under Senate Bill 3 (SB3) (Texas Legislature 2007), the third in a series of three omnibus water bills related to meeting future needs for water for the State of Texas. The BBEST is directed by SB3 to achieve the following:

- *Develop environmental flow analyses and a recommended environmental flow regime* [an environmental flow regime is a schedule of flows varying seasonally and geographically that will support a sound ecological environment] *for the river basin and bay system for which the team is established through a collaborative process designed to achieve a consensus. In developing the analyses and recommendations, the science team must consider all reasonably available science, without regard to the need for the water for other uses, and the science team's recommendations must be based solely on the best science available [§Sec. 11.02362(m)].*
- *Submit its environmental flow analyses and environmental flow regime recommendations to the pertinent basin and bay area stakeholders committee, the advisory group, and the commission in accordance with the applicable schedule specified by or established under [§Sec. 11.02362] Subsection (c), (d), or (e). The basin and bay area stakeholders committee and the advisory group may not change the environmental flow analyses or environmental flow regime recommendations of the basin and bay expert science team [§Sec. 11.02362(n)].*
- *Finalize environmental flow regime recommendations and submit them to the basin and bay area stakeholders committee, the advisory group, and the commission not later than March 1, 2012, except that at the request of the basin and bay area stakeholders committee for good cause shown, the advisory group may extend the deadline provided by this subdivision [§Sec. 11.02362(c-3)].*

The Brazos BBEST was given less than twelve months to meet several objectives:

- Review the state-of-the-art for approaches and analyses to develop environmental flow recommendations.
- Review available studies and data from throughout the Brazos and San Bernard river basins.
- Provide an operational definition of a sound ecological environment within the context of SB3, and evaluate the current status of major stream, river, and estuarine reaches in terms of "ecological soundness."
- Perform analyses and evaluate study findings in order to establish environmental flow regime recommendations for significant stream, river, and estuarine reaches in the basins.
- Provide science-based environmental flow recommendations with guidance for implementation within the context of future water rights and potential usage.
- Assess potential water development scenarios for a subset of study reaches in order to demonstrate implementation rules for the environmental flow regime and to evaluate the degree to which the recommended environmental flow regime achieves the objectives.
- Evaluate information gaps at the present time, and produce a list of potential measures to fill these gaps to achieve the goal of adaptive management to improve water management while protecting the environment.

Under its SB3 charge, the Brazos BBEST used the "best available science" to develop environmental flow regime analyses and environmental flow regimes for 20 major stream and river reaches at locations throughout the Brazos and San Bernard river basins. The Brazos BBEST also evaluated freshwater inflows in support of a sound estuarine environment at the mouths of the Brazos and San Bernard rivers on the Texas coast. These recommendations are provided to the Brazos BBASC, Texas Environmental Flows Advisory Group (EFAG), and the Texas Commission on Environmental Quality (TCEQ).

The Brazos BBEST held nine meetings beginning with its initial meeting on April 19, 2011 at the offices of the Brazos River Authority and subsequent meetings rotated among locations in Waco, Austin, and College Station. Meetings were open to the public and attended by staff members from cooperating natural resources agencies (TCEQ, Texas Water Development Board, Texas Parks and Wildlife Department) plus representatives the Brazos BBASC and environmental advocacy groups. To address specific technical tasks, various subgroups of the BBEST occasionally met in San Marcos and Austin or communicated by email and phone. Two technical subcommittees were formed: hydrology subcommittee (four members) and ecology subcommittee (six members); BBEST members were free to participate in meetings and discussions of both groups.

The Brazos BBEST benefitted from advice provided by the SB3 Science Advisory Committee (SAC), a group of experts that makes recommendations to the EFAG and BBESTs. The SAC has developed several technical guidance documents, and the Brazos BBEST consulted these documents while conducting analyses and evaluation leading to the environmental flows recommendations reported herein. In addition, Dr. Paul Jensen served as the SAC's liaison to the Brazos BBEST, and in that capacity provided invaluable assistance throughout the process.

In its initial meetings, the Brazos BBEST set its ground rules for working together (elected a chair and vice chair, established conventions for keeping and approving meeting minutes, etc.), developed its budget, and set benchmarks for achieving the SB3 directive and a schedule for achieving each benchmark. In order to orient BBEST members without experience working on other BBESTs, the group reviewed SAC guidance documents and reports from other BBESTs. The group completed the following steps to establish environmental flow regimes with the Brazos Basin Study Area:

- Establish geographic scope for the analysis: 20 USGS gage locations were selected.
- Select periods of record available for hydrological analysis: the goal was long records without interruption (data gaps).
- Review and discussion of flow separation methods: the Indicators of Hydrologic Alteration (IHA) method was chosen.
- Review and discuss appropriate temporal scales of variation to include in environmental flow recommendations: decisions were made regarding seasons and dry vs. wet periods based on a combination of statistical and biological evaluations.
- Review and discussion of ecological components: water quality parameters, fishes, mussels, and riparian vegetation were selected as focal components for evaluation of instream flows; fishes and shellfish were selected as focal taxa for evaluation of estuarine inflows.
- Discussion of objective criteria for defining a "sound ecological environment": it was concluded that fishes provided the most detailed and extensive datasets and study interpretations for this objective.
- Review and discussion of methods to evaluate fluvial geomorphology (channel changes that ultimately affect habitat for organisms) and sediment dynamics: it was decided that TWDB staff could assist the hydrology

subcommittee with analysis of sediment transport based on alternative scenarios of water diversion under environmental flow regimes, once established.

- Produce initial flow regime matrices derived from hydrologic separation of flow components within inputs based upon ecological knowledge of functions of subsistence flow, base flow, and high flow pulses during different seasons, etc.: the Hydrology-Based Environmental Flow Regime (HEFR) method was used to perform these analyses.
- Evaluate HEFR matrices with respect to the degree to which flow components would sustain ecological functions and/sustain populations of focal taxa; revise HEFR inputs and repeat analyses and evaluation: this process was repeated several times to obtain environmental flow regime recommendations.
- Evaluate key data gaps and limits of knowledge for watersheds and reaches within the basins, and draft recommendations for future monitoring and research.
- Prepare recommendations report for EFAG, Brazos BBASC, and TCEQ.

Near the outset, the Brazos BBEST recognized that the natural flow regime paradigm provided the most scientifically sound approach for making environmental flow recommendations for rivers and streams within the Study Area. This recognition was based on two basic observations from our literature review.

First, it appears that virtually all contemporary river ecologists accept the natural flow regime as a robust model for establishing environmental flows. In essence, this model proposes that key ecological processes (both physical and biotic) that sustain native species and their habitats and resources derive from flow variation that mimics, at least qualitatively, the natural pattern. This is because native species have been sustained by the natural flow regime for centuries prior to major human interventions. A great deal of recent scientific literature demonstrates that alterations of key components of flow variation, such as high flow pulses, can result in loss of native species from streams, rivers, and estuaries.

The second recognition is that none of the alternative methods developed for deriving environmental flows based on site-specific research would be viable for our BBEST due to the absence of such research in our Study Area. For example, studies that simulate physical habitat of fishes under incremental flow scenarios have not been completed within the Brazos BBEST Study Area. Therefore, the Brazos BBEST decided to analyze HEFR-derived flow regimes in a series of steps, using the collective expertise of the ecology subcommittee and evaluation of the fairly large and recent body of literature from studies conducted within the Brazos River Basin. Several of these studies were conducted by ecology subcommittee members, and, in many cases, the research was specifically focused on fish and ecosystem responses to flow variation. In particular, a group from the Brazos River Authority (T. Morgan, J. Davis, and colleagues) conducted surveys of water quality, aquatic invertebrates, and fishes throughout the Brazos Basin; a group at Texas Tech University (G. Wilde, T. Bonner, and lab members) conducted a series of studies in the upper Brazos River; a group at Texas A&M University (K. Winemiller, F. Gelwick, and lab members) and Texas State University (T. Bonner and lab members) conducted a series of studies on the lower Brazos River; and a group at the University of Houston (G. Guillen and lab members) conducted field studies in the Brazos River estuary. Thus, rich sources of scientific information were available for much of the mainstem Brazos River. For other reaches within the Study Area, there was limited site-specific information to establish direct cause-and-effect relationships, and inferences were necessarily indirect based on any available evidence, such as abundance trends from surveys or basic life history information for species obtained at other locations.

The environmental recommendations were subject to two kinds of post hoc evaluation. First, the influence of several water development scenarios was simulated using the Water Availability Model (WAM) to determine potential ecological impacts, including sediment dynamics and channel evolution, lateral connectivity, and estuarine freshwater inflows. The scenarios ranged from historic conditions (period of record flows), to historic period of record flows subject to current levels of water resources development and management, to three hypothetical scenarios with different amounts of project development, to "infinite infrastructure" in which all water except flows protected by the environmental flow regime are assumed to be diverted. Due to time and personnel constraints, these hydrologic simulations, parts of which were performed by the TWDB technical staff for the BBEST, were conducted on only two focal reaches (Brazos River at Seymour in Baylor County, Brazos River at Richmond in Fort Bend County). The sediment and ecological analyses of these simulated scenarios were viewed as crude approximations due to methodological sensitivities and limitations of data resolution.

The general conclusion was that the three scenarios with varying amounts of diversion/impoundment infrastructure development beyond that which is currently authorized in the basin (scenarios deemed realistic at the present time) would have minimal to moderate effects on sediment yields, lateral connectivity in support of fish populations and ecosystem productivity, and salinity regimes in support of estuarine biodiversity and productivity. In contrast, the "infinite infrastructure" (environmental flows only) scenario tended to have larger impacts, specifically in the moderate to high flow ranges. Subsistence and base flows (flows that historically have been exceeded 90 percent of the time) would change very little and, therefore, protect the associated ecological functions of these flow components. However, there would be significant reductions in higher flows under the infinite infrastructure scenario, with possible changes to sediment/geomorphological dynamics, ecological dynamics within riparian corridors, including reduced lateral connectivity of highly productive aquatic habitats and alteration of salinity regimes in estuaries. Depending on rates of diversion and stream flow, run-of-the river diversions may have minimal effects on the instream regimes, whereas reservoir projects would be expected to have much greater impacts.

This finding, based on modeling at two locations and considering data limitations, produces concerns that if the only flows remaining in these reaches were the environmental flow regimes recommended in this report, there could be damage to the current ecological systems due to reductions in the magnitudes and frequencies of flow pulses. Given the naturally variable nature of precipitation and hydrology in this region, new projects may occasionally reduce instream flows to the levels of the protection targets recommended here. It also is anticipated that, at other times, individual projects would be incapable of capturing or diverting sufficient flows to reduce instream flows to levels matching the average frequencies, magnitudes, and durations embodied in the environmental flow regimes. Clearly, the various entities participating in long-term management of the basin's surface waters will need to estimate cumulative impacts from water rights proposals. The Brazos BBEST urges readers of this report to interpret our recommended environmental flow regimes within this context and with caution. The Brazos BBEST considers these recommendations to be preliminary, based on limited, albeit best available, science at the present time. If considered as the only water passing through the stream reach, the environmental flows proposed in this report are likely to be inadequate for long-term maintenance of a sound ecosystem in many cases, the lower river reaches and estuaries in particular. Adaptive management that involves new efforts in data collection, analysis, and interpretation should facilitate refinement of these recommendations in order to assist water resource managers in protecting *sound ecological environments*.

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Appendix C	**Summary of information obtained for assessment of riparian vegetation communities in the Brazos Study Area; checklist of riparian plant species in the Brazos BBEST Study Area.**
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1 Preamble

1.1 Senate Bill 3 Environmental Flows Process

In 2007, the 80th Texas Legislature passed Senate Bill 3 (SB3), which created a process to set environmental flow standards for river basin and bay systems in Texas. Once established, the environmental flow standards will be used in water rights permitting.

This report from the Brazos River Basin and Associated Bay and Estuary System Expert Science Team (Brazos BBEST) is part of that process and gives recommendations for an environmental flow regime for the Brazos Basin and associated areas. Figure 1 shows the geographic scope assigned to the Brazos BBEST, which is the Brazos Basin in Texas, the San Bernard Basin to the west of the Brazos Basin, and the Austin and Oyster Creeks watersheds in the San Jacinto-Brazos Coastal Basin to the east of the Brazos Basin. The area assigned to the Brazos BBEST is called the *Study Area* in this report.

There are several key players in the overall environmental flow standard setting process as established by SB3:

- The Environmental Flows Advisory Group (EFAG) oversees the environmental flow standard setting process and appoints the statewide Science Advisory Group and the Bay and Basin Stakeholder Committees for each bay and basin system.

- The Texas Environmental Flows Science Advisory Committee (SAC) was appointed by the EFAG and serves as an objective scientific body to advise and make recommendations to the EFAG on issues relating to the science of environmental flow protection and develop recommendations to help provide overall direction, coordination, and consistency for the environmental flow standard setting process.

- The Brazos River and Associated Bay and Estuary System Stakeholder Committee (Brazos BBASC) was appointed by the EFAG and, in turn, appoints the Brazos River and Associated Bay and Estuary System Basin and Bay Expert Science Team. The Brazos BBASC is to review the recommendations of the Brazos BBEST, consider factors such as human water needs, and make recommendations to the Texas Commission on Environmental Quality (TCEQ) regarding streamflow standards for the Study Area.

- The Brazos River and Associated Bay and Estuary System Basin and Bay Expert Science Team (Brazos BBEST) was appointed by the Brazos BBASC and has prepared this report. The Brazos BBEST is asked to develop recommendations for an environmental flow regime based solely on the best available science, as described more fully in Section 1.2. This report gives those recommendations.

- The Texas Commission on Environmental Quality (TCEQ) is the state agency overseeing water right permitting and other environmental concerns. The TCEQ sets environmental flow standards for each basin and bay system. In doing so, the TCEQ is required to consider the environmental flow regime developed by the BBEST, the recommendations of the BBASC, economic factors, human and other water needs, and other appropriate information (Texas Water Code Section 11.1471.)

1.2 Brazos River and Associated Bay and Estuary System Basin and Bay Expert Science Team (Brazos BBEST)

The Brazos BBASC appointed nine members to the Brazos BBEST. Table 1 lists those members, along with their administrative roles, subcommittee assignments, and affiliations.

Table 1. Members of the Brazos BBEST

Member	Role	Committee(s)	Affiliation
Tom Gooch, P.E.	Chair	Hydrology	Freese and Nichols, Inc.
Kirk O. Winemiller, Ph.D.	Vice Chair	Ecology	Texas A&M University
Timothy H. Bonner, Ph.D.		Ecology and Hydrology	Texas State University
Jack Davis		Ecology	Brazos River Authority
David Dunn, P.E.		Hydrology	HDR, Inc.
Dan Gise		Ecology	Freese and Nichols, Inc.
George J. Guillen, Ph.D.		Ecology	University of Houston, Clear Lake City
Tiffany Morgan		Ecology	Brazos River Authority
Phil Price, P.E.		Hydrology	Brazos River Authority

Texas Water Code Section 11.02362 gives the following charge to the BBESTs, including the Brazos BBEST:

> *"(m) Each basin and bay expert science team shall develop environmental flow analyses and a recommended environmental flow regime for the river basin and bay system for which the team is established through a collaborative process designed to achieve a consensus. In developing the analyses and recommendations, the science team must consider all reasonably available science, without regard to the need for the water for other uses, and the science team's recommendations must be based solely on the best science available…"*

Texas Water Code Section 11.002(16) defines an environmental flow regime as:

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

The Brazos BBEST followed a collaborative process and adopted the recommended environmental flow regime set out in this report by consensus. The report is intended to describe the approach to developing the recommended environmental flow regime and the regime itself. Useful data are included as appendices. The organization of the report is discussed in Section 1.4.

1.3 Sound Ecological Environment and Current State of the Fluvial Ecosystems

The SB3 definition of the environmental flow regime to be developed by the BBESTs is:

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

SB3 did not define a sound ecological environment. The Texas Environmental Flows Science Advisory Committee (SAC) initially defined a sound ecological environment as one that

- *Sustains the full complement of native species in perpetuity;*
- *Sustains key habitat features required by these species;*
- *Retains key features of the natural flow regime required by these species to complete their life cycles; and*
- *Sustains key ecosystem processes and services, such as elemental cycling and the productivity of important plant, and animal populations.*

The Brazos BBEST adopted this basic definition of a sound ecological environment to develop the environmental flow recommendations presented in this report.

Our BBEST determined that a sound ecological environment within stream and river reaches of the Brazos Basin would be characterized by fish, macroinvertebrate (e.g., mussels, shrimp, crayfish), and riparian vegetation species assemblages that remain relatively intact compared to historical records. "Relatively intact" and "high integrity" are synonymous for our purposes, and both mean that none of the native species have been eliminated from the reach, and the relative abundances of species have not been greatly altered. Appendix A contains results of our analysis of fish collection data for the study reaches selected for environmental flow analysis. With a few exceptions, we did not find sufficient survey data to make definitive determinations of the current status of macroinvertebrates and riparian vegetation species. The reports cited in sections 2.1.4 and 2.1.5 summarize the available information on these issues.

Figure 1.1 illustrates major subwatersheds of the Brazos BBEST Study Area and the locations of U.S. Geological Survey (USGS) gages on focal reaches that were selected for analysis (see Section 3.2). The current status of the fish assemblages in the reaches selected for environmental flows analysis is summarized below. Assessment of fish assemblage integrity is a qualitative evaluation of historical trends in fish relative abundance summarized in Appendix A. *High integrity* is characterized by fish surveys producing the full complement of native species in relative abundances approximating those recorded in earlier studies or within unimpacted streams within the same zoogeographic region. Fish surveys revealing losses of native species, major changes in species relative-abundance patterns, or invasions by non-native species have *low integrity*.

Lower Brazos River (reach below the mouth of the Bosque River to the coast): Moderate fish assemblage integrity; the majority of the fish community remains intact. Loss of at least one fluvial specialist (smalleye shiner, *Notropis buccula*) (note: *fluvial specialists* are species restricted to channel habitats with flowing water, and generally require flowing water to complete their life cycle) and declines in populations of several other fluvial specialists and increases in abundance of habitat generalists, such as bluegill sunfish (*Lepomis macrochirus*), suggest community changes associated with flow modifications. The most notable change has been a decline in high flow pulses in segments of the river mainstem

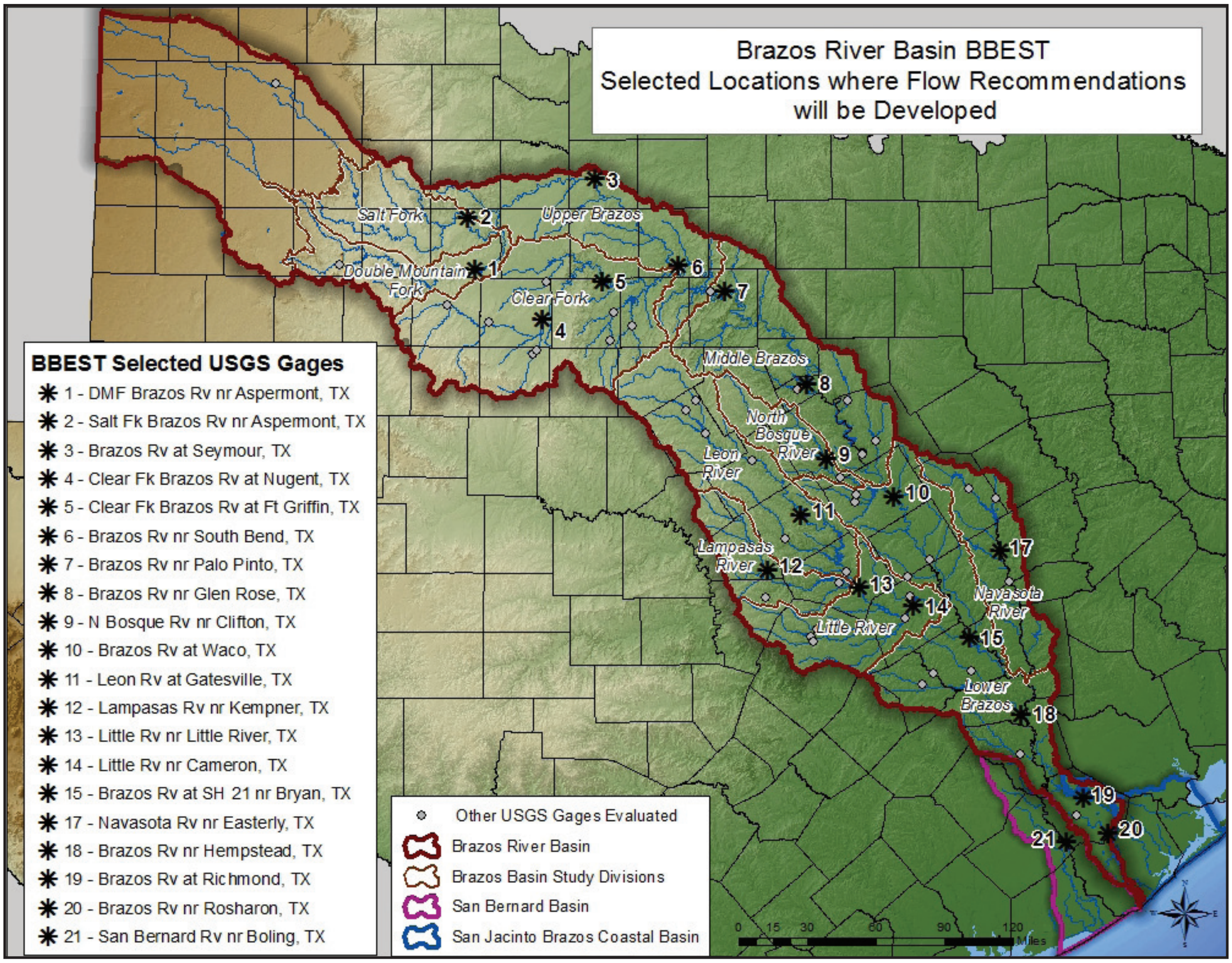


Figure 1.1. Map of the Brazos BBEST Study Area showing major subwatersheds of the Brazos River, San Bernard River, and San Jacinto-Brazos Coastal Basins and locations of gages on focal study reaches.

(Runyan 2007, and see section 3.2.3 below). Lateral connectivity is moderate, with oxbow lakes dominated by native species adapted to exploit floodplain habitats (see sections 4.3 and 7.3). Alligator gar (*Atractosteus spatula*), a species in decline throughout most of its geographic range, maintains a population with very low abundance relative to longnose and spotted gar (*Lepisosteus osseus and L. oculatus,* respectively) (Robertson et al. 2010).

Middle Brazos River (Possum Kingdom Lake to mouth of Bosque River): Low fish assemblage integrity; supports a native fish community dominated by habitat generalists with notable extirpations or abundance declines among fluvial specialists. Community changes are probably associated with flow alterations and related habitat changes and a high degree of stream fragmentation by dams in this reach (Perkin and Gido 2011).

Upper Brazos River (confluence of Salt Fork and Double Mountain Fork to Possum Kingdom Lake): High fish assemblage integrity: dominated by a few, fluvial specialist taxa that are adapted to the variable and sometime extreme conditions of this region. The fish community is similar in structure to other prairie stream communities of central North America.

Salt Fork Brazos: High fish assemblage integrity; dominated by two euryhaline taxa in addition to transitory habitat for other fluvial specialists.

Double Mountain Fork Brazos: High fish assemblage integrity (downstream from Lake Alan Henry); dominated by fluvial specialists.

Clear Fork Brazos: Low fish assemblage integrity; dominated by fishes that are common in reservoirs, habitat generalists, and species most commonly encountered in slackwater habitats when present in channel habitats with flow.

Navasota River: Moderate/High fish assemblage integrity; dominated by species that are ecological generalists; high fish species richness, in part due to the influence of species naturally distributed within the eastern portion of the state.

Little River (below confluence of Leon and Lampasas Rivers): Moderate fish assemblage integrity; dominated by ecological generalists, including species that are common in reservoirs; some species of "big river" fishes, such as gar (*Lepisosteus* spp.) and smallmouth buffalo (*Ictiobus bubalus*), in the lower reach contribute to higher species richness.

Lampasas River: Moderate fish assemblage integrity; dominated by ecological generalists and fishes that are common in reservoirs.

Leon River: Moderate/Low fish assemblage integrity; dominated by ecological generalists and fishes that are common in reservoirs; low species richness.

North Bosque River (mainstem river reaches above Lake Waco): Moderate/Low fish assemblage integrity; dominated by ecological generalists and fishes that are common in reservoirs; low species richness.

San Bernard River: Moderate fish assemblage quality; dominated by ecological generalists.

Additional information for evaluating ecological soundness is available for eight of the reaches that we evaluated (lower Brazos, middle Brazos, Navasota, Lampasas, Little, Leon, North Bosque, San Bernard) in the form of *aquatic life monitoring* data collected for the Texas Clean Rivers Program. Data on fish and benthic macroinvertebrate assemblages, physical habitat, and dissolved oxygen concentrations have been collected and assessed using standard protocols (TCEQ 2007). The purpose of this monitoring is to determine whether TCEQ aquatic life use (ALU) criteria are being attained with regard to water quality. Summary data are presented in Appendix B. With few exceptions, these reaches currently were estimated to have high ALU designations, according to current state surface water quality standards. High ALU was observed in the Navasota, Lampasas, North Bosque, and San Bernard rivers. Although some of the metrics based on fish assemblages show compromised ALU, most of the other monitoring components have shown a high ALU in the lower Brazos, Little and Leon rivers.

The middle Brazos has been an outlier in the ALU assessments. Whereas fish assemblage metrics generally have attained high ALU ratings, benthic macroinvertebrate integrity and physical habitat suitability have been low in most instances. Low habitat scores have resulted primarily from limited instream cover, steep banks, low channel sinuosity, and unstable substrates. Suppressed macrobenthic integrity has been attributed primarily to physical habitat limitations, hydrologic stresses, and water quality factors. Variables creating harsh conditions for macrobenthic assemblages include regions with shifting sand substrate not conducive for invertebrate colonization, alterations of flow resulting from reservoir operations, and high salinity resulting from geological features in the upper Brazos River watershed. It should be noted that an analysis of stream fish and habitat data from central Texas determined that there was relatively low correlation between current ALU indices based on fish assemblage data and habitat quality data, and these indices require revision (Winemiller et al. 2009)

No ALU monitoring data exist for the Salt Fork, Double Mountain Fork, upper Brazos, or Clear Fork. Data collection is needed to provide a better indication of ecological conditions in those streams.

1.4 Introduction to the Brazos River BBEST Environmental Flow Regime Recommendations Report

This report presents the approach adopted, descriptions of data and analyses, the recommended flow regime produced by the Brazos BBEST, examples of future scenarios with implementation of the recommended environmental flow regimes, and recommendations for future research and monitoring to fill information gaps.

Section 2 gives an overview of the Study Area, considering geology and hydrology, land use, water quality, riparian ecology, and aquatic biota. As mentioned in Section 1.1, the Study Area includes the San Bernard Basin and a portion of the San Jacinto-Brazos Coastal Basin as well as the entire Brazos Basin in Texas.

Section 3 summarizes the framework selected for the instream flow analysis and includes an overview of the rationale for the base and pulse flow environmental flow regime used and discussion of the initial steps taken by the Brazos BBEST in the hydrologic analysis (gage selection; determination of flow seasons; criteria for establishing wet, average and dry conditions; and the hydrologic separation of flow components).

Section 4 discusses the ecological analyses considered in the development of the recommended flow regime, including water quality, fish and mussel distribution and abundance, oxbow lakes and floodplain connectivity, riparian vegetation, geomorphology and sediment transport, and estuarine considerations.

Section 5 gives the recommended environmental flow regimes developed based on the work described in Sections 3 and 4.

Section 6 discusses considerations in the development of implementation rules for the recommended flow regime. Section 7 looks at the impact that certain proposed water supply projects would have on flows. Section 8 discusses adaptive management, including recommendations for future efforts to improve our understanding of the Study Area ecosystem and potential issues for adaptive management.

Readers simply seeking the environmental flow regime recommendations of the Brazos BBEST may proceed directly to Section 5. Readers seeking a deeper understanding of the scientific bases for the environmental flow regime recommendations are encouraged to consider summary information in Sections 2, 3, 4, 6, and 7 and the references and appendices cited therein. Appendices are available in electronic format on a compact disc included with this report.

2 Overview of Brazos BBEST Study Area

2.1 Brazos River Basin

2.1.1 Geography, Geology, and Hydrology

The Brazos River is the third largest river in Texas and the largest river between the Rio Grande and the Red River in terms of total watershed area. The headwaters of the Brazos River (Double Mountain Fork, Salt Fork, and Clear Fork) are located at the foot of the south plains near the Texas-New Mexico border. The Brazos River Basin is the largest of the fifteen major river basins in Texas, with a contributing drainage area of approximately 42,000 square miles and 14 major subwatersheds, each with distinctive climate, topography, land-uses, and water needs (Figure 2.1). By the time it reaches the Gulf of Mexico, the river has provided 6.75 billion gallons of water each year for cities, agriculture, industry, and mining; has served more than 3.9 million Texans living within the basin; and has provided abundant recreational opportunities, such as boating, swimming, and fishing.

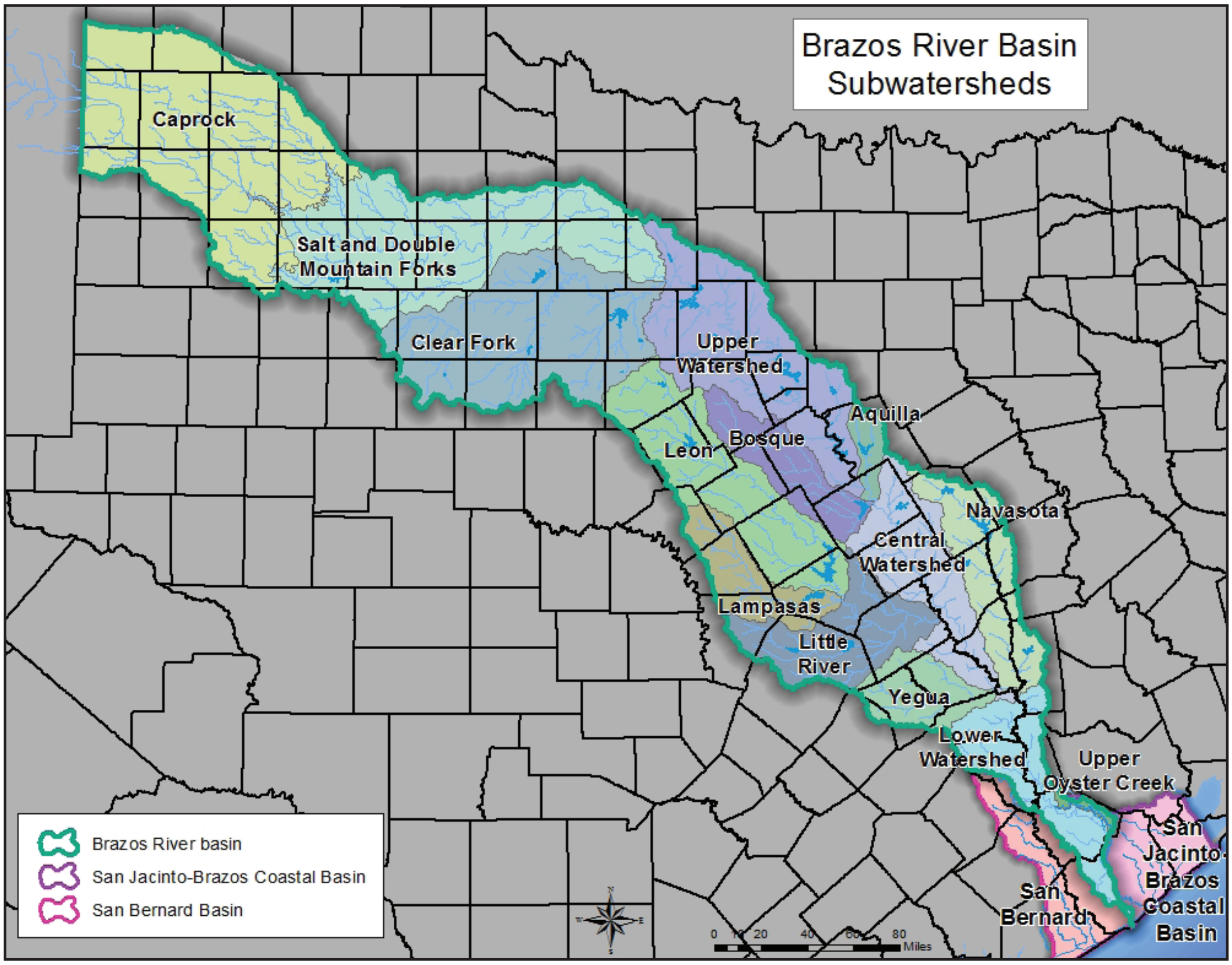


Figure 2.1. Map of the Brazos BBEST study area showing 14 major subwatersheds of the Brazos, San Bernard, and San Jacinto-Brazos Coastal basins.

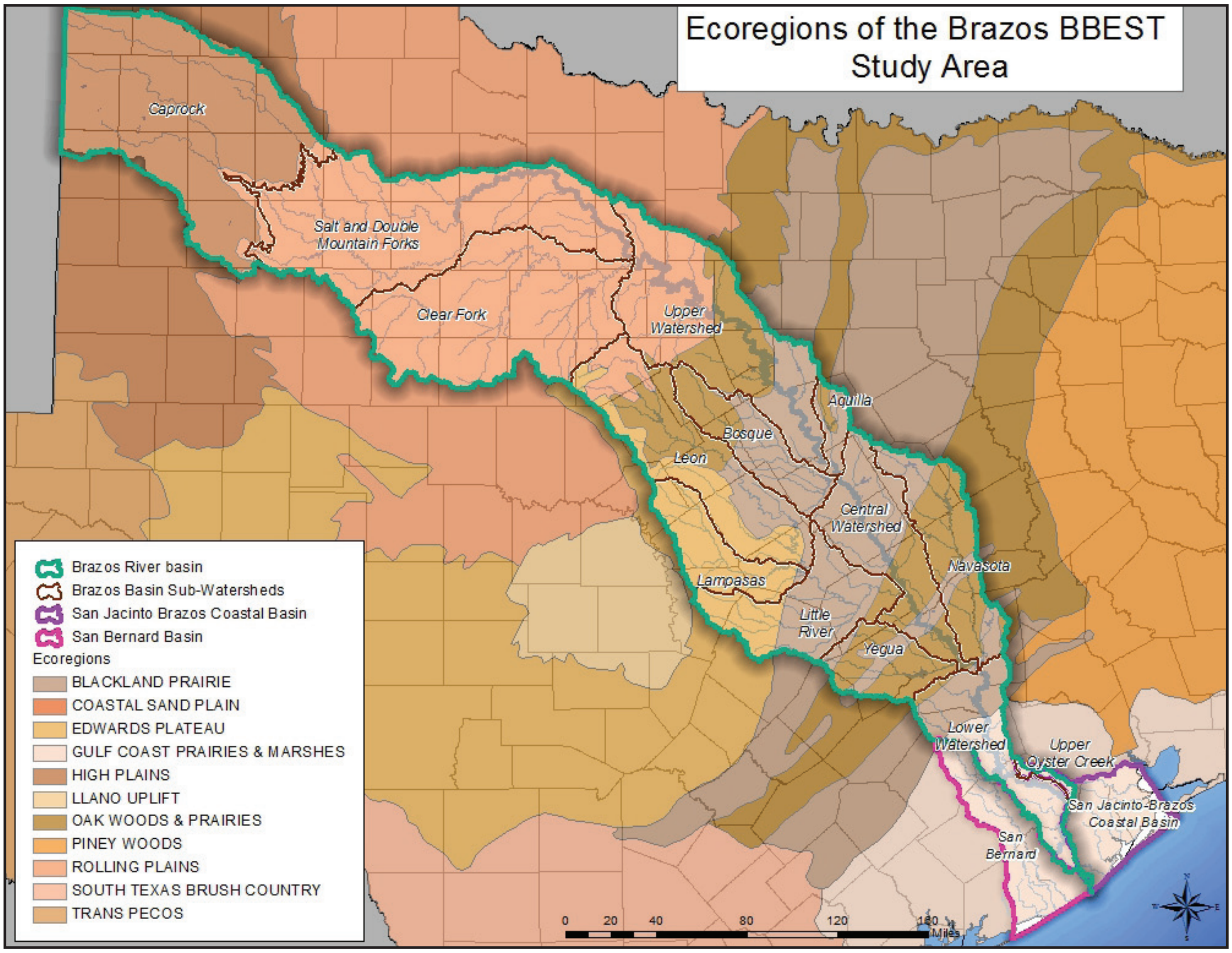


Figure 2.2. Map of the Brazos BBEST study area showing ecoregions within the Brazos River BBEST Study Area.

The Brazos River Basin is one of the most diverse in the state and spans six ecoregions with distinctive geology, soils, vegetation, and climate (Figure 2.2). The basin spans three climatological zones: Continental Steppe zone, characterized by large variations in daily temperatures, low humidity, and irregularly spaced rainfall of moderate amounts; Subtropical Subhumid zone, characterized by hot summers and dry winters; and Subtropical Humid zone, characterized by warm summers and high humidity. Average annual precipitation varies from 15 to 25 inches per year in the northern part of the basin, 35 to 40 inches per year in the central basin, and 45 to 50 inches per year in the southern basin. Topography ranges from just over 4,385 feet in the northern portion of the basin to near sea level at the confluence with the Gulf of Mexico. Terrain is rugged in the northwestern part of the basin and landscapes tend to be flat and forested with richer soils in the southern Gulf prairies.

Aquifers

Portions of six major and nine minor aquifers extend into the Brazos River Basin (Figures 2.3 and 2.4). Major aquifers are defined generally as those aquifers that supply large amounts of water to large areas of the state. Minor aquifers are defined as those that supply large amounts of water to small areas of the State or provide small supplies to wide areas. In the western part of the basin, the Seymour Aquifer is the most significant in terms of usage and yield. The

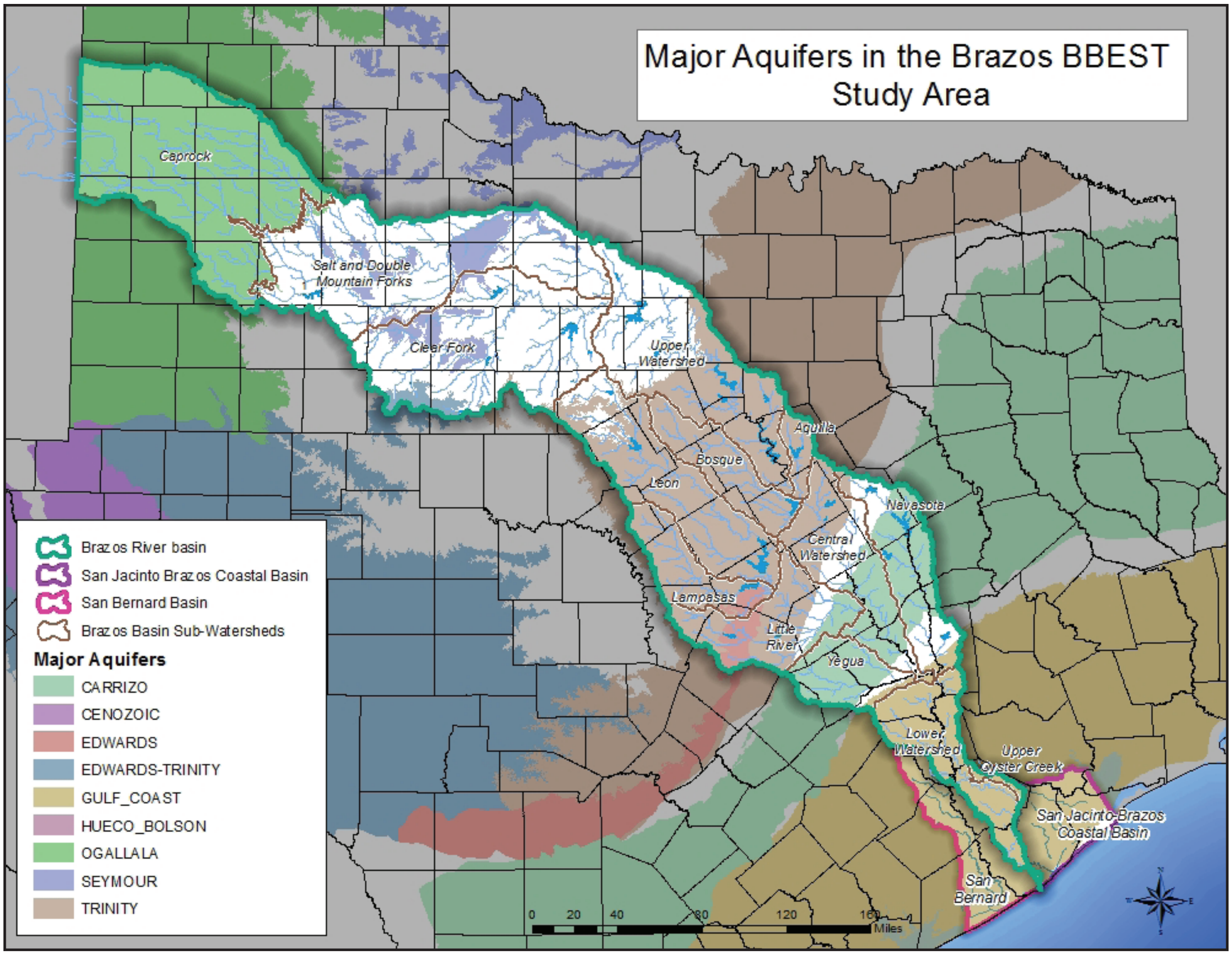


Figure 2.3. Major aquifers in the Brazos BBEST Study Area.

Seymour Aquifer, which has an uneven distribution, is highly developed, and most of its water is used for irrigation. The aquifer is prone to depletion if subjected to a combination of prolonged drought and heavy use, but groundwater supply in the aquifer has remained fairly constant. Also in the west, the fringes of three aquifers, the Dockum, Blaine, and Edwards-Trinity (Plateau), extend into the basin. In the northeastern part of the basin, there is a wide area with no aquifers, including the counties of Throckmorton, Young, Shackelford, Stephens, and Palo Pinto. In these areas, locally occurring groundwater is not associated with a defined major or minor aquifer system and is sufficient only for individual homes and livestock. In the central part of the Brazos River Basin, the Trinity Aquifer is the most significant, and in the southeastern part of the basin, groundwater sources are dominated by the Carrizo-Wilcox System and, to a lesser extent, the Gulf Coast Aquifer. Additionally, the Brazos Alluvium lies directly adjacent to the Brazos River.

Major Springs

The Brazos River Basin contains few major springs, defined as springs with discharges commonly greater than 1 cubic foot per second (cfs). Most of these springs issue from the Edwards-Balcones Fault Zone (BFZ) Aquifer in Bell and Williamson counties and from the Marble Falls Aquifer in Lampasas County. The three largest Edwards Aquifer springs are: 1) Salado Springs at Salado along the Lampasas River; 2) Berry Springs, which is located 5 miles north of

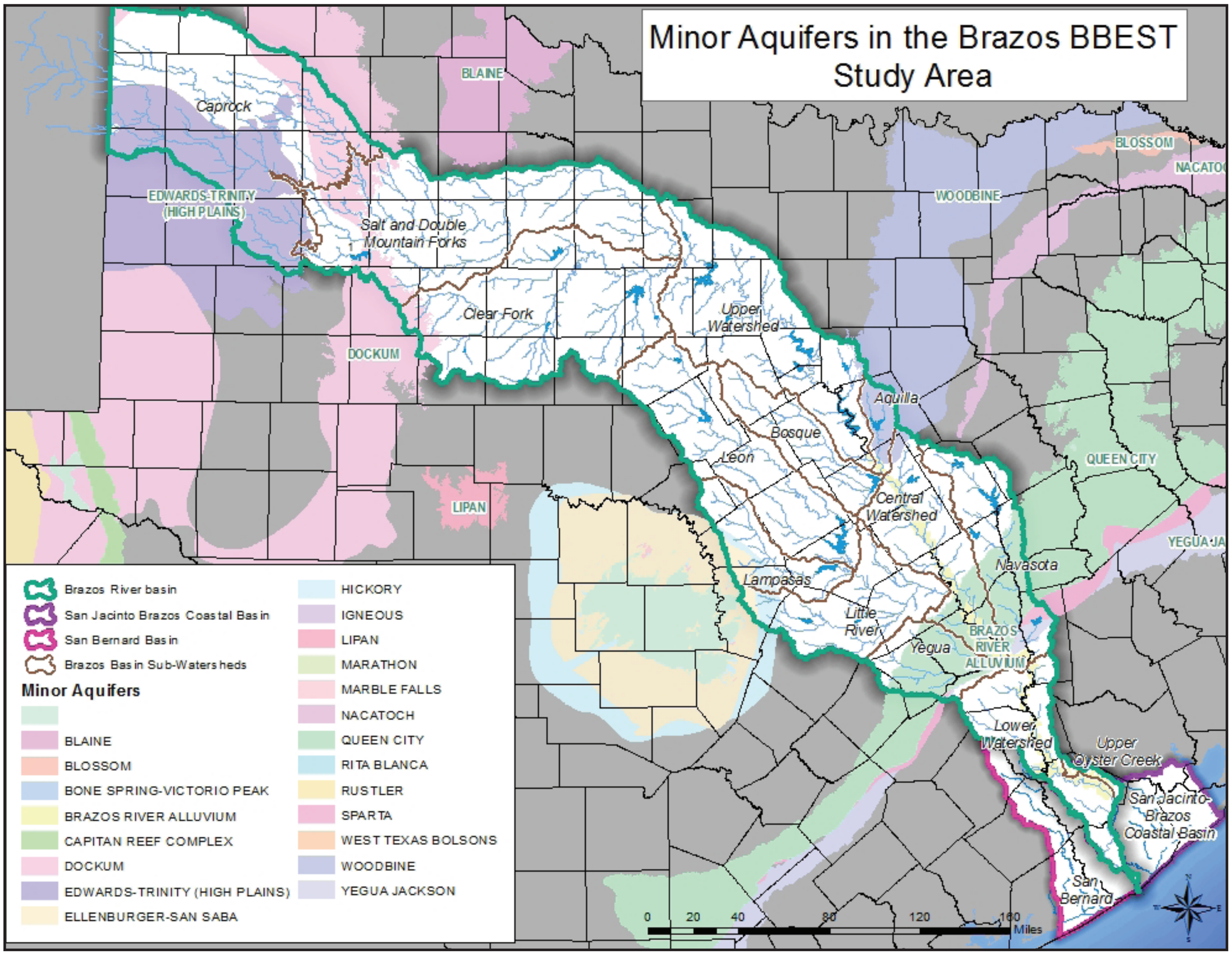


Figure 2.4. Minor aquifers in the Brazos BBEST Study Area.

Georgetown; and 3) San Gabriel Springs at Georgetown. Springs from the Marble Falls Aquifer are both in the City of Lampasas and include Hancock Park Springs along Sulfur Creek, which is a tributary to the Lampasas River, and Swimming Pool Springs at Hancock Park.

Some springs in the region significantly affect water quality in the Brazos River. These are primarily the salt springs and seeps, such as those along Salt Croton and Croton Creeks, in the upper Brazos River Basin. These natural salt-water sources in the main stem of the Brazos River above Possum Kingdom Lake cause the water to be more saline during low flow periods. For example, from 1963 to 1986, total dissolved solids (TDS) and chloride concentrations in Croton Creek near Jayton averaged 7,933 mg/L and 3,169 mg/L, respectively. Mean values for TDS and chlorides in the Salt Croton Creek near Aspermont from 1969 to 1977 were 71,237 mg/L and 41,516 mg/L, respectively. Water in Possum Kingdom Lake usually contains more than 400 mg/L chloride and 1,200 mg/L TDS. The natural chloride pollution in the upper Brazos River affects water quality in the lower basin. In the Brazos River at Richmond, it has been estimated that 85 percent (or about 95 mg/L for the years 1946 to 1986) of the chloride is from the upper basin.

Reservoirs

There are 16 major reservoirs in the Brazos River Basin with authorized storage in excess of 50,000 acre-feet and 13 smaller regional water supply reservoirs with authorized storage in excess of 10,000 acre-feet (Figure 2.5). The current storage capacities of these reservoirs range from approximately 10,000 to over 500,000 acre-feet. The system of reservoirs is managed for both flood control and water supply. Lakes in the Brazos River Basin associated with power generation facilities include: Millers Creek Reservoir, Lake Palo Pinto, Lake Granbury, Squaw Creek Reservoir, Lake Whitney, Tradinghouse Creek Reservoir, Lake Limestone, Twin Oaks Reservoir, Gibbons Creek Reservoir, and Alcoa Lake.

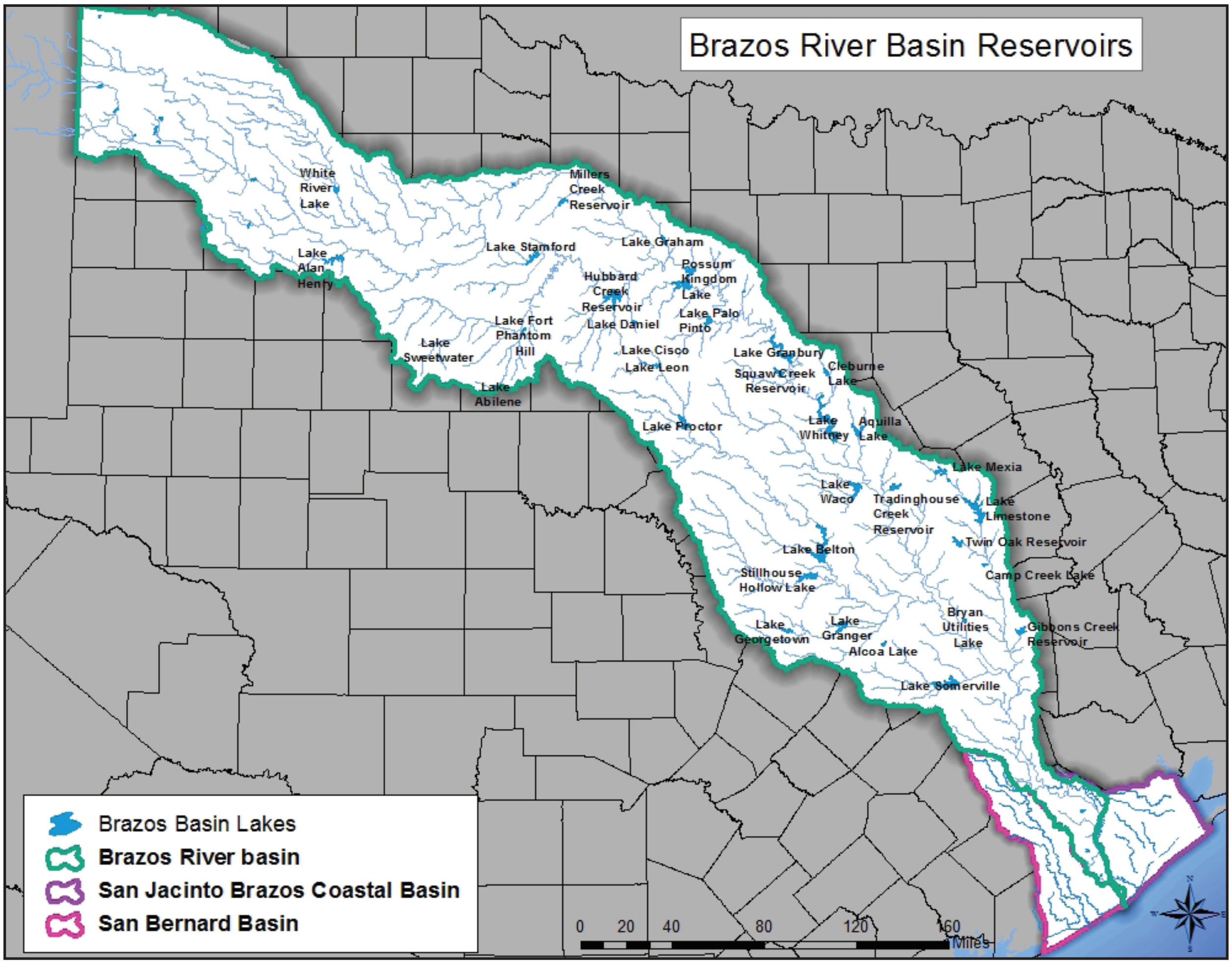


Figure 2.5. Reservoirs within the Brazos BBEST Study Area.

Regional Water Planning

The passage of Senate Bill 1 in 1997 began the regional water planning process in Texas. The State was divided into 16 regions with each region being responsible for developing a long-range (50-year) regional water plan. Significant portions of three of the regions are contained within the Brazos Basin. These are the Llano Estacado in the northwest

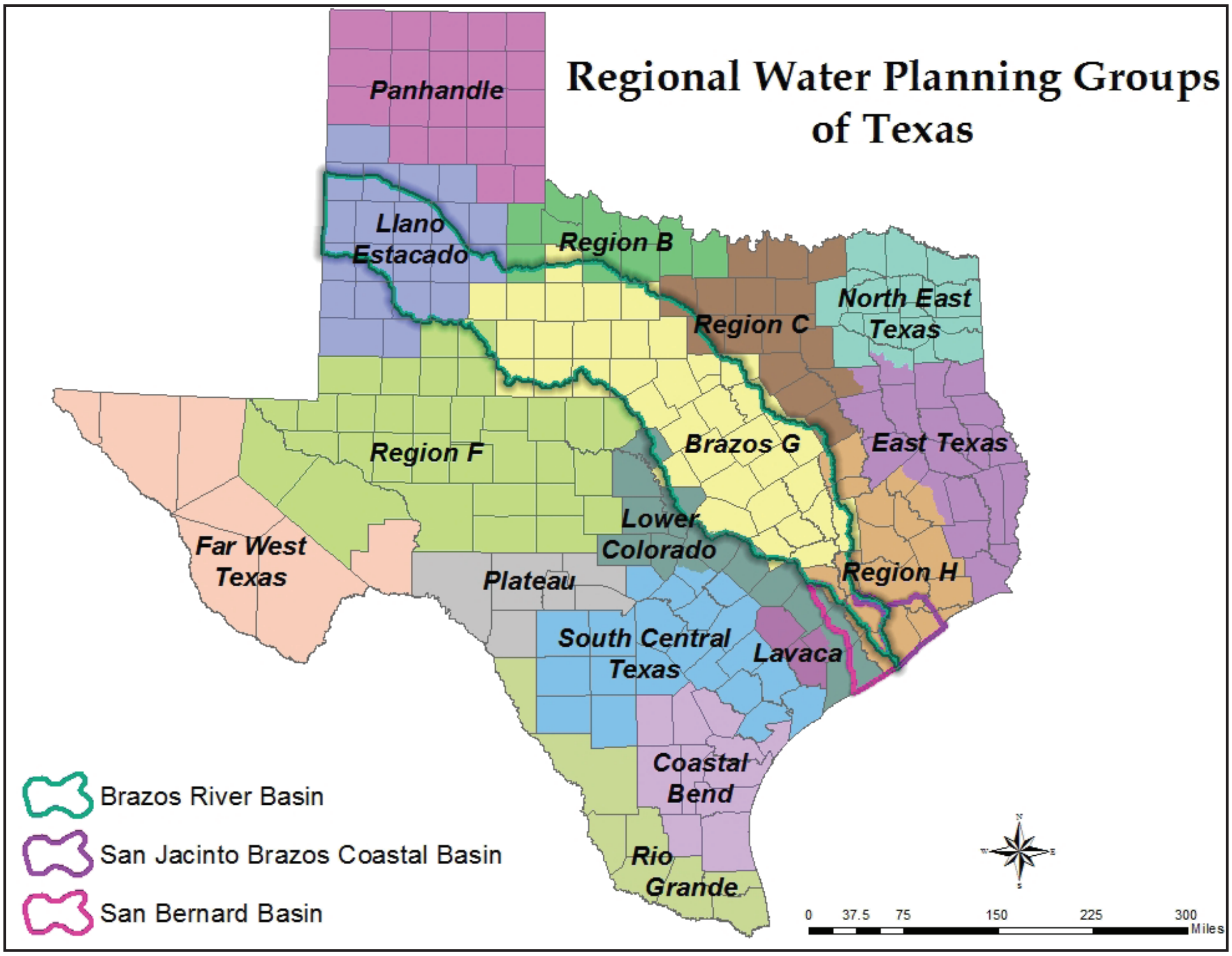
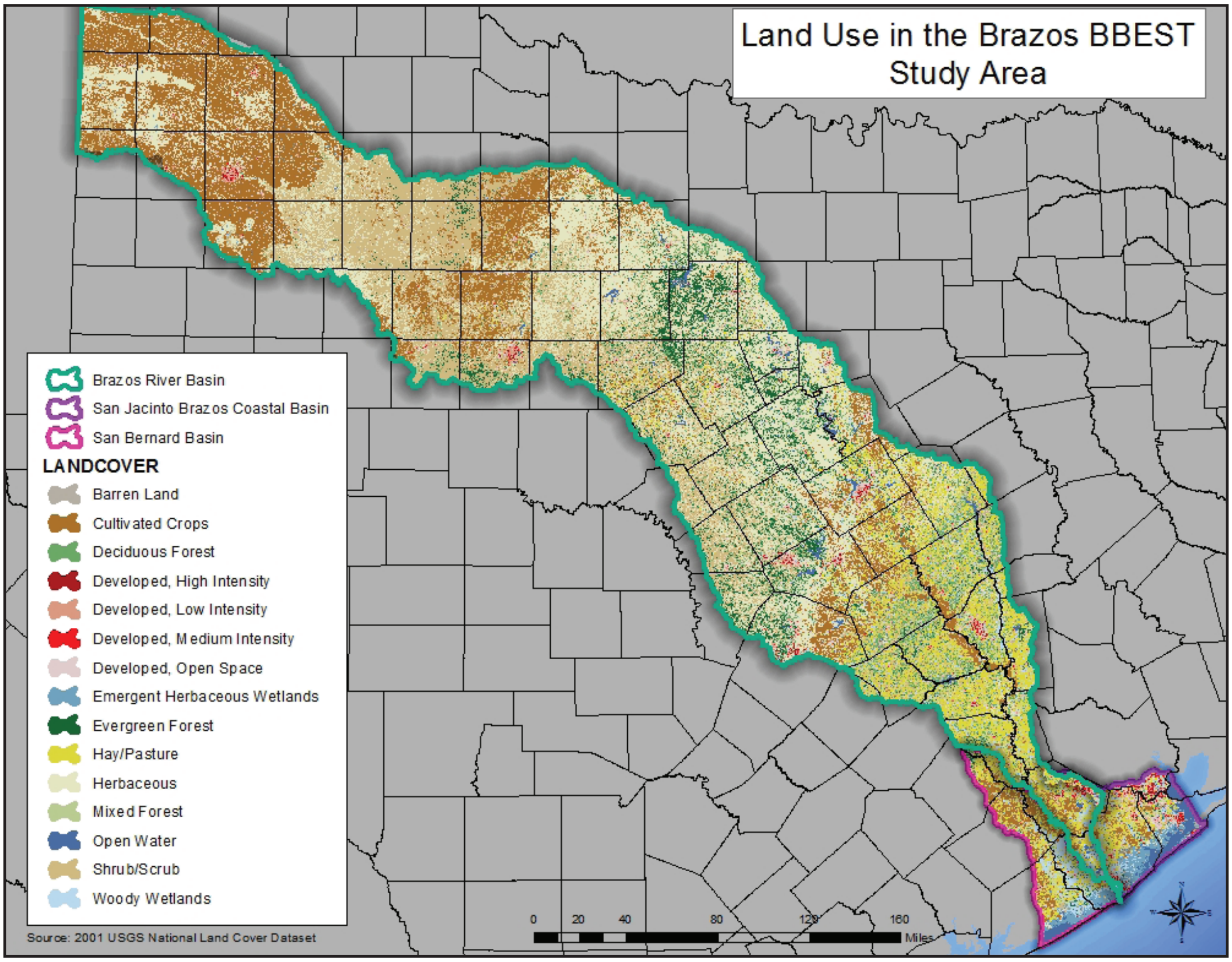


Figure 2.6. Regional water planning groups of Texas.

portion of the basin, the Brazos G Region in the central portion of the basin, and Region H in the extreme southeast portion of the basin (Figure 2.6). In cooperation with the Texas Water Development Board (TWDB), regional stakeholders assist in regional water planning as mandated by the Texas Legislature (Texas Water Code § 16.051, 16.053). At the conclusion of each five-year regional water planning cycle, the regional water plans are submitted to the TWDB, the entity that prepares the comprehensive state water plan.

2.1.2 Watershed Land Use

Layered over the diverse climatic zones, landscapes, and ecosystems within the basin are diverse patterns of land use that range from extreme rural areas with little to no development to areas of scattered development to areas with dense industrial, commercial, and residential development (Figure 2.7). Lubbock, Taylor, Hood, Johnson, McLennan, Bell, Williamson, Brazos, and Fort Bend counties have major cities, and some have industries that use surface waters. Industrial activities in the lowest two counties, Fort Bend and Brazoria, are dominated by the petrochemical industry. Natural gas exploration is increasing basinwide and places further demand on water supplies.



Source: 2001 USGS National Land Cover Dataset

Figure 2.7. Land cover and land use within the Brazos BBEST Study Area.

Agriculture is the mainstay of the rural economy within the basin. In the upper region, major products are row crops, such as cotton and wheat. Hay and silage are also produced in the upper region; however, due to low rainfall, their acreage is much less than those in other regions of the basin. Dairy farming, including confined animal feed operations (CAFOs), have recently begun to shift from central to northern areas of the basin. Dairy farmers have found the arid climate in the northern area to be conducive to production, and lower stormwater runoff in this area reduces nonpoint source pollution problems. As dairy operations move north, the central and lower portions of the basin are experiencing growth in the poultry industry. The central region of the Brazos River Basin is noted for its production of a variety of crops, including hay, silage, peanuts, pecans, vegetables, corn, wheat, and cotton. Comanche, Eastland, Erath, and Somervell counties collectively lead the state in dairy production. This is due to several factors, such as available groundwater, soil suitable for forage production, and existing infrastructure. The lower region of the Brazos River Basin produces hay, silage, beef cattle, and poultry. The Brazos River Bottoms counties (Brazos, Burleson, and Robertson) produce most of the crops in the region, including corn, sorghum, and cotton. Fertile soils of the Gulf Prairies in Fort Bend and Brazoria counties support the production of rice.

2.1.3 Water Quality

While some forms of land cover, such as wetlands, have properties that provide water purification and buffering capabilities, many of the waterways are affected by human impacts. The water quality in the Brazos River Basin is generally good, and the majority of the basin supports aquatic life and recreational uses. Two issues that commonly affect water quality are excessive levels of chloride and nonpoint source pollution. Water quality can also be impacted by the drought/flood cycle.

The primary water quality concern throughout the basin continues to be elevated chloride and TDS concentrations. Chloride in the main stem of the Brazos River comes from natural brine springs in Stonewall, Kent, and Garza counties that discharge into the Salt Fork and Double Mountain Fork of the Brazos. The natural salt produced in the uppermost portion of the Brazos River Basin affects the main stem throughout its entire reach. Elevated chloride and associated TDS concentrations increase drinking water treatment costs and can stress aquatic organisms.

The most common nonpoint source pollution issue in the Brazos River Basin is nutrient loading and increases in suspended solids. It can be difficult to characterize and mitigate nutrient and sediment sources because they originate from multiple locations, and evidence often is most pronounced immediately after rainfall events. Stormwater runoff carries nutrients and sediments into the lakes and streams where they can cause eutrophication. Greater coverage of impervious surfaces associated with urban and suburban development results in faster runoff and delivery of nonpoint source pollution.

In a recent study, Zeng et al. (2011) concluded that human activities dominate the physical and chemical processes controlling the origin and metabolism of dissolved inorganic carbon (DIC) in the Brazos River Basin. Their analysis reflected efficient air–water CO_2 exchange, degradation of relatively young organic matter, and photosynthesis in the middle reaches of the Brazos River as a result of damming and urban-treated wastewater input. They concluded that, in addition to natural soil carbonate, oyster shells and crushed carbonate minerals used in road construction were likely sources of carbonate in the lower reaches of the Brazos. Further understanding of freshwater sources and amounts of carbon contributions to the global carbon cycle is needed (Butman and Raymond 2011). Freshwater contributions to atmospheric CO_2 levels may eventually have a role in future carbon-sequestration strategies.

2.1.4 Riparian Ecology

Riparian vegetation is an important component of maintaining the health of aquatic ecosystems. Riparian vegetation stabilizes stream banks, reduces sediment and anthropogenic pollutants that are entering the aquatic system by filtration, moderates water temperature through shading during periods of high ambient air temperatures, and provides woody debris to the aquatic environment that may be used by aquatic organisms for a variety of life functions. Due to its arid environment and lack of a perennial supply of surface water, the Caprock is generally considered noncontributing to the Brazos River hydrology. Historically, the composition of the riparian corridor of the Brazos Basin above Possum Kingdom Reservoir has been dominated by prairie grasses interspersed with cottonwoods and oaks, and crosses portions of the Rolling Plains, High Plains and Cross Timbers. Poor land management practices combined with the intermittency of stream flow in this portion of the Brazos River Basin have rendered the riparian corridor in the upper Brazos Basin vulnerable to invasion by honey mesquite, ashe juniper, prickly pear, and salt cedar. Salt cedar (*Tamarix ramosissima*), a shrub introduced beginning in the early 19th century to New England from southern Europe, Asia, and Africa, and once cultivated for its ornamental and drought-tolerant characteristics (Stromberg et al. 2009), has been aggressive in its invasion into the riparian corridor north of Possum Kingdom Reservoir. Salt cedar displaces native plant species and lowers the water table and consequently is altering the riparian and aquatic habitats of the upper Brazos Basin. The composition of the riparian corridor varies greatly in the middle and lower basin from the Cross Timbers to the Gulf Coastal Prairie but in general is dominated by bottomland hardwoods consisting of flood tolerant tree and shrub species (Appendix C). The riparian corridor has been highly encroached upon and fragmented throughout the Brazos Basin as a result of land clearing for a variety of human purposes.

2.1.5 Aquatic Biota

Fishes

Fishes are logical choices for focal organisms in environmental flows assessments because 1) species are relatively easy to collect and identify; 2) fishes use a wide array of flow-dependent habitats; 3) fishes exhibit a wide range of life histories, many of which are tied to flow dynamics; 4) fishes tend to be well-studied relative to other aquatic biota; 5) fishes are good integrators of lotic ecosystem conditions; and 6) fishes tend to have a high public profile with some species being commercially or recreationally important (TIFP 2008).

A total of 87 native freshwater fishes and eight sustaining populations of introduced fishes are reported in the Brazos River Basin. In addition, the Brazos River supports a large number of marine-associated fishes that permanently or seasonally inhabit lower reaches of the Brazos River and tributaries. The freshwater fish community includes upland, plains, and lowland forms and a diversity of trophic (piscivore, invertivore, omnivore, herbivore) and reproductive (broadcast, substrate, floodplain, nest-building) guilds. Typical of most western gulf slope drainages, Brazos Basin fish communities are dominated by small-bodied, short-lived minnows, including two endemic species. Sportfish (bass, catfish, sunfish) are abundant in middle and lower reaches of the mainstem Brazos River, western and lower tributaries, and a number of reservoirs throughout the basin.

Brazos River BBEST compiled an extensive list of fish occurrences and abundances throughout the basin from published and unpublished reports (Appendix A) and determined current status of the fish community. At the basin level, two endemic species (sharpnose shiners and smalleye shiners) are candidate species for listing under the U.S. Endangered Species Act (ESA) and six species (alligator gar, American eel, silver chub, blackspot shiner, chub shiner, silverband shiner, blue sucker, and Guadalupe bass) are considered imperiled (Hubbs et al. 2008). Among these, sharpnose shiners, smalleye shiners, and chub shiners are extirpated in the middle Brazos River and populations are declining in the lower Brazos River mainstem (Bonner and Runyan 2007; Perkin et al. 2009). Prior to 2011, sharpnose shiners and smalleye shiners were considered stable in the upper Brazos River, but prolonged drought and stream drying throughout much of the upper Brazos River in 2011 prompted a rescue mission by the Texas Parks and Wildlife Department (TPWD) to capture and retain sharpnose shiners and smalleye shiners in a state fish hatchery. Current population levels are unknown, but stream flows have returned as of January 2011.

Current status of fishes communities in the upper Brazos River Basin ranged from degraded to highly intact (Section 1.3). Upper Brazos River mainstem, Salt Fork, and Double Mountain Fork support natural communities of fishes, ranging from fluvial specialists in the prairie streams of the upper Brazos River and Double Mountain fork to euryhaline specialists in the Salt Fork. The Clear Fork was considered degraded and likely different from the expected community of fishes, but this assessment was based on a limited data set. Large numbers of habitat generalists, slackwater species, and reservoir types suggest contemporary alterations within the drainage.

Fish communities in the middle Brazos River Basin are indicating various levels of degradation. Middle Brazos River mainstem supports a limited number of fluvial specialists and a high abundance of habitat generalists. Likewise, Bosque River is dominated by habitat generalist and reservoir type species.

Fish communities in the lower Brazos River Basin are fairly intact but with indications of some species alterations. The lower Brazos River mainstem supports a large number of fluvial specialists, but population declines in sharpnose shiners, smalleye shiners, and chub shiners and increases in native generalist minnows (red shiners and bullhead minnows) (Bonner and Runyan 2007) suggest early stages of community shifts (Scott and Helfman 2001). Likewise, large tributaries (Navasota River, Yegua Creek, Lampasas River, Little River, Leon River) and small tributaries (Labay 2010) of the lower Brazos River mainstem support diverse and healthy communities of fishes. Several of the fishes in the lower Brazos Basin are at their western most extent of their range, making the lower basin a biodiversity hotspot with recently colonizing and persistent eastern forms (ca. 12,000 YA; east Texas fishes) mixing with older phyletic lineages (Edwards Plateau/Rio Grande fishes) of the western gulf slope drainages (Conner and Suttkus 1986). Nevertheless, habitat generalists and reservoir-type fishes are abundant based on a limited set of data, suggesting that contemporary communities are shifting.

Mussels

Mussels are important components of aquatic ecosystems. As filter feeders, they remove phytoplankton and suspended matter from the water column, enhancing plankton production and improving the overall health of river systems. They have an important influence on nutrient dynamics through excretion and biodeposition. Through bioturbation, mussels release nutrients from sediments into the water column and increase water and oxygen content of sediments. They are extremely sensitive to environmental disturbance and serve as barometers of aquatic ecosystem health (McMahon and Bogan 2001; Vaughn and Hakenkamp 2001; Strayer et al. 2004).

Freshwater mussels are the most threatened and rapidly declining group of freshwater organisms in North America. Mussels are particularly vulnerable to disturbance because of various life history traits, including sensitivity to contaminants, non-selective feeding, long life span, large size/limited mobility, low fertilization rates, high juvenile mortality, irregular recruitment, and unique life cycle involving an obligate larval parasitic stage of fish (Fuller 1974; Downing et al. 1993; McMahon and Bogan 2001). Numerous factors have contributed to population declines, including habitat degradation resulting from sedimentation, channelization, impoundment of rivers, pollution, climate changes, and instream flow alterations; increased competition with non-indigenous species; and overharvesting (Williams et al. 1993; Vaughn and Taylor 1999).

North America is considered the global epicenter of mussel diversity. Approximately 300 species are known from the United States, 53 of which have been reported from Texas and 33 from the Brazos River Basin. Fifteen species are listed as state threatened in Texas, one of which is a candidate for federal protection and 11 others having been petitioned for listing under the ESA. Seven of the 15 have been recorded from the Brazos River drainage (Winemiller et al. 2010).

Two regional studies have provided recent information on mussels in the Brazos River Basin. Karatayev and Burlakova

(2008) conducted field sampling in 2006–2007 to characterize distribution and habitat utilization at 27 locations in the Brazos River Basin, 10 in the San Antonio River Basin, and three on the lower Sabine River. Twelve species and 463 live individuals were collected from the Brazos drainage. Species richness was high compared to the San Antonio River system (four species) and lower Sabine River (one species). The Brazos mainstem and two tributaries (Navasota River and Yegua Creek) exhibited the highest mussel density and diversity of all streams sampled (nine, eight, and seven species, respectively). The survey provided insight on the status of several rare, declining, or peripheral species within the Brazos system. The first two discussed below have been petitioned for listing under the ESA. Smooth pimpleback (*Quadrula houstonensis*), endemic to the Brazos and Colorado basins, is known to be declining across its range (Randklev et al. 2009), but was relatively abundant at several Brazos mainstem sites and in several lower Brazos tributaries (Little Brazos River, Navasota River, Little River, Yegua Creek). The species is also known from a remote tributary, the Leon River (Howells et al. 1996). One live specimen of Texas fawnsfoot (*Truncilla macrodon*), a very rare central Texas endemic, was collected in the lower Brazos River at IH 10. Recently two long-dead shells were found in the Brazos mainstem near Glen Rose at SH 105 and in Deer Creek. The findings verified the imperiled status of *T. macrodon*. Within the Brazos drainage, two additional species, although widely distributed in the Mississippi River system, were collected only in the Navasota River: Rock pocketbook (*Arcidens confragosus*) and Pistolgrip (*Quadrula verrucosa*).

Randklev et al. (2009) conducted a follow-up survey, resampling four sites in both the lower Brazos system and lower Sabine River in 2008–2009. Brazos drainage sites included the mainstem at FM 485 and SH 105, the Navasota River at SH 105, and Yegua Creek at FM 50. The objectives were to generate additional distributional and habitat utilization information, with emphasis on habitat characterizations during varying flow conditions. Within the Brazos drainage, 13 mussel species and 1,086 live individuals were collected during four sampling periods. The Navasota River at SH 105 had the highest densities and the Brazos River at FM 485 the lowest. Six species were collected from the lower Brazos mainstem, eight from the Navasota River, and eight from Yegua Creek. Regarding uncommon species, Smooth pimpleback was collected at all four sites, further identifying the lower Brazos drainage as a remaining stronghold for the species. Texas fawnsfoot was collected on multiple occasions from the Brazos River at SH 105, the second recent locality record from the lower Brazos mainstem for this very rare species. Rock pocketbook and pistolgrip were collected only in the Navasota River, accentuating the unique faunal characteristics of that river among Brazos drainage streams.

Instream flow requirements for mussels are not as well understood as for fishes, with the former being more difficult to characterize because of their low mobility, clumped distribution, and complex hydraulic preferences. The inability of mussels to react quickly to changes in flow precludes use of the types of protocols normally applied for other aquatic species to characterize flow-related habitat suitability (Layzer and Madison 1995; Gore et al. 2001). Furthermore, mussel collecting is costly and time-consuming, often requiring snorkeling or SCUBA techniques, and specimen identification is difficult due to shell morphology irregularities related to geographical occurrence, sexual dimorphism, and ontogenetic variability (USACE 2005). Despite these drawbacks, we are proposing two mussel species for inclusion as target organisms, based on existing knowledge of the distribution and populational status of mussels in the Brazos system, their importance as an ecosystem component, and their known sensitivity to instream flow patterns. Smooth pimpleback is proposed as a focal species for the middle Brazos, lower Brazos, Little, Navasota, and Leon rivers, in light of its limited geographical range and imperiled status. Pistolgrip is proposed as a focal species for the Navasota River, in light of its peripheral occurrence in the Brazos system, apparent geographical restriction there among Brazos streams, and speciose nature of the Navasota mussel fauna. Evidence exists that both species are common enough within the reaches they occupy to make them valuable for adaptive management ecosystem monitoring purposes. We contemplated including Texas fawnsfoot and Rock pocketbook but eliminated them because existing information indicates they are too rare to be useful for instream flow assessments.

Other Aquatic Species

Over the past three decades, the naturally occurring golden alga (*Prymnesium parvum*) has bloomed in water bodies across the United States and Texas, including reservoirs within the Brazos River Basin. Golden alga is tolerant of large variations in temperature and salinity. Under certain environmental conditions, golden alga can produce toxins that can cause massive fish and bivalve kills. In Texas, golden alga blooms are winter phenomena that develop under conditions suboptimal for their reproductive growth but conducive for toxicity generation (Roelke et al. 2010a, 2010b, 2010c; Brooks et al. 2011). During these stressful times, the production of toxins suppresses the golden alga's competitors and deters its predators (Granéli et al. In press). The toxins also immobilize bacterial prey during this period when the alga enters into a heterotrophic mode of growth (*P. parvum* is a mixotroph, an organism that both performs photosynthesis and consumes other organisms to obtain energy), which allows it to feed on bacteria more efficiently and maintain higher densities in the water column (Brooks et al. 2011).

Golden alga blooms are complex and involve changing water flow, salinity, nutrient concentration, light intensity, and temperature, various combinations of which may increase or decrease a golden alga bloom (Brooks et al. 2011). While increased water flow may cause hydraulic disruption of the organism's ecology or dilute salinities to levels that do not support a bloom, in the Brazos River Basin the location of the precipitation event may be important because western portions of the Brazos Basin have naturally high salinity. Runoff can wash more nutrients and suspended sediments into the water body, which may increase or diminish the golden alga blooms depending on time of year and other environmental factors. Currently, the precise combination of factors that initiate or terminate a toxic bloom is not fully understood. Recent research in Texas has addressed alternative approaches for managing impacts of golden alga blooms when they occur (Barkoh et al. 2005; Sager et al. 2007; Roelke et al. 2010c, 2011; Brooks et al. 2011).

Historically, instream flow studies have placed little emphasis on non-fish elements, and their relationships to stream flow are poorly known. Compared to fishes, a general perception exists that macroinvertebrates are more difficult to collect and identify, to derive habitat suitability criteria for, and to assign ecological and economic values. Such complications have led most regulatory agencies to focus on the needs of focal fish species (Gore et al. 2001). For these reasons, fishes were the primary group evaluated for our environmental flow recommendations for the Brazos River system. Here we assume that meeting the ecological requirements of fishes will produce ecological conditions and dynamics protective of riparian plants, aquatic invertebrates, and other aquatic and riparian vertebrates (Williams et al. 2005; Pendergrass 2006; Shattuck 2010). Again, it is assumed that the needs of diverse fish species and habitat guilds (groups of species with the same basic habitat requirements) will be met by maintaining the key components of a natural flow regime (Poff et al. 1997, 2009).

2.2 San Jacinto-Brazos and San Bernard Coastal Basins

2.2.1 Geography, Geology, and Hydrology

The San Jacinto River Basin contains all or parts of four counties, whereas the San Bernard River Basin covers portions of six counties. The soil, vegetative, and mineral diversity of the two basins is a result of the region's subtropical climate and fluvial geologic characteristics. The area receives an average of 45 inches of rain each year, with a strong influence from the Gulf of Mexico. Topography ranges from just over 400 feet in the northern counties, to sea level at the Gulf coast. Surface water bodies include streams, rivers, bayous, lakes, reservoirs, estuaries, and the open waters of the Gulf of Mexico. Flow from the basins into the Gulf of Mexico is generally sluggish due to the gently sloping topography.

Without the inputs of treated effluent, many of the creeks and bayous would not normally flow year-round, although there are a few springs that contribute significantly to base flow. Due to shallow groundwater tables, there is influence of groundwater recharge to some channels. Soils are predominantly clayey with dispersed areas of sandier substrate near and around river channels. Distinct riparian vegetation can be found along river floodplains. Mineral resources include oil and gas fields, lignite, sand and gravel, clay, salt, and sulfur.

The San Bernard River is over 125 miles long and the basin covers approximately 900 square miles. The headwaters of the San Bernard River originate in New Ulm in Austin County. The river flows through Austin, Colorado, Wharton, Fort Bend, and Brazoria counties and ultimately drains to the Gulf of Mexico just beyond the Intracoastal Waterway. The San Bernard Basin is bounded on the north and east by the Brazos Basin and on the south and west by the Colorado River Basin and Caney Creek.

The tidal and nontidal portions of the San Bernard River are separated by a salt barrier dam. This small dam is located on the river near West Columbia approximately one mile north of Highway 35. The purpose of the dam is to prevent saltwater from reaching the upper portions of the river where water is diverted for industrial uses.

Aquifers

The Gulf Coast Aquifer is the only major aquifer in both basins.

Reservoirs

There are no major reservoirs in either the San Jacinto-Brazos Coastal Basin or the San Bernard River Basin.

Regional Water Planning

The San Jacinto-Brazos Coastal Basin is also included in the Region H Water Planning Group, and the San Bernard Basin is included in the Lower Colorado Planning Group.

2.2.2 Watershed Land Use

The setting for the San Jacinto-Brazos Costal Basin and San Bernard Basin is fairly homogenous and much less diverse than that of the Brazos River Basin. Watersheds in the lower San Jacinto and San Bernard basins contain saltwater marshes, wetlands, and transitional estuary ecosystems, which are home to numerous species of birds and aquatic life. Some of the land cover types, such as wetlands, provide water purification and buffering capacity. In addition to the diverse natural setting, this coastal region contains a variety of land cover types, land use types, and ecosystems. Land uses range from scattered development with large acreages of undeveloped land to dense industrial development. The southwestern portion of the San Jacinto-Brazos Coastal Basin and the San Bernard River segments drain through small rural communities, industrial areas, coastal wetlands, and estuaries to bays and then the Gulf of Mexico. Industrial parks are located throughout the San Jacinto and San Bernard basins, extending as far west as the Bastrop Bayou Tidal watershed and the vicinity of Freeport. Agricultural activity is focused in the southwestern watersheds of the San Jacinto-Brazos Coastal Basin as well as the San Bernard River Basin. This portion of the region contains large areas used for cattle and other livestock. Some of the major crops grown in the region include cotton, rice, sorghum, and other grains.

2.2.3 Water Quality

The water quality in the two basins is generally good and supportive of aquatic life and recreational uses. The primary issue that commonly affects the water quality of the basins is nonpoint source pollution. Precipitation is relatively predictable due to proximity to the Gulf of Mexico, and water quality in these basins is less impacted by the drought/flood cycle than it is in the entirety of the Brazos Basin. Common sources of nonpoint source pollution in the San Bernard Basin include wastewater treatment facilities, malfunctioning septic systems, construction site runoff, agricultural sources, and suburban runoff from streets and yards. These sources have led to high levels of nutrients in the San Bernard River and increasing trends in chlorophyll *a*, chloride, and TDS concentrations at some locations.

Like the San Bernard Basin, the San Jacinto-Brazos Coastal Basin is impacted by nonpoint source pollution. Water bodies of the San Jacinto-Brazos watershed routinely reflect concerns for depressed dissolved oxygen, which has led to concerns for aquatic life use. Additionally, these water bodies reveal increasing trends for nutrients and chlorophyll *a*.

The overriding, long-term challenge for regional water quality management in the San Jacinto-Brazos and San Bernard basins is to maintain and, where possible, improve the quality of area waterways despite the cumulative impacts that have come with population growth and urban development. Among the challenges in these basins are:

- Increased wastewater generation that impacts an already high capacity system,
- Increased land disturbance and more impervious surfaces associated with ongoing development, generating nonpoint source pollution from a wider geographic area, and
- Altered drainage patterns resulting from flood control measures.

2.2.4 Riparian Ecology

The San Bernard watershed is located within the Gulf Coast Prairies Ecoregion that is characterized by level to undulating plains rising to the north from the Gulf of Mexico. At the Gulf of Mexico, the San Bernard watershed consists of low-lying landforms that include barrier islands, peninsulas, offshore sand bars, bays, mudflats, dunes, and shoals that result from the actions of tides, waves, wind, and human activities. The riparian corridor of the San Bernard River transitions from north to south, with a belt of hardwood forests in the upper reaches, and a prairie grass-dominated riparian zone in the lower reaches. Riparian corridors of streams within the San Jacinto-Brazos Coastal Basin are dominated by coastal prairie grasses interspersed with limited hardwood trees. Riparian corridors of both the San Bernard Basin and San Jacinto-Brazos Coastal Basin have been fragmented due to a variety of land clearing activities.

2.2.5 Aquatic Biota

Fishes

A total of 24 freshwater fishes, consisting of a fairly diverse community of lentic (sunfish, ribbon shiners, slough darter) and lotic (dusky darter, mimic shiner) species and dominated by minnows, are reported from the San Bernard River (Appendix A). Current survey records are not sufficient to confidently assess integrity of the system or community shifts through time.

Mussels

Data regarding freshwater mussel populations in the San Bernard River basin could not be located. In 2001, the TPWD conducted distributional surveys of freshwater mussel populations within the state to better understand the resource. One site on the San Bernard River was surveyed in 2001 and no bivalves were observed (Howells 2002).

Other Aquatic Species

There was a void regarding the status of aquatic biota other than fishes in the San Bernard Basin and the available fish data are severely limited. For these reasons, aquatic biota have not been explicitly evaluated for our environmental flow recommendations for the San Bernard River system. We assume that by maintaining the key components of a natural flow regime in the San Bernard River in a manner similar to the lower Brazos River, we will produce ecological conditions and dynamics protective of fishes, riparian plants, aquatic invertebrates, and other aquatic and riparian vertebrates (Poff et al. 1997, 2009).

2.3 Estuarine Zones of the Brazos and San Bernard Basins

Very few comprehensive surveys of the aquatic fauna of the coastal estuarine zones of the Brazos and San Bernard rivers have been historically conducted (Johnson 1977; Patillo et al. 1997; Kirkpatrick 1979; Montagna et al. 2008). Due to the distance and lack of a well-developed estuarine bay system, the TPWD has never conducted systematic surveys of this portion of the Texas coast. Very little fishery-dependent data exist (Lance Robinson TPWD personal communication to G. Guillen). Routine fishery-independent data have never been collected in the Brazos or San Bernard estuarine systems.

The earliest report on estuarine benthic and fish communities in the Brazos River downstream of the town of Brazoria was produced by Kirkpatrick (1979). A variety of nekton species (fishes and macroinvertebrates that swim within the water column) were collected in gillnets and trawls during March 1977, including alligator gar, gizzard shad, sand trout, Atlantic croaker, southern flounder, Atlantic Stingray, Gulf menhaden, striped mullet, sea catfish, pigfish, striped bass, blue catfish, brown shrimp, blue crab, river shrimp, gafftopsail catfish, bay anchovy, silver perch, and spot. Sharks were collected at several sites. Conductivities during this period ranged between 9,900 and 31,000 uS depending on depth.

The most comprehensive study of fish and macroinvertebrate communities was conducted by Johnson (1977). His findings were very similar to those summarized by Patillo et al. (1997) (see Table 2.1). This semi-quantitative survey is the only comprehensive study conducted in the area. Extensive use of the lower river by estuarine organisms was documented in the San Bernard, Brazos, and adjoining tidal creeks. In areas 12 miles or more upstream, a mixture of freshwater fish species and estuarine organisms, including blue crabs, was collected. Salinities ranged between 0 and 25 psu at sites located up to 25 miles upstream. Distinct seasonality was observed irrespective of salinity regime, with certain marine species, such as gafftopsail catfish, invading the lower Brazos River during summer months along with other "seasonally migratory" species.

Depending on salinity regime, the lower Brazos River appears to serves as nursery habitat for many immature fish and shellfish species including juvenile white shrimp, brown shrimp, and blue crab. Johnson (1977) found evidence that these species also residence in adjacent marshes, and larger individuals were captured later in the year within deeper areas of the river channel. However, densities of these species in trawl samples declined greatly between the mouth and six miles upstream. Blue catfish and other freshwater fishes were collected in higher numbers during wet years, whereas marine species were more common during drier periods. Similar patterns in species composition and abundance were observed in the San Bernard River.

Benthic surveys recently conducted by Montagna et al. (2008) found that, when compared to open bay systems, the Brazos and San Bernard rivers reveal low densities of benthic infauna (Palmer et al. 2011). These estuarine systems can be classified as oligo-mesohaline with salinities below 17-22 psu.

Recent preliminary field surveys during December 2011 found an extensive blue crab fishery (crab pots) (approximately 100 pots per river mile) in the lower eight miles of the Brazos River (G. Guillen personal observation). Qualitative surveys using seines and trawls indicated the same area was populated by blue crab, brown and/or white shrimp, and juvenile gray snapper (*Lutjanus griseus*). A distinct halocline was found at the bottom of the river along the lower eight miles. Boat and bank fisherman were observed fishing within the Brazos River channel (estuary) and Intracoastal Waterway.

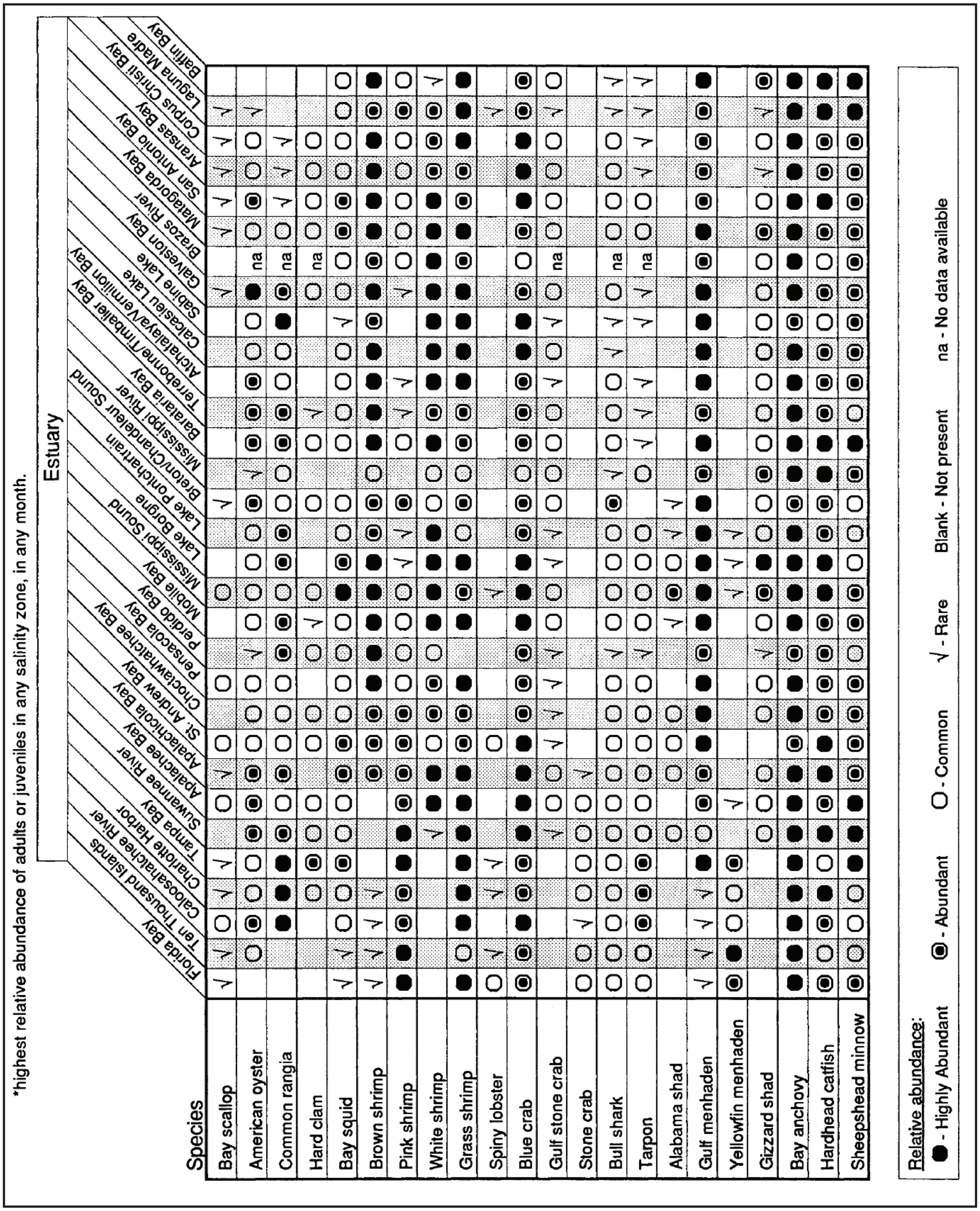
Coastal wetlands (saline to freshwater) are important natural resources that provide essential habitat for fish, shellfish, and other wildlife. Coastal wetlands also serve to filter and process agricultural and urban runoff and buffer coastal areas against storm and wave damage. The condition and distribution of wetland types can be affected by changes in depth and frequency of inundation as well as salinity. Periodic inflows delivering sediment are necessary to support marsh creation and maintenance within areas affected by coastal subsidence or sea-level rise. Extensive wetlands are found along the delta of the Brazos River and fringing marsh lines the banks of the lower-most river channel. Extensive coastal wetlands are present in the adjoining Cedar Lakes area, adjacent coastal areas drained by tidal creeks, and the San Bernard River estuary (White et al. 1988).

In the active Brazos River delta, White et al. (1988) described some of the marshes that occur in the swales between upland ridges (relict beach ridges). Smooth cordgrass (*Spartina alterniflora*) dominates the low-lying saltwater marshes and coexists with saltgrass (*Distichlis spicata*) at higher elevations. There are brackish marshes within the delta that support cattails (*Typha* sp.), saltmarsh bulrush (*Schoenoplectus robustus*), American bulrush (*Schoenoplectus pungens* var. *longispicatus*), jointed flatsedge (*Cyperus articulatus*), black rush (*Juncus roemerianus*), and saltgrass. White et al. (1988) also report extensive stands of black rush and cattails in the swales near Quintana.

Only scattered patch reefs of Eastern oyster are found in the vicinity of the Brazos and San Bernard river estuaries and adjacent marsh areas. Oysters (*Crassostrea virginica*) are not commercially harvested from the Brazos River estuary.

The Freeport area has been classified as restricted by the Texas Department of State Health Services (TDSHS, formerly the Texas Department of Health) and is closed to the harvesting of molluscan shellfish (TDSHS, 2007). In addition, TDSHS and TPWD do not have any bay sampling stations for monitoring oysters within the Brazos River estuary. We therefore conclude that there are no significant oyster reefs in this area.

Table 2.1. List of major fish and invertebrate species observed in the Brazos River estuary (Patillo et al. 1997).



*highest relative abundance of adults or juveniles in any salinity zone, in any month.

	Estuary																														
Species	Florida Bay	Ten Thousand Islands	Caloosahatchee River	Charlotte Harbor	Tampa Bay	Suwannee River	Apalachee Bay	Apalachicola Bay	St. Andrew Bay	Choctawhatchee Bay	Pensacola Bay	Perdido Bay	Mobile Bay	Mississippi Sound	Lake Borgne	Lake Pontchartrain	Breton/Chandeleur Sound	Mississippi River	Barataria Bay	Terrebonne/Timbalier Bay	Atchafalaya/Vermilion Bay	Calcasieu Lake	Sabine Lake	Galveston Bay	Brazos River	Matagorda Bay	San Antonio Bay	Aransas Bay	Corpus Christi Bay	Laguna Madre	Baffin Bay
Bay scallop	√	√	○	√	√		○	√	○		○			○			√							√		√	√	√	√	√	
American oyster		○	◉	○	○	◉	◉	◉	○	○	○	√	○	○	○	○	◉	√	◉	◉	◉	○	○	●	na	○	◉	○	○	√	
Common rangia			●	●	●	◉	○	◉	○	○	○	◉	◉	○	◉	◉	○	○	◉	◉	○	○	●	◉	na	○	√	√	√		
Hard clam				○	◉	○	○		○	○		○	√	○			○		○	√				○	na	○	○	○	○		
Bay squid	√	√	○	○	◉	○	○	◉	◉	○	○	○	○	●	◉	○	○		○	○	○	○	√	○	○	◉	◉	○	○	○	○
Brown shrimp	√	√	√	√				◉	◉	◉	●	●	●	●	●	◉	◉	○	●	●	●	●	◉	●	◉	●	●	●	●	◉	●
Pink shrimp	●	●	◉	◉	●	●	◉	◉	◉	◉	○	○	○	○	√	√	◉		○	√	√			√	○	○	○	○	○	◉	○
White shrimp						√	●	●	○	◉	◉	○	●	●	●	●	○	○	●	◉	●	●	●	●	●	●	●	◉	◉	◉	√
Grass shrimp	●	○	●	●	●	●	●	●	◉	◉	●		●	◉	●	○	◉	○	◉	◉	●	●	●	●	◉	●	◉	◉	●	●	●
Spiny lobster	○	√		√	√				○					√																√	
Blue crab	◉	◉	●	◉	◉	●	●	●	●	◉	◉	◉	●	●	●	◉	◉	○	◉	◉	◉	●	●	◉	○	◉	●	●	●	◉	◉
Gulf stone crab						√	○	○	√	√	√	√	○	○	√	√	○	○	○	○	√	○	√	○	na	○	○	○	○	√	○
Stone crab	○	○	√	○	○	○	○	√																							
Bull shark	○	○	○	○	○	○	○	○	○	○	○	√	○	○	○	○	◉	√	○	○	○	√	√	○	na	○	○	○	○	√	√
Tarpon	○	○	◉	◉	◉	○	○	○	○	○	○	√	○	○	○	○		○	√	√	√		√	√	na	○	○	√	√	√	√
Alabama shad						○		○	○	○			√	◉	○	√	√														
Gulf menhaden	√	√	√	√	●	○	◉	◉	●	●	●	◉	●	●	●	●	●	◉	●	◉	●	●	●	●	◉	●	◉	◉	◉	◉	●
Yellowfin menhaden	◉	●	○	○	◉		√							√	√	√															
Gizzard shad						○	○	○		○	○	√	○	◉	●	○	○	◉	○	○	○	○	○	○	○	◉	○	√	○	√	◉
Bay anchovy	●	●	●	●	●	●	●	●	◉	●	●	◉	●	●	●	●	◉	●	●	●	●	●	◉	●	●	●	●	●	●	●	●
Hardhead catfish	◉	○	◉	●	○	●	◉	●	●	◉	◉	◉	◉	●	●	◉	◉	●	●	◉	◉	◉	○	◉	○	◉	●	◉	◉	●	●
Sheepshead minnow	◉	○	○	○	●	●	●	◉	◉	◉	◉	○	◉	◉	○	○	○	◉	●	○	◉	◉	◉	◉	◉	◉	◉	◉	◉	●	●

Relative abundance:

● - Highly Abundant ◉ - Abundant ○ - Common √ - Rare Blank - Not present na - No data available

Table 2.1. (continued).

Species	Estuary																														
	Florida Bay	Ten Thousand Islands	Caloosahatchee River	Charlotte Harbor	Tampa Bay	Suwannee River	Apalachee Bay	Apalachicola Bay	St. Andrew Bay	Choctawhatchee Bay	Pensacola Bay	Perdido Bay	Mobile Bay	Mississippi Sound	Lake Borgne	Lake Pontchartrain	Breton/Chandeleur Sound	Mississippi River	Barataria Bay	Terrebonne/Timbalier Bay	Atchafalaya/Vermilion Bay	Calcasieu Lake	Sabine Lake	Galveston Bay	Brazos River	Matagorda Bay	San Antonio Bay	Aransas Bay	Corpus Christi Bay	Laguna Madre	Baffin Bay
Gulf killifish	○	◉	○	◉	○	◉	◉	○	○	○	○		◉	○	◉	○	○	◉	●	●	◉	◉	◉	◉	◉	◉	◉	◉	○	◉	◉
Silversides	●	◉	●	●	●	◉	●	●	◉	◉	◉	◉	◉	●	◉	◉	○	◉	●	◉	◉	◉	◉	◉	◉	◉	◉	◉	◉	●	●
Snook	○	◉	◉	◉	○	○	○	○											√					√		√		√	√	○	
Bluefish	○	○		○	○	○	○	○	◉	◉	○	○	○	○			√	√	○	√	√	√	√	○	○	√	√	√	√		
Blue runner	√	○		○	○	○	○	○	◉	○	○	○	○	◉					○	√				√							
Crevalle jack	◉	○	○	◉	◉	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	√	○	○	○	○	○	○	◉	○
Florida pompano	●	○		◉	○	√	○		○	○	○	○	○	◉			○	○	○	○	√	○		○		○	○	○	○	◉	√
Gray snapper	◉	○	√	○	○	○	○	√	○	○	◉	○	○				○		○	√		√		√		√	√	√	√	○	√
Sheepshead	○	○	√	√	○	○	√	○	○	○	○	◉	◉	○	◉	○	○	○	◉	◉	○	○	○	○	○	◉	◉	○	○	◉	○
Pinfish	●	●	●	●	●	●	◉	◉	●	◉	●	◉	◉	●	◉	◉	○	○	◉	◉	○	○	○	◉	◉	●	◉	◉	◉	●	◉
Silver perch	◉	◉	◉	◉	◉	◉	○	◉	◉	○	○	○	○	●	●	○	○	○	◉	◉	○	○	○	○	○	○	○	○	○	◉	◉
Sand seatrout	√	◉	●	●	◉	●	●	●	◉	◉	○	○	●	●	●	◉	○	●	◉	◉	◉	◉	√	◉	○	○	○	○	◉	√	○
Spotted seatrout	◉	○	○	◉	○	◉	○	○	◉	◉	○	○	◉	◉	◉	○	◉	◉	○	◉	◉	○	○	○	○	○	○	○	○	○	○
Spot	○	○	○	○	●	◉	●	◉	◉	●	●	◉	●	●	●	○	◉	◉	●	◉	◉	○	◉	◉	◉	◉	◉	◉	◉	●	●
Atlantic croaker	√	√	√	○	√	○	○	●	◉	◉	●	○	●	●	●	●	◉	●	●	●	●	●	◉	●	●	●	●	◉	◉	◉	◉
Black drum	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	◉	○	◉	◉	○	○	○	○	○	○	○	○	○	○	◉
Red drum	○	√	◉	◉	●	○	○	○	◉	○	○	○	○	○	◉	○	◉	○	○	○	○	◉	○	○	○	○	○	○	○	○	○
Striped mullet	●	●	●	●	●	◉	●	◉	●	◉	◉	◉	◉	●	●	◉	◉	◉	◉	◉	◉	◉	○	◉	○	◉	◉	◉	◉	◉	◉
Code goby	●	●	◉	●	◉	○	○	○	◉	○	○	√		○	◉	○			√					√	na	○	√	○	○	◉	◉
Spanish mackerel	○	○	√	○	○	○	√	√	◉	○	○	◉	○	◉	√	√	○	√	○	○	○	○	○	○	√	√	√	√	√	√	
Gulf flounder	○	○	√	○	○	○	○	○	◉	○	○	○	○	○										√		√	√	√	√	√	√
Southern flounder	√	√		√	√	○	○	○	○	○	○	○	○	◉	○	○	◉	◉	◉	◉	○	◉	●	●	○	◉	◉	○	○	◉	○

Relative abundance:

● - Highly Abundant ◉ - Abundant ○ - Common √ - Rare Blank - Not present na - No data available

3 Instream Flow Analysis

3.1 Rationale and Approach

3.1.1 The Natural Flow Regime Paradigm

The importance of natural flow regimes for the maintenance of ecological processes in flowing water systems is well recognized (Sparks 1995; Poff and Allan 1995; Poff et al. 1997; Bunn and Arthington 2002; Bowen et al. 2003). Conceptual models of biological productivity in large rivers, such as *The Flood Pulse Concept* (Junk et al. 1989) and the *Low Flow Recruitment Hypothesis* (Humphries et al. 1999), propose that flood dynamics significantly influence inter-annual variation in fish recruitment, both positively and negatively (Zeug and Winemiller 2008). The Instream Flow Council (IFC), an organization of state and provincial agencies in the United States and Canada dedicated to improving the effectiveness of instream flow programs, has adopted this principle as a cornerstone of river resource stewardship (Annear et al. 2004; Locke et al. 2008).

The natural flow regime paradigm identifies five critical components of flow that regulate ecological processes in river ecosystems: magnitude, frequency, duration, timing, and rate of change in flow (Richter et al. 1996; Walker et al. 1995; Annear et al. 2004; NRC 2005; Locke et al. 2008). These five components represent attributes of the entire range of flows, such as floods or low flows during periods of drought. The flow regime is the master variable of central importance in sustaining the ecological integrity of flowing water systems (Poff et al. 1997). Ecological integrity was defined by Karr and Dudley (1981) as "*The ability to support and maintain a balanced, integrated adaptive assemblage of organisms having species composition, diversity, and functional organization comparable to that of natural habitat of the region*." Each of the five flow regime components influences multiple aspects of the biological community and their environment, and modification of any of the components of the flow regime can affect the ecological integrity of rivers. Aquatic organisms have life history strategies adapted to the flow regime. Alteration of the natural flow regime has modified the ecology of rivers worldwide (Bunn and Arthington 2002; Postel and Richter 2003; Poff and Zimmerman 2009). In North America, most rivers have been impacted by the construction of dams and levees that modify natural flow regimes crucial for fish reproduction (Junk et al. 1989; Poff et al. 1997) and disconnect productive off-channel habitats from the active river channel (Bayley 1991). Modification of natural flow regimes has been implicated in the establishment of exotic species (Moyle and Light 1996; Tyus and Saunders 2000) and changes in fish distribution, abundance, and assemblage structure (Feyrer and Healy 2003; Sommer et al 2004). In a recent review of the literature on ecological responses to flows, Poff and Zimmerman (2010) determined that fish diversity, abundance, and demographic rates (e.g., survivorship, population growth rate) consistently changed and mostly declined in response to both elevated and reduced flow magnitude. Riparian vegetation communities changed in response to reduced peak flows, with non-woody vegetative cover often increasing and encroaching into stream channels. Restoration strategies for rivers include reestablishment of relatively natural flow regimes (Trexler 1995; Richter et al. 1997; Poff 2009) and increased connectivity with off-channel aquatic habitats (Amoros and Bornette 2002; Tockner and Stanford 2002).

The Scientific Advisory Committee (SAC) and virtually all of the other BBESTs have recognized that the Texas Instream Flow Program (TIFP 2008) has followed the IFC's recommendations in adopting the natural flow regime as the conceptual foundation for their proposed technical approaches. Established under Texas SB2, the TIFP's scientific program was reviewed by an expert committee assembled by the National Academy of Science's National Research Council (NRC 2005). The NRC committee supported use of the natural flow regime as the scientific basis for the

Texas program's objective of determining instream flow needs. Based largely on the recommendation of the NRC (2005), the SAC (2009/5) supported the development of the Hydrology-Based Environmental Flow Regime (HEFR) Methodology. HEFR relies on a framework that quantifies key attributes of four components of the flow regime intended to support a sound ecological environment. These instream flow regime components are: subsistence flows, base flows, high flow pulses, and overbank flows. HEFR was designed to assist in characterizing the attributes of these flow regime components in terms of magnitude, volume, duration, timing, frequency, and the rate of change. These flow regime components are then evaluated in terms of their effectiveness in maintaining a sound ecological environment of the study reaches via a series of what are referred to as *overlays*, which are analyses of likely outcomes for water quality, aquatic and riparian biota, and the geomorphological and sediment dynamics that maintain habitats over the long term.

Various methods of instream flow assessment focus on habitat availability in relation to flow and may produce conflicting assessments depending on the method used (Jowett 1997). While the measurement of physical and hydrologic variables has improved with new technologies (Gard and Ballard 2003), ecological data relevant for establishment of instream flow regimes are lacking in most river systems (Arthington et al. 2006). Species inhabiting river-floodplain systems possess a wide range of life history strategies that allow them to take advantage of the spatial heterogeneity (i.e. patchiness) and flow variability of these systems (Winemiller 1996; Humphries et al. 1999). Fish assemblage structure is strongly influenced by the physicochemical characteristics of habitats that result from physical, chemical, and biological responses to disturbance associated with high flow events or, in some cases, extreme low flow events. Schemes that focus on only one or a few species may create optimal conditions for those species while degrading conditions for other species that depend on alternate conditions (Sparks 1995).

The SAC and all of the other BBESTs have acknowledged that there is no single measure that can be employed to test or determine the soundness of ecological systems under alternative environmental flow regimes. However, many methods and individual measures are commonly used within the environmental flows arena to assess components of a sound ecological environment. These measures include water quality standards; habitat suitability and availability for indicator species or functional groups of species; indices of biologic integrity; estuarine salinity patterns; sediment transport; nutrient delivery; and patterns of occurrence, abundance, and diversity of aquatic and riparian species.

3.1.2 Sequence of Steps

For determining environmental flow recommendations for the fluvial realm of the study area (including tributary streams and mainstem rivers), our BBEST adopted the approaches recommended by the SAC (SAC 2009/1-5) that involve estimating subsistence flow, base flow, and various categories of high flow pulses. A brief outline of these approaches, including excerpts from the SAC guidance document and descriptions of the Brazos BBEST's analyses leading to the recommendations for environmental flows, is presented in this section.

STEP 1. Establish clear, operational objectives for support of a sound ecological environment and maintenance of the productivity, extent, and persistence of key aquatic habitats in and along the affected water bodies. As described in Section 1.3, our BBEST adopted the basic operational definition for a sound ecological environment as defined by the SAC.

STEP 2. Compile and evaluate readily available biological information and identify a list of focal species. Our BBEST reviewed available information for ecosystems and important species in the study area. In addition to reviewing fish and mussel species distribution and abundance records, a list of focal species was identified for evaluation of ecological needs in relation to flows. We also reviewed research reporting species life history information and reliance on general habitat suitability criteria developed for focal species based on studies conducted within as well as outside the basin.

STEP 3. Obtain and evaluate geographically oriented biological data in support of a flow regime analysis. Following initial reviews and deliberations, 20 gages were selected that had sufficient historical flow records to provide broad geographic coverage within the study area. Reports were obtained for studies of historical records of fishes and mussels in the study area. We were especially interested in research findings for population and community-level responses of aquatic organisms to variation in flow. In addition, the available information on the ecology and current status of riparian vegetation communities in the study area was evaluated.

STEP 4. Parameterize the flow regime hydrological analysis using ecological and biological data. Our initial parameterization of Indicators of Hydrologic Alteration (IHA) for separation of flow components to populate the HEFR flow regime matrix was based on methods adopted by previous BBESTs, with the goal being to capture broad-scale patterns of the natural flow regime of each stream reach. The objective here was *not* to reproduce the historic flow regime in our environmental flow recommendation but rather to critically evaluate the ecological functions of various flow components that could be separated from these hydrographic records in order to determine those most critical for maintenance of a sound ecological environment.

STEP 5. Evaluate and refine the initial flow matrix. The flow regime matrix produced by HEFR from the IHA-derived hydrological analysis was evaluated to ensure the needs of the major biological components of the fluvial ecosystems, water quality requirements, and geomorphic processes that create and maintain habitats for species. This final step is critical in the environmental flow evaluation process.

3.2 Geographic Scope

Figure 1.1 shows the geographic scope of the study area assigned to the Brazos Basin and Bay Area Stakeholder Committee (BBASC) and the Brazos BBEST. The study area includes the entire Brazos Basin in Texas, the San Bernard Basin to the west of the Brazos Basin, and the Oyster Creek and Austin Creek watersheds between the San Jacinto and Brazos basins.

3.2.1 Selection of Focal Reaches for Analysis

The Brazos BBEST reviewed available information on the study area. Based on geographic coverage, hydrologic characteristics, land use, and distribution and abundance of aquatic species, the BBEST selected the following major reaches for analysis:

- Double Mountain Fork Brazos River
- Salt Fork Brazos River
- Upper Brazos River (confluence of Salt and Double Mountain Forks to Possum Kingdom Lake)
- Clear Fork Brazos River
- Middle Brazos River (Possum Kingdom Reservoir to mouth of the Bosque River)
- North Bosque River (above Lake Waco)

- Leon River
- Lampasas River
- Little River (below confluence of Leon and Lampasas Rivers)
- Navasota River
- Lower Brazos River (below mouth of Bosque River)
- San Bernard River

These reaches and associated USGS gaging stations are shown in Figure 1.1 in Section 1.3.

3.2.2 Review and Selection of Flow Gaging Stations in the Basin

In selecting streamflow gaging stations at which to develop recommended environmental flow regime recommendations, the Brazos BBEST considered the following factors:

- Geographic coverage of the focal reaches listed in Section 3.2.1
- Length of the available gage record (the longer the better)
- Gage still in operation so it can be used in new water right permits
- Significant drainage area (500 square miles or more)
- Preference where possible for gages with flows that are not significantly disturbed by human activities (reservoir construction, diversions, or wastewater discharges)

The U.S. Geological Survey maintains a network of streamflow gaging stations in the United States, and these gages provide the best available information on historical flows in the study area. Using the criteria above, the Brazos BBEST selected the gages shown in Figure 1.1 as locations at which to develop environmental flow regimes. Appendix D shows the contributing drainage area and the period of record for the selected gages. The period of record for three of the gages begins before 1920, and thus the full record does not appear in Appendix D. The Brazos River at Waco gage began operation in 1898. The Little River near Cameron gage began operation in 1916. The Brazos River near Bryan gage was operated from 1899 to 1903 and began again in 1918.

The bases for the selections made are discussed briefly below:

- The Salt Fork Brazos River near Aspermont and the Double Mountain Fork near Aspermont gages were obvious choices to cover those focal reaches.
- The Brazos River at Seymour gage covers the upper Brazos focal reach above the confluence with the Clear Fork, and the Brazos River at South Bend covers the same reach below the confluence with the Clear Fork.
- The Clear Fork Brazos River at Nugent and Clear Fork Brazos River at Fort Griffin gages cover the Clear Fork focal reach.
- The Brazos River near Palo Pinto and Brazos River near Glen Rose gages cover the middle Brazos focal reach. The Brazos River near Dennis and Brazos River near Highbank gages were also considered, but the selected gages were preferred because of their longer records. The North Bosque River near Clifton gage covers the North Bosque River focal reach. It was selected in preference to the North Bosque River at Valley Mills gage because it has a longer record.
- The Leon River at Gatesville gage was selected for that focal reach because it is not affected by Lake Belton and has a longer period of record than other gages upstream from Lake Belton.

- The Lampasas River near Kempner gage was selected because it covers a more recent period than the Lampasas River at Youngsport gage and is still in operation.
- The Little River at Little River and Little River near Cameron gages cover the Little River focal reach.
- The Navasota River gage near Easterly was selected because it has a continuous record from 1925 to present.
- The Brazos River at Waco, Brazos River at SH 121 near Bryan, Brazos River at Richmond, and Brazos River near Rosharon gages cover the lower Brazos River focal reach. The drainage areas of the Brazos River near Bryan and the Brazos River at SH 21 near Bryan gages differ by less than 2 percent, and the two gage records were combined into a single record for instream flow analysis.
- The San Bernard River near Boling gage covers the San Bernard River.

3.2.3 Initial Assessment of Hydrological Records and Temporal Changes

Human activities that have changed the hydrology of the study area include the development of reservoirs, diversions of water for human needs, changes in land use practices that alter runoff patterns, return flows of treated wastewater, and climate change (Vogel and Lopes 2009). It is likely that the most significant local change has been the development of reservoirs. Figure 3.1 shows the total contributing drainage area above major reservoirs in the Brazos Basin over time (major reservoirs are those with over 5,000 acre-feet of conservation storage). The total contributing drainage area in the Brazos Basin is 35,931 square miles (Gooch and Dunn 2001), and 27,170 square miles are upstream from major reservoirs. The large increase in contributing drainage area above major reservoirs in 1941 reflects the completion of Possum Kingdom Lake.

Figure 3.2 shows the total conservation storage space in major reservoirs in the Brazos Basin over time (Flood storage

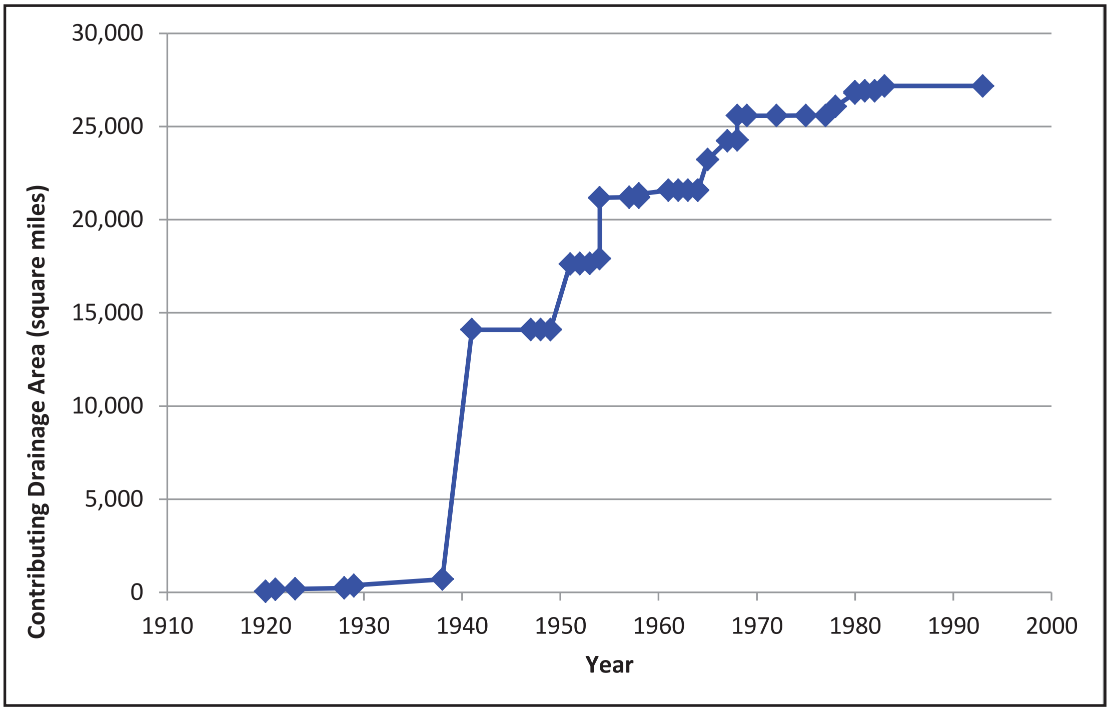


Figure 3.1. Total contributing drainage area in the Brazos Basin above major reservoirs over time.

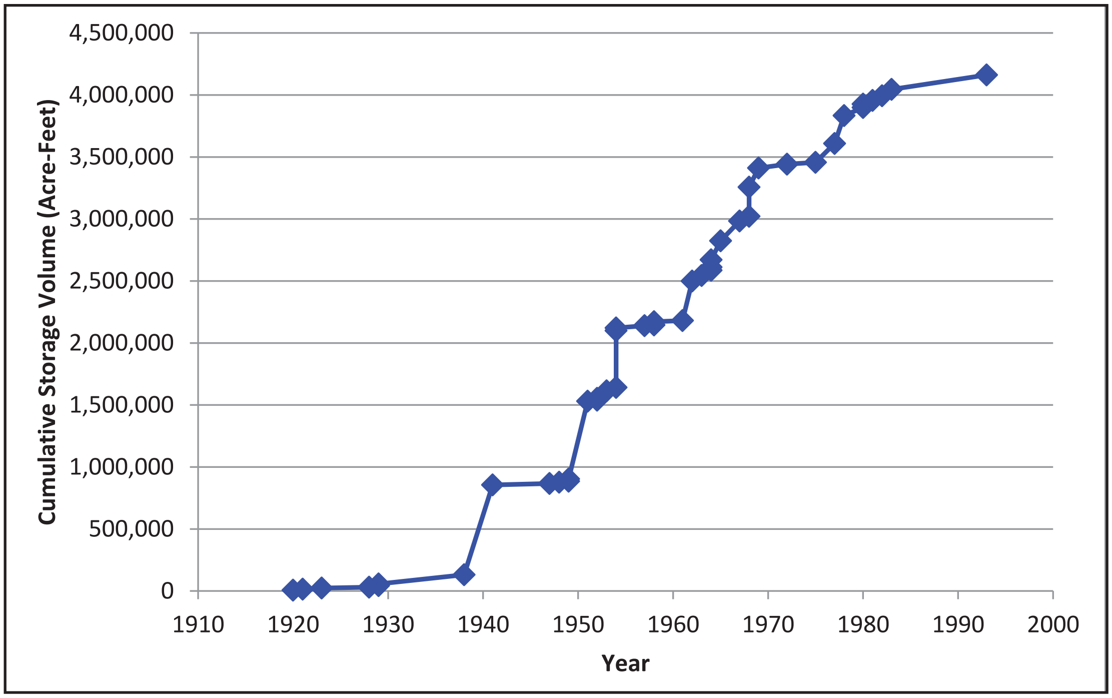


Figure 3.2. Cumulative conservation storage volume in major reservoirs in the Brazos Basin over time.

in flood control reservoirs is not included in the totals). The large increases in conservation storage are associated with specific reservoirs as follows: 1941 is Possum Kingdom Lake, 1951 is Lake Whitney, and 1954 is Belton Lake.

For an initial assessment of temporal change in the Study Area, the Brazos BBEST looked at hydrologic parameters for the following USGS gages with long periods of record available:

- Brazos River near South Bend
- Brazos River near Glen Rose
- Brazos River at Waco
- Little River near Cameron
- Navasota River near Easterly
- Brazos River at Richmond

Appendix E shows the information considered at each of these gages:

- Annual flow and 9-year average flow
- Cumulative annual flow over time
- Comparison of early (before most dam development) and late (after completion of most dam development) annual flow frequency statistics
- Flow frequency statistics for the gage by the time of year
- Monthly median flows for various time periods
- Annual peak flood flows

A review of the information in Appendix E shows that:

- The drought of the 1950s shows up as a period of low flow for all of the gages.
- For most gages, flows are typically higher in the spring (May–June) and lower in the summer. The period of higher flows is longer for the Navasota River near Easterly gage, extending from January through June.
- The South Bend and Glen Rose gages show low flows over the last few years. This is true to a lesser extent for the Waco gage.
- Flood peaks at Waco are definitely lower in recent years, after the completion of Lake Whitney and Lake Waco, both flood control reservoirs.
- There may be a trend of flood peaks reducing with time at the South Bend and Cameron gages.

3.2.4 Comments on Geographic Interpolation and Extrapolation for Other Basin Reaches

The Brazos BBEST has provided flow regime recommendations supporting a sound ecological environment at USGS streamflow gaging stations distributed throughout the study area (Figure 1.1). These reference locations cover the key focal reaches identified by the BBEST, including major stream reaches upstream and downstream of existing reservoirs. The Brazos BBEST recommends that the Texas Commission on Environmental Quality (TCEQ) develop appropriate methods for interpolation and extrapolation of flow conditions to other locations in the study area. Such methods could include drainage area adjustments and may also include consideration of springflow contributions, channel losses, aquifer recharge zones, geologic conditions, soil cover complexes, and other factors as necessary and appropriate.

3.3 Initial Analysis of Flow Regimes

In the initial analysis of flow regimes for the study area, the Brazos BBEST established the appropriate period of record to use for each location, the appropriate division into seasons, and the appropriate definition of wet, average, dry, and subsistence conditions.

3.3.1 Periods of Record

The Brazos BBEST decided to use the full period of record of available data in developing the recommended flow regime at each location, subject to the constraints of the HEFR model used in flow separation. The BBEST also made some specific adjustments to create usable records for flow separation:

- HEFR can only use continuous records. For this reason, early years followed by a period with no records were not used at some gages.
- HEFR can only use full years of record. For this reason, partial years of record were not used, and the period of record for all gages ended at the end of 2010.
- The flow records for the Brazos River near Bryan and the Brazos River at State Highway 21 near Bryan gages were combined to a single record given the small difference in drainage area.

The Brazos BBEST gave particular attention to the Brazos River near Palo Pinto, Brazos River near Glen Rose, and Brazos River at Waco gages, which seemed to exhibit the greatest changes in flow characteristics over time. Ultimately, BBEST decided to use the full period of record available for each of these gages.

The specific period of records used to develop environmental flow regimes are as follows:

- Double Mountain Fork Brazos River near Aspermont: 1940–2010
- Salt Fork Brazos River near Aspermont: 1940–2010
- Brazos River at Seymour: 1924–2010
- Clear Fork Brazos River near Nugent: 1925–2010
- Clear Fork Brazos River near Fort Griffin: 1924–2010
- Brazos River near South Bend: 1939–2010
- Brazos River near Palo Pinto: 1925–2010
- Brazos River near Glen Rose: 1924–2010
- North Fork Bosque River at Clifton: 1924–2010
- Brazos River at Waco: 1900–2010
- Leon River near Gatesville: 1951–2010
- Lampasas River near Kempner: 1963–2010
- Little River at Little River: 1963–2010
- Little River near Cameron: 1917–2010
- Brazos River near Bryan: 1928–2010
- Navasota River near Easterly: 1925–2010
- Brazos River near Hempstead: 1939–2010
- Brazos River at Richmond: 1923–2010
- Brazos River at Rosharon: 1972–2010
- San Bernard River near Boling: 1955–2010

3.3.2 Definition of Seasons

The Brazos BBEST conducted an extensive evaluation of available biology, hydrology, and water quality data to determine the appropriate grouping of months to apply to the HEFR methodology to reflect naturally occurring variations in flow. A thorough description of the analysis undertaken can be located in Appendix F. The Brazos BBEST selected three 4-month seasons as follows: winter (November–February), spring (April–June), and summer (July–September). The BBEST believes this seasonal separation will ensure that the BBEST's instream flow recommendations reflect observed, natural, intra-annual variability in flow conditions.

3.3.3 Definition of Hydrologic Condition—Wet, Average, Dry

The Brazos BBEST recommends that hydrologic condition for base flows should be defined on the basis of the Palmer Hydrological Drought Index (PHDI). The PDHI was designed to reflect longer-term hydrological drought impacts that are usually slow to develop and persist longer than a meteorological drought. The index uses an arbitrary scale from -6.0 and +6.0 and represents the severity of moisture conditions from extremely dry to extremely wet (Hayes 1998).

Texas is divided into ten climatic divisions structured to coincide with county boundaries and cover the total area of the state. The National Weather Service maintains near-real-time updates of climatic data in each of the divisions in cooperation with the National Climatic Data Center (CDC). The divisional dataset of climatic variables has been compiled for the period of record beginning in 1895. These data have been used by the CDC to compute and publish a historical account of the monthly PHDI indices for the entire period of record from 1895 to present. Updates to the PHDI are available from the CDC weekly and monthly (Guttman 1996). The Brazos BBEST used the monthly PHDI published by the CDC to characterize the hydrologic condition at each gage station. The monthly PHDI data are available at http://www.ncdc.noaa.gov/pub/data/cmb/data/drought/nadm/palmer/phdi-us-div.txt.

Recognizing the geographical extent of the study area, the Brazos BBEST decided that a PHDI index should be computed specific to each gage location. Watershed delineation was superimposed with the ten climatic divisions to determine the percentage of each climatic division in each watershed upstream of a gage location (Figure 3.3). A local PHDI is computed for each gage location as a weighted average of the percentage of the drainage area in each climatic division (Table 3.1).

To be consistent with the methodology for computing base flow statistics, the monthly PHDI values for the entire period of record from 1895 through 2010 were ranked with the upper and lower quartile representing high (*wet*) and

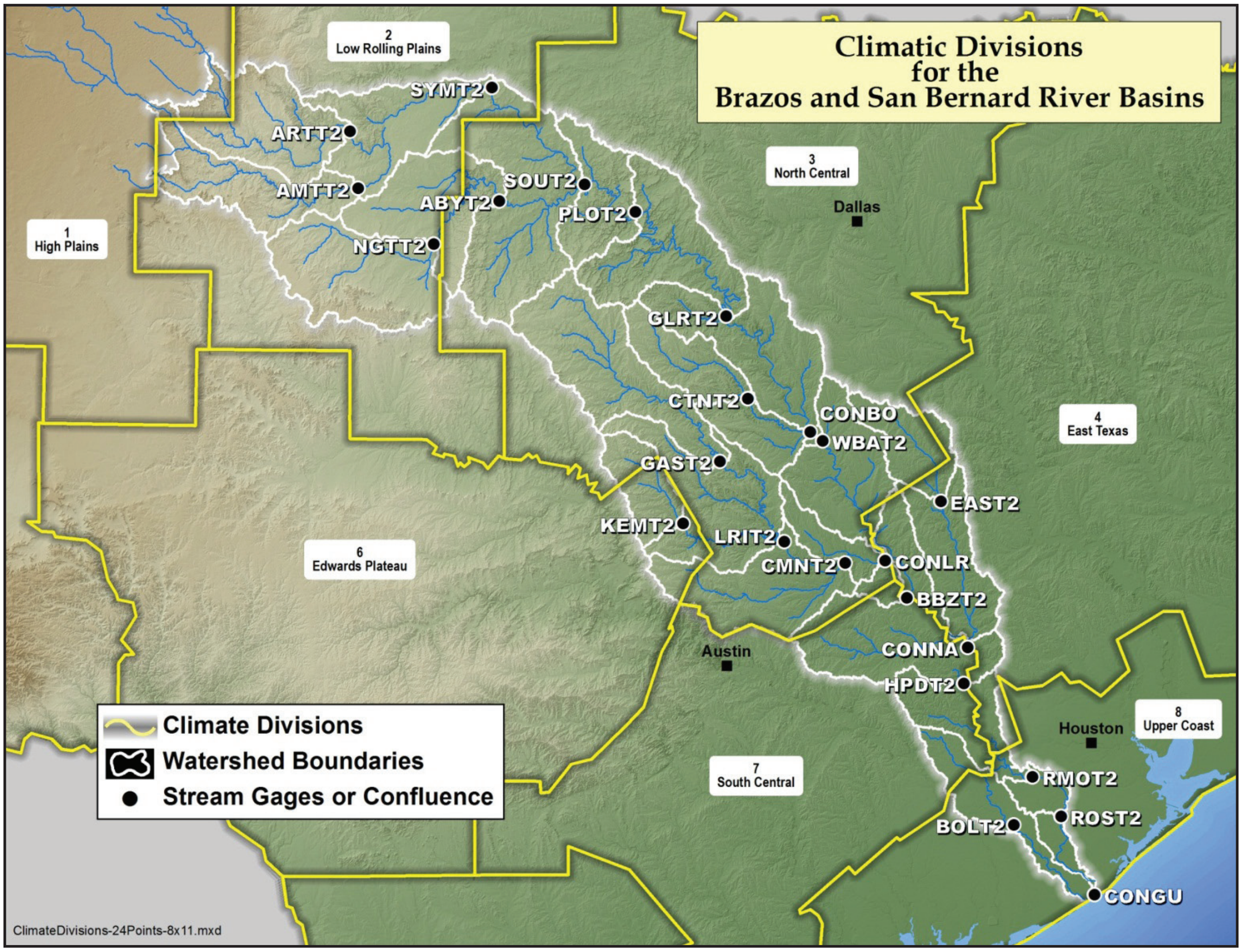


Figure 3.3. Climatic divisions for the Brazos and San Bernard river basins.

Table 3.1. Climatic zones to determine Palmer Hydrologic Drought Index by gage.

Watershed ID	Watershed Name	Climatic Zone									
		High Plains Zone 1	Low Rolling Plains Zone 2	North Central Zone 3	East Texas Zone 4	Trans Pecos Zone 5	Edwards Plateau Zone 6	South Central Zone 7	Upper Coast Zone 8	Southern Zone 9	Lower Valley Zone 10
ARTT2	South Fork at Aspermont	14.6%	85.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AMTT2	Double Mountain Fork at Aspermont	4.4%	95.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
NGTT2	Clear Fork at Nugent	0.0%	98.2%	1.8%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
ABYT2	Total Clear Fork at Ft Griffin	0.0%	82.8%	17.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SYMT2	Total Brazos River at Seymour	6.9%	93.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SOUT2	Total Brazos River at South Bend	2.9%	69.6%	27.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PLOT2	Total Brazos River at Palo Pinto	2.6%	63.7%	33.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
GLRT2	Total Brazos River at Glen Rose	2.3%	55.4%	42.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CTNT2	North Bosque River at Clifton	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CONBO	Confluence Bosque River at Brazos Rv	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
WBAT2	Brazos River at Waco	1.9%	44.6%	53.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
GAST2	Leon River at Gatesville	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
KEMT2	Lampasas River at Kempner	0.0%	0.0%	35.4%	0.0%	0.0%	64.6%	0.0%	0.0%	0.0%	0.0%
LRIT2	Total Little River at Little Rv	0.0%	0.0%	84.3%	0.0%	0.0%	15.7%	0.0%	0.0%	0.0%	0.0%
CMNT2	Total Little River at Cameron	0.0%	0.0%	85.2%	0.0%	0.0%	14.7%	0.1%	0.0%	0.0%	0.0%
CONLR	Total Confluence of Brazos at Little Rv	0.0%	0.0%	86.2%	0.0%	0.0%	13.7%	0.1%	0.0%	0.0%	0.0%
BBZT2	Total Brazos River at Bryan	1.2%	29.8%	64.7%	0.3%	0.0%	3.6%	0.3%	0.0%	0.0%	0.0%
EAST2	Navasota River at Easterly	0.0%	0.0%	72.6%	27.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CONNA	Confluence Navasota River at Brazos Rv	0.0%	0.0%	30.9%	69.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HPDT2	Total Brazos River at Hempstead	1.1%	25.5%	57.9%	7.2%	0.0%	3.1%	5.1%	0.0%	0.0%	0.0%
RMOT2	Total Brazos River at Richmond	1.0%	24.8%	56.1%	7.8%	0.0%	3.0%	6.9%	0.4%	0.0%	0.0%
ROST2	Total Brazos River at Rosharon	1.0%	24.5%	55.6%	7.7%	0.0%	3.0%	6.9%	1.3%	0.0%	0.0%
CONGU	Total Brazos River at Gulf of Mexico	1.0%	24.3%	55.2%	7.6%	0.0%	3.0%	6.8%	2.0%	0.0%	0.0%
BOLT2	San Bernard River near Boling	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	30.4%	69.6%	0.0%	0.0%

Table 3.2. Palmer Hydrologic Drought Index for 25th and 75th percentile by gage.

Watershed ID	Watershed Name	Percentile	
		25th	75th
ARTT2	South Fork at Aspermont	-1.88	2.19
AMTT2	Double Mountain Fork at Aspermont	-1.92	2.21
NGTT2	Clear Fork at Nugent	-1.93	2.25
ABYT2	Clear Fork at Ft Griffin	-1.84	2.21
SYMT2	Brazos River at Seymour	-1.90	2.21
SOUT2	Brazos River at South Bend	-1.79	2.19
PLOT2	Brazos River at Palo Pinto	-1.78	2.19
GLRT2	Brazos River at Glen Rose	-1.80	2.21
CTNT2	North Bosque River at Clifton	-1.96	2.39
CONBO	Confluence Bosque River at Brazos	-1.96	2.39
WBAT2	Brazos River at Waco	-1.84	2.22
GAST2	Leon River at Gatesville	-1.96	2.39
KEMT2	Lampasas River at Kempner	-1.78	2.23
LRIT2	Little River at Little Rv	-1.84	2.31
CMNT2	Little River at Cameron	-1.85	2.32
CONLR	Confluence of Brazos Rv at Little Rv	-1.85	2.32
BBZT2	Brazos River at Bryan	-1.83	2.24
EAST2	Navasota River at Easterly	-1.84	2.20
CONNA	Confluence Navasota River at Brazos	-1.79	2.13
HPDT2	Brazos River at Hempstead	-1.75	2.16
RMOT2	Brazos River at Richmond	-1.74	2.14
ROST2	Brazos River at Rosharon	-1.74	2.13
CONGU	Brazos River at Gulf of Mexico	-1.73	2.13
BOLT2	San Bernard River near Boling	-1.83	2.02

low (*dry*) hydrologic conditions. PHDI value between the 25th and 75th percentiles represents medium (*average*) hydrologic conditions (Table 3.2).

The Brazos BBEST recommends that the hydrologic condition be updated monthly as the monthly PHDI values are published by the CDC. The three hydrologic conditions are applicable to the base flow recommendations. The high flow pulse and overbank flow recommendations are not subject to hydrologic condition criteria.

3.3.4 Hydrographic Separation of Flow Components—Regime Matrices

As discussed in Section 3.1.1, the Brazos BBEST followed the HEFR methodology to establish flow components for the environmental flow regime (SAC 2009/1). The HEFR methodology is supported by a Microsoft Excel program developed by the Texas Parks and Wildlife Department (TPWD). Development of environmental flow regimes using the HEFR methodology requires substantial hydrologic analysis. For the Brazos BBEST, this analysis was provided by Dan Opdyke and other staff at the TPWD.

The first step in the development of an environmental flow regime for a specific location using the HEFR methodology is the separation of flows into flow components. HEFR defines all flows in the historical record under analysis as subsistence flows, base flows, pulse flows, or overbank flows. The HEFR program developed by the TPWD supports two methods for flow separation:

- MBFIT (Modified Base Flow Index with Threshold)
- IHA (Indicators of Hydrologic Alteration)

Each of these methods has multiple parameters that are used to define and control the flow separation process.

The Brazos BBEST first reviewed sample flow separation analyses for the Salt Fork Brazos River near Aspermont as an example of an upstream gage with less drainage area and the Brazos River near Hempstead as an example of a mainstem gage with greater drainage area. On the basis of that information, the BBEST tentatively selected the IHA methodology for the separation of gage flows. This selection was confirmed after review of the hydrograph separation for all of the selected gages.

The IHA methodology uses seven parameters to separate flows into subsistence, base, pulse, and overbank flows:

- **Subsistence Flow Limit:** flows below this value are subsistence flows.
- **Minimum Flow for Pulse Flows:** flows below this limit cannot be pulse or overbank flows. They are subsistence or base flows.
- **Maximum Flow for Base Flows:** flows above this limit cannot be base or subsistence flows. They are pulse or overbank flows.
- **Percent Increase That Changes Base Flow to Pulse Flow (Applies for Flows between the Maximum and Minimum):** This applies if the previous day's flow is base or subsistence flow and if flows are between the maximum and minimum. It is the percent increase in flow that will change a base/subsistence flow to a pulse/overbank flow. If the increase is less than this value (or if there is a decrease), the flow remains a base or subsistence flow, like the previous day's flow.
- **Percent Decrease Below Which Pulse Flow Changes to Base Flow (Applies for Flows between the Maximum and Minimum):** This applies if the previous day's flow is pulse or overbank flow and if flows are between the maximum and minimum. If percent decrease in flow is less than this value, the flow is a base or subsistence flow. If the increase is greater than this value or if the flow increases, the flow remains a pulse/overbank flow, like the previous day's flow.
- **Overbank Flow Limit:** flows above this value are overbank flows.
- **Large Flood Flow:** flows above this value are large flood flows. The Brazos BBEST did not use this parameter and did not define large floods.

Recent SAC Guidance (SAC 2011) describes the IHA flow separation process in greater detail. Table 3.3 shows the parameters selected by the Brazos BBEST for flow separation, and the process of parameter selection is described below.

Table 3.3. IHA parameters used for flow separation.

Environmental Flow Location	Subsistence Flow Limit (cfs)	Minimum Flow for Pulse Flows (cfs)	Maximum Flow for Base Flows (cfs)	Parameters That Apply between Minimum and Maximum		Overbank Flow Limit (cfs)
				If Increase is Greater, Go from Base to Pulse	If Decrease is less, Go from Pulse to Base	
Double Mtn Fork nr Aspermont	0.1	8.4	43	25%	5%	31,800
Salt Fork near Aspermont	0.1	6.0	27	25%	5%	3,130
Brazos River at Seymour	0.1	42	153	25%	5%	11,400
Clear Fork Brazos at Nugent	0.1	6.0	29	25%	5%	5,350
Clear Fork Brazos at Fort Griffin	0.1	5.5	73	25%	5%	5,980
Brazos near South Bend	1.3	115	387	25%	5%	14,200
Brazos River near Palo Pinto	17	169	689	25%	5%	23,500
Brazos River near Glen Rose	16	180	927	25%	5%	29,500
North Bosque near Clifton	0.4	24	104	25%	5%	29,200
Brazos River at Waco	56	300	1,960	25%	5%	41,000
Leon River at Gatesville	0.4	43	223	25%	5%	6,290
Lampasas Rv near Kempner	9.8	40	114	25%	5%	23,000
Little River near Little River	55	242	1,040	25%	5%	10,000
Little River near Cameron	32	190	1,720	25%	5%	20,300
Brazos at SH 21 near Bryan	299	833	5,370	25%	5%	41,200
Navasota River near Easterly	0.9	27	106	25%	5%	2,090
Brazos River near Hempstead	508	1,200	7,633	25%	5%	60,000
Brazos River At Richmond	550	1,260	8,390	25%	5%	60,000
Brazos River near Rosharon	430	1,310	9,640	25%	5%	52,100
San Bernard River near Boling	11	120	360	25%	5%	3,120

Note: Although subsistence flow values less than 1 cfs were used in flow separation, 1 cfs was adopted as the minimum subsistence flow for the environmental flow regimes.

Subsistence Flow Limit: All flows less than this value are classified as subsistence flows. The BBEST elected to use the 5th percentile of all flows as the subsistence flow limit (That is the flow that is exceeded 95 percent of the time in the historical flow record). This decision was confirmed by a review of water quality data and the variation of water quality with flow, which found no significant variation of quality with flow. For four environmental flow locations (Double Mountain Fork Brazos River near Aspermont, Salt Fork Brazos River near Aspermont, Brazos River near Seymour, and Clear Fork Brazos River near Fort Griffin), the 5th percentile flow was less than 0.1 cfs and was set to 0.1 cfs.

Minimum Flow for Pulse Flows: Flows less than this value are classified as subsistence or base flows—they cannot be pulse flows. The Brazos BBEST spent considerable effort on determining this parameter. In general, it is between the 25th and 50th percentile flow. Since the purpose of the parameter is to sort flows that *may* fulfill the ecological function of high flow pulses from flows that clearly do not fulfill the ecological functions of high flow pulses, the BBEST considered information on channel width versus flows (provided by TWDB staff) to determine where flows appeared to leave the relatively narrow low flow channel and spread to a wider channel. Table 3.3 summarizes the data considered and the adopted minimum flows for a low flow pulse. The criteria the BBEST used to select this parameter were as follows:

- If flow at the top of the low flow channel is less than the 25th percentile, use the 25th percentile flow.
- If the flow at the top of the low flow channel is greater than the 50th percentile, use the 50th percentile flow.
- If flow at the top of the low flow channel is between the 25th and 50th percentile, use the flow at the top of the low flow channel.
- If the top of the low flow channel is unclear, use the 25th percentile.

Maximum Flow for Base Flows: All flows greater than this flow are classified as pulse or overbank flows; they cannot be base flows. The 75th percentile flow (the flow that is exceeded 25 percent of the time) was selected for this parameter.

Overbank Flow Limit: This is the flow at which overbank flow begins. The U.S. Army Corps of Engineers discharge flow targets for releases from its flood control reservoirs were used as estimates of overbank flows for three gages (Little River near Cameron, Brazos River near Hempstead, and Brazos River near Richmond). Discharges at the lowest National Weather Service flood stage were used to establish overbank flows at other gages.

Flows between the minimum flow for pulse flows and the maximum flow for base flows can be classified as either base/subsistence flows or pulse/overbank flows. Flows remain at the classification of the previous day unless certain criteria are met.

Percent Increase That Changes Base Flow to Pulse Flow: If the previous day's flow is a base/subsistence flow and the current day's flow is between the minimum flow for pulse flows and the maximum flow for base flows, the day is classified as a pulse if the flow increases by more than this value. Based on a review of alternative values, the BBEST selected 25 percent.

Percent Decrease Below Which Pulse Flow Changes to Base Flow: If the previous day's flow is a pulse/overbank flow and the current day's flow is between the minimum flow for pulse flows and the maximum flow for base flows, the day is classified as a base flow day if the flow decreases by less than this value. The BBEST selected 5 percent for this parameter.

Once the flow separation was completed, members of the Brazos BBEST reviewed the hydrograph for each gage to make sure that there were no major concerns. The separated hydrographs were then used in development of the environmental flow regimes.

3.3.5 Development of Flow Regimes

3.3.5.1 Subsistence Flows

The subsistence flows in the environmental flow regimes were based on the 5th percentile flow, and the resulting values for subsistence flows are shown in Table 3.3. The Brazos BBEST also decided to adopt a minimum subsistence flow of 1 cfs. (The one cfs minimum was not used in flow separation but was used in the environmental flow regimes.) The Brazos BBEST recognizes that flows are less than 1 cfs for extended periods at some of the environmental flow locations. The purpose of setting a minimum value in the flow regimes of 1 cfs is to make it less likely that future water rights will extend or exacerbate these periods of extreme low flow conditions.

3.3.5.2 Base Flows

The Brazos BBEST decided to set base flow requirements by season for dry, average, and wet conditions (Section 3.3.2 discusses the Brazos BBEST's recommendation for definition of seasons). HEFR generates base flow statistics for the environmental flow conditions on the basis of all days in the current season defined as base flows in the flow separation analysis. The default values for low, medium, and high base flows are 25th percentile, 50th percentile, and 75th percentile. The Brazos BBEST adopted those percentile values. The low base flows apply under dry conditions, the medium base flows under average conditions, and the high base flows under wet conditions. (Section 3.3.3 discusses the Brazos BBEST's recommendation for definition of hydrologic condition.)

3.3.5.3 High Flow Pulses

HEFR analyzes high flow pulses by determining the characteristics of high flow pulses that occur with a given frequency. The frequencies are average frequencies over the period of record. Thus, the one-time-per-season winter high flow pulse may occur three times in one winter and not occur at all in another. The peak of the high flow pulse is defined by the value that occurs with the required frequency. HEFR then analyzes the duration and volume of all peaks that meet the peak flow requirement. HEFR produces a range of volume and duration for pulses meeting the peak requirement and a typical value for the volume and duration.

The Brazos BBEST considered high flow pulses that occur with the following frequencies:

- Four times per season
- Three times per season
- Two times per season
- Once per season
- Once per year
- Twice per year
- Once per year
- Once per two years
- Once per five years

After reviewing the HEFR results, the Brazos BBEST eliminated the twice-per-year high flow pulse at all locations because it was similar to the once-per-season and once-per-year flows. The BBEST then reviewed all of the pulses and retained those that appeared to have ecological significance based on factors such as differences in magnitude with other pulses and lateral connectivity of aquatic habitats. The recommended environmental flow regimes in Chapter 5 have five to seven levels of high flow pulses and overbank events at each location.

3.3.5.4 Definition of Overbank Flows

Overbank flows are the subset of high flow pulse events that are large enough to connect the floodplain to the main river channel. These overbank events have ecological significance by depositing nutrient-rich sediments onto the floodplain and allowing certain species access between the river channel and aquatic habitats in the floodplain. The values used to define overbank flows are listed in Table 3.3. They are based on National Weather Service flood flows and U.S. Army Corps of Engineers channel capacities for flood releases. At most instream flow locations, the BBEST has recommended high flow pulses only up to the smallest high flow pulse that equals or exceeds the overbank discharge. High flow pulses exceeding the first overbank flow level are recommended only at a few gages where relatively low flows qualify as overbank flows.

4 Ecological Analysis of Regime Matrices for Estimation of Environmental Flows

4.1 Water Quality

Water quality data at or near the BBEST selected stream-flow gaging stations were compiled and analyzed for variations in quality with discharge. Several water quality parameters are essential for aquatic ecosystem integrity, and most of these are directly influenced by flows. For example, dissolved oxygen levels can decline during periods of low flow and high temperature. Therefore, dissolved oxygen and temperature are two parameters of particular interest for assessing subsistence flows and base flows under dry conditions.

For this analysis, the Brazos BBEST reviewed available water quality data in the Texas Commission on Environmental Quality's (TCEQ) Surface Water Quality Monitoring Information System database collected at or near the 20 gages selected by the BBEST. Figure 4.1 is a map of the BBEST-selected gaging stations and associated water quality monitoring locations. The entire period of record of water quality data was used for this assessment. Water quality analysis techniques followed minimum frequency and duration requirements as stipulated in TCEQ's Surface Water Quality Monitoring Team's 2010 Guidance for Assessing and Reporting Surface Water Quality Data in Texas (TCEQ 2010/1). If a site did not have the data required by the Guidance for an individual parameter, that parameter was not assessed. Additionally, for each site, regression analysis was used to determine whether there is a relationship between flow and the individual parameter. Compliance with Texas Surface Water Quality Standards (TSWQS) (Texas Administrative Code 307.1-307.10) was also assessed at each site.

The water quality parameters identified as being of interest were water temperature, dissolved oxygen (DO), total suspended solids (TSS), total dissolved solids (TDS), chloride (Cl^-), ammonia-nitrogen (NH_3), nitrate-nitrogen (NO_3), orthophosphate-phosphorus (PO_4), total phosphorus (TP), total kjeldahl nitrogen (TKN), and bacteria. The range of available water quality data varied by site and parameter and this information is summarized in Appendix B. A summary of the Texas Water Quality Inventory (TWQI) status of each river segment investigated by the Brazos BBEST also appears in Appendix B (TCEQ 2010/2).

The relationship between chloride and TDS levels in the major tributaries of the Brazos (Little River, Lampasas River, Leon River, North Bosque River, Clear Fork, and Navasota River) and the San Bernard River was largely expected and was not a cause for flow-related water quality issues. In these segments, conductivity, TDS, and chloride levels were observed to decrease with increasing flow. This observation is expected since stormwater runoff contains lower levels of dissolved solids than waters originating from karstic limestone or subterranean systems at low flows.

In the mainstem of the Brazos, the Salt Fork, and the Double Mountain Fork, the relationship between chlorides, conductivity, and TDS is tied to the drought-flood cycle and to flow rates in the Salt and Double Mountain Forks. Elevated chloride and TDS levels in the mainstem of the Brazos River Basin come from natural brine springs in Stonewall, Kent, and Garza counties that deposit highly concentrated groundwater into the watershed of the Salt Fork and Double Mountain Fork of the Brazos (Figure 4.2). Rainfall then flushes this residual salt into the rivers. The natural salt produced in the uppermost portion of the basin can affect chloride and TDS concentrations in the mainstem all the way to the Gulf of Mexico.

Nutrient parameters were included in the water quality analysis because they can contribute significantly to oxygen demand; eutrophication and increased primary productivity; algal blooms; and nuisance levels of macrophytes. Ad-

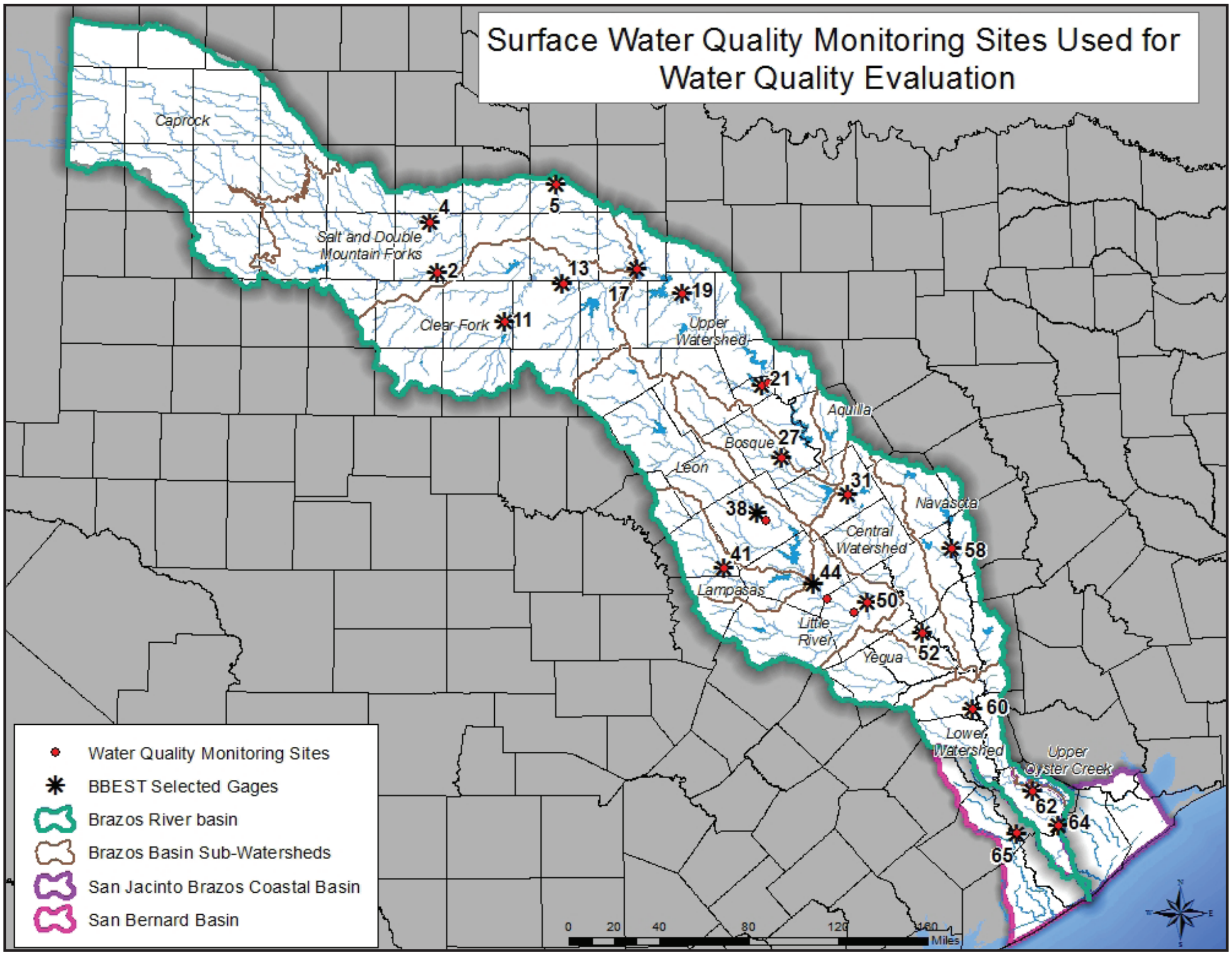


Figure 4.1. Water quality monitoring sites used for water quality analysis.

ditionally, high levels of ammonia (NH_3) can be toxic to aquatic organisms, especially when pH and water temperature are low. Nutrient concentrations in wastewater discharges have decreased in recent decades due to the use of alternatives to phosphorous in detergents, better wastewater treatment technologies, and more stringent discharge permit limits that have been implemented. However, the increasing population in the basin has led to increased numbers of permitted wastewater treatment facilities and increased volumes of treated wastewater. In some locations, this has negated some of the positive changes mentioned above. Additionally, improved agricultural practices have led to lower nutrient concentrations in runoff from some agricultural operations. However, agricultural nutrient contributions in stormwater runoff remain problematic for water bodies with high concentrations of concentrated animal feeding operations. Another source of concern is nutrient inputs from stormwater runoff in urbanized areas. As the population concentrates in urban and suburban areas, increased nutrient runoff from landscaped areas has led to water quality concerns in urban streams.

The BBEST's water quality analysis revealed an interesting set of circumstances regarding nutrient concentrations. The evaluation revealed that levels of nutrients could increase or decrease with flow, depending on the sampling location's proximity to a wastewater treatment discharge, an urbanized area, or an area with intensive agricultural activity. At sites below a wastewater discharge and without a significant urban nonpoint source contribution, nutrient concentrations often decrease with increasing flow from runoff events. At other sites, nutrients may increase during runoff

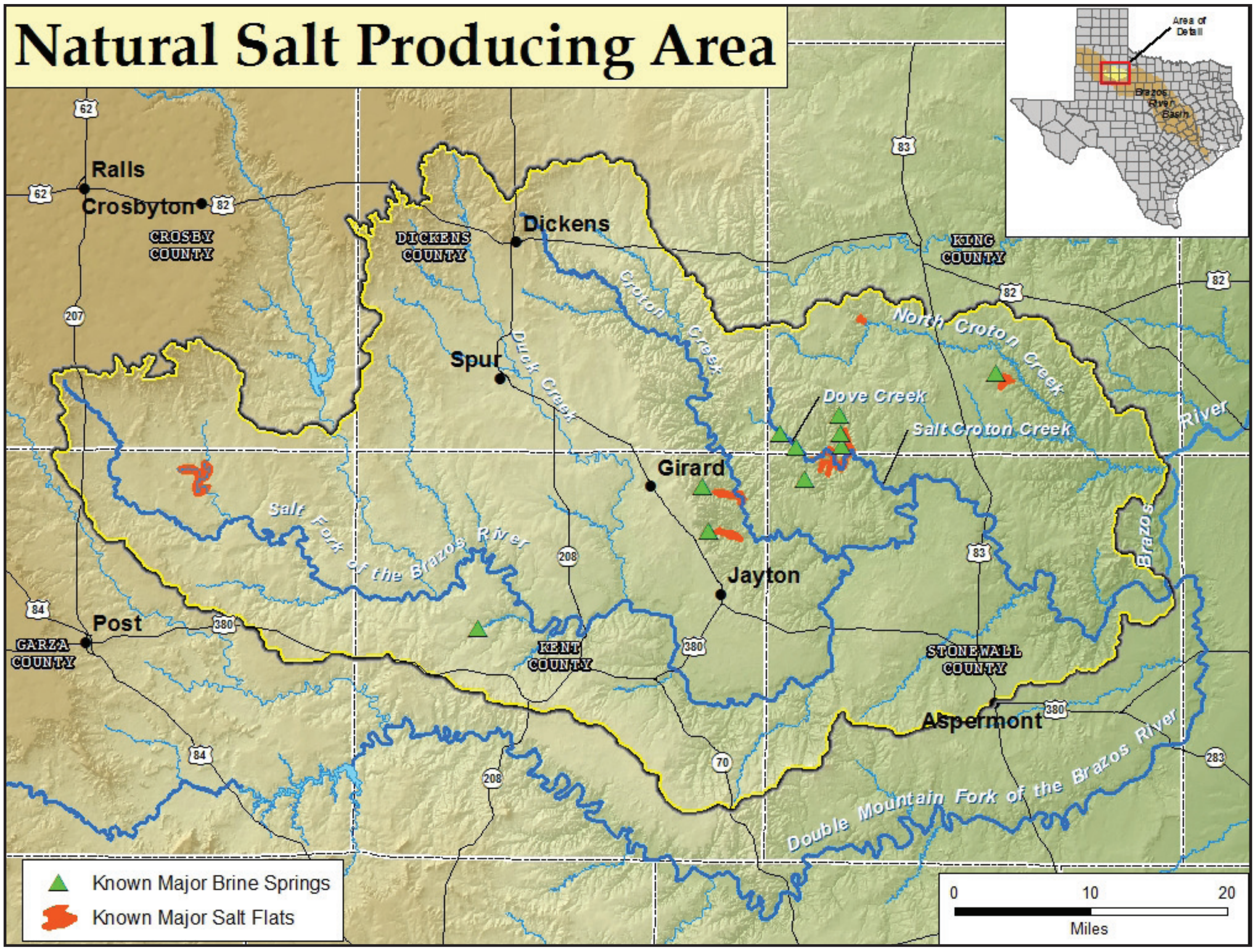


Figure 4.2. Known brine springs in the upper Brazos River Basin.

events as a result of land use practices (Figure 4.3). Even so, correlation coefficients between flow and nutrient levels were generally low for all nutrients at all sites. As long as wastewater and agricultural practices continue to improve and education regarding urban nonpoint source nutrient contributions is focused in problem communities, nutrient levels at any flow rate do not appear to be of a magnitude that will adversely affect instream ecosystems by depleting oxygen or creating toxicity.

The entire mainstem of the San Bernard River is impaired for bacteria, while most of the impaired streams in the Brazos Basin are small, rural prairie streams characterized by low to intermittent flows. Generally, there is a relationship between high flows and increased levels of bacteria, indicating a nonpoint source of bacterial pollution. The actual source of the pollution (whether of wildlife, livestock, or human origin) is difficult to determine based on the ever-present nature of bacteria in the environment. Several programs are currently in place in both basins to address bacterial impairments, including recreational use attainability analyses to assess the efficacy of the stream bacteria standards, total maximum daily load development for some water bodies, and development of watershed protection plans.

TSS generally revealed a positive relationship with flow (Figure 4.4). As flow from surface water runoff increases, TSS concentrations in the streams also increase. This was most apparent in water bodies with large drainages, areas with increasing development, and areas with high concentrations of agricultural operations that routinely disturb the soil.

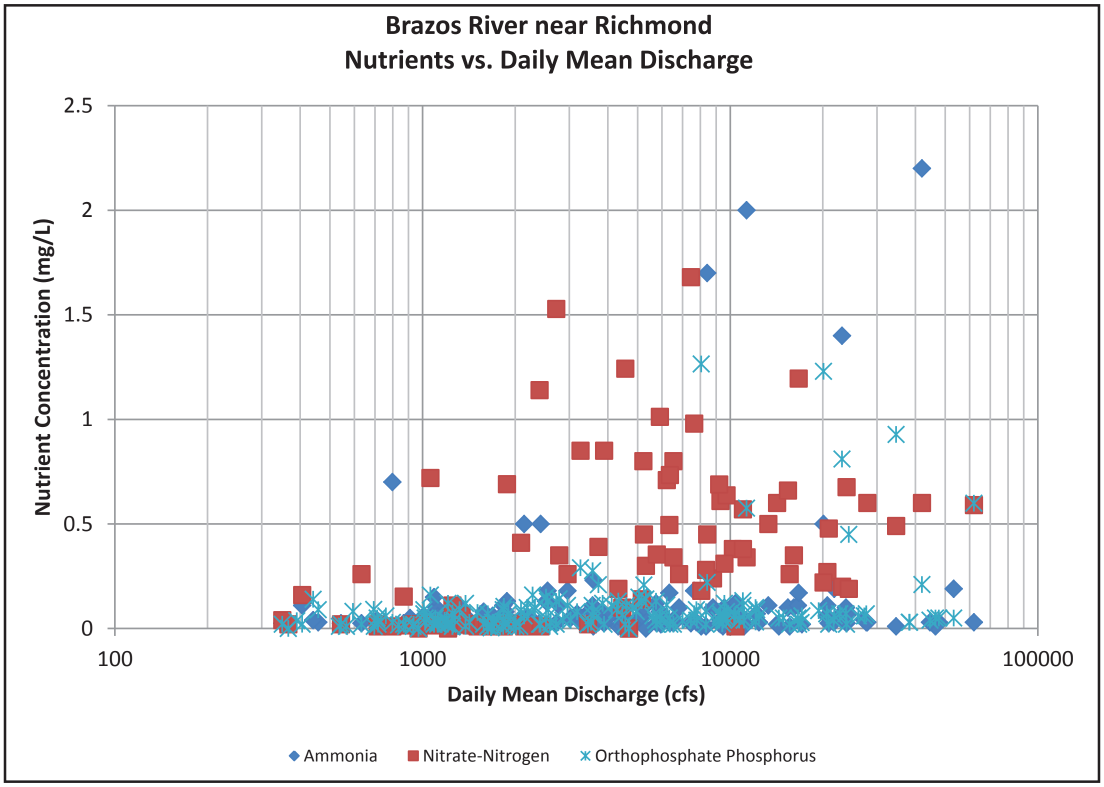


Figure 4.3. Relationship between daily mean discharge and concentrations of ammonia, nitrate, and orthophosphate measured in the lower Brazos River near Richmond.

At BBEST-selected subsistence flow levels, analysis of DO and water temperature was given special attention. At all sites, non-compliance of DO and water temperature levels with TSWQS stream standards was rarely observed (Figures 4.5, 4.6, and 4.7). At all locations where DO or water temperatures were non-compliant with stream standards, these exceedances occurred at flows greater than the BBEST-recommended subsistence flows and more often occurred during high flow events.

Our water quality analysis suggested that, for the selected parameters, water quality is generally acceptable and most locations are compliant with TSWQS. Our analysis of currently available data did not identify low flows at which water quality would be unable to support a sound ecological environment. Some water quality parameter concentrations, including bacteria, TSS, and nutrients, increased with high flow pulses and overbank flows. At some locations DO concentrations were lower during higher flows. However, none of these water quality changes associated with high flow pulses appear to pose a concern for TSWQS compliance or attainment of a sound ecological environment.

Although certain water quality parameters were correlated with streamflow in some reaches, DO remained well within concentrations supportive of diverse aquatic communities (> 5 mg/L) with very few exceptions. In some cases, low DO values were associated with high flow pulses (Figures 4.5, 4.6, and 4.7). Consequently, we did not adjust flow component criteria based on analysis of available water quality data.

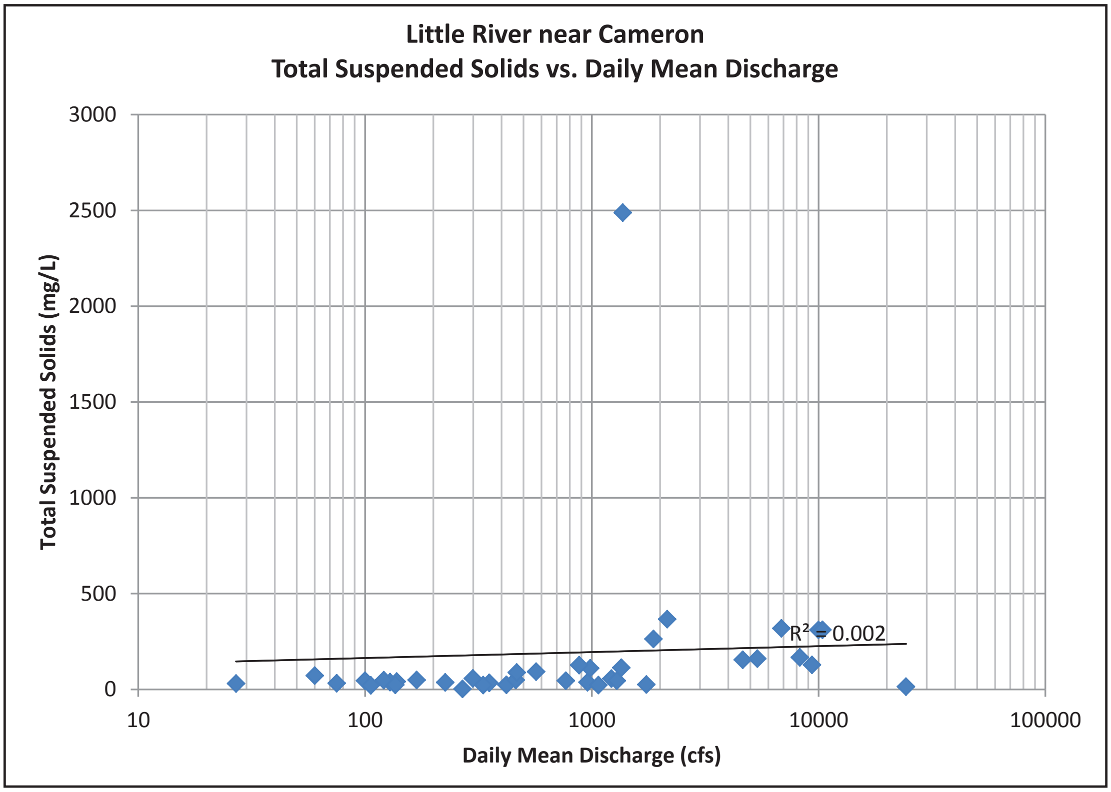


Figure 4.4. Relationship between daily mean discharge and total suspended solids in the Little River near Cameron.

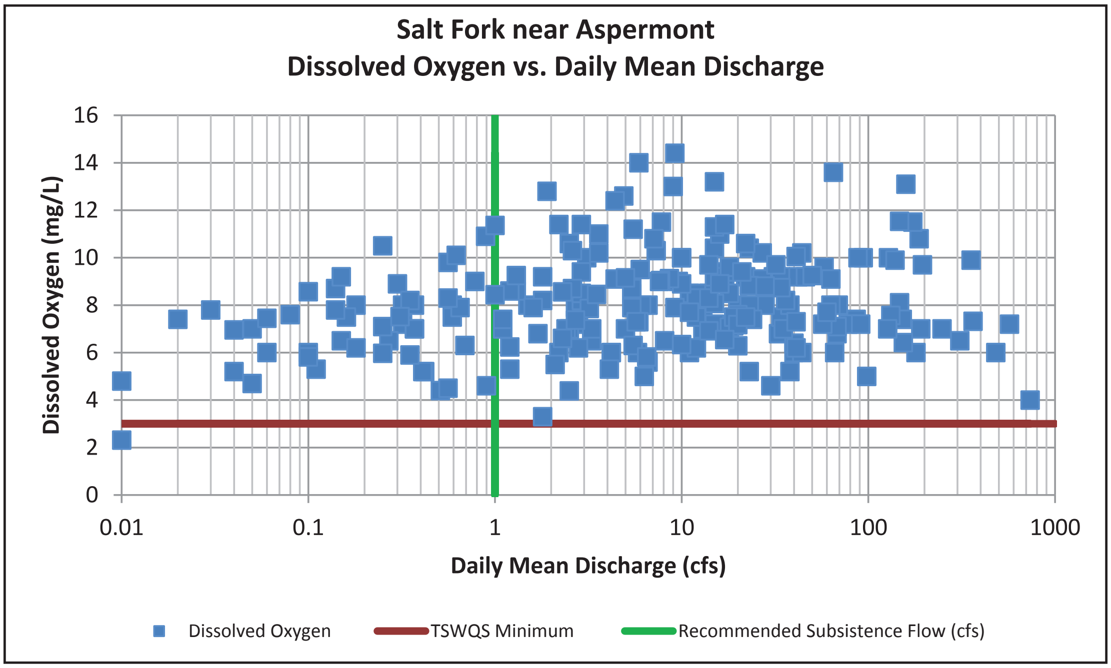


Figure 4.5. Relationship between daily mean discharge and dissolved oxygen concentration in the Salt Fork Brazos River near Aspermont. The horizontal red line is the minimum DO according to the Texas Surface Water Quality Standards. The green vertical line is the Brazos BBEST-recommended subsistence flow.

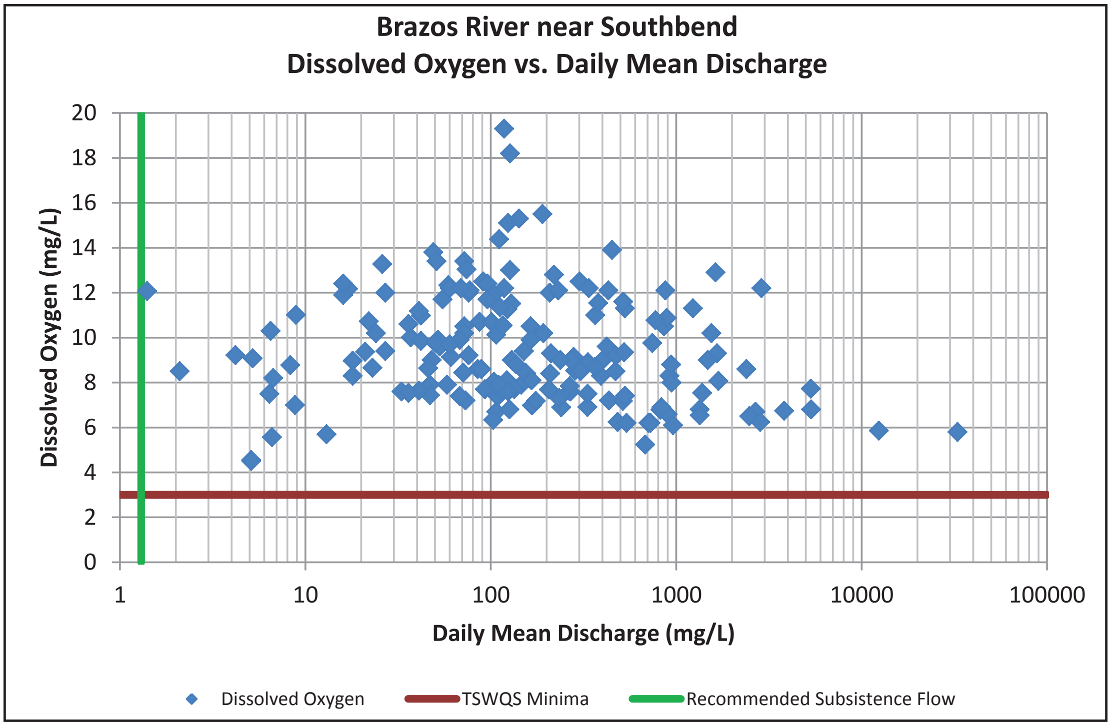


Figure 4.6. Relationship between daily mean discharge and dissolved oxygen concentration in the Brazos River near South Bend. The horizontal red line is the minimum DO according to the Texas Surface Water Quality Standards. The green vertical line is the Brazos BBEST-recommended subsistence flow.

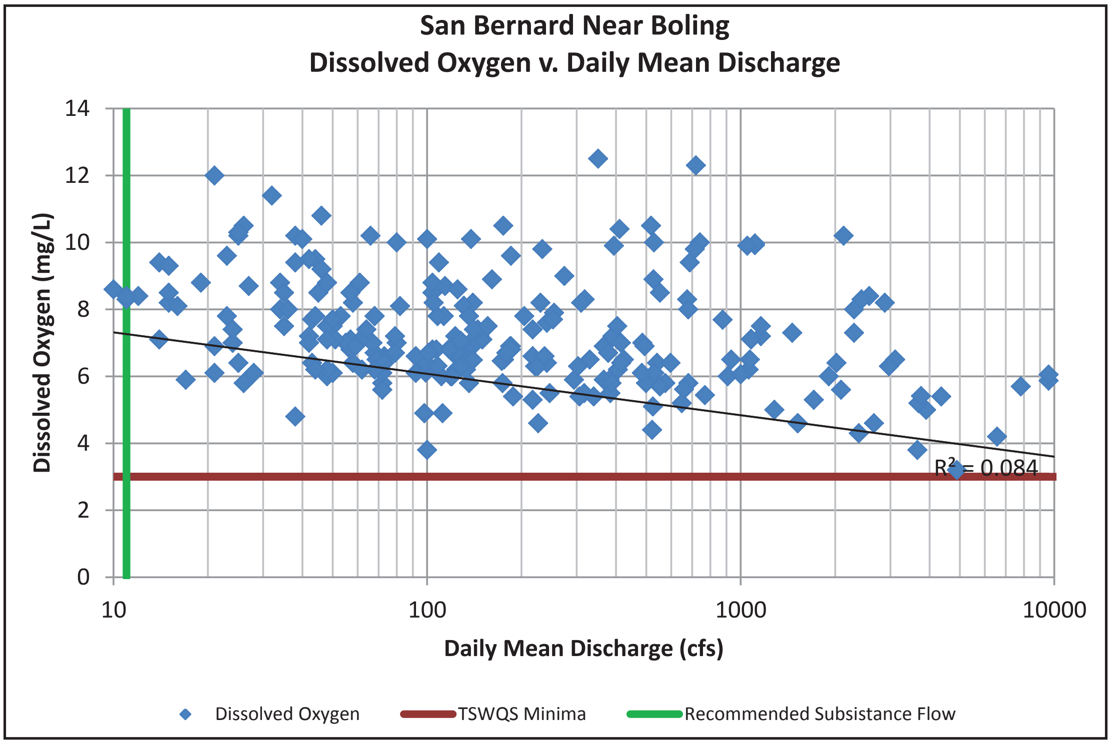


Figure 4.7. Relationship between daily mean discharge and dissolved oxygen concentration in the San Bernard River near Boling. The horizontal red line is the minimum DO according to the Texas Surface Water Quality Standards. The green vertical line is the Brazos BBEST-recommended subsistence flow.

4.2 Fish and Mussel Species Distribution and Abundance

4.2.1 Subsistence Flows

Subsistence flow is the minimum streamflow needed during critical drought periods to maintain tolerable water quality conditions and provide a minimal amount of aquatic habitat for the survival of aquatic organisms (NRC 2005). Droughts are a natural component of the Brazos River Basin climate and naturally produce no to very low flow conditions throughout the basin. The influence of drought is most pronounced on stream discharge in upper reaches of the basin, especially in areas with little groundwater contribution.

Aquatic community response varies with length, areal coverage, severity, and periodicity of drought. Generally, community responses are predictable with below average streamflow, intermittent streamflow, or no flow conditions. With reduction of overall habitat volume, aquatic organisms are confined to smaller habitat patches, populations are reduced in abundance and spatial distribution, and biotic processes (e.g., predation, competition, stress) are more pronounced (Matthews and Marsh-Matthews 2003; Walters and Post 2011). In geographic regions with drought-prone climates, droughts and subsequent low flow conditions are one of many natural regulators of aquatic communities and shape contemporary communities and species adaptations (Lake 2011). In the Brazos River Basin, a drought-prone climate has existed since the last glacial maximum (12,000 years ago) and likely during each inter-glacial period of the Pleistocene. As such, initial community responses will be detectable and predictably severe, but responses are likely not persistent (Matthews and Marsh-Matthews 2003), assuming that the mechanisms of community resiliency (e.g., recolonization potential) (Perkin and Gido 2010) are not altered by humans. It is important to note that dams have fragmented many of the major reaches within the Brazos Basin, particularly the area we have defined as the middle Brazos, and this has likely been a major cause of the reduction in biotic integrity that we noted in Section 1.3. Perkin and Gido (2010) documented reductions in fluvial specialist fishes in the middle Brazos and other rivers of the southern Great Plains and attributed this to longitudinal fragmentation from dams that inhibit the natural process of recolonization of reaches following droughts.

The Brazos River BBEST quantified seasonal subsistence flows as 95th percentile (Q95) of historical flows, except at stations where the Q95 was <1 cfs. In these instances, subsistence flow was set at 1 cfs. Subsistence flow recommendations are similar to previous BBEST's recommendations. However, subsistence flow recommendations will need to be validated in each river segment of the Brazos River to ensure that protection is provided as intended for the aquatic communities since the ecological effects of low flow conditions have not been specifically assessed within the basin. We note that recommended subsistence flows should not greatly alter the occurrences and length of zero flow days, which are a periodic and natural occurrence in many stream reaches in the upper Brazos and in tributaries.

4.2.2 Base Flows

Base flow refers to the normal flow conditions found in a river in between storm events (high flow pulses). Base flows provide adequate habitat for the support of native aquatic communities and maintain groundwater levels to support riparian vegetation (NCR 2005). Base flows (800 to 4,200 cfs) in the lower Brazos River support a heterogeneous mix of shallow, marginal habitats (such as shoals and sand banks) as well as deep-water habitats (Osting et al. 2004a; Li and Gelwick 2005). Shallow river margins provide essential habitat for short-lived, small-bodied fishes (Li and Gelwick 2005) as well as many larval and juvenile fishes (Williams 2011), whereas deep waters provide essential habitat for longer-lived, larger-bodied fishes, such as smallmouth buffalo, gars, and catfishes (Li and Gelwick 2005). Consequently, these "normal" flow conditions support a range of habitat types and diverse fish communities. Natural departures from base flows, such as subsistence flows and high flow pulses, disrupt habitats and biological communities and influence physical habitats (via geomorphological processes) and communities in ways that are different than base flows (Resh et al. 1988). Nevertheless, base flows are a critical component of the natural hydrograph. Some mussel species flourish under base flow conditions (Rypel et al. 2009), and reductions in base flow and stream discharge change the abiotic and biotic characteristics of both in-channel and riparian habitats and the biological communities they support.

Dewson et al. (2007) synthesized and summarized 26 published studies that assessed the effects of streamflow reduction on instream habitats and biotic communities. Consistent habitat responses to decreases in streamflow include reductions in current velocities, depths, and wetted parameters and alterations of water temperature and sedimentation rates. Reductions in stream flow generally are followed by changes in algal biomass and invertebrate diversity, abundance, and composition. Similar responses are observed in stream fish communities. Reductions in flow (either from natural inter-annual variation or hydrologic alteration) and modifications of habitats favor fishes that are habitat generalists and species, such as largemouth bass, that are well-adapted for lentic (lake) conditions (Schlosser 1985; Poff and Allan 1995; Roy et al. 2005).

The Brazos BBEST was consistent with the work of previous BBESTs and quantified seasonal base flows as the 25th, 50th, and 75th percentile values of the base flow component derived from IHA/HEFR to represent central tendencies of base flows during low, medium, and high hydrological conditions for each season (HEFR default calculations; see 3.3.4.2). New field research investigating environmental flow needs (research undertaken by state agencies under a mandate in Senate Bill 2 (SB2) has been initiated in the lower Brazos River. To date, the SB2 studies have tended to emphasize surveys of fishes and mussels in order to estimate habitat suitability models (models that estimate weighted usable habitat, in terms of area, under different instream flows for a given channel segment) that can be employed to estimate habitat availability for species or habitat guilds (groups of species with similar habitat requirements) under simulated flow scenarios. These kinds of studies often can be used to refine base flow recommendations; however, findings from the new research on the Brazos River are not yet available.

4.2.3 High Flow Pulses

The role of high flow pulses in supporting aquatic and riparian/floodplain plants and animals has been discussed extensively by river scientists (Junk et al. 1989; Poff et al. 1997; Winemiller et al. 2000; Lytle and Poff 2004; Richter et al. 1997, 2003, 2006; Zeug et al. 2005, 2009; Zeug and Winemiller 2007, 2008), and this evidence has been summarized in the Scientific Adfisory Committee (SAC) Biological Overlays Guidance Document (SAC 2009/5). High flow pulses shape physical habitat of the river channel, contribute to sediment transport and flushing of silt and fine particulate matter, and provide other geomorphic and water quality functions. High flow pulses provide environmental cues that elicit reproductive behavior (migration, spawning); produce lateral connectivity, allowing movement of organisms between the main channel and off-channel aquatic habitats (floodplain lakes, oxbows, sloughs, ephemeral ponds); and provide foraging opportunities in newly flooded riparian habitats (Kwak 1988). Any evaluation of the functions of high pulses for maintaining fluvial ecosystems must focus on two components: time (or more precisely, the timing and duration of the pulse in relation to requirements for spawning cues, feeding opportunities of juveniles, etc.) and space (or more specifically, how the rise in water level interacts with local topography to produce connections with, and enhancement of, marginal and off-channel aquatic habitats). In evaluating the spatial aspects of high flow pulses, various kinds of maps are useful (topographic, digital elevation, wetland classifications, vegetation classifications, etc.). Periodic inundation provides opportunities for aquatic organisms to move into off-channel floodplain habitats, such as oxbow lakes, sloughs, and marshes, that promote growth and reproduction of certain species (Swales et al. 1999; Winemiller et al. 2000; Sommer et al. 2001, 2004) and support fish diversity and production in the overall river ecosystem (Welcomme 1979; Winemiller 1996; Zeug and Winemiller 2007, 2008a, 2008b; Lyon et al. 2010). For certain species, lateral connections and movement of individuals of various life stages among habitat units are essential for population persistence (discussed further below).

4.2.3.1 High Flow Pulse Requirements for Fish Spawning and Recruitment

Based on available information in the scientific literature, the Brazos BBEST examined the life history requirements of individual fish species with regard to high flow pulses. Fluvial specialists (species with life histories that require variable flow regimes to complete their life cycles) and species of high value for recreational fisheries were a particular focus of this evaluation. The shoal chub (*Macrhybopsis hyostoma*), ghost shiner (*Notropis buchanani*), chub shiner (*Notropis potteri*), silverband shiner (*Notropis shumardi*), and Mississippi silvery minnow (*Hybognathus nuchalis*) are cyprinid fishes characteristic of large mainstem rivers but rare or absent from smaller tributary streams of the Brazos Basin. Shoal chubs and ghost shiners require broad sandbanks for foraging. Availability of submerged sandbank habitats increases during high flows. Importantly, the current velocities associated with high flow pulses transport eggs/larvae of these broadcast spawners (species that scatter their eggs and sperm in the water column where they drift with the current). Consequently, these species are sensitive biotic indicators for instream high flow pulse requirements of an environmental flow regime in the Brazos River.

In the upper and middle Brazos River, the threatened plains minnow (*Hybognathus placitus*), smalleye shiner (*Notropis buccula*), and sharpnose shiner (*Notropis oxyrhynchus*) are sensitive indicator species for environmental flows. These fluvial specialists have life histories similar to the shoal chub, ghost shiner, silverband shiner, and Mississippi silvery minnow, and their abundance within the upper and especially within the middle reaches of the Brazos River has declined in recent decades. All of these fluvial specialists require high flow pulses during spring and summer that trigger spawning and maintain currents that transport eggs and larvae into hydraulic retention zones where they develop (Rees et al. 2005; Durham and Wilde 2009a). Flowing water also resuspends silt particles and prevents eggs from becoming covered by a layer of sediment within retention zones. If eggs or newly hatched larvae become covered with silt, they generally die due to insufficient oxygen exchange (Hynes 1973). There also is some evidence from southeastern U.S. coastal plain streams that large flow pulses of short duration can displace eggs from retention zones and reduce survivorship (Craven et al. 2010). Durham and Wilde (2008) examined egg development, gonadosomatic index, and egg size distribution to determine reproductive activity in the smalleye shiner in the upper Brazos River. They found that spawning occurs between April and September and that the population spawns asynchronously with individual fish spawning small batches of eggs throughout the reproductive season except during periods of elevated streamflow when spawning becomes more intense and is synchronized within the population.

Durham and Wilde (2009a) investigated the influence of streamflow and intermittency on the production of young sharpnose shiner and smalleye shiner in the upper Brazos River. Both species successfully produced offspring throughout the four to five months in which spawning was observed. Their study determined that recruitment of both species was related to streamflow in two principal ways. First, the greatest proportion of young-of-year produced during the reproductive season was associated with high flow pulses. Second, no young-of-year were successfully produced during periods of reduced flow when stream pools became isolated. Their results suggest that, in addition to providing proper conditions for spawning, flows also must be maintained for survival of eggs and larvae (see also Durham and Wilde 2006).

Field research conducted in the upper Brazos Basin (Durham and Wilde 2009b) indicated that reduction in high flow pulses from dam operations would reduce populations of the smalleye shiner (*Notropis buccula*). The smalleye shiner is a threatened minnow endemic to the upper Brazos River and has been greatly reduced or possibly eliminated from many reaches of the middle and lower Brazos River where it formerly occurred. Their simulation model was supported by catch data and indicated that an average discharge of at least 6.43 m^3/s (227 cfs) is needed for maintenance of the smalleye shiner population in the upper Brazos River drainage. Their model did not examine responses to high flow pulses.

Based on six years of field data (Wilde and Durham 2008), a similar life history model of peppered chub (*Macrohybopsis tetranema*, a species closely related to the shoal chub in the Brazos River) accurately predicted how reductions in flows in the Canadian River in Texas and New Mexico reduced population abundance. Like the smalleye shiner model, discharge had the greatest relative effect on survival of juvenile fish, thus influencing population recruitment dynamics. In one of their model simulations, discharge was reduced 6.5 percent from observed levels. This reduction was simulated by estimating the effects of proposed salinity control projects on the Canadian River downstream from Ute Reservoir. Abundance of peppered chub generally declined throughout the simulation, and the projected population ended up 23 percent smaller than the abundance predicted under the observed flow regime. Other model simulations predicted that in a year in which discharge was 10 percent less than the long-term average, discharge the following year would have to exceed that average by 11 percent for the peppered chub population to recover. The additional 1 percent compensated for the reduced population size, and hence breeding potential, that was caused by low discharge in the previous year. When discharge was decreased to 30 percent or 50 percent below the long-term mean, progressively greater increases in discharge in the following year, 41 percent and 91 percent, respectively, were required for population recovery.

Spotted and largemouth bass (*Micropterus* spp.), sunfishes (*Lepomis* spp.), and channel and blue catfish (*Ictalurus* spp.), juveniles in particular, feed opportunistically in flooded marginal and off-channel habitats. Sunfishes (Centrarchidae) nest on open substrates and ictalurid catfishes nest in cavities. Both groups of fishes benefit from relatively stable flows (high or low) during the one to three weeks the male guards the nest and young (nesting period is February–May). High flow pulses during the nesting period can be detrimental to recruitment for these species, while these same flows may enhance recruitment of fluvial specialist minnows and shiners. Prolonged periods without significant high flow pulses, such as occurred in the Brazos River during the drought of 2011, can result in severe reductions of fluvial specialists, while enhancing recruitment of nesting species of predatory fishes, such as channel catfish, blue catfish, largemouth bass, and spotted bass (K. Winemiller, unpublished data and personal observations on the lower Brazos River, summer 2011). These nesting species are piscivores that feed on minnows among other prey taxa, and increases in their population abundances during periods of extended drought would further impact fluvial specialist cyprinids via direct predation mortality on both juveniles and adults.

Riffle-dwelling species, such as darters (*Percina* and *Etheostoma* species) and juvenile flathead catfish (*Pylodictus olivaris*), do not respond to high pulses by entering marginal or off-channel habitats, but they feed on drifting invertebrates within the main channel. During high flow pulses, they receive increased food resources in the form of dislodged aquatic macroinvertebrates and terrestrial insects. Aquatic insect drift among woody debris patches, and presumably other structurally complex substrates such as rocky shoals, is a major aspect of benthic ecology in the Brazos River (Schneider and Winemiller 2008).

During early spring (late February to early March), schools of white bass (*Morone chrysops*) migrate from major reservoirs in the basin upstream and enter tributary streams where they spawn in flowing waters. Most white bass reside in reservoirs during other times of the year, but some individuals also inhabit pools of the river channel or oxbow lakes during the non-reproductive period. Higher flows are believed to stimulate larger migrations that penetrate further upstream; under low flow spring conditions, more white bass spawn along the shorelines of reservoirs. Higher flows enhance passive transport of the eggs and larvae of these broadcast spawners, maintain DO levels during development, and probably allow juveniles to move into and out of marginal lentic habitats where they feed on abundant food resources. Winemiller et al. (2000) captured juvenile white bass from oxbow lakes in the floodplain of the lower Brazos River, indicating lateral exchanges of adults and/or juveniles during high flow pulses.

A great deal of ecological literature demonstrates that gars (*Atractosteus spatula*, *Lepisosteus* spp.), catfish (*Ictalurus* spp., *Pylodictus olivaris*), smallmouth buffalo (*Ictiobus bubalus*), and other large fish species characteristic of the lower Brazos River have significant requirements for high flow pulses during spring. Spawning by these species occurs during early spring, and eggs are either scattered and drift some distance to settle into retention zones (marginal channel habitats with slow back eddies) or spawning takes place within these retention zones, where larvae develop and then feed on zooplankton. In the case of the alligator gar and other gar species, spawning takes place over submerged vegetation of perhaps sticks. In the case of smallmouth buffalo and other suckers (Catostomidae), spawning takes place in the main channel and eggs drift into deep pools within the main channel. Even for the suckers, larvae and early juvenile stages probably require lentic backwaters for feeding and survival, and high flow pulses provide more of this habitat. Flood pulses also are needed during other times of the year to connect off-channel habitats with the channel so that gar can move in and out for feeding (Robertson et al. 2008). In the lower Brazos River, oxbows and sloughs have much greater aquatic primary and secondary productivity than main-channel habitats (Winemiller et al. 2000). Many species, including gizzard shad (*Dorosoma cepedianum*), pugnose minnow (*Opsopoeodus emiliae*), and white crappie (*Pomoxis annularis*), can build up large numbers in oxbow lakes.

Given the diversity of fish species and fish life history strategies documented for the various river and stream reaches within the Study Area, the Brazos BBEST evaluated the high flow pulse elements within the HEFR-derived matrices in the context of the natural flow regime paradigm. Each matrix was evaluated to ensure that high flow pulses of distinctly different magnitudes, durations, and times of year would be likely to occur under the implementation guidelines (Section 6). The first major evaluation of proposed environmental flows was analysis of species life histories and population recruitment. The life history strategies and flow pulse requirements of fluvial specialists, in particular species of minnows, shiners, and chubs of the family Cyprindae, were of particular concern in this regard. Lower tier HEFR-derived high flow pulses (i.e., four per season, two per season, one per season) were deemed necessary to provide a reasonable probability that one or more high flow events would allow these fishes to spawn and have periodic recruitment of juvenile individuals into the adult populations (see Durham and Wilde 2006, 2009a, 2009b). These cyprinids, some of which are endemic to the basin and/or have experienced population reductions, are short-lived (one to two years average, two to four years maximum life expectancy) and therefore require significant levels of recruitment at least every other year. Lower-tier high flow pulses would be particularly critical during spring and summer months, when most of these fluvial specialists spawn in response to flow events.

4.2.3.2 High Flow Pulses and Freshwater Mussels

The responsiveness of mussels to high flows is manifested in their patchy occurrence within flow refuges that protect them from scour and high shear stress. Studies have shown reduced survival, recruitment, and growth during years having higher average discharge (Vaughn and Taylor 1999; Rypel et al. 2009). High flows can be stressful in a number of ways. Scouring can disrupt mussel beds by dislodging individuals and transporting them downstream. Growth rates may be reduced during high flows due to increased energy requirements necessary to maintain position in the substrate and greater food processing costs because mussels must filter and egest higher quantities of non-digestible, particulate inorganic matter associated with increased turbidity. Out-of-season pulsed flows (relative to the natural hydrograph) can disrupt reproductive success during sperm release and fertilization, glochidia release and encystment on the host fish, and juvenile disengagement from the host, posing a particular threat in light of mussels' naturally low reproductive success. A high flow pulse that falls rapidly is another threat, because mussels can become stranded along stream edges.

Despite these negative effects of high flow pulses, all of which are comparatively short-term, high flow pulses also are critical for the long-term maintenance of mussel assemblages. Periodic high flows maintain high quality mussel habitat by flushing fine sediments that otherwise would accumulate and compact streambeds. For some mussel species, excessive fine sediments on the streambed negatively impacts growth, feeding efficiency, and juvenile survival. Furthermore, many fish species in lowland streams, such as the lower Brazos, depend on seasonal flooding for successful reproduction, ultimately affecting the availability of host fishes for mussel glochidia. A diverse native fish assemblage is required to support a diverse mussel assemblage (SRES 2007; Rypel et al. 2009). To derive environmental flow prescriptions that will sustain native mussel assemblages, research is needed to characterize species reproductive cycles and habitat use within the Brazos Basin. A recent flow-related habitat-use study in the lower portion of the basin correlated several hydraulic variables with mussel occurrence under low flow conditions (Randklev et al. 2009). Similar studies are needed to elucidate mussel responses to high flow pulses. Given the lack of research to inform the high flow pulse requirements of mussels in the Brazos Study Area, we were not able to refine our environmental flow recommendations based on specific needs of freshwater mussels.

4.2.3.3 High Flow Pulses and Lateral Connectivity

The second major evaluation criterion involving high flow pulses and fishes was the frequency of lateral connections between oxbow lakes and the river channel. Studies demonstrating the importance of these periodic connections for maintenance of fish populations in the lower Brazos River were cited and briefly discussed above. Much research on the dynamics of lowland river flood pulses, connections with oxbow lakes, and fish community ecology has been conducted on the lower Brazos River near Bryan (work by K. Winemiller, Texas A&M University and collaborators). In 2003, the Texas Water Development Board (TWDB), Texas Parks and Wildlife Department (TPWD), TCEQ, Texas State University, and Texas A&M University conducted a collaborative study that quantified the flows needed to make connections with six oxbow lakes located in the Brazos River floodplains between Bryan and Lake Jackson (Osting et al. 2004b; Winemiller et al. 2004). The six oxbow lakes (Figures 4.8 and 4.9) had a range of ages and geomorphologies that resulted in a range of connection frequencies under the observed flow regime (Table 4.1). This information is used in Section 7.2 to evaluate the suitability of higher-tier high flow pulses from the HEFR-derived matrices for maintaining this critical ecological function in the lower Brazos and, by inference, the suitability of similar criteria for high flow pulses for the lower Navasota and San Bernard rivers that also have oxbow lakes and other floodplain depressions in their floodplains that provide important aquatic habitats.

Daily flow data indicated that Big Bend Oxbow near College Station had connected with the river channel six times over the 12-month study period, yielding at least 19 total days of connection. Moehlman Slough near Bryan connected on three occasions for a total of six days. Hog Island Oxbow, the youngest oxbow and located near Rosharon, was connected for a greater number of days than it was isolated during the study period. Prior to surveys in August 2003, Korthauer Bottom near Hempstead had been last connected in April 2003 and Cut Off Lake near Lake Jackson had

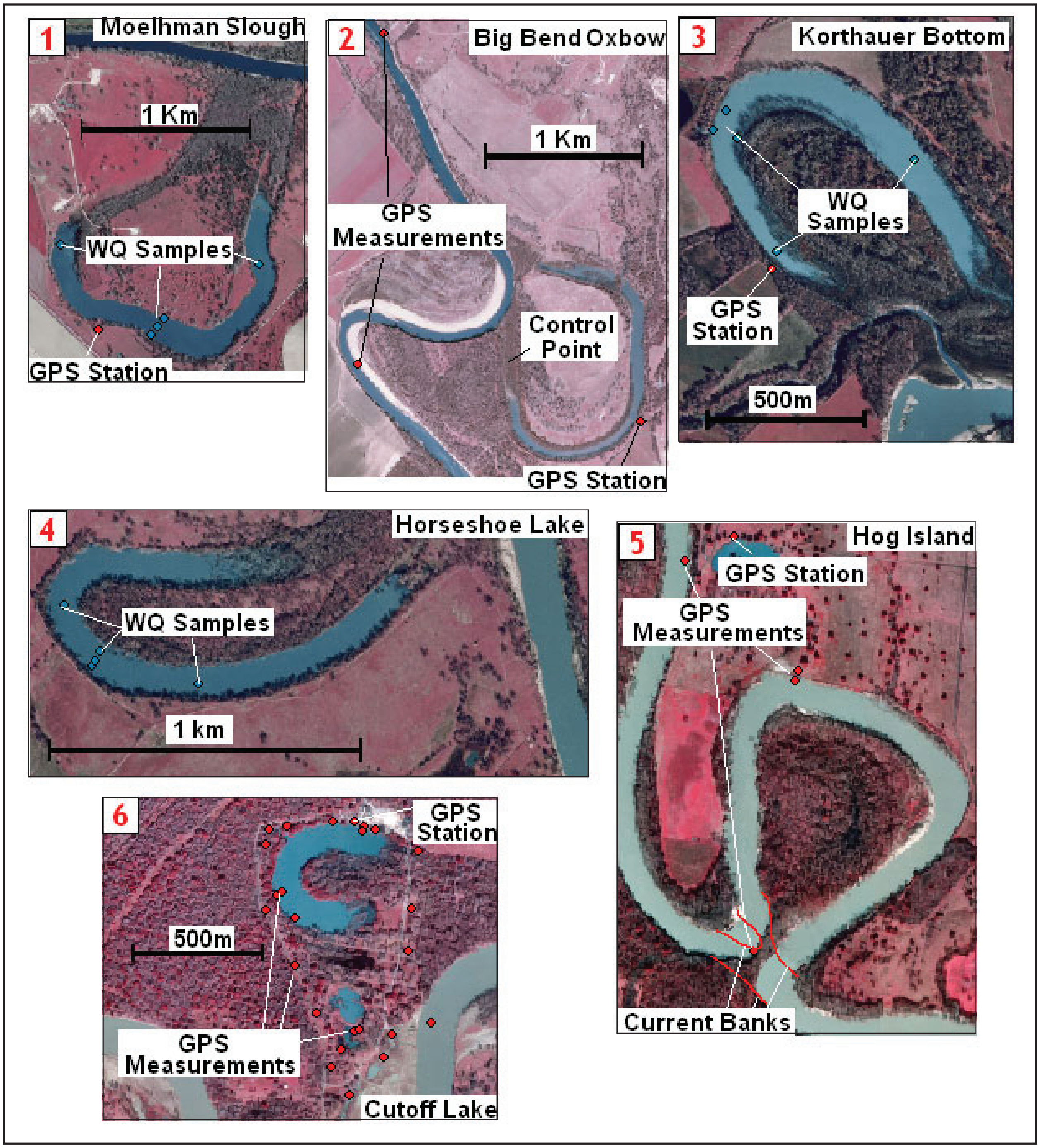


Figure 4.8. DOQQ images of the six oxbow lakes in the lower Brazos River studied by Osting et al. (2004b).

been last connected in November 1998. An isotopic analysis performed by TWDB indicated that surface connections with the river channel (rather than subsurface exchanges) were the primary source of oxbow water (Chowdhury et al. 2010). A more detailed analysis of Brazos River oxbow lake topography and connectivity in relation to hydrologic variation appears in Osting et al. (2004b). The season with the most river channel–oxbow connections was spring, with 44-54 percent of connections occurring during spring for five of the six oxbows. Spring also was the most important season for connections for Hog Island, the youngest and most frequently connected oxbow, but the percentage of total connections in the spring for Hog Island was only 30 percent.

Several of these oxbow lakes were also surveyed in an earlier study by Winemiller et al. (2000), a study that compared the fish assemblage composition of 10 oxbow lakes in the lower Brazos River in relation to local-scale environmental factors and a reference site in the river channel. More recent research on ecological aspects of oxbow lake connections in the lower Brazos River (Zeug and Winemiller 2005) revealed that white crappie (*Pomoxis annularis*) populations attain high densities within the lentic and highly productive environment of oxbows, while crappie numbers within the active river channel are exceedingly low. Other species show

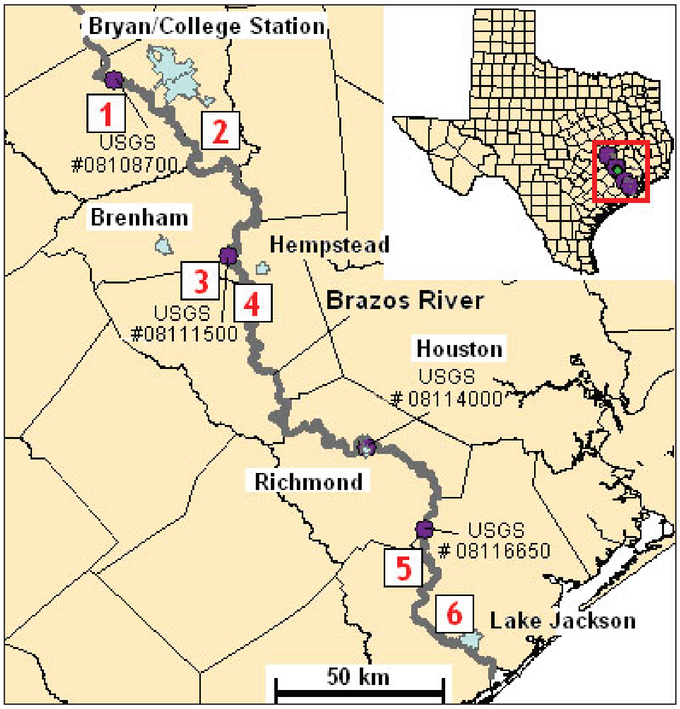


Figure 4.9. Map showing locations of six oxbow lakes in the lower Brazos River floodplain that were studied by Osting et al. (2004b) and Winemiller et al. (2004) (map reproduced here from the latter document; 1 = Moehlman Slough, 2 = Big Bend Oxbow, 3 = Korthauer Bottom, 4 = Perry Lake, 5 = Hog Island Oxbow, and 6 = Cut Off Lake).

Table 4.1. Table from Osting et al. (2004b) showing the number of lateral connections between the lower Brazos River channel and six oxbow lakes during 2004 and two decadal time intervals, the flow value from the nearest USGS gage that would produce a connection, and the expected average interval between connection events (based on recent hydrologic records). Korthauer Bottom and Hog Island are the youngest oxbows, and both connect with the main river channel multiple times each year (on average). Their estimates of flows to connect each oxbow and the average interval between connection events are approximate based on measurements of elevation at the oxbow control point (lowest place in the river bank) and nearest USGS gage, estimated slope in elevation between the two positions, and the full period of record for the gage.

	Connections			Flood Description	
Oxbow	2004	1994-2004	1984-1994	Flow	Interval
Moelhman Slough	3	12	14	45,000 cfs	1.93-year
Big Bend	6	41	32	20,000 cfs	1.13-year
Korthauer Bottom	6	50	32	20,500 cfs	< 1.0-year
Horseshoe Lake	0	0	1	99,000 cfs	9239-year
Hog Island	5	68	61	3,625 cfs	< 1.0-year
Cut Off Lake	0	3	2	76,200 cfs	4.42-year

similar patterns of relative abundance in oxbow lakes of the main channel of the lower Brazos, including gizzard shad (*Dorosoma cepedianum*), smallmouth buffalo (*Ictiobus bubalus*), black bullhead (*Ameirus melas*), and pugnose minnows (*Opsopoeodus emiliae*). Oxbow lakes and periodic connections with the river channel during high flow pulses are essential for maintaining the full complement of species within the native fish assemblage of the lower reaches of the Brazos River. The Brazos BBEST infers that similar ecological dynamics occur in the lower reaches of the Navasota River, Oyster Creek, and San Bernard River where oxbow lakes and other kinds of natural floodplain depressions provide aquatic habitat.

The timing and frequency of high flow pulses interacts with habitat features to determine the structure of oxbow and river channel fish assemblages as evidenced by multivariate ordinations and cross-correlation analyses. Predation may control the ability of small minnows typical of river channel assemblages from colonizing oxbow habitats (Zeug et al. 2005), and piscivore abundance was lowest during fall and winter surveys of Big Bend. Most oxbow fishes reproduced prior to floods in May and June 2004, and lateral connectivity allowed juveniles to move from oxbow habitats to the river channel (Zeug and Winemiller 2007, 2008). Species-specific responses to hydrologic variability appeared to be related to fish abundance patterns in oxbow and channel habitats at the time of connection. Although fishes move in both directions through temporary aquatic corridors, the analysis by Winemiller et al. (2004) indicated a net movement of fish biomass from oxbows into the river channel.

Patterns of species richness (the number of species in a sample) were influenced by the frequency of connections. Surveys in the Brazos River yielded an average of 39 species, and Hog Island, the most frequently connected oxbow, produced 38 species during only four surveys. The average species richness of samples from Big Bend and Moehlman Sloughs was 31 and 27, respectively. The position of Hog Island Oxbow in the Brazos River may have influenced estimates of species richness because several estuarine species were captured that were not collected in oxbows further upstream. In their survey of 10 Brazos River oxbows, Winemiller et al. (2000) found that depth was a significant predictor of fish assemblage structure. Shallow oxbows that dry out with greater frequency tend to have smaller species capable of rapid colonization and would be less likely to function as sources of fish production to the river channel (Zeug et al. 2005). The study was conducted during a relatively wet year that probably tended to increase the similarity of physicochemical characteristics among oxbow lakes.

Throughout the series of studies of the lower Brazos cited above, several fish species were almost always captured from oxbow lakes and other species were entirely restricted to the river channel (see also Roach and Winemiller 2011). Overall, Brazos oxbow fish assemblages were dominated by centrarchids (sunfishes and bass), clupeids (shads), and ictalurids (catfishes). Adult and juvenile centrarchids were less abundant in the river channel, and emigration from oxbow lakes apparently augments the channel stocks. Adult gizzard shad were common in the river channel, but juveniles were primarily captured in oxbows following floods. Oxbows may function as rearing habitats for juvenile fishes that feed on zooplankton, a resource that is much more abundant in oxbows (Winemiller et al. 2000).

Findings from these studies clearly demonstrated that Brazos River oxbow lakes support diverse fish species and play a particularly important role in supporting production of species that are relatively uncommon in the river channel, including sport fish (crappie, largemouth bass) and forage species (shad, smallmouth buffalo) for predators (gars, catfishes). Fish assemblage structure in both the river channel and oxbow lakes is influenced by local-scale habitat characteristics, and oxbows in various stages of geomorphic succession probably maintain overall fish diversity and productivity of the fluvial ecosystem. Modification of the flow dynamics that cause oxbow formation and succession or reduction in floodplain connectivity would be expected to reduce fish productivity and biodiversity both locally and regionally. Although lateral connectivity to off-channel floodplain habitats is less important in smaller headwater streams and tributaries than larger reaches located downstream, it nonetheless is still critical, from an ecological standpoint, to have periodic high flow pulses to permit organisms to occupy marginal habitats for feeding and/or reproduction (Freeman et al. 2001).

4.2.3.4 Requirements for High Flow Pulses of Other Aquatic and Riparian Organisms

The third evaluation criterion for high flow pulses was the ecological requirements of freshwater mussels, riparian trees, and other flow-dependent organisms. These organisms are integral constituents of lotic ecosystems, but unfortunately, in most cases, their responses to streamflows are poorly understood. Our environmental flow recommendations are nonetheless expected to be protective of riparian vegetation, mussels and other kinds of aquatic macroinvertebrates, and other kinds of aquatic vertebrates besides fishes. In other words, the requirements of fishes encompass the flow dependencies of habitat and ecological requirements that also should sustain other aquatic and riparian species native to the streams and rivers. Because site-specific studies for the basin are very limited, our assessment of non-fish taxonomic groups was based largely on qualitative analysis and information derived from both within and outside the basins of the Brazos BBEST Study Area. The study by Duke (2011) on riparian vegetation in relation to flows in the lower Brazos River was useful, especially in light of additional information gathered on geographic distributions of highly flow-dependent species, such as bald cypress, which are naturally scarce in the basin, and their general life history characteristics (Middleton 2004). The BBEST attempted to identify important riparian communities and their relationships to instream flows in the Brazos and San Bernard river systems. The BBEST contacted biologists and scientists familiar with riparian communities in the region, conducted a literature review, and compiled data to support a riparian component analysis (Appendix C).

Duke (2011) examined the relationship between historic flows along the lower Brazos River and riparian tree productivity. She determined that black willow (*Salix nigra*), green ash (*Fraxinus pennsylvanica*), and box elder (*Acer negundo*) were useful indicator species for describing healthy riparian zones, and Southern hackberry (*Celtis laevigata*) was an indicator of degrading riparian zones. Loss of connectivity to saturated soils occurred rapidly with distance from the river channel. Excessively high flows suppressed basal increment for green ash; in contrast, black willow and box elder thrived under those flow conditions. According to Duke, early life stages of the indicator species require periodic flooding in their locations to provide proper soil saturation to disperse seedlings and maintain saplings, recharge groundwater in near-bank regions to support root mass, and allow for optimal productivity of mature trees so that they are resilient and can recover rapidly from stressed conditions. Species of interest for future monitoring include Southern hackberry, as it is seen to be expanding along the lower Brazos, and green ash and cottonwood (*Populus deltoides*) because of their low recruitment along the Brazos River. Duke found no evidence of vegetation encroachment into the active channel.

Land cover analysis revealed that the riparian corridor has been degraded in many locations within the Brazos and San Bernard basins. This degradation is a result of historically poor grazing practices; clearing of land for agricultural and industrial activities and urban development; and fire suppression. Currently, the largest threat to riparian corridors in the Brazos and San Bernard basins is from further habitat destruction and fragmentation, which can lead to deterioration of genetic diversity of individual species and invasion by upland and/or non-native vegetation. An additional problem is invasion of the upper Brazos Basin by saltcedar (*Tamarix ramosissima*) and invasion of the coastal region by Chinese tallow (*Sapium sebiferum*), two species that appear to outcompete native riparian plant species, possibly due to less damage from native insect herbivores (Lankau et al. 2004).

The Brazos BBEST recognizes that to maintain native vegetation communities within riparian corridors of the basin, lateral connectivity with groundwater tables must be maintained and high flow pulses and occasional overbank flows must occur. Conversely, the BBEST also recognizes that subsistence flow and no flow conditions will occur within certain stream reaches, particularly in the upper basin. Given the limited accounting of riparian corridor areas, composition, and flow requirements, the Brazos BBEST is unable to make specific flow recommendations for riparian vegetation maintenance and therefore did not estimate or adjust flow regime recommendations based on maintenance of riparian vegetation. The BBEST reviewed each HEFR-generated flow regime and believes our recommended subsistence, high flow pulse, and overbank flow components should be adequate to maintain connectivity between the river and the groundwater tables to sustain native riparian vegetation. This conclusion assumes minimal competition from exotic plant species, such as saltcedar in the upper basin and Chinese tallow near the coast. It is also assumed that high flow pulses sufficient to meet the needs of lateral connectivity of aquatic habitats will also be sufficient to maintain seed dispersal, seed germination, and seedling recruitment to maintain native vegetation communities in riparian areas that are otherwise minimally impacted by other factors, such as agricultural practices.

4.3 Assessment and Adjustments to Draft Instream Environmental Flows Regimes

Once the hydrographic separation and HEFR-derived flow matrices had been calculated and configured to best reflect ecological requirements within the focal reaches, the final step in arriving at our proposed environmental flows regime was to determine if any of the flow categories could be eliminated based on a lack of clear evidence for ecological functions. In other words, any flow components that could not be linked to a known ecological function or benefit for our focal species and functional groups were evaluated and either retained or eliminated as a component of the environmental flow regime. Again, the 1-per-5-year pulse flow level was not included in these matrices. Another topic of discussion pertained to whether, in some cases (e.g., Double Mountain Fork Brazos River at Aspermont), there are large gaps between the high base flow and the lowest tier for pulse flows. Some BBEST members (ecologists) proposed that smaller pulses are critically important, for fluvial specialist cyprinids in particular, and must be included in the environmental flow matrices. Some members argued that some of the large pulse categories might be considered for elimination depending on the season and range of high flow pulse components derived from the hydrological analyses. The BBEST evaluated the pulse flow tiers for the HEFR matrix for each gage/reach. These evaluations focused largely on factors such as degrees of similarity in magnitudes, durations, etc. between successive tiers in the matrix, relationship of a pulse to the overbank condition as defined previously, and most importantly, the ecological functions that might be lost and the likely impact of alteration or loss of these functions. The following decisions resulted:

- Brazos River at Richmond: removed four per season and one per five year
- Brazos River near Hempstead: removed four per season and one per five year
- Navasota River near Easterly: removed one per five year
- Brazos River at SH 21 near Bryan: removed one per five year
- Little River near Cameron: removed one per five year
- Little River near Little River: removed three per season
- Lampasas River near Kempner: removed four per season
- Leon River at Gatesville: removed one per five year
- Brazos River at Waco: removed three per season and one per five year
- North Bosque River near Clifton: removed winter and summer four per season and spring three per season
- Brazos River near Glen Rose: removed three per season and one per five year

- Brazos River near Palo Pinto: removed three per season and one per five year
- Brazos River near South Bend: removed one per five year
- Clear Fork Brazos River at Fort Griffin: removed three per season and one per five year
- Clear Fork Brazos River at Nugent: removed three per season
- Brazos River at Seymour: removed winter three per season and one per five year
- Salt Fork Brazos River near Aspermont: removed winter three and four per season and one per five year
- Double Mountain Fork Brazos River near Aspermont: removed winter three per season
- Brazos River near Rosharon: removed four per season and one per five year
- San Bernard River near Boling: removed one per five year

4.4 Estuarine Inflows

Numerous studies have documented the importance of freshwater inflows to marine and estuarine organisms (Gillson 2011; Olsen et al. 2011). Important services include sediment supply, nutrient loading, and provision of a spatially and temporally variable habitat based on salinity regime. The Brazos River would be classified as having a *river-mouth estuary* or *riverine estuary* because sediments are carried offshore and typically form deltas (Rodriguez et al. 2000). The strong vertical and lateral salinity gradient creates a mosaic of habitats near the lower coast (Olsen et al. 2011). The coastal portions of the Brazos and San Bernard rivers are unique in geomorphology since this type of estuary is not found along most of the Texas coast. This is due in part to the geology of this portion of the Texas coast (Orlando et al. 1993), as well as the Brazos River delivering more sediment to the Texas coast than any other river (Anderson 2007). During the past 15,000 years, while sea levels rose, the Brazos River transported sufficient sediment to keep up with increasing water depths. Hence, it never flooded to create a bay. As a result the Brazos River lacks a well-developed estuary. During this period the river meandered extensively creating multiple channels that eventually filled (Rodriguez et al. 2000). These combined channels now comprise an extensive area that is referred to as the Brazos Alluvial Plain (Anderson 2007). Prior to 1929, the natural mouth of the Brazos River was located in what is now known as Freeport (Figure 4.10). The river discharged through the Freeport Jetties to the Gulf of Mexico next to the town of Surfside, Texas. In 1929, the U.S. Army Corps of Engineers, in an effort to improve navigational access to the industrial complex of the Port of Freeport, diverted the lower part of the river to a location six miles west of Freeport and cut off the upstream portion of the Brazos River that discharged through the original course (Figure 4.11). As a result of this action, the old delta has eroded while the new mouth of the river has exhibited progradation of the delta as new sediment has been deposited.

The current Brazos River delta is an arcuate, wave-dominated delta that protrudes two kilometers into the Gulf of Mexico (Gibeaut et al. 2000). Multiple beach ridges are present on the Brazos River delta progradation, spit progradation and downdrift shoreline offset are associated with the San Bernard River entrance, and fine-grained-sand beaches characterize the shoreline in this region. Large flood events are mostly responsible for deposition and delta enlargement (Rodriguez et al. 2000).

Another factor that may affect delta formation is upstream reservoir development in the Brazos River watershed that, while essential for water supply and flood control, has most likely reduced the delivery of sand and other sediment at the relocated Brazos River mouth. A major factor in coastal erosion is the amount of sand supplied to the system (Mathewson and Minter 1976).

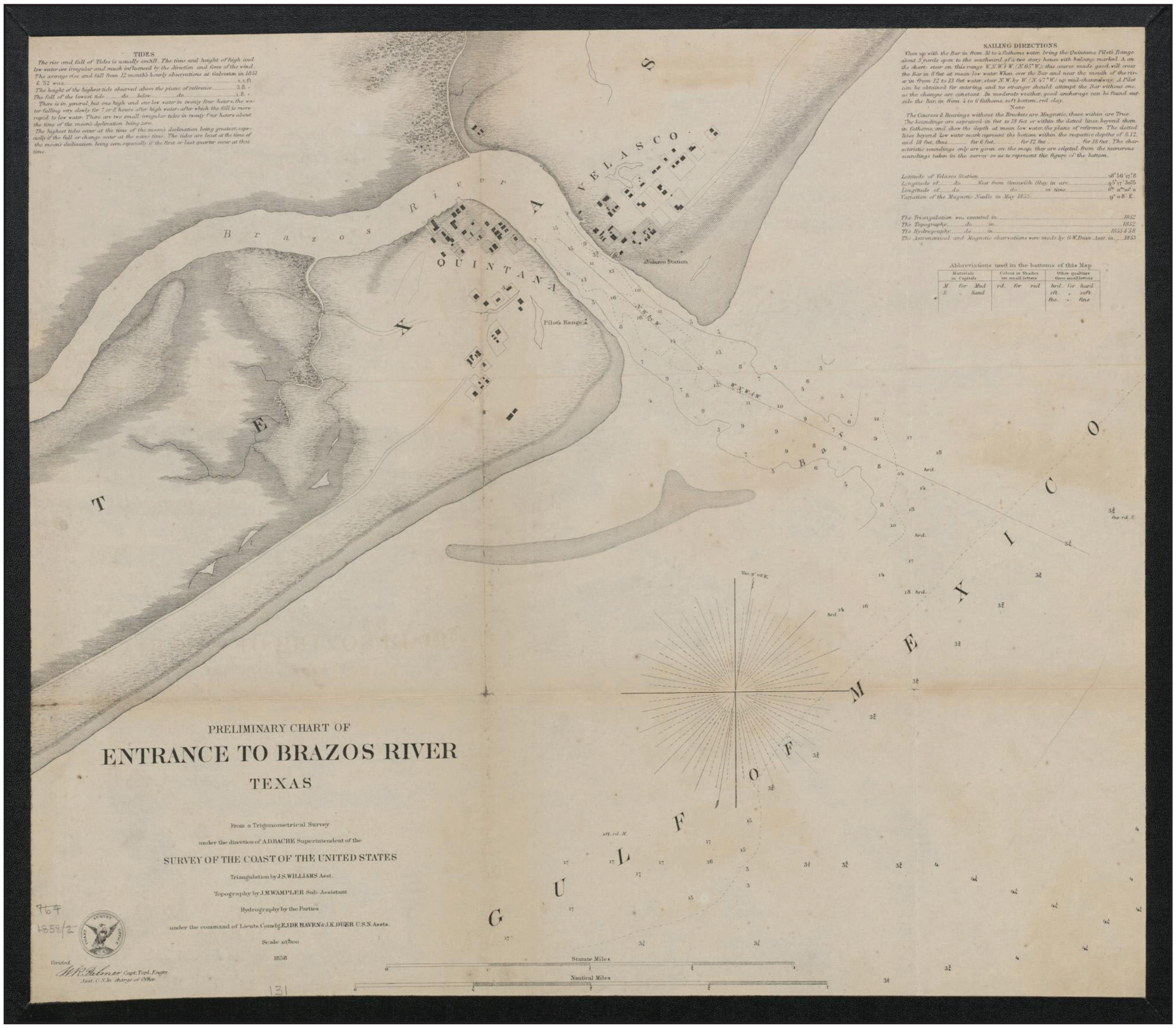


Figure 4.10. Location of the original mouth of the Brazos River prior to being diverted during 1929 (U.S. Coastal Survey).

The primary beneficial functions of the flow regime in the lower estuarine portion of the Brazos and San Bernard rivers include:

1. Sediment supply to the deltaic region for support of emerging wetlands and maintenance of barrier island sediment supply. Maintenance of these systems is critical for support of nursery habitat for immature fish and invertebrates and protection of human uses (e.g. Intracoastal Waterway, Freeport industrial corridor, recreational and commercial fishing).

2. Maintenance of a varying salinity regime that promotes a diverse estuarine fish and invertebrate community that supports recreational fishing and commercial offshore shrimp fishery.

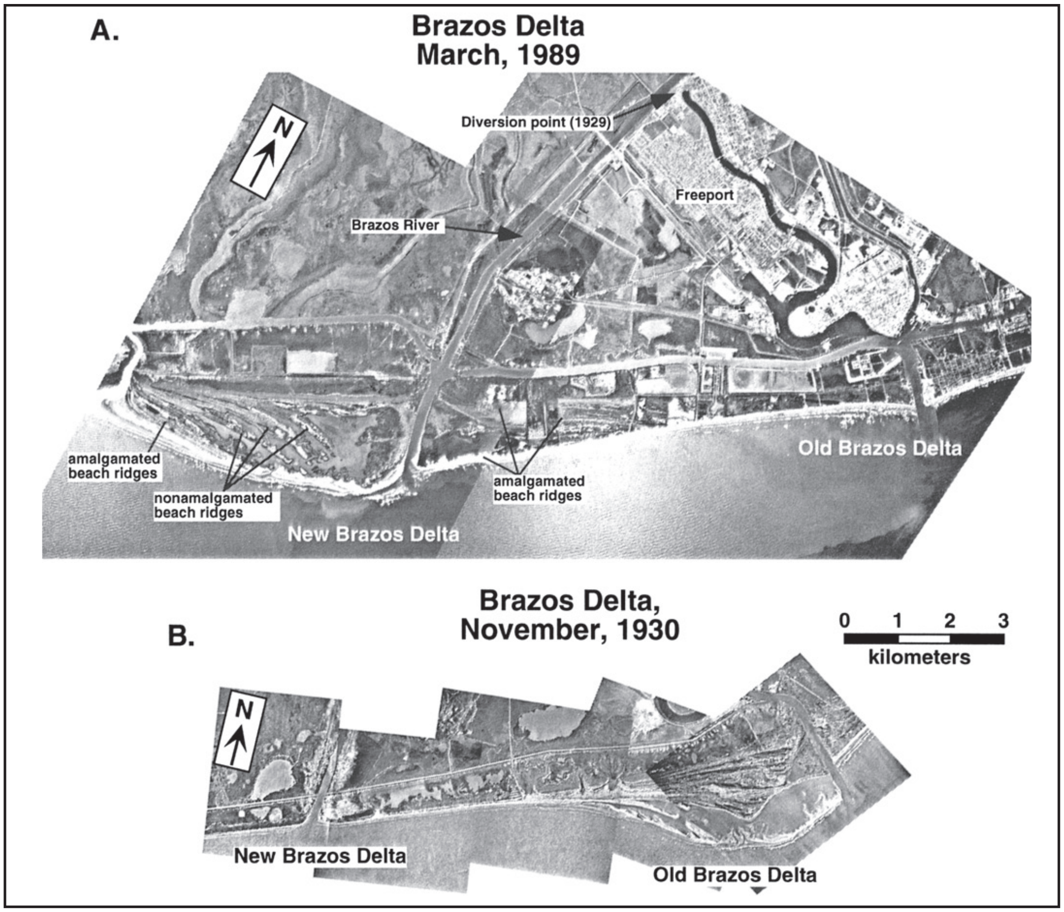


Figure 4.11. Historical and current locations of the Brazos River mouth. Note the loss of the original delta and the extensive delta formation at the new mouth (Rodriguez et al. 2000.) (http://gulf.rice.edu/modBdel.html#BDdiversion).

3. Maintenance of appropriate nutrient loading in support of estuarine and nearshore ecosystem productivity. However, this relation is very complex given the role of human sources both upstream and along the coasts. Recent reports of offshore hypoxia may indicate that excessive nutrients are being discharged, which may be due to both nonpoint and point source loading within the watershed.

4.4.1 Approaches for Evaluating Scenarios with Respect to Inflows to Coastal Habitats

Various approaches, methods, and guidance for determining the amount of freshwater to maintain a healthy estuarine system have been developed (SAC 2009/3). Productive and biodiverse estuarine ecosystems are influenced by freshwater inflow regimes that affect three major environmental components: salinity, nutrients, and suspended solids (SAC 2009/3). The characterization of inflow data including time/space variation is important in identifying major "regime" components and exposing relations of salinity and/or biology on inflows. This includes not just the relatively predictable, seasonal patterns of rainfall and runoff but also episodic events such as "freshets" that can greatly influence the distribution and survival of aquatic and riparian organisms. In addition, other less direct factors can influence the distribution and survival of estuarine organisms on longer time periods, such as the impacts of increased turbidity and nutrients on submerged seagrasses.

The SAC concluded that a combination of methodologies should be used by BBESTs to develop sound freshwater inflow recommendations. These inflow regimes should be designed to cover the full flow spectrum from very low conditions, during which refuge habitats become important for maintaining species populations, to very high flows that deliver nutrients and sediments to the bay system and influence the freshwater/saltwater gradient. Similar to the reliance on the "natural flow regime paradigm" in freshwater instream flow assessment, estuarine recommendations should focus on multiple flow components that encompass seasonality, frequency, and magnitude to reflect the natural variability of the system. This is a major challenge because many coastal systems have been highly modified by urbanization, water diversions, and land-use modification. Moreover, little historical information may be available on natural variability in these systems. Each estuary in Texas is unique due to the state's natural east-to-west gradient in rainfall, runoff, temperature, and geology (Estaville and Earl 2008; Sansom et. al. 2008; Orlando et. al. 1993).

The principal findings and approaches the SAC (2009/3) recommends are listed below. These include:

1. The scientific objective of the BBEST's should be to quantify, as far as possible, cause-and-effect relations identified in a simple conceptual model that focuses on the effects of the inflow regime on salinity, nutrients, and sediments that in turn influence aquatic organisms.

2. The SAC further recognized that in many systems data may be lacking to establish causal mechanisms that relate aquatic community response to changing inflow regimes. *Consequently, the evaluation of historical inflow data may be the only means of quantifying an inflow requirement in the absence of detailed biological data.*

3. When data and findings from site-specific studies exist and causal relationships are understood, this information should be exploited to improve analyses to establish environmental flow recommendations.

4. The SAC cautioned the BBESTs from using past recommendations made by TPWD and TWDB based upon application of the *State Methodology*. For example, monthly flow recommendations derived from this methodology (e.g. maxH) are intended to optimize the productivity of a set of key species. However, this method has sometimes produced patterns of monthly inflows that do not occur in the historical record. Moreover, these estimates of "beneficial inflows" are not always consistent with the requirements of SB3 that focuses on the health of the entire ecosystem. The SAC nevertheless acknowledged that the State Methodology generally provides useful insights for establishing estuarine inflow recommendations.

5. In delineating the desired state of the estuarine ecosystem, consideration must be given to present (or relatively recent) conditions. As previously mentioned, each bay system has been extensively modified, and it is highly unlikely these systems can return to its historical, *natural* state. Therefore, consideration should to be given to maintenance or restoration of the ecosystem to achieve *soundness* as defined in Section 1 of this report.

6. While it is unlikely that the flow recommendations for the riverine environment and the estuarine environment will align with perfect consistency, major discrepancies should be evaluated with care. Because the river and bay system evolve under similar conditions, a significant misalignment between instream and freshwater inflow recommendations should signal the need for a cross check of methods (SAC 2009/3).

Some of the approaches examined and reviewed by the SAC included the 1) State Methodology; 2) Salinity Zone approach; 3) Hydrology-Based approaches (e.g. HEFR and National Wildlife Federation [NWF] approach); and

4) LCRA-SAWS Inflow Criteria method (SAC 2009/3). We will not offer a review of these methods; however, the reader is encouraged to review reports describing these methods and SAC documents to obtain more information. Here we will summarize basic features of the principal methodologies that have been employed in Texas and their data requirements.

4.4.2 State Methodology

The State Methodology uses a quantitative model to determine inflows likely to support the productivity of economically and ecologically important estuarine fish and shellfish species. The State Methodology is extensively documented in Longley (1994). The model solution is a sequence of monthly inflows to the estuary that achieve productivity benchmarks. Two sets of relationships are required to achieve this: 1) salinity at specific points in an estuary as a function of inflow and 2) abundances of several key species as a function of inflow. These relationships are developed using statistical models and fitting empirical data to these models. The eventual result of several steps is production of management goals such as maximum total annual fishery harvest and stock abundance as functions of freshwater inflow and salinity regimes. However, the State Methodology was never used to produce recommendations for the Brazos or San Bernard estuarine systems (Longley 1994). We therefore could not use this approach. In addition, there are insufficient data on commercial fish and shellfish landings or stock abundances to use a method such as this.

4.4.3 Salinity Zone Approach

Essentially, the Salinity Zone method depends on:

1. Use of simulated time series of salinity in key areas of a bay system generated from a hydrodynamic circulation model, TXBLEND, to choose a flow regime that produces the most favorable salinity range;

2. Application of TPWD coastal fisheries data for selected species to determine their spatial distribution of abundance patterns in the bay and their association with salinity;

3. Application of the simulated salinity distributions from TXBLEND to examine areas encompassing preferential salinity ranges for estuarine organisms, with inflow regimes yielding maximal areas being considered preferable.

Since the Brazos and San Bernard river estuaries are not routinely monitored by TPWD and there is no TXBLEND model for these systems currently available, this approach is impractical.

4.4.4 Hydrology-Based Approaches

Using information obtained from the HEFR methodology (SAC 2009/1), the Hydrology-Based approach assumes that a flow regime that maintains the qualitative pattern of variation among key elements of the natural flow regime will support the essential short-term and long-term processes that maintain a sound ecological system (Poff et al. 1997). For instream purposes, this is done by identifying components of the hydrograph associated with specific functions (e.g. overbank flows to oxbow lakes). The challenge for application of hydrology-based methods to estuaries is to identify analogous flow components with associated ecological roles. To date, however, HEFR or other similar methods have not been sufficiently developed to address estuaries. Intuitively though, since estuaries and their natural communities have co-evolved and are dependent on inputs from riverine systems, then all things being equal, it should follow that conservation of the natural instream flow regime should protect key functions of the estuary. These functions would include provision of seasonal freshwater inflows, such as freshets, that may trigger spawning, reduce parasitism for oysters, etc. This assumption, however, has not been tested. For example, seasonal components of freshwater inflow in Texas estuaries often involve wet winter and spring months followed by drier summer months, interrupted by hurricane-induced storms and local thunderstorms. Although HEFR focuses on short time steps (daily flows) and most traditional estuarine methods have used longer time steps (months or seasons), it is possible to translate or adapt a HEFR-type approach to estuaries. The challenge is to identify the functional needs and benefits of various flow components, which are often lacking (e.g. overbank flooding) or are reduced in the estuarine system. In conclusion, some modification of this method can be used for the Brazos and San Bernard estuarine systems given the fact that they are *riverine* estuaries and continue to exhibit many attributes of river ecosystems until they empty into the Gulf of Mexico.

4.4.5 LCRA-SAWS Inflow Criteria Method

Another method that is currently being used in Texas is the LCRA-SAWS Inflow Criteria method that entailed extensive quantitative modeling to make predictions for the Matagorda Bay system (MBHE 2008; SAC 2009/3). That effort involved extensive acquisition of data on salinity, nutrient concentrations, habitat conditions, species abundance patterns, and benthic community structure. These kinds of datasets are essentially lacking for the Brazos and San Bernard systems; therefore, this method will not be discussed further.

4.4.6 Methodology Selected

As described earlier, the Brazos River and, to a lesser extent, the San Bernard River lack a large open-bay, estuarine zone typical of most Texas estuaries (McGowan et al. 1976; Orlando 1993). Both systems discharge directly into the Gulf of Mexico. However, the Brazos River is a larger and more dynamic system that carries more water and sediment. The Brazos River estuary extends from the head of the tide (approximately five kilometers upstream of the Missouri Pacific Railroad) to the Gulf of Mexico (Orlando 1993). The Brazos River estuary would be classified as a *riverine estuary* having a relatively high freshwater inflow, low volume, moderate area, moderate depth, moderate salinity, and very low tidal amplitude (Engle et al. 2007). Until recently, our general understanding of the relationship between river flow, salinity and the life history of freshwater fishes had been limited because little ecological research had been conducted in low salinity habitats that are considered to be an ecotone between freshwater streams and the estuarine zone (Peterson and Meador 1994). Past studies of riverine estuaries in southwest Florida have documented positive relationships between freshwater inflow and growth and recruitment among estuarine fishes (Purtlebaugh and Allen 2010). Spatial segregation of unique species assemblages between main channel and side-pond and backwater areas have been documented in tidal rivers in Mississippi (Rakocinski et al. 1997). Fish diversity typically appeared higher in littoral channel habitats than in side-pond habitats of tidal rivers. Stevens et al. (2010) also observed distinct species assemblages in southwest Florida tidal rivers that used mainstem and backwater areas. Mainstem fish assemblages were dominated by striped mullet *Mugil cephalus* and pinfish *Lagodon rhomboides*, while common snook *Centropomus undecimalis* and bluegill *Lepomis macrochirus* were abundant in backwater areas. They suggested that mainsteam species would likely be more affected by freshwater inflow and resulting salinity gradients. In contrast, backwater species would be influenced by both geomorphology and hydrology. As mentioned in Section 2, due to the small size of the estuarine zone, the Brazos River delta lacks some of the commercially and ecologically important fish stocks typically found in large lagoon-type estuaries such as Galveston Bay or Matagorda Bay. Also absent are extensive oyster reefs and seagrass beds (White et al. 1988). In addition, there is a lack of time series data for biological components of the estuary. For example, the TPWD Coastal Fisheries group has never collected either fisheries-dependent or fisheries-independent data in this system as part of their ongoing monitoring program (Lance Robinson, TPWD, personal communication). The last and most comprehensive survey effort in the system was a semi-quantitative survey conducted by Johnson (1977). Data on commercially and recreationally important species from this report are summarized in Patillo et al. (1997). Supplementary data on benthic communities and fishes have been collected and compiled by Montagna et al. (2008) and Kirkpatrick (1979), respectively.

Given the lack of extensive biological data sets and the unique riverine nature of these estuaries, we chose to use a Hydrological-Based approach to characterize the historical inflow patterns to the estuaries. The primary beneficial functions of the flow regime in the lower estuarine portion of the Brazos and San Bernard rivers include:

1. Sediment supply to the deltaic region for support of emerging wetlands and maintenance of barrier island sediment supply. Maintenance of these systems is critical for support of nursery habitat for immature fish and invertebrates and protection of human uses (e.g. Intracoastal Waterway, Freeport industrial corridor, and recreational and commercial fishing).

2. Maintenance of a varying salinity regime that promotes a diverse estuarine fish and invertebrate communities that support recreational and commercial fisheries.

3. Maintenance of appropriate nutrient loading for support of estuarine and nearshore productivity. However, this relation is very complex given the role of human sources both upstream and along the coasts. Recent reports of offshore hypoxia may indicate that too many nutrients are being discharged, which may be due to both nonpoint and point source loading within the watershed.

We focused our analysis on the influence of environmental flow regimes developed for the Brazos and San Bernard rivers on the inflows that would be provided to the estuarine zone. Smaller tidal streams and rivers were not evaluated. Historical estuarine inflows were estimated from previous published estimates from the TWDB and extended using regression models that relate flows at USGS gages in both rivers (longer time series) to downstream inflow estimates (shorter time series). Although this was done to extend the time series, we attempted to display statistical properties based on the time frame used in the HEFR instream analysis to evaluate how proposed instream flow regimes may translate to downstream monthly estuarine flows. The TWDB data were extracted from the agency web page representing freshwater inflows to Texas estuaries (http://midgewater.twdb.texas.gov/bays_estuaries/hydrologypage.html).

Estuarine freshwater inflow comes primarily from precipitation over each estuary's drainage basin. Runoff enters streams and rivers, makes its way to the mouth of each watershed, and eventually reaches the estuary. Along the way, some water is diverted for human use. Diverted water that is not consumed can be returned to the streams. The TWDB accounts for these diversions and return flows when calculating inflow estimates. USGS stream gages have historically been located far upstream from the estuary to remove them from the influence of tidal variations in flow and water level. Downstream of these gages, between the gage and the point where the stream meets the estuary, streamflow is ungaged. In some estuaries, significant runoff originates in these ungaged areas.

The TWDB develops estimates of total flow from the drainage basin by summing flows originating in both gaged and ungaged watersheds (Schoenbaechler and Guthrie 2011). Gaged flows are obtained from USGS streamflow records. Ungaged runoff is the sum of: 1) computed runoff, using a rainfall-runoff simulation model, based on precipitation over the watershed; 2) flow diverted from streams by municipal, industrial, agricultural, and other users; and 3) unconsumed flow returned to streams.

Thus, total surface inflow reaching the estuary consists of:

Surface Inflow = Sum over all gaged watersheds (USGS Gaged Flow) + Sum over all ungaged watersheds (Modeled Flow) - Sum over all ungaged watersheds (Diverted Flow) + Sum over all ungaged watersheds (Returned Flow).

Finally, when TWDB considers total freshwater balance, evaporation and precipitation at the water surface of the estuary are considered:

Fresh Water Balance = Surface Inflow - Evaporation from the estuary surface + Precipitation on the estuary surface.

In the case of the San Bernard and Brazos rivers, these sources are negligible and hence not considered further here.

The above methodology and data were used to develop time series of monthly inflows to the Gulf of Mexico from the Brazos River Basin, reflecting several different scenarios involving hypothetical new projects subject to the recommended instream flow regimes. The resulting evaluation of estuarine inflows from the Brazos River Basin is presented in Section 7.3. No scenarios were tested for the San Bernard River; however, an analysis of estimated historical estuarine inflows is presented in Section 7.4.

5 Environmental Flow Regime Recommendations

This section presents the instream flow recommendations from the Brazos BBEST and a summary of our approach for dealing with estuarine inflows. The environmental flow regime recommendation for each focal reach is presented in a matrix (table). The matrix format is as follows:

1. Flows and volumes in the tables are rounded to avoid indicating unwarranted precision.
2. Flows values of less than one cfs are given as one cfs. (See the discussion in Section 3.3.5.)
3. The tables show the central tendency on pulse volume and the upper value on pulse duration.
4. The tables show the rules for termination of a pulse as a footnote. They are:
    a. When volume requirements are met, or
    b. When duration requirements are met, or
    c. When the flow drops below the minimum value for a pulse (The minimum value for a pulse for the particular gage is given.), or
    d. When the flow is below the maximum value for base flow and the change in flow is a decrease of less than 5 percent. (The maximum value for base flow for the particular gage is given.)

Our series of draft HEFR-derived matrices from preliminary analyses are provided in Appendix G.

5.1 Description of Instream Flow Regime Elements

Overbank events and high flow pulses appear at the top of the table, descending from the largest and least frequent recommended pulse to the smallest and most frequent. For annual events (once per five years, once per two years, and once per year), overbank flows are labeled as such to the left and are shaded in blue. Darker blue represents larger and less frequent events. Non-overbank high flow pulses are labeled as such to the left and are shaded in black and gray. Black and darker gray represents larger and less frequent events.

Seasonal events are also shaded. Some of the larger and less frequent seasonal events for some gages are overbank events, and they are shaded in blue. Non-overbank seasonal events are shaded in gray. As with seasonal events, larger and less frequent events have darker shading.

If a seasonal high flow pulse box is empty for a given frequency and season, that means that there are not, on average, that many high flow pulses of any size in that season (For example, if there are on average only 2.8 high flow pulses of any size in winter, the winter three per season high flow pulse box would be empty, and no three per season pulse is recommended for winter).

The overbank and high flow pulse boxes list the peak flow required for a pulse (Qp) and the volume and duration that define the end of the pulse.

Base flows are listed below the high flow pulses. For each location, three base flows are listed for each season. From top to bottom, these are the high base flow (applicable during wet conditions), the medium base flow (applicable during average conditions) and the low base flow (applicable during dry conditions).

The subsistence flows are listed below the base flows, and they are applicable under subsistence conditions.

The months in each season are shown below the subsistence flows. The period of record used to develop the flow statistics is given toward the bottom right of the table, just above the definition for conditions that terminate a high flow pulse or overbank flow.

5.2 Instream Flow Recommendations

5.2.1 Double Mountain Fork Brazos River near Aspermont

<table>
<tr><td rowspan="7">High Flow Pulses</td><td colspan="12">Qp: 16,300 cfs with Average Frequency 1 per 5 years
Regressed Volume is 77,100
Duration Bound is 31</td></tr>
<tr><td colspan="12">Qp: 9,490 cfs with Average Frequency 1 per 2 years
Regressed Volume is 44,900
Duration Bound is 27</td></tr>
<tr><td colspan="12">Qp: 5,130 cfs with Average Frequency 1 per year
Regressed Volume is 24,300
Duration Bound is 23</td></tr>
<tr><td colspan="4">Qp: 92 cfs with Average Frequency 1 per season
Regressed Volume is 610
Duration Bound is 12</td><td colspan="4">Qp: 2,730 cfs with Average Frequency 1 per season
Regressed Volume is 12,500
Duration Bound is 17</td><td colspan="4">Qp: 2,540 cfs with Average Frequency 1 per season
Regressed Volume is 11,900
Duration Bound is 19</td></tr>
<tr><td colspan="4">Qp: 30 cfs with Average Frequency 2 per season
Regressed Volume is 180
Duration Bound is 8</td><td colspan="4">Qp: 1,120 cfs with Average Frequency 2 per season
Regressed Volume is 5,120
Duration Bound is 14</td><td colspan="4">Qp: 1,040 cfs with Average Frequency 2 per season
Regressed Volume is 4,750
Duration Bound is 14</td></tr>
<tr><td colspan="4"></td><td colspan="4">Qp: 570 cfs with Average Frequency 3 per season
Regressed Volume is 2,600
Duration Bound is 12</td><td colspan="4">Qp: 480 cfs with Average Frequency 3 per season
Regressed Volume is 2,160
Duration Bound is 12</td></tr>
<tr><td colspan="4"></td><td colspan="4">Qp: 280 cfs with Average Frequency 4 per season
Regressed Volume is 1,270
Duration Bound is 10</td><td colspan="4">Qp: 230 cfs with Average Frequency 4 per season
Regressed Volume is 990
Duration Bound is 9</td></tr>
<tr><td rowspan="3">Base Flows (cfs)</td><td colspan="4">15</td><td colspan="4">8</td><td colspan="4">7</td></tr>
<tr><td colspan="4">4</td><td colspan="4">3</td><td colspan="4">2</td></tr>
<tr><td colspan="4">1</td><td colspan="4">1</td><td colspan="4">1</td></tr>
<tr><td>Subsistence Flows (cfs)</td><td colspan="4">1</td><td colspan="4">1</td><td colspan="4">1</td></tr>
<tr><td></td><td>Nov</td><td>Dec</td><td>Jan</td><td>Feb</td><td>Mar</td><td>Apr</td><td>May</td><td>Jun</td><td>Jul</td><td>Aug</td><td>Sep</td><td>Oct</td></tr>
<tr><td></td><td colspan="4">Winter</td><td colspan="4">Spring</td><td colspan="4">Summer</td></tr>
</table>

<table>
<tr><td rowspan="3">Base Flow Levels</td><td>High (75th %ile)</td></tr>
<tr><td>Medium (50th %ile)</td></tr>
<tr><td>Low (25th %ile)</td></tr>
</table>

Pulse volumes are in units of acre-feet and durations are in days.

Period of record used : 1/1/1940 to 12/31/2010.

Episodic events are terminated when the volume or duration criteria are met, or when the flow drops below 8 cfs, or when the flow is below 45 cfs and the flow drops from one day to the next by less than 5%.

May 6, 2008, 75 cfs (left); May 26, 2009, 14 cfs (right)

5.2.2 Salt Fork Brazos River near Aspermont

	Winter	Spring	Summer
Overbank Events	Qp: 6,040 cfs with Average Frequency 1 per 2 years Regressed Volume is 29,400 Duration Bound is 26		
	Qp: 3,610 cfs with Average Frequency 1 per year Regressed Volume is 17,500 Duration Bound is 23		
High Flow Pulses	Qp: 71 cfs with Average Frequency 1 per season Regressed Volume is 510 Duration Bound is 14	Qp: 1,790 cfs with Average Frequency 1 per season Regressed Volume is 8,310 Duration Bound is 16	Qp: 1,580 cfs with Average Frequency 1 per season Regressed Volume is 7,680 Duration Bound is 18
	Qp: 31 cfs with Average Frequency 2 per season Regressed Volume is 210 Duration Bound is 10	Qp: 670 cfs with Average Frequency 2 per season Regressed Volume is 3,070 Duration Bound is 13	Qp: 520 cfs with Average Frequency 2 per season Regressed Volume is 2,310 Duration Bound is 13
		Qp: 300 cfs with Average Frequency 3 per season Regressed Volume is 1,350 Duration Bound is 11	Qp: 260 cfs with Average Frequency 3 per season Regressed Volume is 1,090 Duration Bound is 10
		Qp: 160 cfs with Average Frequency 4 per season Regressed Volume is 720 Duration Bound is 10	Qp: 140 cfs with Average Frequency 4 per season Regressed Volume is 560 Duration Bound is 8
Base Flows (cfs)	9	5	3
	4	2	1
	1	1	1
Subsistence Flows (cfs)	1	1	1
	Nov Dec Jan Feb	Mar Apr May Jun	Jul Aug Sep Oct
	Winter	Spring	Summer

Base Flow Levels	
	High (75th %ile)
	Medium (50th %ile)
	Low (25th %ile)

Pulse volumes are in units of acre-feet and durations are in days.

Period of record used : 1/1/1940 to 12/31/2010.

Episodic events are terminated when the volume or duration criteria are met, or when the flow drops below 6 cfs, or when the flow is below 28 cfs and the flow drops from one day to the next by less than 5%.

May 26, 2009, 25 cfs (left); August 18, 2009, 0.47 cfs (right)

5.2.3 Brazos River at Seymour

	Winter	Spring	Summer
Overbank Events	Qp: 16,800 cfs with Average Frequency 1 per 2 years Regressed Volume is 125,000 Duration Bound is 35		
High Flow Pulses	Qp: 10,400 cfs with Average Frequency 1 per year Regressed Volume is 74,100 Duration Bound is 29		
	Qp: 250 cfs with Average Frequency 1 per season Regressed Volume is 1,560 Duration Bound is 10	Qp: 4,730 cfs with Average Frequency 1 per season Regressed Volume is 30,500 Duration Bound is 20	Qp: 4,570 cfs with Average Frequency 1 per season Regressed Volume is 28,600 Duration Bound is 21
	Qp: 97 cfs with Average Frequency 2 per season Regressed Volume is 490 Duration Bound is 6	Qp: 2,000 cfs with Average Frequency 2 per season Regressed Volume is 12,000 Duration Bound is 15	Qp: 1,560 cfs with Average Frequency 2 per season Regressed Volume is 8,910 Duration Bound is 14
		Qp: 1,040 cfs with Average Frequency 3 per season Regressed Volume is 5,870 Duration Bound is 12	Qp: 800 cfs with Average Frequency 3 per season Regressed Volume is 4,290 Duration Bound is 11
		Qp: 560 cfs with Average Frequency 4 per season Regressed Volume is 2,960 Duration Bound is 10	Qp: 370 cfs with Average Frequency 4 per season Regressed Volume is 1,870 Duration Bound is 8
Base Flows (cfs)	46	35	32
	25	19	13
	10	7	4
Subsistence Flows (cfs)	1	1	1
	Nov Dec Jan Feb	Mar Apr May Jun	Jul Aug Sep Oct
	Winter	Spring	Summer

Base Flow Levels	
	High (75th %ile)
	Medium (50th %ile)
	Low (25th %ile)

Pulse volumes are in units of acre-feet and durations are in days.

Period of record used : 1/1/1924 to 12/31/2010.

Episodic events are terminated when the volume or duration criteria are met, or when the flow drops below 42 cfs, or when the flow is below 152 cfs and the flow drops from one day to the next by less than 5%.

September 11, 2007, 217 cfs – upstream (left), downstream (right)

5.2.3 Brazos River at Seymour (continued)

October 18, 2007, 51 cfs – upstream (left), downstream (right)

July 6, 2011, Subsistence 0.02 cfs – upstream (left), downstream (right)

5.2.4 Clear Fork Brazos River near Nugent

Overbank Events	Qp: 7,850 cfs with Average Frequency 1 per 5 years Regressed Volume is 41,700 Duration Bound is 28		
High Flow Pulses	Qp: 4,460 cfs with Average Frequency 1 per 2 years Regressed Volume is 23,400 Duration Bound is 24		
	Qp: 2,390 cfs with Average Frequency 1 per year Regressed Volume is 12,300 Duration Bound is 21		
	Qp: 110 cfs with Average Frequency 1 per season Regressed Volume is 710 Duration Bound is 15	Qp: 1,290 cfs with Average Frequency 1 per season Regressed Volume is 6,220 Duration Bound is 15	Qp: 980 cfs with Average Frequency 1 per season Regressed Volume is 4,980 Duration Bound is 16
	Qp: 26 cfs with Average Frequency 2 per season Regressed Volume is 160 Duration Bound is 9	Qp: 590 cfs with Average Frequency 2 per season Regressed Volume is 2,800 Duration Bound is 12	Qp: 390 cfs with Average Frequency 2 per season Regressed Volume is 1,890 Duration Bound is 12
		Qp: 180 cfs with Average Frequency 4 per season Regressed Volume is 860 Duration Bound is 9	Qp: 100 cfs with Average Frequency 4 per season Regressed Volume is 460 Duration Bound is 8
Base Flows (cfs)	13	12	9
	8	6	4
	5	3	1
Subsistence Flows (cfs)	1	1	1
	Nov Dec Jan Feb	Mar Apr May Jun	Jul Aug Sep Oct
	Winter	Spring	Summer

Base Flow Levels	High (75th %ile)
	Medium (50th %ile)
	Low (25th %ile)

Pulse volumes are in units of acre-feet and durations are in days.

Period of record used : 1/1/1925 to 12/31/2010.

Episodic events are terminated when the volume or duration criteria are met, or when the flow drops below 6 cfs, or when the flow is below 29 cfs and the flow drops from one day to the next by less than 5%.

March 31, 2005, 7.0 cfs – upstream (left), downstream (right)

5.2.5 Clear Fork Brazos River near Fort Griffin

Overbank Events	Qp: 8,630 cfs with Average Frequency 1 per 2 years Regressed Volume is 53,500 Duration Bound is 27		
High Flow Pulses	Qp: 4,970 cfs with Average Frequency 1 per year Regressed Volume is 30,700 Duration Bound is 24		
	Qp: 240 cfs with Average Frequency 1 per season Regressed Volume is 1,740 Duration Bound is 16	Qp: 2,970 cfs with Average Frequency 1 per season Regressed Volume is 17,700 Duration Bound is 18	Qp: 1,980 cfs with Average Frequency 1 per season Regressed Volume is 11,900 Duration Bound is 20
	Qp: 61 cfs with Average Frequency 2 per season Regressed Volume is 430 Duration Bound is 11	Qp: 1,230 cfs with Average Frequency 2 per season Regressed Volume is 7,310 Duration Bound is 15	Qp: 700 cfs with Average Frequency 2 per season Regressed Volume is 4,110 Duration Bound is 16
		Qp: 360 cfs with Average Frequency 4 per season Regressed Volume is 2,120 Duration Bound is 12	Qp: 110 cfs with Average Frequency 4 per season Regressed Volume is 620 Duration Bound is 10
Base Flows (cfs)	34	27	20
	17	13	5
	8	4	1
Subsistence Flows (cfs)	1	1	1
	Nov Dec Jan Feb	Mar Apr May Jun	Jul Aug Sep Oct
	Winter	Spring	Summer

Base Flow Levels	
	High (75th %ile)
	Medium (50th %ile)
	Low (25th %ile)

Pulse volumes are in units of acre-feet and durations are in days.

Period of record used : 2/1/1924 to 12/31/2010.

Episodic events are terminated when the volume or duration criteria are met, or when the flow drops below 6 cfs, or when the flow is below 73 cfs and the flow drops from one day to the next by less than 5%.

May 6, 2011, 10 cfs, (left); June 15, 2011, 0 cfs (right); – downstream

5.2.5 Clear Fork Brazos River near Fort Griffin (continued)

August 6, 2011, 0 cfs – downstream

5.2.6 Brazos River near South Bend

<table>
<tr><td rowspan="2">Overbank Events</td><td colspan="12">Qp: 25,400 cfs with Average Frequency 1 per 2 years
Regressed Volume is 228,000
Duration Bound is 35</td></tr>
<tr><td colspan="12">Qp: 15,800 cfs with Average Frequency 1 per year
Regressed Volume is 133,000
Duration Bound is 29</td></tr>
<tr><td rowspan="4">High Flow Pulses</td><td colspan="4">Qp: 960 cfs with Average Frequency 1 per season
Regressed Volume is 6,870
Duration Bound is 12</td><td colspan="4">Qp: 9,560 cfs with Average Frequency 1 per season
Regressed Volume is 72,100
Duration Bound is 21</td><td colspan="4">Qp: 7,440 cfs with Average Frequency 1 per season
Regressed Volume is 57,200
Duration Bound is 23</td></tr>
<tr><td colspan="4">Qp: 280 cfs with Average Frequency 2 per season
Regressed Volume is 1,640
Duration Bound is 7</td><td colspan="4">Qp: 4,550 cfs with Average Frequency 2 per season
Regressed Volume is 31,100
Duration Bound is 16</td><td colspan="4">Qp: 2,560 cfs with Average Frequency 2 per season
Regressed Volume is 17,000
Duration Bound is 15</td></tr>
<tr><td colspan="4"></td><td colspan="4">Qp: 2,480 cfs with Average Frequency 3 per season
Regressed Volume is 15,700
Duration Bound is 13</td><td colspan="4">Qp: 1,180 cfs with Average Frequency 3 per season
Regressed Volume is 7,050
Duration Bound is 11</td></tr>
<tr><td colspan="4"></td><td colspan="4">Qp: 1,260 cfs with Average Frequency 4 per season
Regressed Volume is 7,280
Duration Bound is 10</td><td colspan="4">Qp: 580 cfs with Average Frequency 4 per season
Regressed Volume is 3,140
Duration Bound is 8</td></tr>
<tr><td rowspan="3">Base Flows (cfs)</td><td colspan="4">120</td><td colspan="4">100</td><td colspan="4">95</td></tr>
<tr><td colspan="4">73</td><td colspan="4">60</td><td colspan="4">46</td></tr>
<tr><td colspan="4">36</td><td colspan="4">29</td><td colspan="4">16</td></tr>
<tr><td>Subsistence Flows (cfs)</td><td colspan="4">1</td><td colspan="4">1</td><td colspan="4">1</td></tr>
<tr><td></td><td>Nov</td><td>Dec</td><td>Jan</td><td>Feb</td><td>Mar</td><td>Apr</td><td>May</td><td>Jun</td><td>Jul</td><td>Aug</td><td>Sep</td><td>Oct</td></tr>
<tr><td></td><td colspan="4">Winter</td><td colspan="4">Spring</td><td colspan="4">Summer</td></tr>
</table>

Base Flow Levels	
	High (75th %ile)
	Medium (50th %ile)
	Low (25th %ile)

Pulse volumes are in units of acre-feet and durations are in days.

Period of record used : 1/1/1939 to 12/31/2010.

Episodic events are terminated when the volume or duration criteria are met, or when the flow drops below 115 cfs, or when the flow is below 388 cfs and the flow drops from one day to the next by less than 5%.

May 10, 2007, HFP event 3,820 cfs (left); March 3, 2005, 414 cfs (right)

5.2.6 Brazos River near South Bend (continued)

October 18, 2007, 115 cfs – upstream (left), downstream (right)

August 3, 2011, Subsistence 0.00 cfs – upstream (left), downstream (right)

5.2.7 Brazos River near Palo Pinto

Overbank Events	Qp: 25,800 cfs with Average Frequency 1 per 2 years Regressed Volume is 301,000 Duration Bound is 32		
High Flow Pulses	Qp: 17,500 cfs with Average Frequency 1 per year Regressed Volume is 182,000 Duration Bound is 26		
	Qp: 1,890 cfs with Average Frequency 1 per season Regressed Volume is 10,900 Duration Bound is 8	Qp: 10,700 cfs with Average Frequency 1 per season Regressed Volume is 88,000 Duration Bound is 18	Qp: 7,440 cfs with Average Frequency 1 per season Regressed Volume is 61,100 Duration Bound is 17
	Qp: 1,390 cfs with Average Frequency 2 per season Regressed Volume is 7,180 Duration Bound is 7	Qp: 3,370 cfs with Average Frequency 2 per season Regressed Volume is 20,200 Duration Bound is 10	Qp: 2,260 cfs with Average Frequency 2 per season Regressed Volume is 13,000 Duration Bound is 9
	Qp: 850 cfs with Average Frequency 4 per season Regressed Volume is 3,690 Duration Bound is 5	Qp: 1,400 cfs with Average Frequency 4 per season Regressed Volume is 6,600 Duration Bound is 6	Qp: 1,230 cfs with Average Frequency 4 per season Regressed Volume is 5,920 Duration Bound is 6
Base Flows (cfs)	100	120	120
	61	75	72
	40	39	40
Subsistence Flows (cfs)	17	17	17
	Nov Dec Jan Feb	Mar Apr May Jun	Jul Aug Sep Oct
	Winter	Spring	Summer

Base Flow Levels	High (75th %ile)
	Medium (50th %ile)
	Low (25th %ile)

Pulse volumes are in units of acre-feet and durations are in days.

Period of record used : 1/1/1925 to 12/31/2010.

Episodic events are terminated when the volume or duration criteria are met, or when the flow drops below 169 cfs, or when the flow is below 693 cfs and the flow drops from one day to the next by less than 5%.

March 29, 2005, 150 cfs – upstream (left), downstream (right)

5.2.7 Brazos River near Palo Pinto (continued)

July 20, 2005, 717 cfs – upstream (left), downstream (right)

October 17, 2007, 68 cfs – upstream (left), downstream (right)

5.2.8 Brazos River at Glen Rose

Overbank Events	Qp: 33,600 cfs with Average Frequency 1 per 2 years Regressed Volume is 327,000 Duration Bound is 29		
High Flow Pulses	Qp: 22,200 cfs with Average Frequency 1 per year Regressed Volume is 203,000 Duration Bound is 24		
	Qp: 3,230 cfs with Average Frequency 1 per season Regressed Volume is 22,600 Duration Bound is 13	Qp: 13,400 cfs with Average Frequency 1 per season Regressed Volume is 109,000 Duration Bound is 19	Qp: 7,760 cfs with Average Frequency 1 per season Regressed Volume is 62,500 Duration Bound is 17
	Qp: 1,700 cfs with Average Frequency 2 per season Regressed Volume is 10,800 Duration Bound is 10	Qp: 6,480 cfs with Average Frequency 2 per season Regressed Volume is 46,700 Duration Bound is 14	Qp: 3,090 cfs with Average Frequency 2 per season Regressed Volume is 21,200 Duration Bound is 12
	Qp: 930 cfs with Average Frequency 4 per season Regressed Volume is 5,400 Duration Bound is 8	Qp: 2,350 cfs with Average Frequency 4 per season Regressed Volume is 14,300 Duration Bound is 10	Qp: 1,320 cfs with Average Frequency 4 per season Regressed Volume is 7,830 Duration Bound is 8
Base Flows (cfs)	160	170	160
	77	92	70
	42	47	37
Subsistence Flows (cfs)	16	16	16
	Nov Dec Jan Feb	Mar Apr May Jun	Jul Aug Sep Oct
	Winter	Spring	Summer

Base Flow Levels	High (75th %ile)
	Medium (50th %ile)
	Low (25th %ile)

Pulse volumes are in units of acre-feet and durations are in days.

Period of record used : 1/1/1924 to 12/31/2010.

Episodic events are terminated when the volume or duration criteria are met, or when the flow drops below 180 cfs, or when the flow is below 920 cfs and the flow drops from one day to the next by less than 5%.

November 13, 2007, 44 cfs – upstream (left), downstream (right)

5.2.8 Brazos River at Glen Rose (continued)

January 22, 2006, 28 cfs – upstream (left), downstream (right)

May 10, 2007, HFP event 3,770 cfs – upstream (left), downstream (right)

5.2.9 North Bosque River at Clifton

<table>
<tr><td rowspan="7">High Flow Pulses</td><td colspan="12">Qp: 19,800 cfs with Average Frequency 1 per 5 years
Regressed Volume is 91,100
Duration Bound is 30</td></tr>
<tr><td colspan="12">Qp: 13,900 cfs with Average Frequency 1 per 2 years
Regressed Volume is 64,300
Duration Bound is 27</td></tr>
<tr><td colspan="12">Qp: 8,650 cfs with Average Frequency 1 per year
Regressed Volume is 40,300
Duration Bound is 24</td></tr>
<tr><td colspan="4">Qp: 1,490 cfs with Average Frequency 1 per season
Regressed Volume is 8,720
Duration Bound is 18</td><td colspan="4">Qp: 5,820 cfs with Average Frequency 1 per season
Regressed Volume is 25,900
Duration Bound is 19</td><td colspan="4">Qp: 1,080 cfs with Average Frequency 1 per season
Regressed Volume is 4,300
Duration Bound is 12</td></tr>
<tr><td colspan="4">Qp: 420 cfs with Average Frequency 2 per season
Regressed Volume is 2,500
Duration Bound is 13</td><td colspan="4">Qp: 2,170 cfs with Average Frequency 2 per season
Regressed Volume is 10,100
Duration Bound is 15</td><td colspan="4">Qp: 350 cfs with Average Frequency 2 per season
Regressed Volume is 1,380
Duration Bound is 8</td></tr>
<tr><td colspan="4">Qp: 120 cfs with Average Frequency 3 per season
Regressed Volume is 750
Duration Bound is 10</td><td colspan="4"></td><td colspan="4">Qp: 130 cfs with Average Frequency 3 per season
Regressed Volume is 500
Duration Bound is 6</td></tr>
<tr><td colspan="4"></td><td colspan="4">Qp: 710 cfs with Average Frequency 4 per season
Regressed Volume is 3,490
Duration Bound is 12</td><td colspan="4"></td></tr>
<tr><td rowspan="3">Base Flows (cfs)</td><td colspan="4">25</td><td colspan="4">33</td><td colspan="4">17</td></tr>
<tr><td colspan="4">12</td><td colspan="4">16</td><td colspan="4">8</td></tr>
<tr><td colspan="4">5</td><td colspan="4">7</td><td colspan="4">3</td></tr>
<tr><td>Subsistence Flows (cfs)</td><td colspan="4">1</td><td colspan="4">1</td><td colspan="4">1</td></tr>
<tr><td></td><td>Nov</td><td>Dec</td><td>Jan</td><td>Feb</td><td>Mar</td><td>Apr</td><td>May</td><td>Jun</td><td>Jul</td><td>Aug</td><td>Sep</td><td>Oct</td></tr>
<tr><td></td><td colspan="4">Winter</td><td colspan="4">Spring</td><td colspan="4">Summer</td></tr>
</table>

Base Flow Levels	High (75th %ile)
	Medium (50th %ile)
	Low (25th %ile)

Pulse volumes are in units of acre-feet and durations are in days.

Period of record used : 1/1/1924 to 12/31/2010.

Episodic events are terminated when the volume or duration criteria are met, or when the flow drops below 24 cfs, or when the flow is below 104 cfs and the flow drops from one day to the next by less than 5%.

February 22, 2005, 276 cfs – upstream (left), downstream (right)

5.2.9 North Bosque River at Clifton (continued)

January 3, 2006, 17 cfs – upstream (left), downstream (right)

July 5, 2006, 2.9 cfs – upstream (left), downstream (right)

5.2.10 Brazos River at Waco

Overbank Events	Qp: 42,600 cfs with Average Frequency 1 per 2 years Regressed Volume is 427,000 Duration Bound is 26		
High Flow Pulses	Qp: 30,800 cfs with Average Frequency 1 per year Regressed Volume is 288,000 Duration Bound is 22		
	Qp: 8,450 cfs with Average Frequency 1 per season Regressed Volume is 61,100 Duration Bound is 13	Qp: 23,500 cfs with Average Frequency 1 per season Regressed Volume is 197,000 Duration Bound is 18	Qp: 10,000 cfs with Average Frequency 1 per season Regressed Volume is 77,900 Duration Bound is 16
	Qp: 4,180 cfs with Average Frequency 2 per season Regressed Volume is 25,700 Duration Bound is 9	Qp: 13,600 cfs with Average Frequency 2 per season Regressed Volume is 102,000 Duration Bound is 14	Qp: 4,160 cfs with Average Frequency 2 per season Regressed Volume is 26,400 Duration Bound is 10
	Qp: 2,320 cfs with Average Frequency 4 per season Regressed Volume is 12,400 Duration Bound is 7	Qp: 5,330 cfs with Average Frequency 4 per season Regressed Volume is 32,700 Duration Bound is 10	Qp: 1,980 cfs with Average Frequency 4 per season Regressed Volume is 10,500 Duration Bound is 7
Base Flows (cfs)	480	690	590
	210	270	250
	120	150	140
Subsistence Flows (cfs)	56	56	56
	Nov Dec Jan Feb	Mar Apr May Jun	Jul Aug Sep Oct
	Winter	Spring	Summer

Base Flow Levels	High (75th %ile)
	Medium (50th %ile)
	Low (25th %ile)

Pulse volumes are in units of acre-feet and durations are in days.

Period of record used : 1/1/1900 to 12/31/2010.

Episodic events are terminated when the volume or duration criteria are met, or when the flow drops below 300 cfs, or when the flow is below 1960 cfs and the flow drops from one day to the next by less than 5%.

July 27, 2005, 130 cfs – upstream (left), downstream (right)

5.2.10 Brazos River at Waco (continued)

May 25, 2006, 202 cfs – upstream (left), downstream (right)

July 19, 2007, HFP event 28,300 cfs – upstream

5.2.11 Leon River near Gatesville

Overbank Events	Qp: 7,580 cfs with Average Frequency 1 per 2 years Regressed Volume is 80,200 Duration Bound is 39		
High Flow Pulses	Qp: 5,300 cfs with Average Frequency 1 per year Regressed Volume is 52,300 Duration Bound is 33		
	Qp: 1,010 cfs with Average Frequency 1 per season Regressed Volume is 7,160 Duration Bound is 16		
	Qp: 280 cfs with Average Frequency 2 per season Regressed Volume is 1,890 Duration Bound is 10	Qp: 1,390 cfs with Average Frequency 2 per season Regressed Volume is 10,600 Duration Bound is 18	Qp: 340 cfs with Average Frequency 2 per season Regressed Volume is 1,640 Duration Bound is 9
	Qp: 100 cfs with Average Frequency 3 per season Regressed Volume is 540 Duration Bound is 6	Qp: 630 cfs with Average Frequency 3 per season Regressed Volume is 4,050 Duration Bound is 13	Qp: 140 cfs with Average Frequency 3 per season Regressed Volume is 600 Duration Bound is 6
		Qp: 340 cfs with Average Frequency 4 per season Regressed Volume is 1,910 Duration Bound is 10	Qp: 58 cfs with Average Frequency 4 per season Regressed Volume is 220 Duration Bound is 4
Base Flows (cfs)	52	54	27
	20	24	12
	9	10	4
Subsistence Flows (cfs)	1	1	1
	Nov Dec Jan Feb	Mar Apr May Jun	Jul Aug Sep Oct
	Winter	Spring	Summer

Base Flow Levels	
	High (75th %ile)
	Medium (50th %ile)
	Low (25th %ile)

Pulse volumes are in units of acre-feet and durations are in days.

Period of record used : 1/1/1951 to 12/31/2010.

Episodic events are terminated when the volume or duration criteria are met, or when the flow drops below 43 cfs, or when the flow is below 225 cfs and the flow drops from one day to the next by less than 5%.

January 10, 2007, 3.3 cfs – upstream (left), downstream (right)

5.2.11 Leon River near Gatesville (continued)

April 17, 2007, 122 cfs – upstream (left), downstream (right)

5.2.12 Lampasas River near Kempner

High Flow Pulses	Qp: 13,000 cfs with Average Frequency 1 per 5 years Regressed Volume is 77,000 Duration Bound is 38		
	Qp: 7,960 cfs with Average Frequency 1 per 2 years Regressed Volume is 46,000 Duration Bound is 32		
	Qp: 4,690 cfs with Average Frequency 1 per year Regressed Volume is 26,300 Duration Bound is 26		
	Qp: 740 cfs with Average Frequency 1 per season Regressed Volume is 4,990 Duration Bound is 18	Qp: 2,650 cfs with Average Frequency 1 per season Regressed Volume is 14,000 Duration Bound is 20	Qp: 540 cfs with Average Frequency 1 per season Regressed Volume is 2,040 Duration Bound is 9
	Qp: 190 cfs with Average Frequency 2 per season Regressed Volume is 1,150 Duration Bound is 11	Qp: 1,310 cfs with Average Frequency 2 per season Regressed Volume is 6,860 Duration Bound is 16	Qp: 190 cfs with Average Frequency 2 per season Regressed Volume is 680 Duration Bound is 6
	Qp: 78 cfs with Average Frequency 3 per season Regressed Volume is 430 Duration Bound is 8	Qp: 780 cfs with Average Frequency 3 per season Regressed Volume is 4,020 Duration Bound is 13	Qp: 77 cfs with Average Frequency 3 per season Regressed Volume is 270 Duration Bound is 4
Base Flows (cfs)	39	43	32
	27	29	23
	18	21	16
Subsistence Flows (cfs)	10	10	10
	Nov Dec Jan Feb	Mar Apr May Jun	Jul Aug Sep Oct
	Winter	Spring	Summer

Base Flow Levels	
	High (75th %ile)
	Medium (50th %ile)
	Low (25th %ile)

Pulse volumes are in units of acre-feet and durations are in days.

Period of record used : 1/1/1963 to 12/31/2010.

Episodic events are terminated when the volume or duration criteria are met, or when the flow drops below 40 cfs, or when the flow is below 96 cfs and the flow drops from one day to the next by less than 5%.

October 11, 2006, 21 cfs – upstream (left), downstream (right)

5.2.12 Lampasas River near Kempner (continued)

April 17, 2007, 133 cfs – upstream (left), downstream (right)

July 3, 2007, HFP event 10,700 cfs – upstream (left), downstream (right)

5.2.13 Little River at Little River

	Winter	Spring	Summer
Overbank Events	Qp: 11,700 cfs with Average Frequency 1 per 5 years Regressed Volume is 198,000 Duration Bound is 38		
High Flow Pulses	Qp: 8,890 cfs with Average Frequency 1 per 2 years Regressed Volume is 134,000 Duration Bound is 32		
	Qp: 6,740 cfs with Average Frequency 1 per year Regressed Volume is 89,800 Duration Bound is 27		
	Qp: 2,960 cfs with Average Frequency 1 per season Regressed Volume is 28,300 Duration Bound is 17	Qp: 5,310 cfs with Average Frequency 1 per season Regressed Volume is 63,400 Duration Bound is 23	Qp: 2,470 cfs with Average Frequency 1 per season Regressed Volume is 20,300 Duration Bound is 13
	Qp: 1,600 cfs with Average Frequency 2 per season Regressed Volume is 11,800 Duration Bound is 11	Qp: 3,290 cfs with Average Frequency 2 per season Regressed Volume is 32,200 Duration Bound is 17	Qp: 1,060 cfs with Average Frequency 2 per season Regressed Volume is 5,890 Duration Bound is 8
	Qp: 520 cfs with Average Frequency 4 per season Regressed Volume is 2,350 Duration Bound is 5	Qp: 1,420 cfs with Average Frequency 4 per season Regressed Volume is 9,760 Duration Bound is 10	Qp: 430 cfs with Average Frequency 4 per season Regressed Volume is 1,560 Duration Bound is 4
Base Flows (cfs)	190	340	200
	110	150	120
	82	95	84
Subsistence Flows (cfs)	55	55	55
	Nov Dec Jan Feb	Mar Apr May Jun	Jul Aug Sep Oct
	Winter	Spring	Summer

Base Flow Levels	
	High (75th %ile)
	Medium (50th %ile)
	Low (25th %ile)

Pulse volumes are in units of acre-feet and durations are in days.

Period of record used : 1/1/1963 to 12/31/2010.

Episodic events are terminated when the volume or duration criteria are met, or when the flow drops below 242 cfs, or when the flow is below 1110 cfs and the flow drops from one day to the next by less than 5%.

No photos available.

5.2.14 Little River near Cameron

<table>
<tr><td>Overbank Events</td><td colspan="12">Qp: 29,900 cfs with Average Frequency 1 per 2 years
Regressed Volume is 324,000
Duration Bound is 29</td></tr>
<tr><td rowspan="5">High Flow Pulses</td><td colspan="12">Qp: 19,700 cfs with Average Frequency 1 per year
Regressed Volume is 198,000
Duration Bound is 24</td></tr>
<tr><td colspan="4">Qp: 9,550 cfs with Average Frequency 1 per season
Regressed Volume is 85,600
Duration Bound is 19</td><td colspan="4">Qp: 12,800 cfs with Average Frequency 1 per season
Regressed Volume is 121,000
Duration Bound is 20</td><td colspan="4">Qp: 4,800 cfs with Average Frequency 1 per season
Regressed Volume is 35,300
Duration Bound is 14</td></tr>
<tr><td colspan="4">Qp: 4,630 cfs with Average Frequency 2 per season
Regressed Volume is 36,700
Duration Bound is 14</td><td colspan="4">Qp: 7,550 cfs with Average Frequency 2 per season
Regressed Volume is 65,400
Duration Bound is 17</td><td colspan="4">Qp: 2,070 cfs with Average Frequency 2 per season
Regressed Volume is 13,200
Duration Bound is 10</td></tr>
<tr><td colspan="4">Qp: 2,140 cfs with Average Frequency 3 per season
Regressed Volume is 14,900
Duration Bound is 10</td><td colspan="4">Qp: 4,790 cfs with Average Frequency 3 per season
Regressed Volume is 38,400
Duration Bound is 14</td><td colspan="4">Qp: 990 cfs with Average Frequency 3 per season
Regressed Volume is 5,550
Duration Bound is 8</td></tr>
<tr><td colspan="4">Qp: 1,080 cfs with Average Frequency 4 per season
Regressed Volume is 6,680
Duration Bound is 8</td><td colspan="4">Qp: 3,200 cfs with Average Frequency 4 per season
Regressed Volume is 23,900
Duration Bound is 12</td><td colspan="4">Qp: 560 cfs with Average Frequency 4 per season
Regressed Volume is 2,860
Duration Bound is 6</td></tr>
<tr><td rowspan="3">Base Flows (cfs)</td><td colspan="4">460</td><td colspan="4">760</td><td colspan="4">330</td></tr>
<tr><td colspan="4">190</td><td colspan="4">310</td><td colspan="4">160</td></tr>
<tr><td colspan="4">110</td><td colspan="4">140</td><td colspan="4">97</td></tr>
<tr><td>Subsistence Flows (cfs)</td><td colspan="4">32</td><td colspan="4">32</td><td colspan="4">32</td></tr>
<tr><td></td><td>Nov</td><td>Dec</td><td>Jan</td><td>Feb</td><td>Mar</td><td>Apr</td><td>May</td><td>Jun</td><td>Jul</td><td>Aug</td><td>Sep</td><td>Oct</td></tr>
<tr><td></td><td colspan="4">Winter</td><td colspan="4">Spring</td><td colspan="4">Summer</td></tr>
</table>

Base Flow Levels	High (75th %ile)
	Medium (50th %ile)
	Low (25th %ile)

Pulse volumes are in units of acre-feet and durations are in days.

Period of record used : 1/1/1917 to 12/31/2010.

Episodic events are terminated when the volume or duration criteria are met, or when the flow drops below 190 cfs, or when the flow is below 1730 cfs and the flow drops from one day to the next by less than 5%.

January 31, 2006, 299 cfs – upstream (left), downstream (right)

5.2.15 Brazos River near Bryan

Overbank Events	Qp: 66,900 cfs with Average Frequency 1 per 2 years Regressed Volume is 989,000 Duration Bound is 35		
	Qp: 49,400 cfs with Average Frequency 1 per year Regressed Volume is 675,000 Duration Bound is 30		
High Flow Pulses	Qp: 22,600 cfs with Average Frequency 1 per season Regressed Volume is 243,000 Duration Bound is 20	Qp: 32,900 cfs with Average Frequency 1 per season Regressed Volume is 421,000 Duration Bound is 25	Qp: 12,100 cfs with Average Frequency 1 per season Regressed Volume is 114,000 Duration Bound is 16
	Qp: 11,200 cfs with Average Frequency 2 per season Regressed Volume is 100,000 Duration Bound is 14	Qp: 17,800 cfs with Average Frequency 2 per season Regressed Volume is 193,000 Duration Bound is 18	Qp: 5,000 cfs with Average Frequency 2 per season Regressed Volume is 38,100 Duration Bound is 10
	Qp: 5,570 cfs with Average Frequency 3 per season Regressed Volume is 41,900 Duration Bound is 10	Qp: 10,400 cfs with Average Frequency 3 per season Regressed Volume is 97,000 Duration Bound is 14	Qp: 2,990 cfs with Average Frequency 3 per season Regressed Volume is 20,100 Duration Bound is 8
	Qp: 3,230 cfs with Average Frequency 4 per season Regressed Volume is 21,100 Duration Bound is 7	Qp: 6,050 cfs with Average Frequency 4 per season Regressed Volume is 49,000 Duration Bound is 11	Qp: 2,060 cfs with Average Frequency 4 per season Regressed Volume is 12,700 Duration Bound is 7
Base Flows (cfs)	1,760	2,460	1,470
	860	1,260	920
	540	710	630
Subsistence Flows (cfs)	300	300	300
	Nov Dec Jan Feb	Mar Apr May Jun	Jul Aug Sep Oct
	Winter	Spring	Summer

Base Flow Levels	High (75th %ile)
	Medium (50th %ile)
	Low (25th %ile)

Pulse volumes are in units of acre-feet and durations are in days.

Period of record used : 1/1/1928 to 12/31/2010.

Episodic events are terminated when the volume or duration criteria are met, or when the flow drops below 833 cfs, or when the flow is below 5080 cfs and the flow drops from one day to the next by less than 5%.

June 4, 2009, 278 cfs (left); June 20, 2010, 2,640 cfs (right)

5.2.15 Brazos River near Bryan (continued)

Arial view – Moehlman’s Slough oxbow in Brazos floodplain (left), Big Bend oxbow (right)

5.2.16 Navasota River near Easterly

	Winter	Spring	Summer
Overbank Events	Qp: 16,700 cfs with Average Frequency 1 per 2 years Regressed Volume is 142,000 Duration Bound is 30		
	Qp: 10,800 cfs with Average Frequency 1 per year Regressed Volume is 88,500 Duration Bound is 26		
High Flow Pulses	Qp: 4,390 cfs with Average Frequency 1 per season Regressed Volume is 34,300 Duration Bound is 21	Qp: 5,470 cfs with Average Frequency 1 per season Regressed Volume is 41,100 Duration Bound is 19	Qp: 410 cfs with Average Frequency 1 per season Regressed Volume is 2,340 Duration Bound is 10
	Qp: 1,700 cfs with Average Frequency 2 per season Regressed Volume is 12,300 Duration Bound is 16	Qp: 2,380 cfs with Average Frequency 2 per season Regressed Volume is 16,700 Duration Bound is 15	Qp: 120 cfs with Average Frequency 2 per season Regressed Volume is 580 Duration Bound is 7
	Qp: 800 cfs with Average Frequency 3 per season Regressed Volume is 5,440 Duration Bound is 12	Qp: 1,340 cfs with Average Frequency 3 per season Regressed Volume is 8,990 Duration Bound is 13	Qp: 49 cfs with Average Frequency 3 per season Regressed Volume is 220 Duration Bound is 5
	Qp: 260 cfs with Average Frequency 4 per season Regressed Volume is 1,610 Duration Bound is 9	Qp: 720 cfs with Average Frequency 4 per season Regressed Volume is 4,590 Duration Bound is 11	
Base Flows (cfs)	23	29	16
	14	19	8
	9	10	3
Subsistence Flows (cfs)	1	1	1
	Nov Dec Jan Feb	Mar Apr May Jun	Jul Aug Sep Oct
	Winter	Spring	Summer

Base Flow Levels	
	High (75th %ile)
	Medium (50th %ile)
	Low (25th %ile)

Pulse volumes are in units of acre-feet and durations are in days.

Period of record used : 1/1/1925 to 12/31/2010.

Episodic events are terminated when the volume or duration criteria are met, or when the flow drops below 27 cfs, or when the flow is below 108 cfs and the flow drops from one day to the next by less than 5%.

November 9, 2005, 14 cfs – upstream (left), downstream (right)

5.2.16 Navasota River near Easterly (continued)

November 9, 2005, 11 cfs – upstream (left), downstream (right)

February 2, 2006, HFP event 801 cfs – upstream (left), downstream (right)

5.2.17 Brazos River near Hempstead

Overbank Events	Qp: 63,900 cfs with Average Frequency 1 per 2 years Regressed Volume is 1,331,000 Duration Bound is 40		
High Flow Pulses	Qp: 50,000 cfs with Average Frequency 1 per year Regressed Volume is 952,000 Duration Bound is 35		
	Qp: 24,800 cfs with Average Frequency 1 per season Regressed Volume is 368,000 Duration Bound is 23	Qp: 34,200 cfs with Average Frequency 1 per season Regressed Volume is 589,000 Duration Bound is 29	Qp: 10,300 cfs with Average Frequency 1 per season Regressed Volume is 104,000 Duration Bound is 14
	Qp: 11,200 cfs with Average Frequency 2 per season Regressed Volume is 125,000 Duration Bound is 15	Qp: 16,800 cfs with Average Frequency 2 per season Regressed Volume is 219,000 Duration Bound is 19	Qp: 5,090 cfs with Average Frequency 2 per season Regressed Volume is 40,900 Duration Bound is 9
	Qp: 5,720 cfs with Average Frequency 3 per season Regressed Volume is 49,800 Duration Bound is 10	Qp: 8,530 cfs with Average Frequency 3 per season Regressed Volume is 85,000 Duration Bound is 13	Qp: 2,620 cfs with Average Frequency 3 per season Regressed Volume is 17,000 Duration Bound is 7
Base Flows (cfs)	2,890	3,440	2,050
	1,440	1,900	1,330
	920	1,130	950
Subsistence Flows (cfs)	510	510	510
	Nov Dec Jan Feb	Mar Apr May Jun	Jul Aug Sep Oct
	Winter	Spring	Summer

Base Flow Levels	High (75th %ile)
	Medium (50th %ile)
	Low (25th %ile)

Pulse volumes are in units of acre-feet and durations are in days.
Period of record used : 1/1/1939 to 12/31/2010.
Episodic events are terminated when the volume or duration criteria are met, or when the flow drops below 1200 cfs, or when the flow is below 7680 cfs and the flow drops from one day to the next by less than 5%.

August 4, 2005, 965 cfs (left); November 10, 2005 1,060 cfs (right) – upstream

5.2.17 Brazos River near Hempstead (continued)

December 20, 2006, 506 cfs (left); July 19, 2007, Overbank event 74,700 cfs (right)

March 29, 2007, HFP event 30,500 cfs (left); September 20, 2007, HFP event 14,300 cfs (right)

5.2.18 Brazos River near Richmond

<table>
<tr><td>Overbank Events</td><td colspan="12">Qp: 68,100 cfs with Average Frequency 1 per 2 years
Regressed Volume is 1,487,000
Duration Bound is 41</td></tr>
<tr><td rowspan="4">High Flow Pulses</td><td colspan="12">Qp: 51,600 cfs with Average Frequency 1 per year
Regressed Volume is 1,019,000
Duration Bound is 35</td></tr>
<tr><td colspan="4">Qp: 24,600 cfs with Average Frequency 1 per season
Regressed Volume is 383,000
Duration Bound is 23</td><td colspan="4">Qp: 35,000 cfs with Average Frequency 1 per season
Regressed Volume is 617,000
Duration Bound is 29</td><td colspan="4">Qp: 12,900 cfs with Average Frequency 1 per season
Regressed Volume is 144,000
Duration Bound is 15</td></tr>
<tr><td colspan="4">Qp: 12,400 cfs with Average Frequency 2 per season
Regressed Volume is 150,000
Duration Bound is 16</td><td colspan="4">Qp: 16,300 cfs with Average Frequency 2 per season
Regressed Volume is 215,000
Duration Bound is 19</td><td colspan="4">Qp: 5,430 cfs with Average Frequency 2 per season
Regressed Volume is 46,300
Duration Bound is 10</td></tr>
<tr><td colspan="4">Qp: 6,410 cfs with Average Frequency 3 per season
Regressed Volume is 60,600
Duration Bound is 11</td><td colspan="4">Qp: 8,930 cfs with Average Frequency 3 per season
Regressed Volume is 94,000
Duration Bound is 13</td><td colspan="4">Qp: 2,460 cfs with Average Frequency 3 per season
Regressed Volume is 16,400
Duration Bound is 6</td></tr>
<tr><td rowspan="3">Base Flows (cfs)</td><td colspan="4">3,310</td><td colspan="4">3,980</td><td colspan="4">2,190</td></tr>
<tr><td colspan="4">1,650</td><td colspan="4">2,140</td><td colspan="4">1,330</td></tr>
<tr><td colspan="4">990</td><td colspan="4">1,190</td><td colspan="4">930</td></tr>
<tr><td>Subsistence Flows (cfs)</td><td colspan="4">550</td><td colspan="4">550</td><td colspan="4">550</td></tr>
<tr><td></td><td>Nov</td><td>Dec</td><td>Jan</td><td>Feb</td><td>Mar</td><td>Apr</td><td>May</td><td>Jun</td><td>Jul</td><td>Aug</td><td>Sep</td><td>Oct</td></tr>
<tr><td></td><td colspan="4">Winter</td><td colspan="4">Spring</td><td colspan="4">Summer</td></tr>
</table>

Base Flow Levels	High (75th %ile)
	Medium (50th %ile)
	Low (25th %ile)

Pulse volumes are in units of acre-feet and durations are in days.

Period of record used : 1/1/1923 to 12/31/2010.

Episodic events are terminated when the volume or duration criteria are met, or when the flow drops below 1260 cfs, or when the flow is below 8430 cfs and the flow drops from one day to the next by less than 5%.

September 20, 2007, HFP event 15,600 cfs – upstream (left), downstream (right)

5.2.18 Brazos River near Richmond (continued)

December 19, 2007, Receding HFP event 5,910 cfs – upstream (left), downstream (right)

5.2.19 Brazos River at Rosharon

	Winter	Spring	Summer
Overbank Events	Qp: 60,900 cfs with Average Frequency 1 per 2 years Regressed Volume is 1,463,000 Duration Bound is 42		
High Flow Pulses	Qp: 51,000 cfs with Average Frequency 1 per year Regressed Volume is 1,133,000 Duration Bound is 38		
	Qp: 25,700 cfs with Average Frequency 1 per season Regressed Volume is 415,000 Duration Bound is 23	Qp: 33,700 cfs with Average Frequency 1 per season Regressed Volume is 665,000 Duration Bound is 31	Qp: 13,300 cfs with Average Frequency 1 per season Regressed Volume is 153,000 Duration Bound is 16
	Qp: 13,600 cfs with Average Frequency 2 per season Regressed Volume is 168,000 Duration Bound is 16	Qp: 14,200 cfs with Average Frequency 2 per season Regressed Volume is 184,000 Duration Bound is 18	Qp: 4,980 cfs with Average Frequency 2 per season Regressed Volume is 39,100 Duration Bound is 9
	Qp: 9,090 cfs with Average Frequency 3 per season Regressed Volume is 94,700 Duration Bound is 12	Qp: 6,580 cfs with Average Frequency 3 per season Regressed Volume is 58,500 Duration Bound is 10	Qp: 2,490 cfs with Average Frequency 3 per season Regressed Volume is 14,900 Duration Bound is 6
Base Flows (cfs)	4,700	4,740	2,630
	2,090	2,570	1,420
	1,140	1,250	930
Subsistence Flows (cfs)	430	430	430
	Nov Dec Jan Feb	Mar Apr May Jun	Jul Aug Sep Oct
	Winter	Spring	Summer

Base Flow Levels	
	High (75th %ile)
	Medium (50th %ile)
	Low (25th %ile)

Pulse volumes are in units of acre-feet and durations are in days.

Period of record used : 1/1/1972 to 12/31/2010.

Episodic events are terminated when the volume or duration criteria are met, or when the flow drops below 1310 cfs, or when the flow is below 9850 cfs and the flow drops from one day to the next by less than 5%.

February 23, 2005, HFP event 10,800 cfs (left); July 19, 2007, overbank event 60,000 cfs (right)

5.2.19 Brazos River at Rosharon (continued)

December 20, 2006, 838 cfs – upstream (left), downstream (right)

September 20, 2007, HFP event 14,700 cfs – upstream (left), downstream (right)

5.2.20 San Bernard River near Boling

<table>
<tr><td rowspan="2">Overbank Events</td><td colspan="12">Qp: 8,820 cfs with Average Frequency 1 per 2 years
Regressed Volume is 123,000
Duration Bound is 32</td></tr>
<tr><td colspan="12">Qp: 6,110 cfs with Average Frequency 1 per year
Regressed Volume is 79,200
Duration Bound is 27</td></tr>
<tr><td rowspan="4">High Flow Pulses</td><td colspan="4">Qp: 3,310 cfs with Average Frequency 1 per season
Regressed Volume is 39,400
Duration Bound is 21</td><td colspan="4">Qp: 3,220 cfs with Average Frequency 1 per season
Regressed Volume is 36,100
Duration Bound is 20</td><td colspan="4">Qp: 2,330 cfs with Average Frequency 1 per season
Regressed Volume is 25,000
Duration Bound is 19</td></tr>
<tr><td colspan="4">Qp: 1,940 cfs with Average Frequency 2 per season
Regressed Volume is 20,100
Duration Bound is 16</td><td colspan="4">Qp: 1,570 cfs with Average Frequency 2 per season
Regressed Volume is 14,900
Duration Bound is 14</td><td colspan="4">Qp: 780 cfs with Average Frequency 2 per season
Regressed Volume is 7,250
Duration Bound is 13</td></tr>
<tr><td colspan="4">Qp: 1,060 cfs with Average Frequency 3 per season
Regressed Volume is 9,370
Duration Bound is 12</td><td colspan="4">Qp: 680 cfs with Average Frequency 3 per season
Regressed Volume is 5,300
Duration Bound is 10</td><td colspan="4">Qp: 470 cfs with Average Frequency 3 per season
Regressed Volume is 4,050
Duration Bound is 10</td></tr>
<tr><td colspan="4">Qp: 510 cfs with Average Frequency 4 per season
Regressed Volume is 3,710
Duration Bound is 8</td><td colspan="4">Qp: 350 cfs with Average Frequency 4 per season
Regressed Volume is 2,360
Duration Bound is 7</td><td colspan="4">Qp: 300 cfs with Average Frequency 4 per season
Regressed Volume is 2,480
Duration Bound is 9</td></tr>
<tr><td rowspan="3">Base Flows (cfs)</td><td colspan="4">73</td><td colspan="4">85</td><td colspan="4">140</td></tr>
<tr><td colspan="4">43</td><td colspan="4">53</td><td colspan="4">98</td></tr>
<tr><td colspan="4">23</td><td colspan="4">32</td><td colspan="4">64</td></tr>
<tr><td>Subsistence Flows (cfs)</td><td colspan="4">11</td><td colspan="4">11</td><td colspan="4">11</td></tr>
<tr><td></td><td>Nov</td><td>Dec</td><td>Jan</td><td>Feb</td><td>Mar</td><td>Apr</td><td>May</td><td>Jun</td><td>Jul</td><td>Aug</td><td>Sep</td><td>Oct</td></tr>
<tr><td></td><td colspan="4">Winter</td><td colspan="4">Spring</td><td colspan="4">Summer</td></tr>
</table>

Base Flow Levels	
Base Flow Levels	High (75th %ile)
	Medium (50th %ile)
	Low (25th %ile)

Pulse volumes are in units of acre-feet and durations are in days.

Period of record used : 1/1/1955 to 12/31/2010.

Episodic events are terminated when the volume or duration criteria are met, or when the flow drops below 120 cfs, or when the flow is below 367 cfs and the flow drops from one day to the next by less than 5%.

July 26, 2011, 37 cfs

5.3 Estuarine Inflows

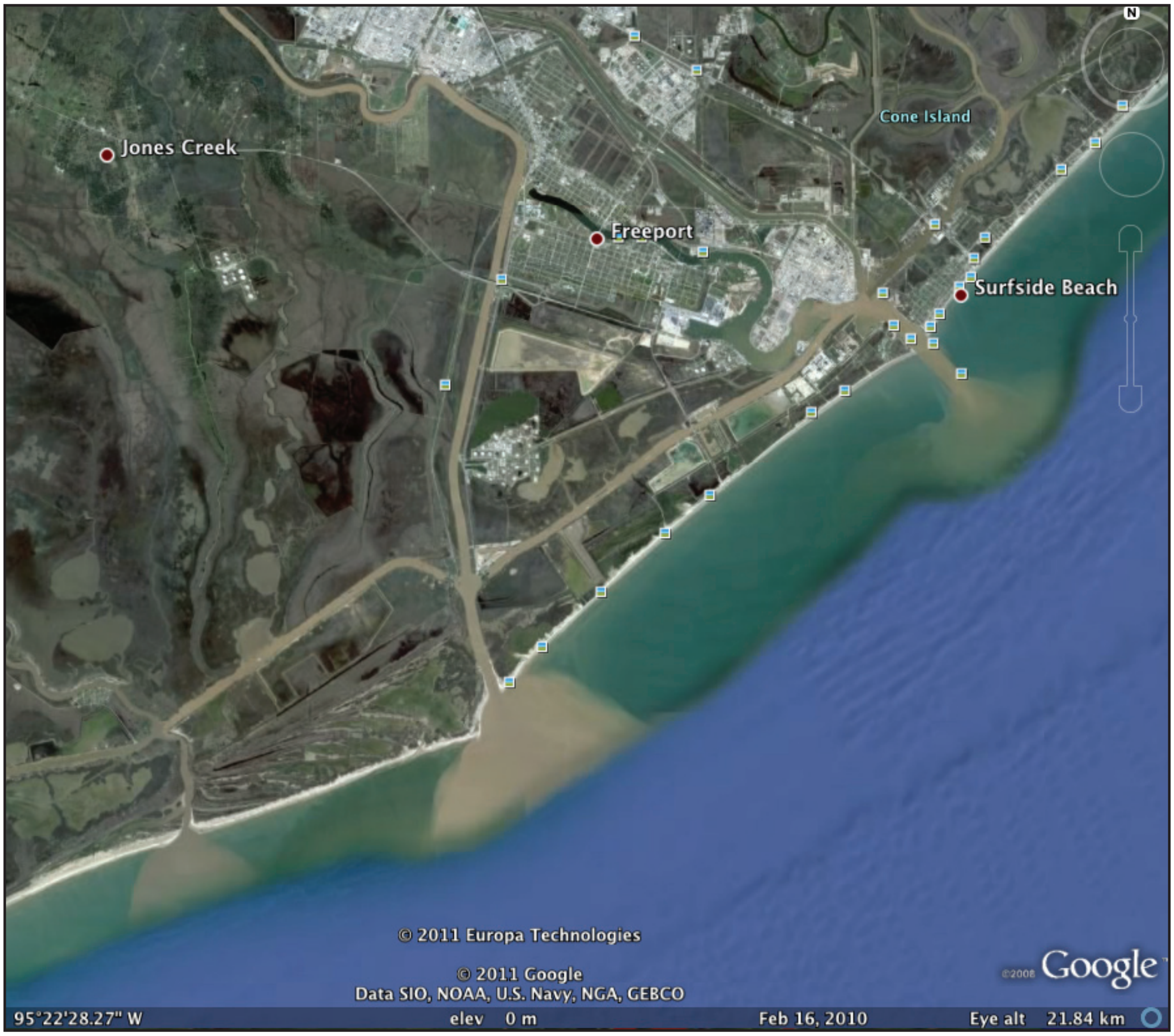


Figure. 5.1. *Google Earth* image of the mouth of the Brazos River near Freeport, Texas. On this date (February 16, 2010), the river was discharging plumes of sediment into the Gulf of Mexico. In addition to water that enters the Gulf via the main estuarine outlet in the delta (seen in the center of the image), smaller volumes water discharges from the Brazos estuary via the Intracoastal Waterway via outlets located to the northeast (near Surfside Beach in upper right corner) and to the southwest (lower left corner).

Estuarine ecological needs were not *directly* estimated during our initial assessment of environmental flow regimes based on IHA flow components separation and HEFR-derived matrices. Our reasoning was as follows:

1. Virtually no site-specific information was available regarding ecological dynamics of the Brazos and San Bernard estuaries and adjacent coastal wetlands in response to variation in flow.

2. Consequently, we made an initial assumption that environmental flows that would satisfy the needs of the instream freshwater and riparian ecological components within the Study Area would, in turn, support requirements to maintain a sound estuarine ecosystem. This assumption was considered reasonable, particularly in light of the very limited extent of the Brazos and San Bernard estuaries when compared with other Texas estuarine/bay systems. Both of these estuaries can be classified as *riverine estuaries* in contrast to the *lagoon-type estuaries* (shallow bays) that dominate the Texas coast. Due to their dynamic nature and riverine geomorphology, the Brazos and San Bernard estuaries provide a longitudinal continuum of habitats used by both freshwater and estuarine organisms.

3. Hence, evaluation of estuarine inflow needs was restricted to post hoc analyses of our recommended environmental flow regimes for the lower Brazos River at Richmond and San Bernard River at Boling plus flow data for small, independent coastal drainages (see Section 7.3). In the case of the lower Brazos River, these instream flows were translated into monthly freshwater inflows, using statistical models, and compared to historical inflow data.

4. Given the valuable natural resources within these estuaries, the major concerns of our estuarine analysis were to: 1) maintain sufficient variability in freshwater inflow to insure natural fluctuations in salinity that can support the needs of diverse estuarine organisms in the lower river and associated estuary; 2) support nutrient transport to maintain estuarine and nearshore Gulf of Mexico productivity; and 3) maintain sufficient sediment supply to form and maintain the delta.

5. In the case of the Brazos River estuary, with the exception of the *E-flow only* scenario, simulated project scenarios (see Section 7.3) did not appear to deviate significantly from historical freshwater inflow patterns when viewed on a monthly or seasonal time scale. There is concern that sediment transport necessary for maintenance of the delta landform would be insufficient under the *E-flow only* scenario. This conclusion is based in part on estimated reductions in sediment transport based on analyses for the Richmond gage.

6 Implementation Rules for Flow Regime Recommendations

6.1 Subsistence Flows

It is the consensus of the Brazos BBEST that environmental flow standards and permit conditions should not result in more frequent occurrences of flows at the recommended subsistence values as a result of the issuance of new surface water appropriations or amendments. Recognizing ecological risks associated with potential increases in the frequency of flow occurrences near the subsistence level, the Brazos BBEST further recommends that 50 percent of the difference between daily flow and the recommended subsistence flow be passed when inflows are between the specified seasonal base low flow and subsistence values under dry hydrologic conditions.

6.2 Base Flows

Base flows represent the normal streamflow conditions between storm events. Hydrologic conditions, as defined in Section 3.3.3, are applicable when the mean daily streamflow is less than the lowest applicable pulse peak flow in the same season or when all pulse recommendations have been satisfied. If the mean daily streamflow is less than the lowest applicable pulse peak trigger flow and greater than the seasonal base flow for the current hydrologic condition, then only the seasonal base flow must be passed, and the remaining balance may be impounded or diverted to the extent available, subject to senior water rights.

Under dry hydrologic conditions, if the mean daily streamflow is less than the seasonal base flow and greater than the subsistence flow, then 50 percent of the difference between streamflow and the recommended subsistence flow should be passed.

Under average and wet hydrologic conditions, if the mean daily streamflow is less than the seasonal base flow, then all streamflow must be passed, and none may be impounded or diverted.

6.3 High Flow Pulses

The high flow pulse is a short-duration, within-channel, high flow event following a storm event. High flow pulses maintain important physical habitat features and provide longitudinal connectivity along the river channel. High flow pulses also provide lateral connectivity between aquatic habitats in the main channel and aquatic habitats in floodplains, such as oxbow lakes and ephemeral pools. The largest high flow pulse events may result in overbank flows that exceed the channel capacity. While obviously undesirable in settings with human infrastructure located in floodplains, overbank events nonetheless maintain riparian habitats and ecological communities and provide greater lateral connectivity between the river channel and aquatic habitats within the active floodplain.

A qualifying high flow pulse or overbank event is initiated when flow exceeds the prescribed pulse peak trigger flow (i.e. pulse peak flow magnitude). Qualifying events are counted in the season or year in which they begin and are assumed to continue into the following season or year as necessary to meet prescribed high flow pulse characteristics.

If, during a qualifying event at one magnitude, flows increase to a magnitude that exceeds a greater magnitude event trigger, the pulse recommendations of the higher qualifying pulse control passage of the flows. In this case, the higher magnitude event is considered to satisfy any and all lower magnitude events in the same season. For example, if the streamflow during a two-per-season event increases and exceeds the one-per-year event target, then the one-per-year flow recommendations (i.e., volume and duration) control the passage of flow during the remainder of the high flow pulse event. The one-per-year event also would count for the smaller two-per-season event.

The qualifying event continues (which means flows are passed up to that trigger magnitude) until one of the following conditions identifies its termination:

- The prescribed volume is passed;
- The mean daily streamflow recedes to less than or equal to *minimum flow for pulse flows* as defined in Section 3.3.4 and summarized for each focal reach in Table 6.1;
- The prescribed duration is met; or
- The mean daily streamflow recedes to less than or equal to *maximum flow for base flows* and decreases by 5 percent or less in a day. The *maximum flow for base flows* is defined in Section 3.3.4 and summarized for each focal reach in Table 6.2.

Table 6.1. Minimum flow to define a high flow pulse event at the 20 focal reaches.

Focal Stream Reach	Minimum Flow for Pulse Flows (cfs)
DMF Brazos Rv nr Aspermont, TX	8
Salt Fk Brazos Rv nr Aspermont, TX	6
Brazos Rv at Seymour, TX	42
Clear Fk Brazos Rv at Nugent, TX	6
Clear Fk Brazos Rv at Ft Griffin, TX	6
Brazos Rv nr South Bend, TX	115
Brazos Rv nr Palo Pinto, TX	169
Brazos Rv nr Glen Rose, TX	180
N Bosque Rv nr Clifton, TX	24
Brazos Rv at Waco, TX	300
Leon Rv at Gatesville, TX	43
Lampasas Rv nr Kempner, TX	40
Little Rv nr Little River, TX	242
Little Rv nr Cameron, TX	190
Brazos Rv at SH 21 nr Bryan, TX	833
Navasota Rv nr Easterly, TX	27
Brazos Rv nr Hempstead, TX	1,200
Brazos Rv at Richmond, TX	1,260
Brazos Rv nr Rosharon, TX	1,310
San Bernard Rv nr Boling, TX	120

If all applicable pulse recommendations have been satisfied and inflow is greater than the seasonal base flow value for the current hydrologic condition, then that seasonal base flow value must be passed and the balance may be impounded or diverted to the extent available, subject to senior water rights.

Table 6.2. Maximum flow for defining base flows at the 20 focal reaches.

Focal Stream Reach	Maximum Flow for Base Flows (cfs)
DMF Brazos Rv nr Aspermont, TX	45
Salt Fk Brazos Rv nr Aspermont, TX	28
Brazos Rv at Seymour, TX	152
Clear Fk Brazos Rv at Nugent, TX	29
Clear Fk Brazos Rv at Ft Griffin, TX	73
Brazos Rv nr South Bend, TX	388
Brazos Rv nr Palo Pinto, TX	693
Brazos Rv nr Glen Rose, TX	920
N Bosque Rv nr Clifton, TX	104
Brazos Rv at Waco, TX	1,960
Leon Rv at Gatesville, TX	225
Lampasas Rv nr Kempner, TX	96
Little Rv nr Little River, TX	1,110
Little Rv nr Cameron, TX	1,730
Brazos Rv at SH 21 nr Bryan, TX	5,080
Navasota Rv nr Easterly, TX	108
Brazos Rv nr Hempstead, TX	7,680
Brazos Rv at Richmond, TX	8,430
Brazos Rv nr Rosharon, TX	9,850
San Bernard Rv nr Boling, TX	367

7 Testing Flow Regimes under Simulated Project Scenarios for Selected Reaches

7.1 Geomorphology Overlay

This section presents results of an analysis, often referred to as a "geomorphology overlay," which was completed for the Brazos BBEST by the Texas Water Development Board (TWDB December 22, 2011).

The channel shape (geometry or bathymetry) of an alluvial river adjusts in response to the range of flows that mobilize the boundary sediments. When viewed over the long term, virtually all rivers and streams undergo natural changes in channel morphology and the position of the channel in the landscape. However, when considered over shorter time scales, a relatively stable channel configuration can maintain specific habitat conditions used by biota. An environmental flow regime is successful when aquatic habitats are maintained for the biota over both short-term and long-term time scales. Changes in the flow regime can cause subsequent changes in channel geometry as rates of sediment transported into, deposited within, and transported out of a river reach modify the continuity of sediment movement through the reach.

Natural hydrologic variation results in channel morphology and position constantly changing to some degree as a river channel adjusts to changes in flows and the sediment transported into the reach. Consequently, a "stable channel" exhibits what river engineers call "dynamic equilibrium," with the river channel exhibiting continual adjustment to the natural hydrologic variation it experiences. When dynamic equilibrium is disrupted by large, long-term changes in flow regime or sediment supply, the channel will be unstable while channel forming processes work to reestablish equilibrium by changing the channel geometry (width, depth, and sinuosity) and slope (Schumm 1969). Changes to flow regime or sediment supply can result from changes in land use (urbanization, agricultural management, and land clearing), water resources management (diversions, reservoir construction, wastewater effluent, and stormwater discharges), and climatic variation.

When significant changes to a river's flow regime are proposed, a geomorphic analysis should be conducted to determine if the proposed regime can be expected to maintain the current channel shape. The need for performing such a geomorphic analysis is discussed in the Science Advisory Committee (SAC) guidance document "Fluvial Sediment Transport as an Overlay to Instream Flow Recommendations for the Environmental Flows Allocation Process" (SAC 2009/4) and Addendum (SAC 2011). The foundation of the SAC guidance is the calculation of the average annual sediment yield as a means to estimate whether or not a future hydrologic regime is capable of maintaining the existing channel shape. The analysis performed by the TWDB for the Brazos BBEST followed the methods outlined in the SAC documents.

7.1.1 Selection of Study Locations

Because the Brazos River Basin is a large, diverse system, the size and geomorphic characteristics of its various rivers and streams vary substantially from watershed to watershed and even from reach to reach along the same stream. Consequently, a comprehensive geomorphic analysis of the entire system is beyond the time and resources available to the BBEST. The BBEST decided to focus this analysis on two sites where cumulative effects of processes occurring throughout the basin might be observed. The two locations selected by the Brazos BBEST for sediment transport analysis in support of the Geomorphology Overlay are:

- Brazos River at Seymour – USGS Gage Number 08082500, Baylor County.
- Brazos River at Richmond – USGS Gage Number 08114000, Fort Bend County.

The Seymour site was selected to represent sites in the arid upper basin. Flows and channel conditions at this site reflect processes occurring throughout the upper Brazos Basin. The Richmond site is the second to last stream gage on the Brazos River and demonstrates the accumulated effects of flows and processes occurring throughout the entire basin.

7.1.2 Indicators of the Current Stability of Study Locations

Using available USGS measurement data, the sites were evaluated for stability. Results are shown in Figures 7.1 and 7.2 for the Seymour and Richmond gages, respectively. In these figures, stage discharge data collected during various time periods are compared to assess how quickly the channel may be changing at the location of these two gages.

For the Seymour gage, stage-discharge measurement data were readily available from the USGS for the time period 1985–2011. Data from two different time periods (1986–1990 and 2006–2010) are plotted in Figure 7.1. These data indicate that the channel has degraded (incised) in the time period from 1986 to 2010. During that time period,

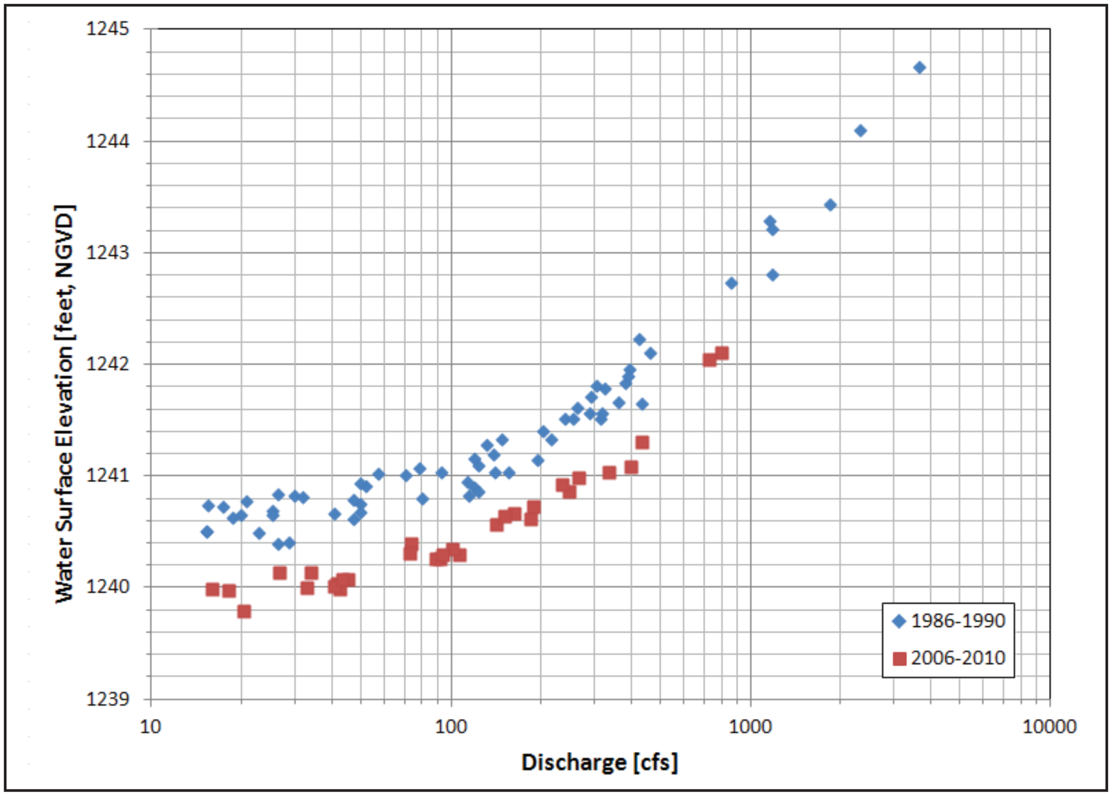


Figure 7.1. Stage-discharge measurements for the Brazos River at Seymour (data from USGS).

the water surface elevation associated with a flow of 20 cfs has decreased by about 0.6 feet. A similar decrease in water surface elevation is evident for flows as high as 400 cfs. Shifts in the stage-discharge relationship at the Seymour gage are apparent at relatively modest discharges. The Brazos River channel at this location is capable of conveying substantially greater discharges than 400 cfs. At these relatively modest discharges, such decreases in water surface elevation are consistent with a general widening of the river channel or some gradual adjustment of a downstream control, such as a sand bar that is migrating downstream. Data are not available to assess changes at greater discharges that would provide a stronger indicator of actual channel incision.

Measurement data for the Richmond gage are available for the time period from 1939 through 2011. Data displayed in Figure 7.2 are for four different time periods (1940–1944, 1966–1970, 1993–1997, and 2006–2010). Again, the data suggest that the channel has degraded over the time period of measurement. For example, a flow of 2,000 cfs had a water surface elevation of about 46 feet during the period 1940–1944. By 2006–2010, a 2,000-cfs flow had a water surface elevation of about 39 feet, indicating that the channel had incised approximately 7 feet since the earlier time period. A similar decrease in water surface elevation is evident for flows as high as 20,000 cfs.

The analysis of stage-discharge measurement data from the Brazos River at Seymour and Richmond indicates that the channel is undergoing modest geomorphic change at both sites. This change is consistent with the findings of Heitmuller and Greene (2009) and Dunn and Raines (2001). In channels that are changing (either aggrading as the channel is built up with excess sediment or degrading as sediment is transported from the reach), it is difficult to estimate sediment transport capacity over time. As the channel geometry changes over time, the relationships between discharge and slope, velocity, flow depth, and sediment transport also change. In such circumstances, the methods

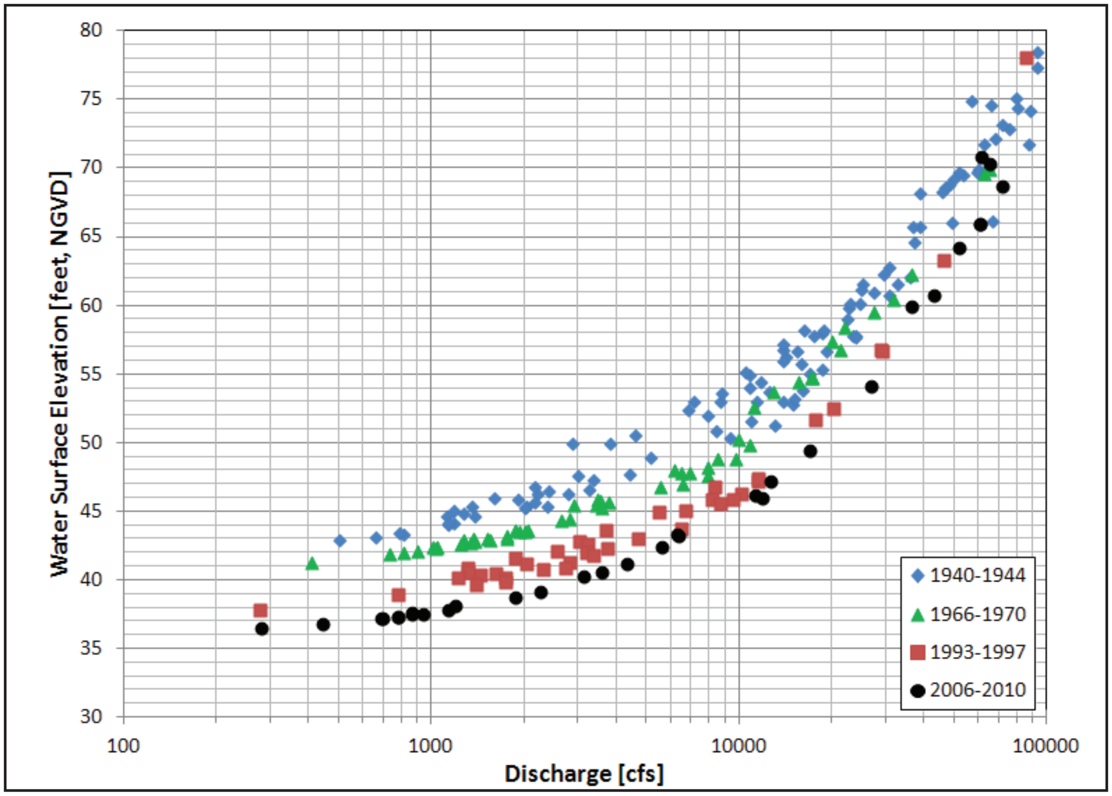


Figure 7.2. Stage-discharge measurements for the Brazos River at Richmond (data from USGS).

described in this report do not provide an accurate, quantitative estimate of the amount of sediment moved by the river. Despite the potential for changing conditions at both sites, sediment transport analysis was completed to provide a qualitative comparison of the sediment transport capability of alternative flow scenarios. A more detailed and thorough investigation would be required to adequately evaluate the impact of a large reservoir or diversion project on these sites.

7.1.3 Sediment Rating Curves

No sediment data were available for the Seymour site, but suspended sediment data collected by the USGS between 1966 and 1984 are available for the Richmond site. Daily average discharge data and field measurements of channel parameters (e.g., velocity, discharge, channel width, channel depth, computed energy slope, and bed gradation) were available from the USGS for both sites. Channel slope and bed material data are available for the Richmond site from the US Army Corps of Engineers (Soar and Thorne 2001). For the Seymour site, channel slope and bed material was collected by TWDB. Bed material gradations for the two sites are shown in Figures 7.3 and 7.4. The bed material in the channel of the Brazos River near the Seymour and Richmond sites is mainly sand with occasional pockets of gravel. This is evidenced by the gradation curves presented in Figures 7.3 and 7.4.

Using available data, sediment rating curves were developed for both sites to estimate the amount of bed material that could be transported by various magnitudes of discharge. For the Seymour site, the SAMWin package was used to select an equation to estimate sediment transport capacity. Based on the bed material and channel characteristics, the

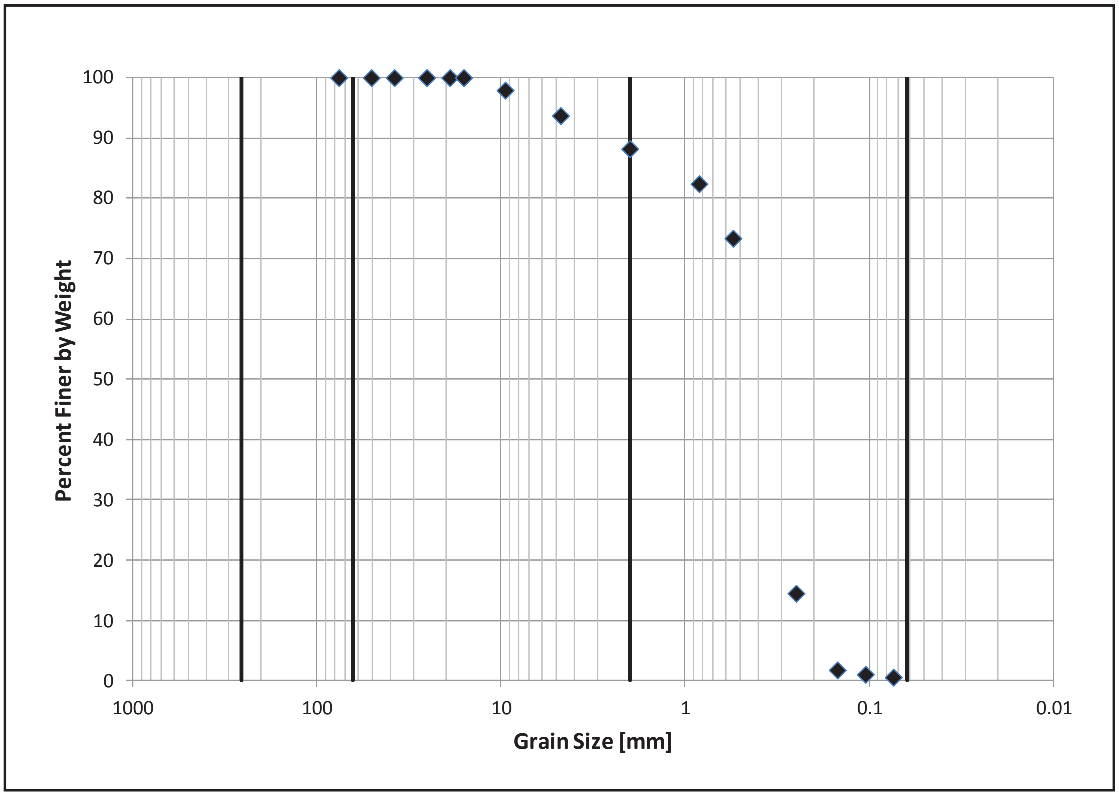


Figure 7.3. Bed material gradation for the Brazos River at Seymour (data collected by TWDB).

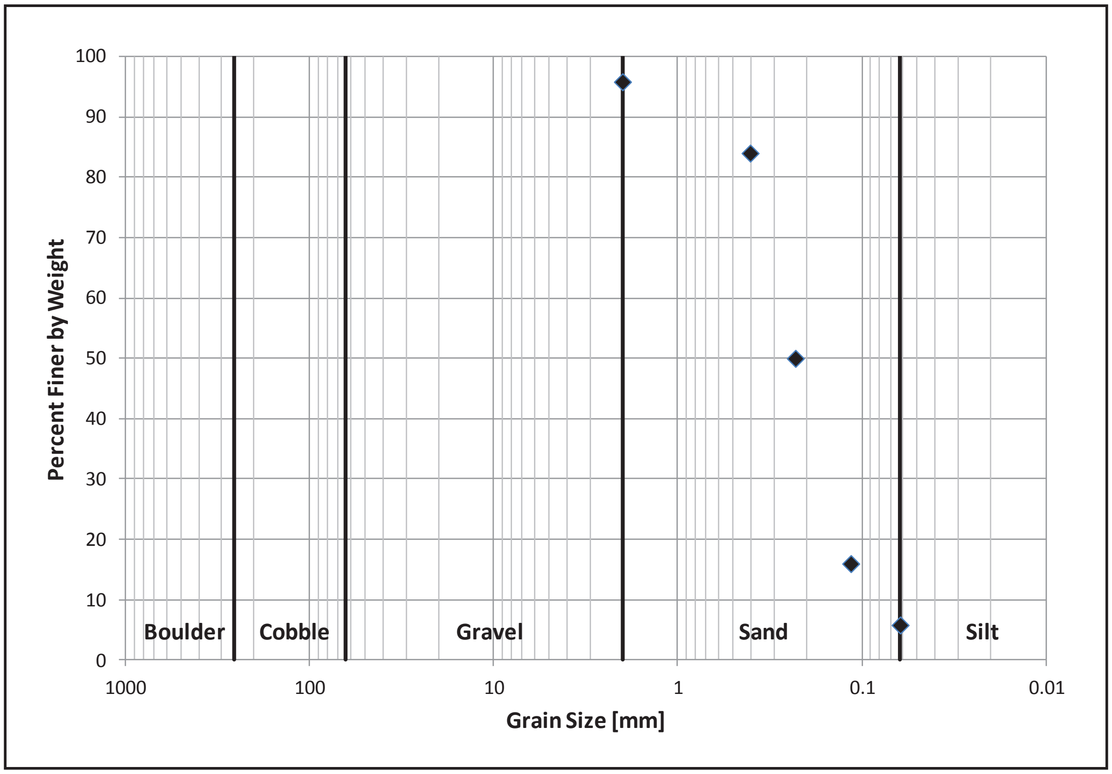


Figure 7.4. Bed material gradation for the Brazos River at Richmond (data from Soar and Thorne 2001).

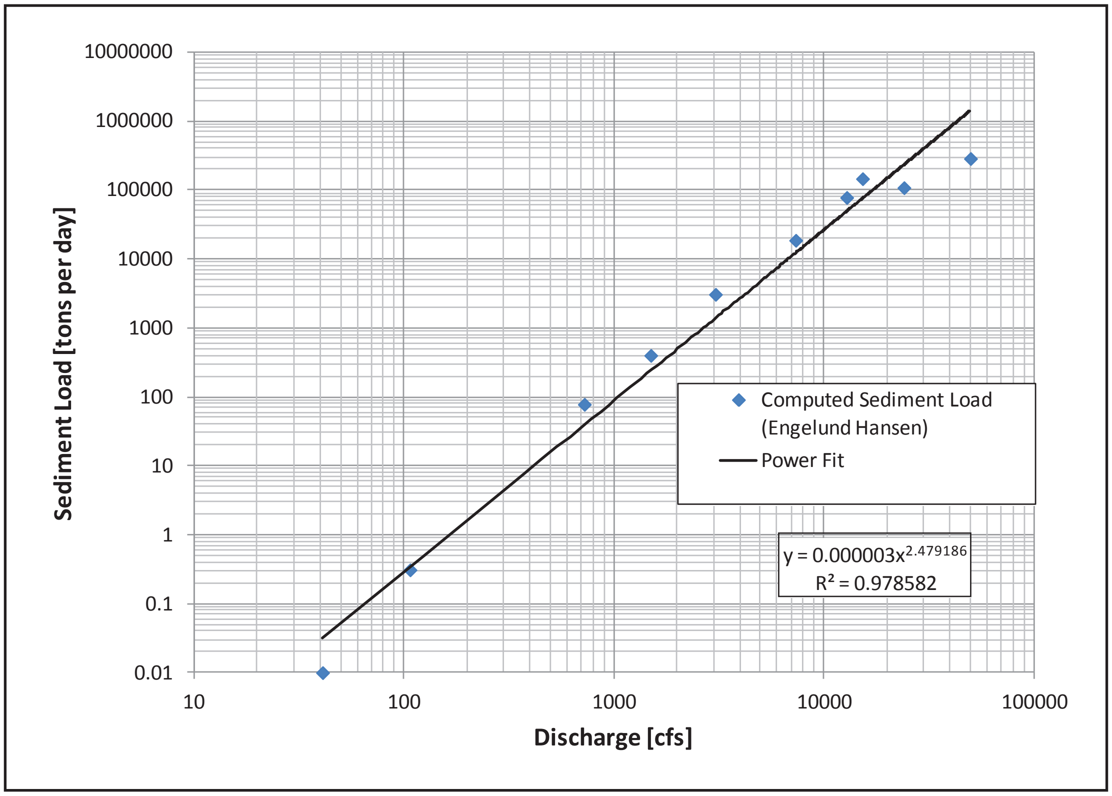


Figure 7.5. Total bed material sediment rating curve for the Brazos River at Seymour.

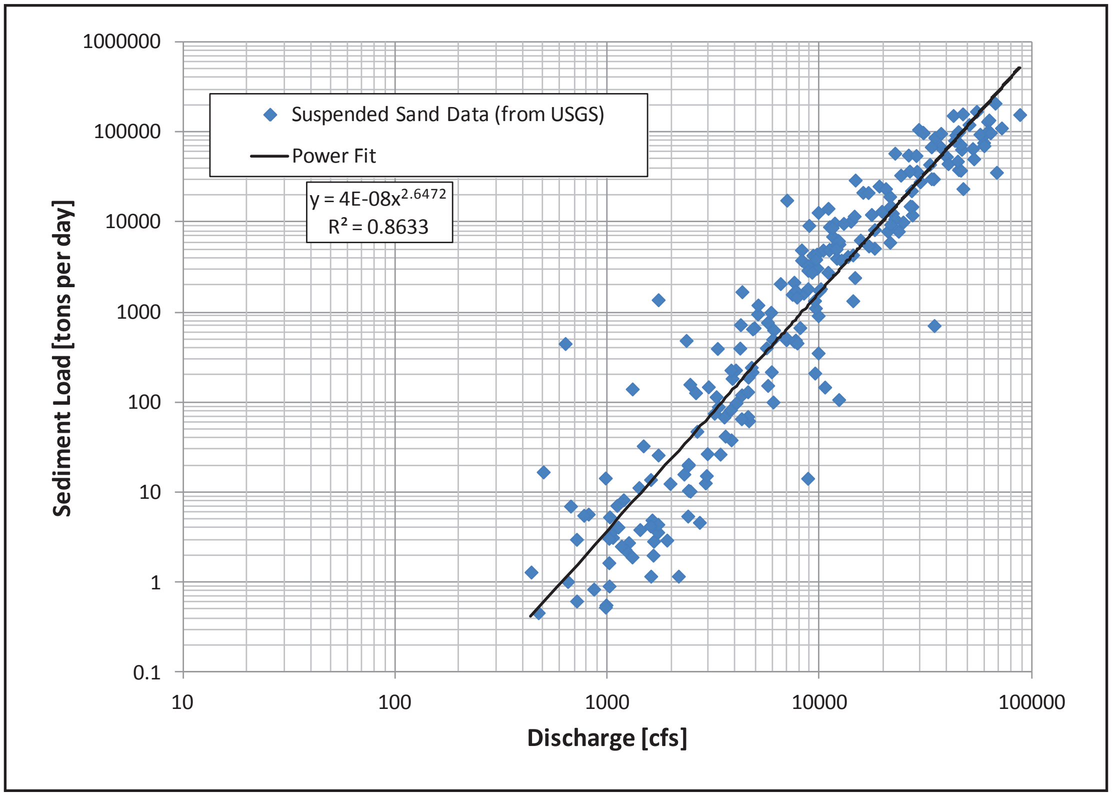


Figure 7.6. Suspended sand rating curve for the Brazos River at Richmond.

Engelund-Hansen equation was selected for the Seymour site to estimate total bed material loads. Sediment loads for various flow rates were calculated using this equation and a power function was fit through the results to develop a convenient rating curve to apply to all daily discharges. The sediment rating curve for the Seymour site is shown in Figure 7.5. For the Richmond site, measured suspended sand load data collected by the USGS were available. Suspended sand data do not include the bed load component of the total sediment discharged in a stream but, being actual measured data, are considered to be a more accurate representation of sediment transport in a stream than values derived from the transport formulas. These data were used as a substitute for estimated total bed material load for the Richmond site. A power function was fit through the data to provide an estimated sediment rating curve, as shown in Figure 7.6.

The two sediment rating curves were then applied to daily mean discharges at the two locations to compute daily sediment discharges over the period of analysis for several different scenarios, as explained in the next section.

7.1.4 Hydrologic Scenarios Tested

In addition to the sediment rating curves discussed in the previous section, a flow duration curve developed from a time series of flow values is required to complete the geomorphic analysis. Several time series of flows, or hydrologic scenarios, were analyzed for this geomorphic overlay. All of the scenarios consisted of daily flows that covered the time period from January 1, 1940 through December 31,1997. The various scenarios are described below:

1. **Gaged** — The daily flows for this scenario were downloaded directly from the Internet for the USGS gages 08082500 Brazos River at Seymour, TX and 08114000 Brazos River at Richmond, TX. Over the time period from 1940 to 1997, conditions in the basin such as land use, diversions, impoundments, return flows, etc. have changed. Nevertheless, this is the time series of flows that has sculpted the channel as it exists today, and it is appropriate to include it for purposes of comparison.

2. **WAM 8** — This is a set of daily flows disaggregated from the monthly flows output from the Water Availability Model Run 8 (2008 version). These monthly flows are an attempt to represent current conditions with respect to water rights use, operated on a monthly time step. In order to get daily flows, the total volume of monthly flows output from the WAM 8 model were disaggregated to individual days in each month following the pattern of historical flows recorded at the USGS gages at either Seymour or Richmond. This scenario was selected by the BBEST as the baseline for comparison of results from other scenarios.

3. **G WAM** — This is a set of daily flows disaggregated from the monthly flows resulting from the WAM model used by the Brazos G Regional Water Planning Group. It represents conditions expected to be in place at the end of the planning horizon (2060) and includes various assumptions related to water rights utilization, return flows, and reservoir sedimentation. Daily flows were obtained by disaggregating the monthly flows in the same manner as described for *WAM 8* above.

4. **With Project/s** — This is a set of daily flows that represent conditions at Seymour and Richmond expected in the future if various water supply projects were completed. It is based on the *G WAM* scenario with the addition of several hypothetical projects. Analysis of these projects does not reflect any opinion regarding the merits of the projects or likelihood that they will be constructed. Inflows to the projects were estimated using *G WAM* results disaggregated to daily flows.

   The Flow Regime Analysis Tool (FRAT) was used to estimate daily project outflows based on daily inflows, reservoir capacity, and operations (including the recommended environmental flow requirements). After routing through the hypothetical reservoir projects, daily outflows were aggregated into monthly flows, which were then placed back into the *G WAM* model to route flows downstream to Seymour and Richmond. Monthly flows obtained at those sites were then disaggregated to daily flows as described previously.

   For Seymour, *With project/s* includes consideration of a hypothetical upstream reservoir patterned after the Double Mountain Fork-West Reservoir. For Richmond, *With project/s* includes consideration of two hypothetical upstream reservoirs (Double Mountain Fork-West and Millican-Panther Creek). The Double Mountain Fork-West project is located on a fork of the Brazos, about 100 miles upstream of the USGS gage at Seymour and about 850 miles upstream of the USGS gage at Richmond. The Millican-Panther Creek project is located on the Navasota River, which confluences with the Brazos River downstream of the USGS gage at Seymour. It is located about 150 miles upstream of the USGS gage at Richmond. Both projects were evaluated by the Brazos G Regional Water Planning Group but are not recommended water management strategies in the 2011 Brazos G Regional Water Plan. They are used here only as hypothetical examples of large reservoir projects.

5. **E-flow only** — This set of daily flows was developed by imposing the environmental flow recommendations only on the daily flows from *G WAM* for the Seymour and Richmond sites. Under this scenario, the flow remaining in the river is the lower of two values: either the environ-

mental flow recommendation or the daily flow from *G WAM* (the flow is not "topped up" to the environmental flow recommendation in cases where the *G WAM* flow is below the recommendation).

This scenario is unrealistic for several reasons. First, it supposes "infinite infrastructure," essentially the capacity to divert or impound all water in excess of the environmental flow recommendations upstream of the site. In reality, a project with finite size would have limits on either the rate of diversion or total volume that could be diverted or impounded, resulting in water in excess of the environmental flow recommendations "spilling" and remaining in the river. Second, it does not consider downstream water rights. Some of the water that could physically be diverted from the river via a new project is legally obligated to remain in the river to satisfy senior water rights downstream. Those water rights would act to keep water beyond the environmental flow recommendations themselves in the river. Nevertheless, the *E-flow only* scenario does provide some idea of the amount of protection provided by the environmental flow recommendations themselves, in the absence of infrastructure limitations and considerations of current Texas water law, which protects downstream senior water rights.

Daily values for the scenarios *WAM 8*, *G WAM*, and *With project/s* were provided by the BBEST. Daily values for *E-flow only* were provided by the TPWD. Flow duration curves for the various scenarios at the Seymour and Richmond sites are shown in Figures 7.7 and 7.8 and selected results are presented in Tables 7.1 and 7.2.

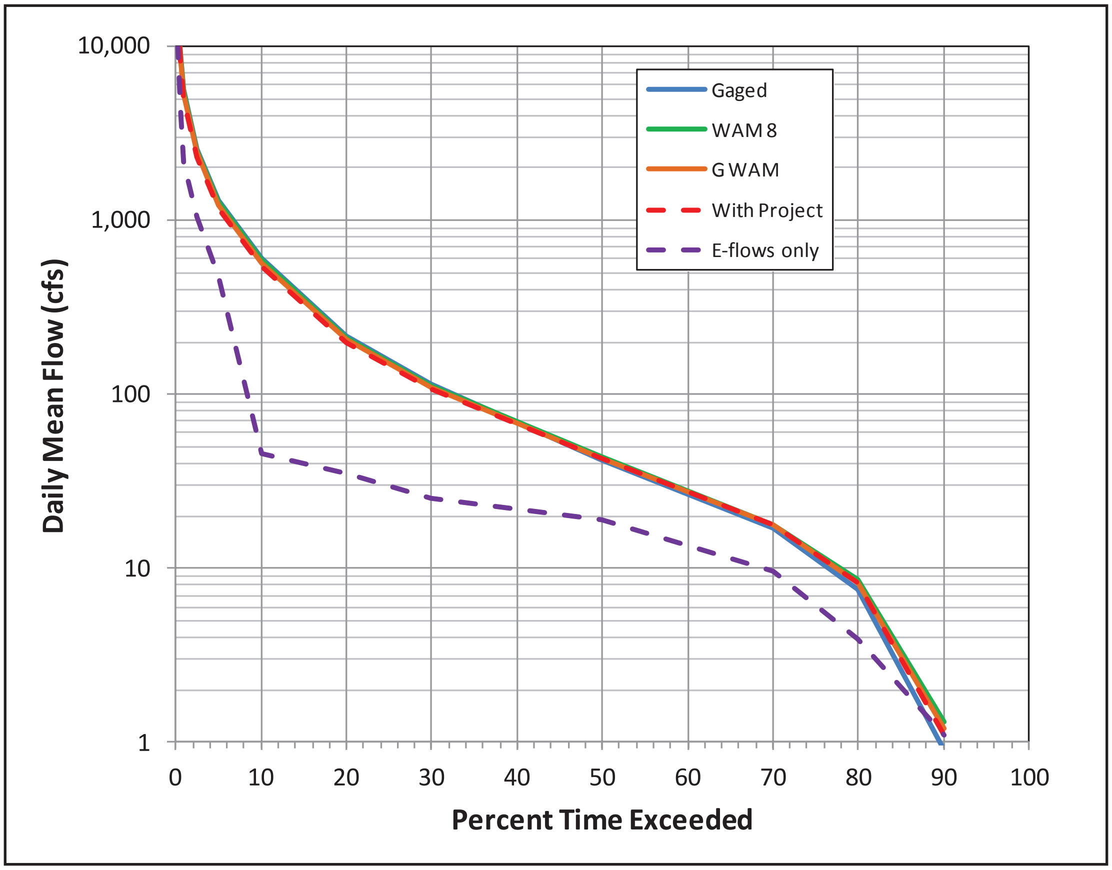


Figure 7.7. Flow duration curves for the Brazos River at Seymour.

Table 7.2 reveals substantial differences in the daily flows among different scenarios. For example, the maximum daily mean flow recorded at the USGS gage at Richmond during the time period from January 1, 1940 through December 31, 1997 was 118,000 cfs, which occurred on May 5, 1957. In contrast, the flow on May 5, 1957 from the *WAM 8* daily flow regime is 148,826 cfs.

The most substantial differences in the daily flows between the scenarios occur between the gaged and WAM-modeled flows. The gaged flows represent historical operations of water supplies in the basin, whereas the WAM-modeled flows represent operations of all water rights under the doctrine of prior appropriation, considering full utilization of all rights (with the exception of the *WAM 8*, where water right use is estimated at current diversion rates). These differences in daily flows are directly attributable to differences in the monthly flows computed by the WAMs, which occurred historically. These differences are apparent from inspection of Figure 7.9, which displays daily flows at the Richmond gage from each of the scenarios for the months of November and December 1991. In November 1991, daily gaged flows are consistently greater than those of any of the scenarios, whereas in December 1991, the inverse occurs. During November, historical operation of water supply impoundments and diversions allowed more water to pass through the Richmond gage than would have been passed under full exercise of all rights in the basin. In contrast, the larger WAM flows in December indicate substantially less appropriation of water upstream of Richmond under full utilization of water rights than occurred historically. Since the monthly in the WAMs are based upon historical gage data and are disaggregated to daily using the daily gage record as a pattern, differences between the scenarios and

Table 7.1. Flow exceedance values for the Brazos River at Seymour.

Exceedance Probability [%]	Flow [cfs]				
	Gaged	WAM 8	G WAM	with project	E-flow only
0.0	46,800	46,300	44,200	40,100	16,800
0.1	21,900	21,500	20,500	19,400	13,000
0.5	9,250	9,070	8,740	8,300	4,570
1.0	5,690	5,490	5,340	4,990	2,170
2.5	2,550	2,520	2,440	2,301	1,040
5	1,310	1,280	1,220	1,160	474
10	601	586	564	541	46.0
20	216	212	205	198	35.0
30	114	113	109	106	25.0
50	42.0	43.3	42.8	42.4	19.0
70	17.0	17.9	17.7	17.6	9.7
80	7.5	8.6	8.3	8.3	3.9
90	0.9	1.3	1.2	1.1	1.1
95	0.0	0.0	0.0	0.0	0.0
97.5	0.0	0.0	0.0	0.0	0.0
99.0	0.0	0.0	0.0	0.0	0.0
99.5	0.0	0.0	0.0	0.0	0.0
99.9	0.0	0.0	0.0	0.0	0.0
100	0.0	0.0	0.0	0.0	0.0

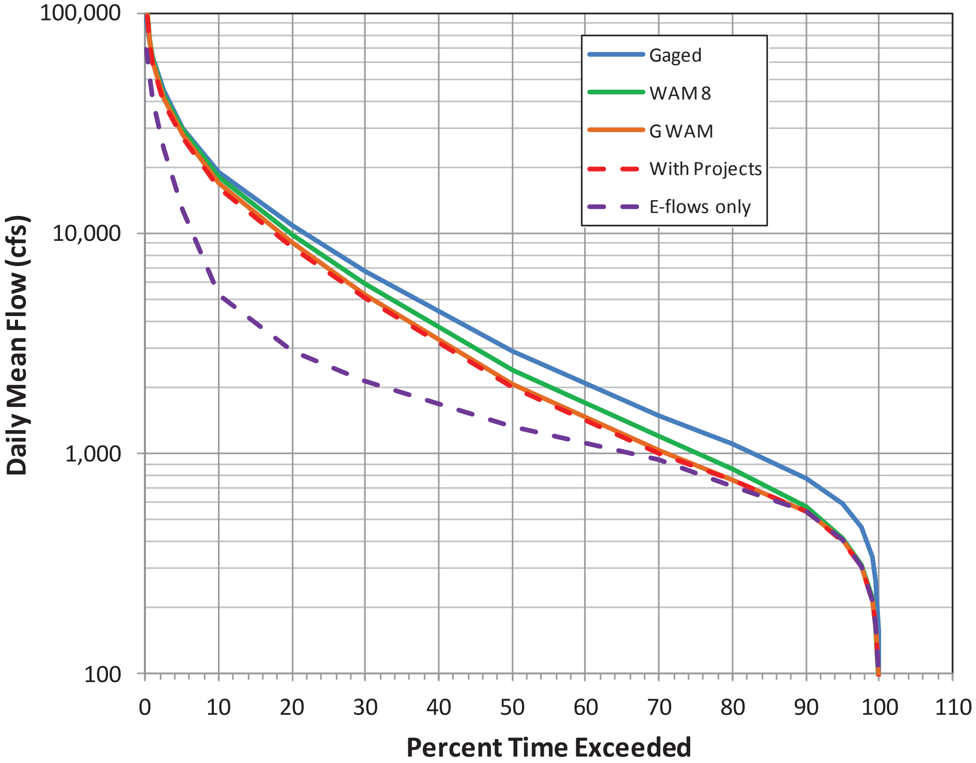


Figure 7.8. Flow duration curves for the Brazos River at Richmond.

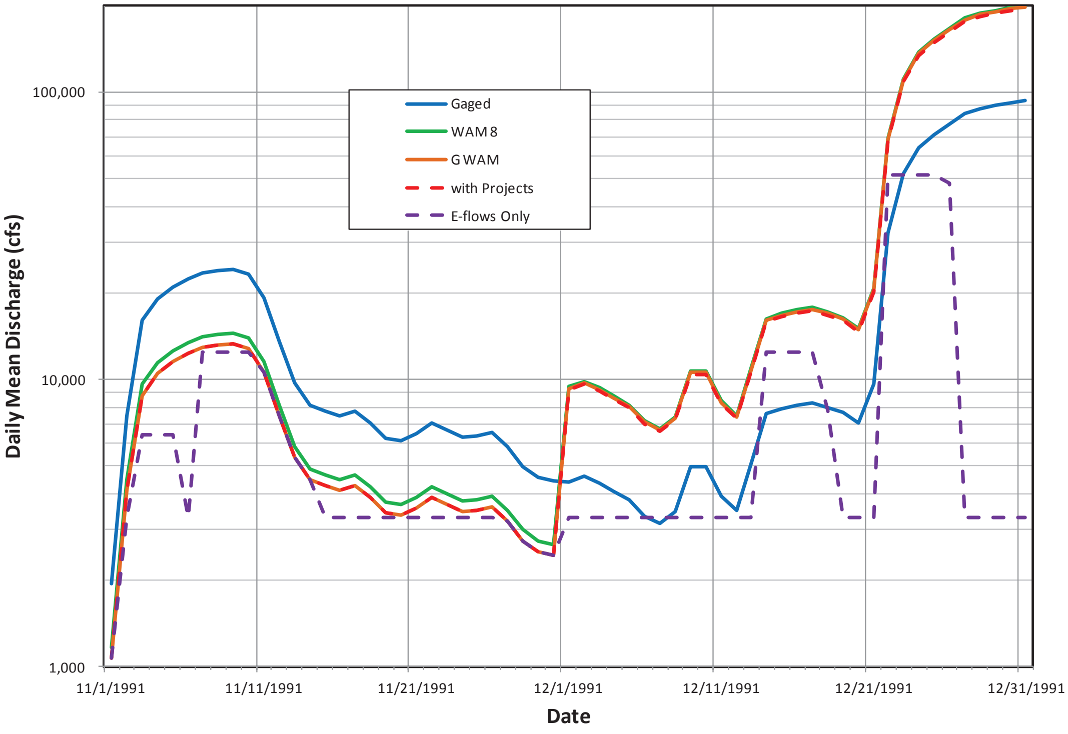


Figure 7.9. Daily flows from various flow scenarios for the Brazos River at Richmond (November 1, 1991–December 31, 1991).

Table 7.2. Flow exceedance values for the Brazos River at Richmond.

Exceedance Probability [%]	Flow [cfs]				
	Gaged	WAM 8	G WAM	with projects	E-flow only
0.0	118,000	200,000	198,000	195,000	68,100
0.1	93,400	113,000	110,000	108,000	68,100
0.5	74,000	77,300	75,100	72,800	51,600
1.0	62,700	62,200	60,000	58,200	40,600
2.5	44,700	42,800	41,000	39,300	24,400
5	30,200	29,700	28,200	27,200	12,900
10	19,100	18,000	17,000	16,100	5,290
20	10,800	9,790	9,080	8,570	2,930
30	6,750	5,890	5,300	5,070	2,140
50	2,920	2,380	2,060	2,000	1,330
70	1,500	1,200	1,030	1,010	940
80	1,110	856	765	754	715
90	777	576	544	543	544
95	590	413	409	403	408
97.5	465	313	309	307	309
99.0	342	221	214	214	214
99.5	266	162	167	167	167
99.9	157	89.2	96.4	96.4	96.4
100	55.0	8.9	9.8	9.8	9.8

historical gage flows are due to differences in operations of water supply systems in the basin between the WAMs and those operations that occurred historically.

7.1.5 Sediment Transport Capacity Under the Scenarios Tested

7.1.5.1 Mean Annual Sediment Yield

Using the daily flows and the sediment rating curves developed for each site, sediment yield computations were completed for each of the flow scenarios. The daily mean flows were used with the sediment rating curve equation for each site to estimate daily sediment yields for each scenario tested. Daily values were summed and the results divided by the number of years in the period of analysis (1940–1997) to obtain mean annual sediment yields. Results are presented in Table 7.3. Mean annual water yield (the amount of water that would remain in the channel at this location) is also provided in Table 7.3.

Note that the sediment yields computed are not actual sediment supplies that would be transported but are instead an estimate of the transport capacity of the channel given the various hydraulic and hydrologic factors assumed. The results can be reliably compared between scenarios but should not be used as accurate estimates of the load of sediment that would actually be transported by the stream under each scenario. Sediment loads depend greatly on the rates of sediment transported into any given reach from upstream and differences in channel transport capacity between adjacent reaches of the river.

The results of the sediment transport analysis are very sensitive to the methodologies used to estimate the sediment transport rating curves. The TWDB used a regression approach to estimate the sediment rating curves at the two sites by fitting a least-squared power function to the data, resulting in a linear relationship when plotted on a log-log scale (Figures 7.5 and 7.6). Inspection of the function plotted on Figure 7.5 reveals that at larger discharges, the linear relationship can overstate sediment transported by an order of magnitude. This would tend to overestimate annual sediment yields for scenarios with more frequent large discharges. An alternative methodology would be to develop a non-linear rating curve, using the data available (either computations from the sediment transport function, i.e., Seymour site or the plotted suspended sand discharge data) and apply each of the daily discharges to this rating curve. This approach was tested at the Seymour gage, and under this alternative approach, the *E-flow only* scenario would produce 35 percent of the baseline sediment yield in comparison to the 20 percent presented in Table 7.3.

Table 7.3. Results of sediment transport analysis at two sites on the Brazos River.

Average Annual Water and Sediment Yields		
	Average Annual Yield	
Hydrologic Scenarios	**Water** **Acre-Feet (% of Baseline)**	**Sediment** **Tons per Year (% of Baseline)**
BRAZOS RIVER AT SEYMOUR		
Historical Flows		
1940-1997 Gaged Flows	246,000 (102%)	296,000 (103%)
Simulated Flows		
WAM 8 Flows (Baseline)	242,000 (100%)	288,000 (100%)
G WAM	233,000 (96%)	262,000 (91%)
G WAM with Project	223,000 (92%)	233,000 (81%)
E Flow Only	93,400 (39%)	56,600 (20%)
BRAZOS RIVER AT RICHMOND		
Historical Flows		
1940-1997 Gaged Flows	5,480,000 (107%)	3,010,000 (85%)
Simulated Flows		
WAM 8 Flows (Baseline)	5,130,000 (100%)	3,530,000 (100%)
G WAM	4,780,000 (93%)	3,190,000 (90%)
G WAM with Projects	4,580,000 (89%)	2,930,000 (83%)
E Flow Only	2,340,000 (46%)	797,000 (23%)

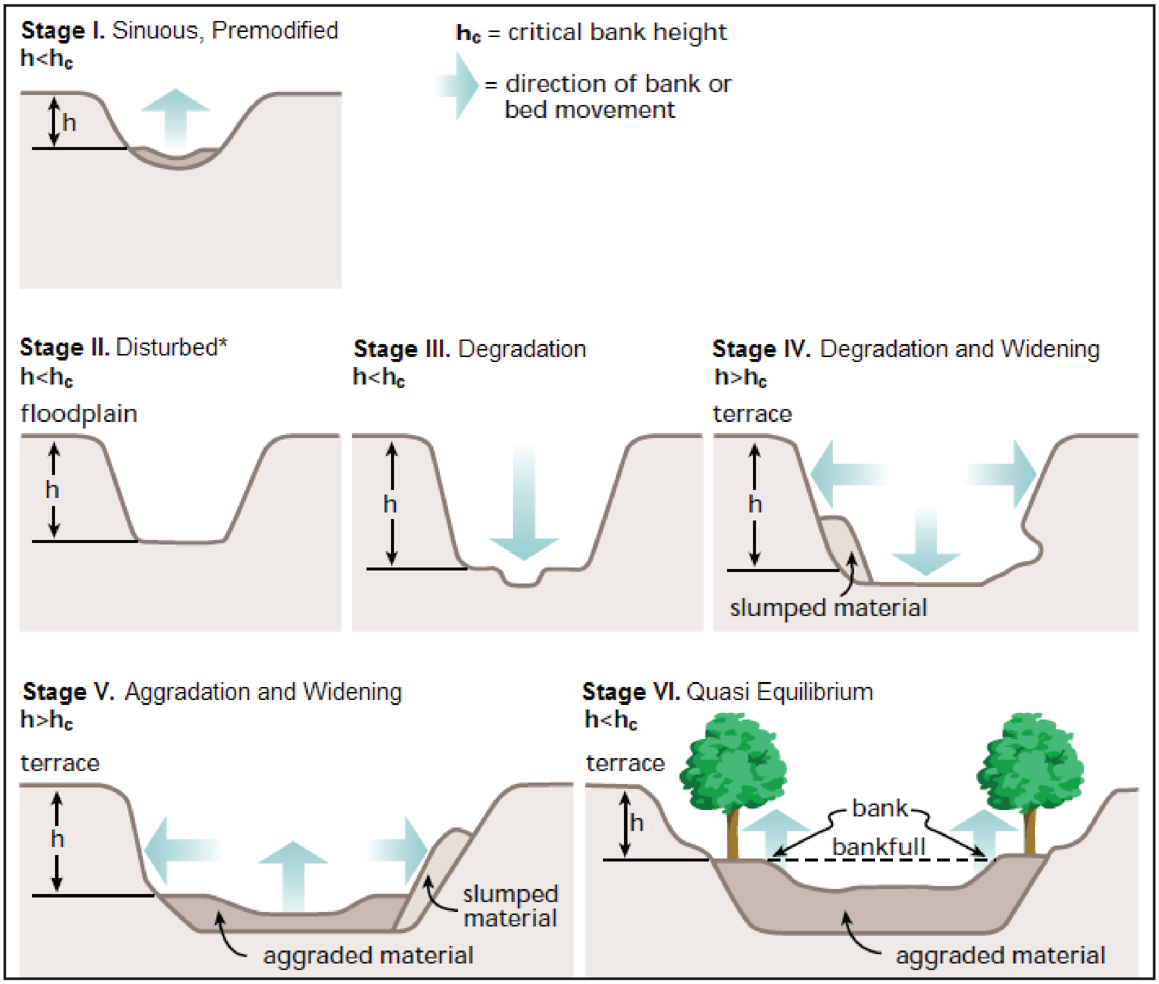
7.1.5.2 Sediment Analysis of Incising Channels

The findings of Dunn and Raines (2001), Heitmuller and Green (2009), and the current analysis (Figures 7.1 and 7.2) support the observation that the Brazos River channels near Seymour and Richmond are incising. These observations, coupled with the observations made by Gillespie and Giardino (1997) suggesting that the rate of channel migration has slowed substantially in the lower Brazos, indicate that the Brazos River has been undergoing long-term adjustments in response to the multiple changes in the river basin that have occurred since the early 1900s and has not yet reached a state of dynamic equilibrium. Predicting the response of the system to a specific disturbance (such as a major impoundment) is difficult in such an environment.

Channel alteration in the forms of incision and migration has the potential to result in the loss of productive agricultural land and valuable infrastructure such as bridges, pipelines, and other structures that are near or cross the river. Incising channels are known to follow a pattern of development that may take many years, often multiple decades, from an originally stable condition (relatively constant geometry under dynamic equilibrium) to an unstable, actively incising condition, and ultimately to a final stable configuration (but with different geometry than the original configuration). Simon (1989) developed a six-stage Channel Evolution Model. The six stages, also shown in Figure 7.10, are as follows:

Stage I	The waterway is a stable, undisturbed natural channel.
Stage II	The channel is disturbed by some drastic change such as forest clearing, urbanization, dam construction, or channel dredging.
Stage III	Instability sets in with scouring of the bed.
Stage IV	Destructive bank erosion and channel widening occur by collapse of bank sections.
Stage V	The banks continue to cave into the stream, widening the channel. The stream also begins to aggrade, or fill in, with sediment from eroding channel sections upstream.
Stage VI	Aggradation continues to fill the channel, re-equilibrium occurs, and bank erosion ceases. Riparian vegetation once again becomes established.

The impact of flow alteration on an unstable channel cannot be determined from a simple sediment transport analysis, as was completed for the Seymour and Richmond sites. The future configuration of the channel at these sites will depend on changes to the flow regime, sediment input to the channel, and the stage of evolution that the channel is undergoing. Large reservoir and diversion projects have the potential to impact both the flow regime and the sediment delivered to the channel downstream of the project, as will changes in land use and other watershed alterations. When a proposed impoundment or diversion project is being planned, a detailed and thorough investigation should be conducted to evaluate the potential effects of the project on the flow and sediment transport regime. Once those effects are determined, measures can be taken to maintain or promote the desired downstream channel condition. Information from such analyses should be evaluated within the context of the overall processes occurring in the watershed, which are often complex and persistent on timelines measured by decades. Guidance on the planning, analysis, and design of systems to maintain channels in a state of dynamic equilibrium and to restore incising channels can be found in Watson et al. (1999).



* "Disturbed" refers to any major change that may impact the site, including forest clearing, urbanization, dam construction, or channel dredging.

Figure 7.10. Simon's Channel Evolution Diagram (modified from FISRWG 1998).

7.1.6 Summary Points

1. Stream channel shape (geometry or bathymetry) is determined by the movement of bed material (sediment) by flow. Substantial, long-term changes in flow will change stream channel shape and consequently change existing habitat conditions for aquatic life.

2. There is considerable doubt as to whether the existing channel at the two study sites is stable under a dynamic equilibrium. A brief analysis of this type cannot determine if a new project operated subject to the proposed flow alterations would move these channels toward stability or result in less stable conditions.

3. If all flows were to be reduced to just the flow regime targets of the proposed environmental flow regimes, there would only be 20 and 23 percent of the average annual sediment yield compared to the baseline conditions at the Seymour and Richmond sites, respectively. The environmental flow regimes as they might be implemented (in combination with senior water rights and a particular set of hypothetical future water projects) provide 81 and 83 percent, respectively, of the average annual sediment yield compared to the baseline conditions at the

Seymour and Richmond sites. Note that these results are very sensitive to the choice of analysis methodology, and alternative methods could compute smaller reductions in annual sediment yield.

4. More detailed hydrologic and geomorphic studies are required to adequately evaluate the potential effects of large impoundment or diversion projects within the Brazos River Basin. Those effects can often be reduced with proper project design.

7.2 Oxbow Connectivity

The hydrologic calculations provided in Section 7.1 allowed for an analysis of the frequency of connections between the active river channel and oxbow lakes under alternative future scenarios of water appropriation operated subject to the proposed environmental flow regime. None of the six oxbow lakes for which we have elevation data and estimates of flow levels establishing lateral connections (Osting et al. 2004b) are located near the Richmond gage. Of these six, the four nearest oxbows to the gage are Korthauer Bottom (10.5 river-miles downstream of USGS gage 08111500 on the Brazos River near Hempstead), Horseshoe Lake (approximately 15.8 river-miles downstream of the USGS gage near Hempstead), Hog Island (approximately 8.8 river-miles downstream of USGS gage 08116650 on the Brazos River near Rosharon), and Cutoff Lake (located near Lake Jackson, TX, approximately 38 river-miles downstream of the Rosharon USGS gage). Because these oxbows are not close to the Richmond gage, their connection dynamics in relation to flows recorded at the Richmond gage should be considered approximate. It should also be noted that the youngest oxbows with the greatest connection frequencies are the most important off-channel aquatic habitats because they retain water longer and permit more frequent exchanges between the river channel and floodplain habitats.

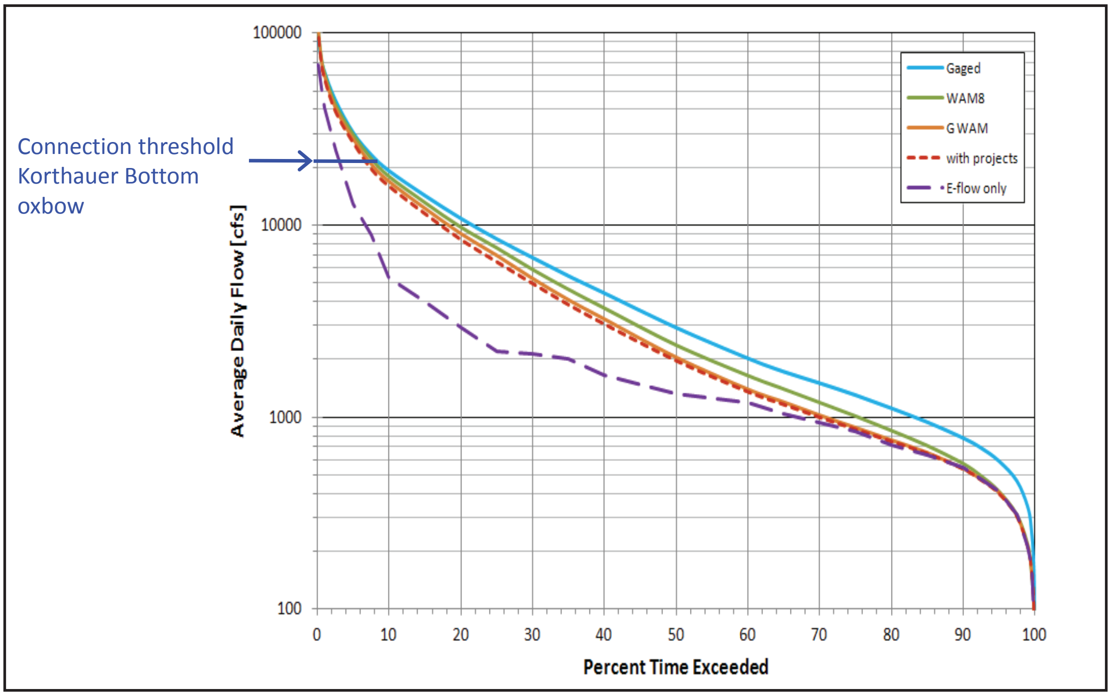


Figure 7.11. Flow threshold for lateral connection between the Brazos River channel and Korthauer Bottom oxbow in relation to the flow duration curve at the Richmond gage under five flow scenarios.

Korthauer Bottom connects with the river more than once per year on average at 20,500 cfs (Table 4.1). There would be negligible influence on the frequency of connections for this oxbow lake under the scenarios *WAM8*, *G WAM*, and *With projects* compared with the current conditions (Figure 7.11). However, the *E-flow only* scenario would result in a greater than 50 percent reduction in flow levels that induce lateral connections (from about 10 percent of flows to less than 5 percent of flows). As discussed in Section 4.2, these higher flows allow for exchanges of water, resources, and aquatic organisms between the oxbow and the river channel. This level of reduction could represent a significant negative ecological impact.

Horseshoe Lake is a very old feature and connects very infrequently and only at very high discharge levels (Table 4.1). Consequently, the influence of the five different flow scenarios had negligible influence on connection frequency of Horseshoe Lake (Figure 7.12).

Hog Island oxbow is a relatively young oxbow that connects with the river multiple times per year at discharges equal to or greater than 3,625 cfs (Table 4.1). Under the *WAM8* scenario, this oxbow would see about 2.5 percent fewer connections compared with the historical period (Figure 7.13). Under the *G WAM* and *With projects* scenarios, there would be a further decline in the frequency of connections of about 2.5 percent (i.e., about a 5 percent reduction in connections compared with the current conditions) (Figure 7.13). The *E-flow only* scenario would result in about a 60 percent reduction in connections (from 50 percent of flows to about 20 percent) (Figure 7.13). Younger oxbows with greater connection frequencies are the most important ones in fulfilling critical ecological functions for biotic components of the lower basin reaches.

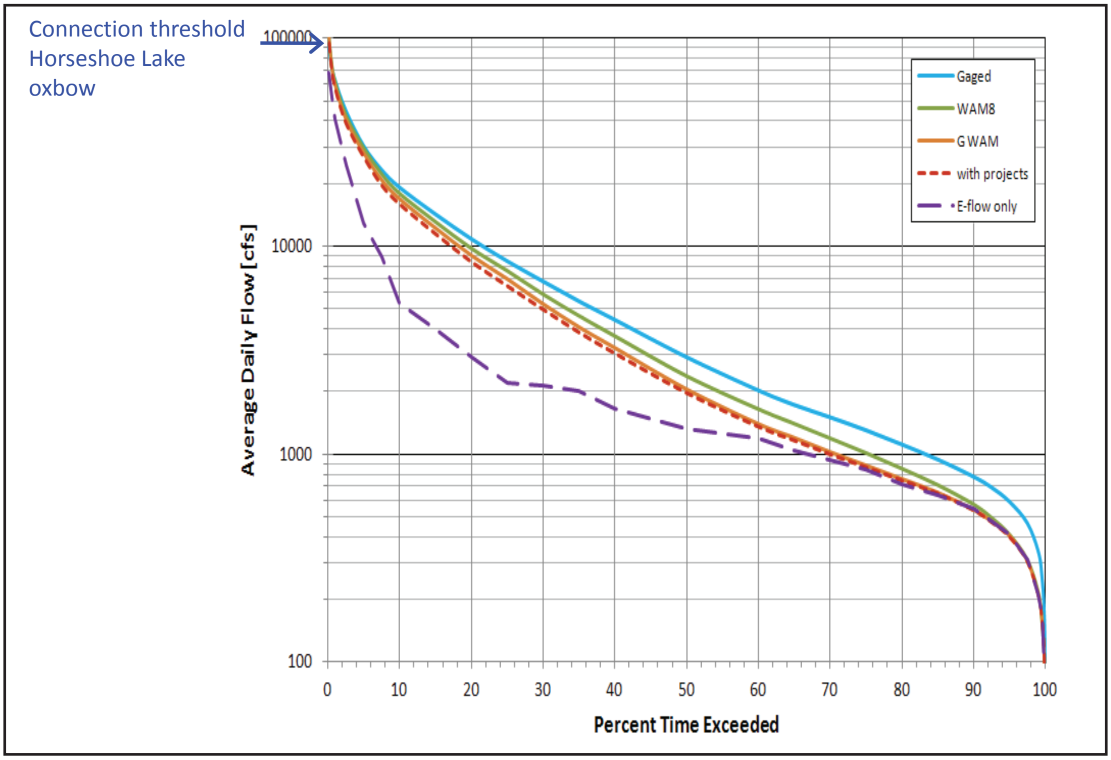


Figure 7.12. Flow threshold for lateral connection between the Brazos River channel and Horseshoe Lake oxbow in relation to the flow duration curve at the Richmond gage under five flow scenarios.

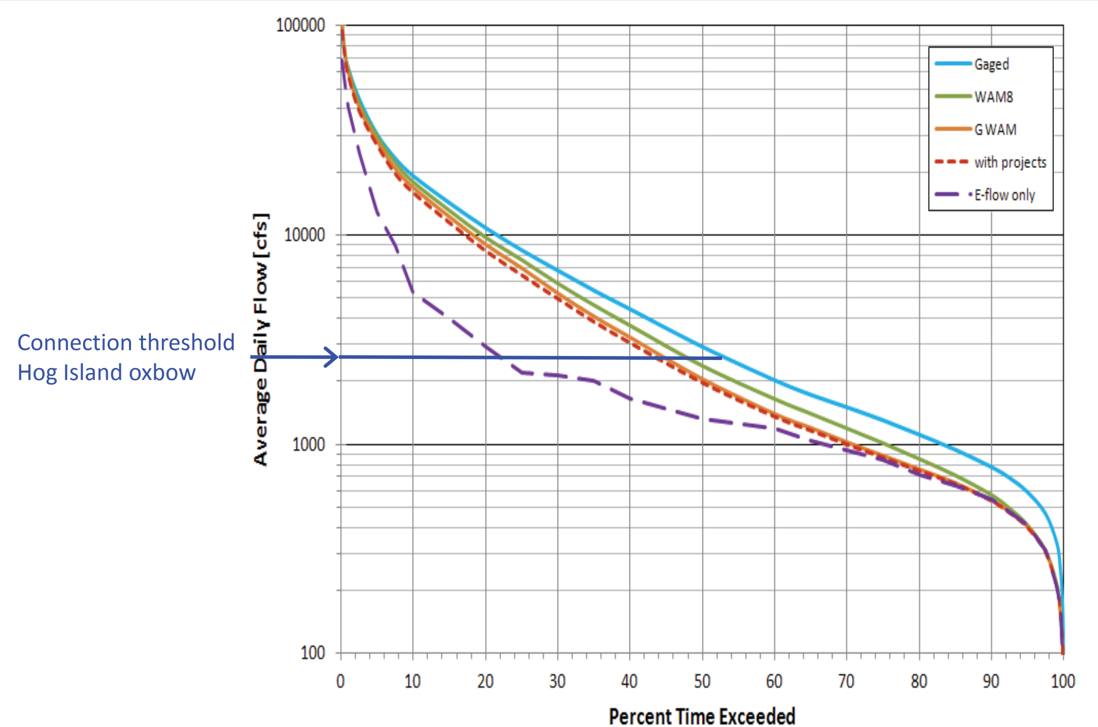

Connection threshold
Hog Island oxbow

Figure 7.13. Flow threshold for lateral connection between the Brazos River channel and Hog Island oxbow in relation to the flow duration curve at the Richmond gage under five flow scenarios.

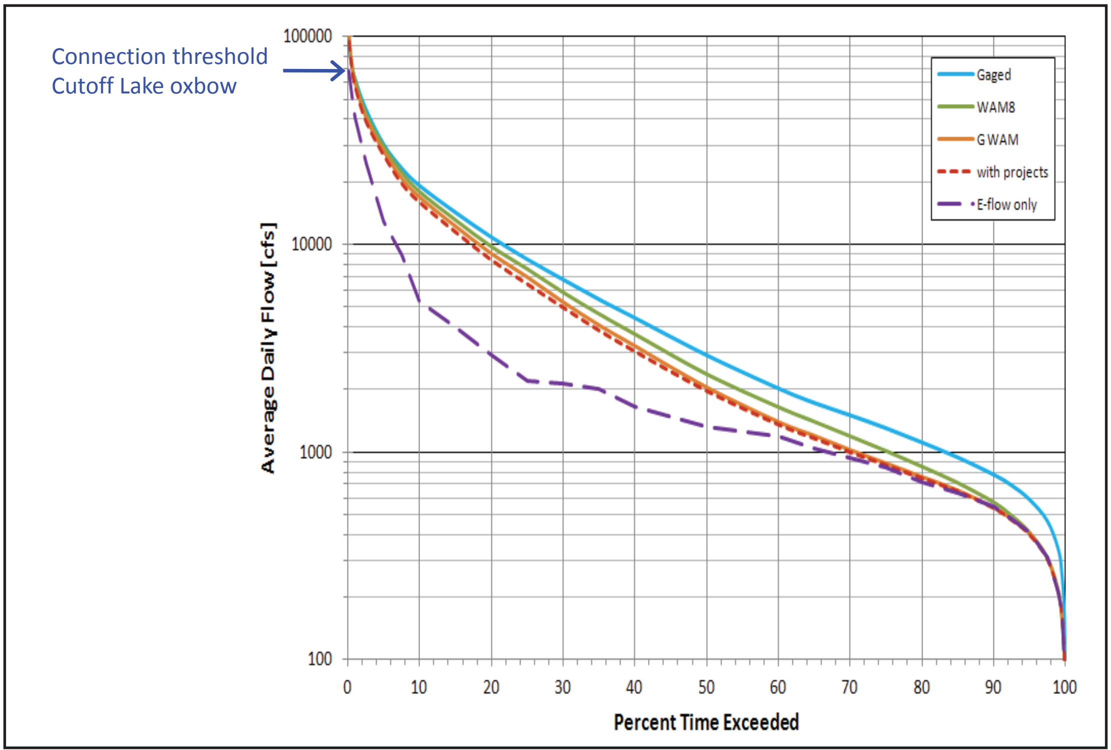

Connection threshold
Cutoff Lake oxbow

Figure 7.14. Flow threshold for lateral connection between the Brazos River channel and Cutoff Lake oxbow in relation to the flow duration curve at the Richmond gage under five flow scenarios.

The E-flow only scenario would cause a substantial ecological impact if flows were reduced to those levels and the frequency of connections consequently diminished to the extent estimated here.

Cutoff Lake also is a very old oxbow that connects infrequently and only at very high discharge levels (Table 4.1). The five different flow scenarios had negligible influence on connection frequency of this oxbow (Figure 7.14).

It is important to note that these four oxbows are the only ones that were measured by Osting et al. (2004b) to estimate lateral connection frequencies and intervals under variable flow regimes. During the 1990s, aerial surveys of the lower Brazos River between Bryan and Lake Jackson revealed at least 40 oxbows containing water (Winemiller et al. 2000). Oxbow formation arises from continual processes of erosion and deposition that drive geomorphic channel evolution of meandering of floodplain rivers (Coffman et al. 2011). If one assumes a dynamic equilibrium over time, then about 40 oxbows containing water during relatively wet periods would be considered the natural, and hence desirable, number for this river reach. These oxbows would exhibit a range of geomorphic and environmental characteristics that support diverse aquatic communities and maintain higher species richness within the basin (Winemiller et al. 2000; Zeug et al. 2005). Our estimates of connectivity for the two younger oxbows yield significant concerns that our environmental flow regime recommendations for the lower reaches of the Brazos, Navasota, and San Bernard rivers, under the *E-flows only* scenario, would yield unacceptably high risk with respect to a critical ecological aspects of these ecosystems: lateral connectivity and maintenance of aquatic floodplain habitats and species populations.

7.3 Estuarine Inflows from the Brazos River Basin

Monthly time series for freshwater inflow in acre-feet per month were developed as described in Section 4.4.6 and used to determine historical monthly and seasonal frequencies and volumes of flows. In addition, data from downstream, non-tidal USGS stations were used to supplement or extend the estimates both back and into the future. Although the TWDB explicitly considers return flows and diversions, we also assembled data on diversions and returns below the Brazos River Rosharon USGS gage.

We focused our analysis on both longer time periods (record of the USGS gage) and the WAM period of record (1940–1997) primarily using the Richmond gage and TWDB estimates. The Rosharon gage with a shorter time period and data gaps were also examined. Several flow regimes evaluated using HEFR in the instream assessment were "translated" into monthly flows in acre-feet to allow for comparison to historical flow conditions and TWDB estimated flows (Schoenbaechler and Guthrie 2011). For the Richmond gage on the Brazos River, we also evaluated the *E-flow only* scenario, values that were unavailable for the downstream Rosharon gage. The *E-flow only* (purple curve in Figures 7.7 and 7.8) is the flow resulting from full implementation of the instream flow regime, assuming an infinite infrastructure that can capture all flows not otherwise required to be passed. In a basin as large as the Brazos, a project or even a group of projects that might approach that level of water capture is extremely unlikely but is being considered as a worst-case scenario. The Rosharon gage is the furthest downstream Brazos River gage; however, it has a shorter time series and has some data gaps. Therefore, we primarily worked with the Richmond gage, which still showed a very high correlation with the downstream Rosharon gage and TWDB freshwater inflows.

There are large diversions in the lower Brazos River. Much of the historical discharge during low flow times is reservoir releases, of which much is diverted before reaching the mouth of the river near Freeport industries. In many cases, much of the gaged flow during low flow and moderate flow months was diverted before reaching the coast. According to the TWDB, this is taken into account in its estimates.

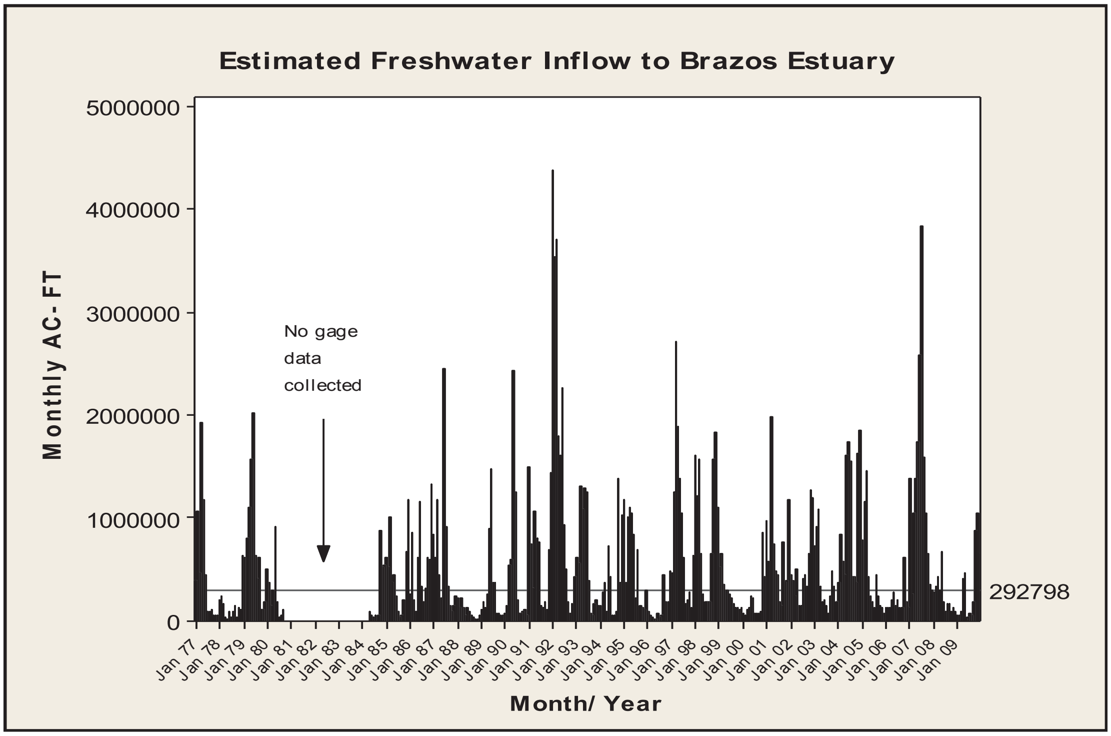


Figure 7.15. Estimated monthly freshwater inflows to the lower Brazos River estuary and Gulf of Mexico based on TWDB estimates results (Period of record January 1977–December 2009). Horizontal reference line denotes median flow estimate. (http://midgewater.twdb.texas.gov/bays_estuaries/hydrologypage.html)

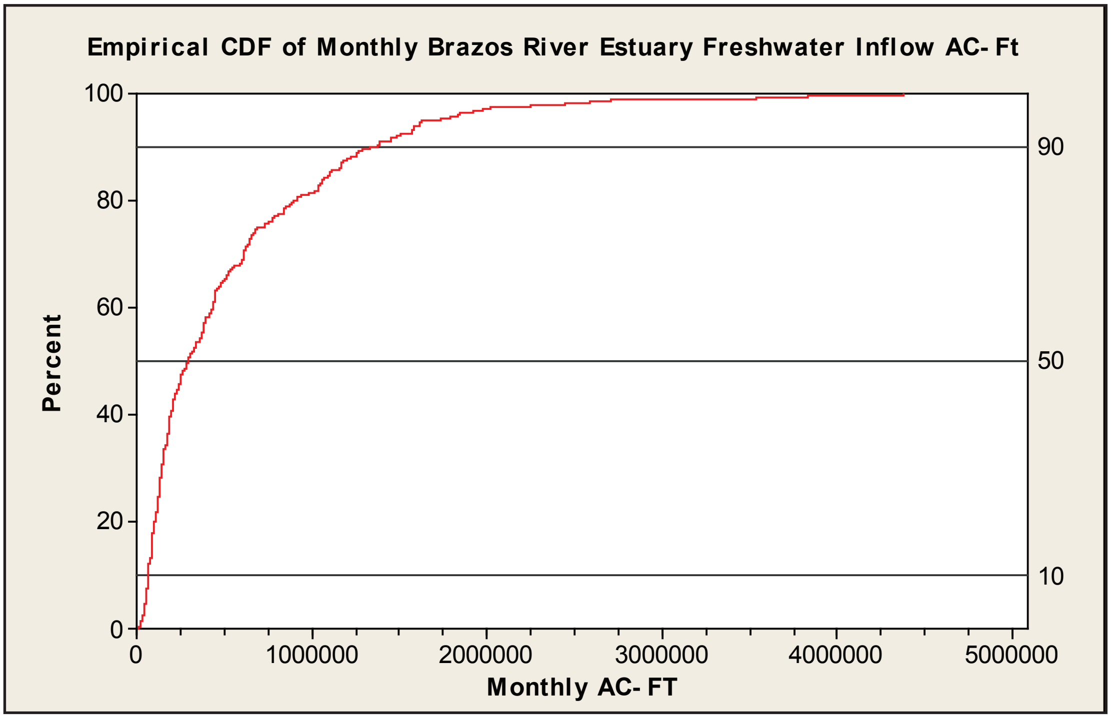


Figure 7.16. Empirical cumulative distribution of estimated monthly freshwater inflows to the Brazos River estuary based on TWDB estimates (Period of record January 1977–December 2009). (http://midgewater.twdb.texas.gov/bays_estuaries/hydrologypage.html)

The freshwater inflows generated by the TWDB extend from January 1977 to September 2009 (Figure 7.15). The flows have been highly variable with the highest flows occurring 1992 and 2007. The distribution of flows is presented in Figure 7.16. Approximately 50 percent of the monthly flows are less than 400,000 acre-feet. Higher flows are quite variable and extend up to approximately 4.5 million acre-feet per month.

TWDB inflow estimates were highly correlated with upstream average monthly flows recorded at the Rosharon and Richmond gages (Figures 7.17 and 7.18). Since Richmond had a longer and more complete period of record, we decided to use this site to extend our downstream inflow estimate by using our previous regression equation to predict both past and later estimates of freshwater inflows (Figures 7.19 to 7.24).

Seasonal variation in freshwater inflow was also evaluated. Seasonal periods were primarily defined based on seasonal use of tidal streams and rivers by major groups of fishes and aquatic invertebrates (Day et al. 1989; Monaco et al. 1989). High flows typically occur in the early spring (Figures 7.23 and 7.24); however, unpredictable and variable flows have been observed in the past. August and September typically have the lowest flows (Figures 7.21 and 7.22).

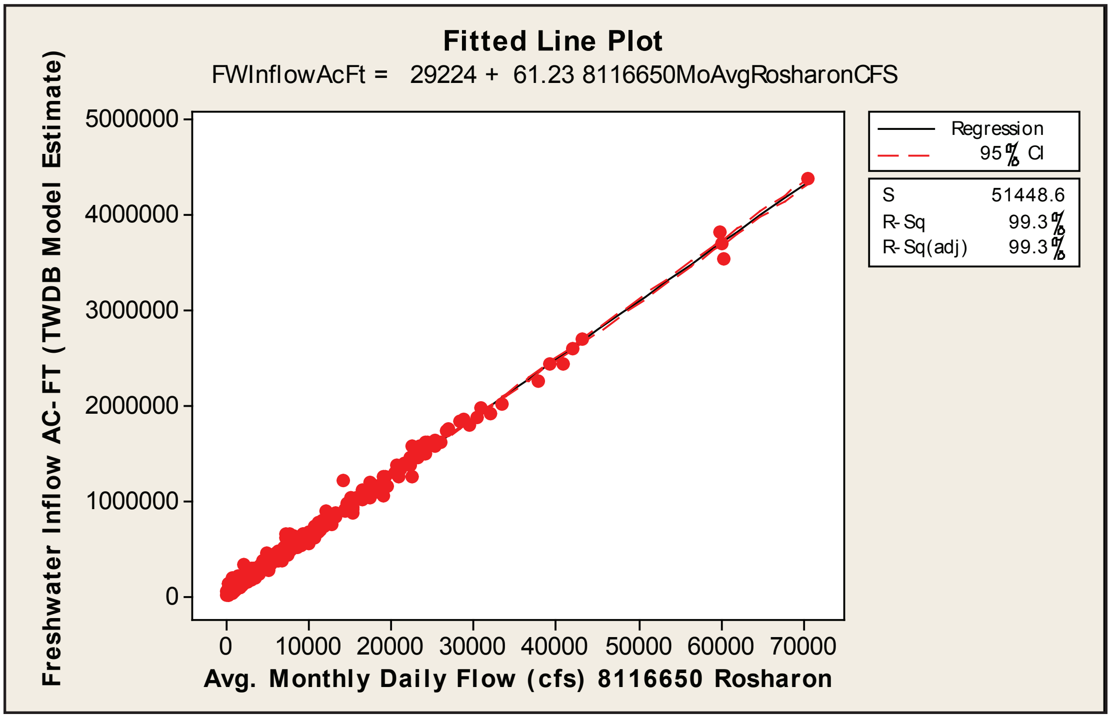


Figure 7.17. Empirical relationship between estimated freshwater inflows to the Brazos River estuary based on TWDB estimates and average monthly daily flow at the USGS Rosharon gage 8116650 (Period of record January 1977–December 2009). (http://midgewater.twdb.texas.gov/bays_estuaries/hydrologypage.html)

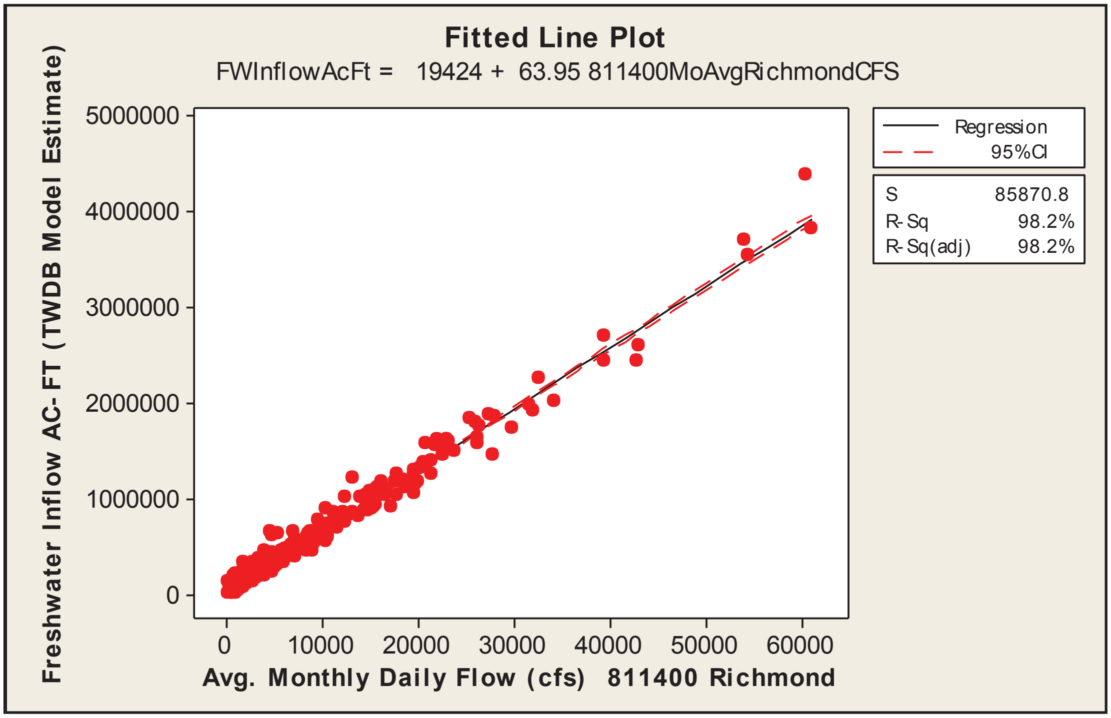


Figure 7.18. Empirical relationship between estimated freshwater inflows to the Brazos River estuary based on TWDB estimates and average monthly daily flow at the USGS Richmond gage 0811400 (Period of record January 1977–December 2009). (http://midgewater.twdb.texas.gov/bays_estuaries/hydrologypage.html)

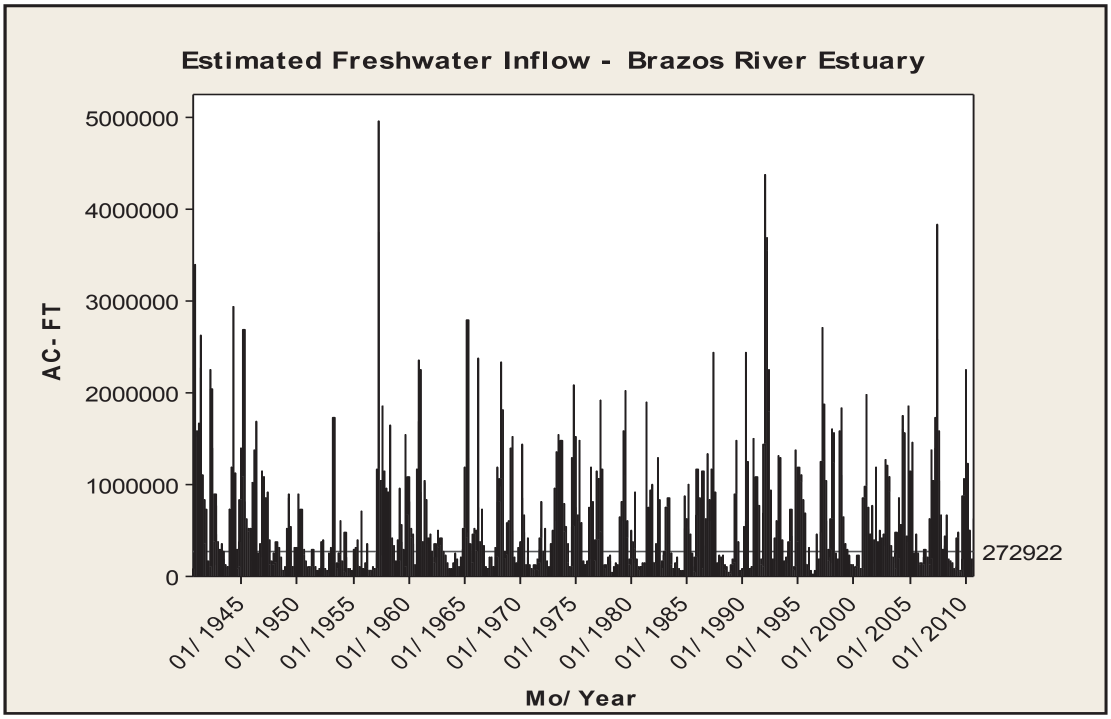


Figure 7.19. Estimated monthly freshwater inflows to the lower Brazos River estuary and Gulf of Mexico based on combined TWDB predicted inflows using the TWDB inflow/Richmond gage instream flow estimates (Period of record October 1944–September 2010). Horizontal reference line denotes median flow estimate. (http://midgewater.twdb.texas.gov/bays_estuaries/hydrologypage.html)

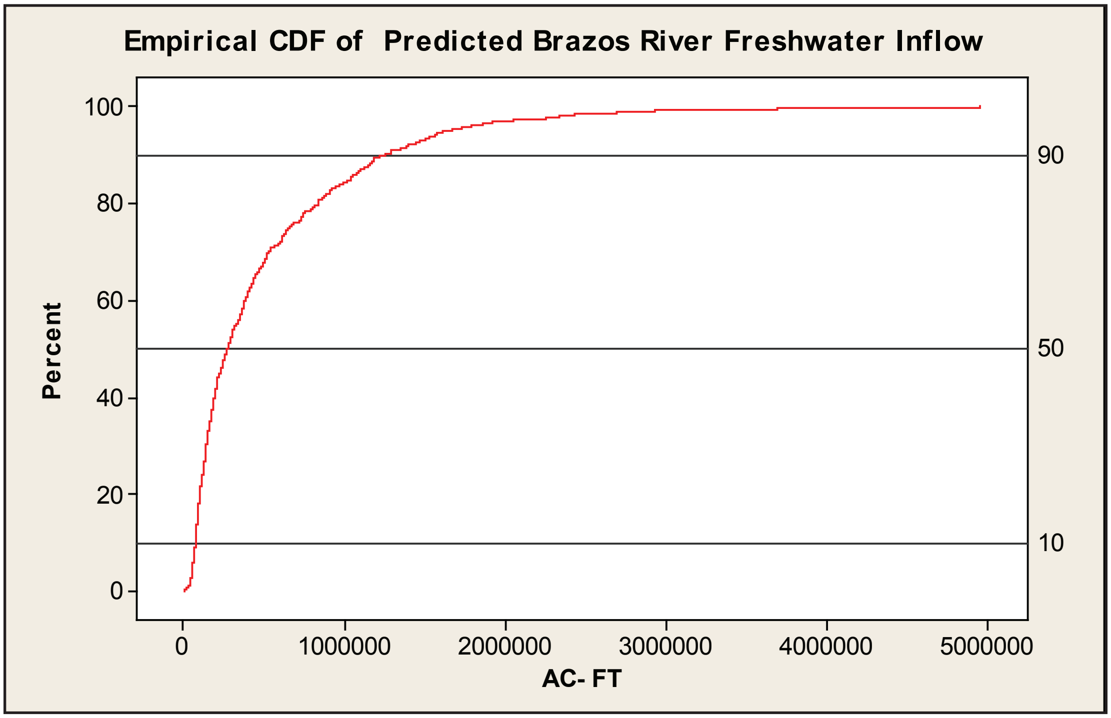


Figure 7.20. Empirical cumulative distribution of estimated monthly freshwater inflows to the Brazos River estuary based on combined TWDB estimates and supplemental predicted values from regression of Richmond gage and TWDB predictions (Period of record October 1944–September 2010); from Schoenbaechler and Guthrie 2011. (http://midgewater.twdb.texas.gov/bays_estuaries/hydrologypage.html)

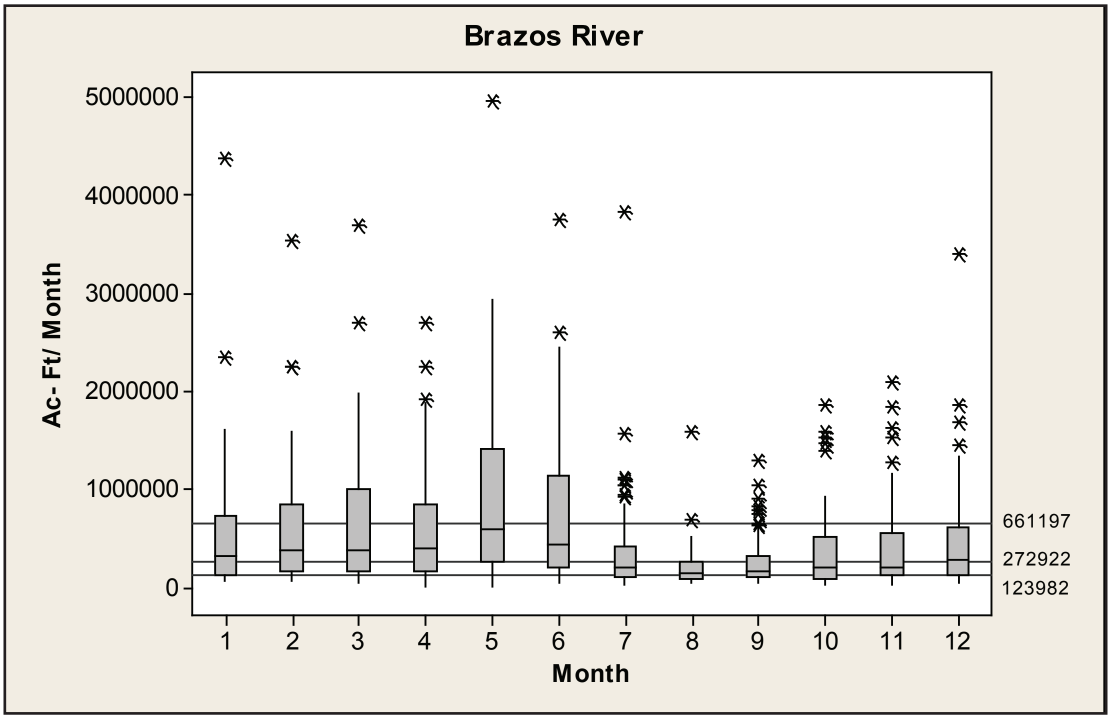


Figure 7.21. Estimated monthly Brazos estuary freshwater inflow based on TWDB estimated flows generated from Richmond gage and TWDB inflow estimate regression model. Numbers on the right vertical axis denote overall upper and lower quartile and median (Period of record October 1944–September 2010). (http://midgewater.twdb.texas.gov/bays_estuaries/hydrologypage.html)

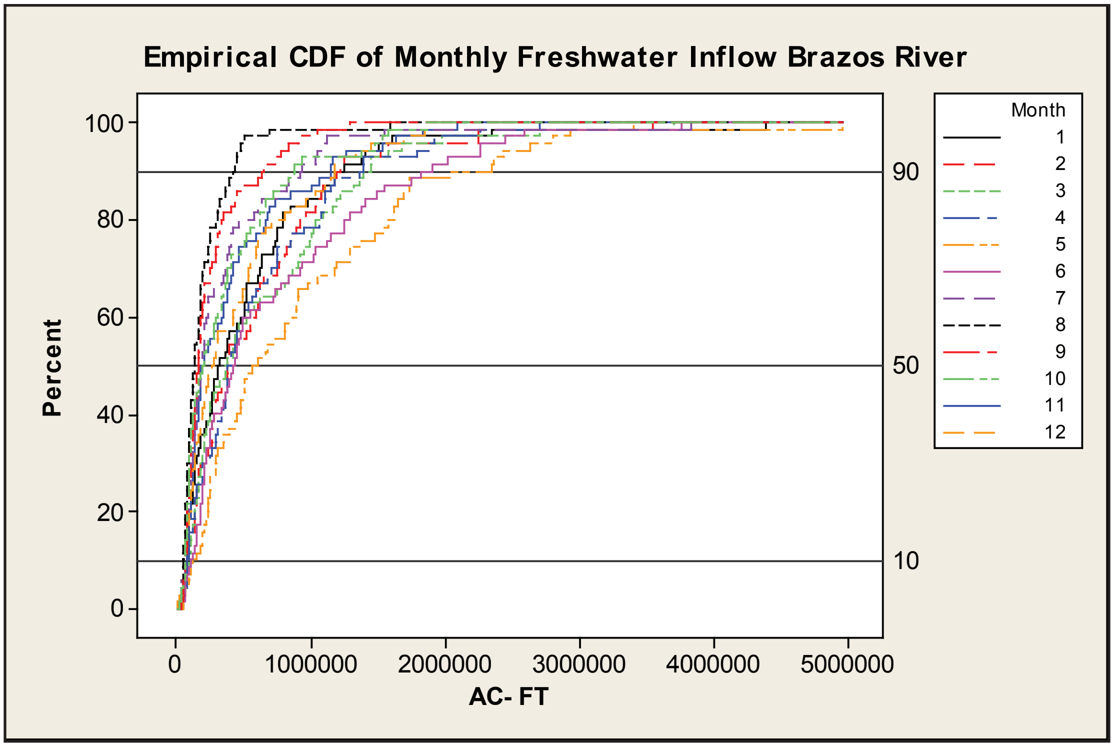


Figure 7.22. Empirical cumulative distribution of monthly estimated freshwater inflows to the Brazos River estuary based on combined TWDB estimates and supplemental predicted values from regression of Richmond gage and TWDB estimates (Period of record October 1944–September 2010). (http://midgewater.twdb.texas.gov/bays_estuaries/hydrologypage.html)

To more accurately reflect conditions assessed in the instream portion of our analysis, we reanalyzed our relationships and predictive regression models based on the instream period of assessment (January 1940–December 1997) (Figures 7.25 and 7.26). As before, there was a high correlation between TWDB inflow estimates and upstream gaged flows. We then used the Richmond regression model (Figure 7.25) to predict freshwater inflow under the various project scenarios considered during the geomorphic overlay presented in Section 7.1.4 (Figures 7.27 and 7.28).

Based on the scenarios presented, it appears that the *E-flows only* scenario would cause significant reductions in freshwater inflows and sediment delivery to the Brazos River estuary. All other scenarios also produced reductions in freshwater inflows; however, these reductions likely would not be biologically significant. As previously stated in Section 7.1.5, if all flows were reduced to just the environmental flow regime targets, the resulting flows would only provide 23 percent of the average annual sediment yield compared to the baseline conditions at Richmond (Table 7.3). The environmental flow regimes as they might be implemented (in combination with senior water rights and a particular set of hypothetical, future water supply projects) provide 83 percent of the average annual sediment yield at Richmond compared to the baseline conditions (Table 7.3). As noted previously, these results are sensitive to the choice of method for analysis.

These reductions in sediment load may reduce the supply necessary for long-term maintenance of the river delta and associated wetlands. These predicted values should be evaluated to determine if significant reductions in sediment transport that would result from some of the more likely scenarios would lead to reduced or negative delta formation along the coast. The biological significance of these potential changes is difficult to evaluate given the unique *riverine*

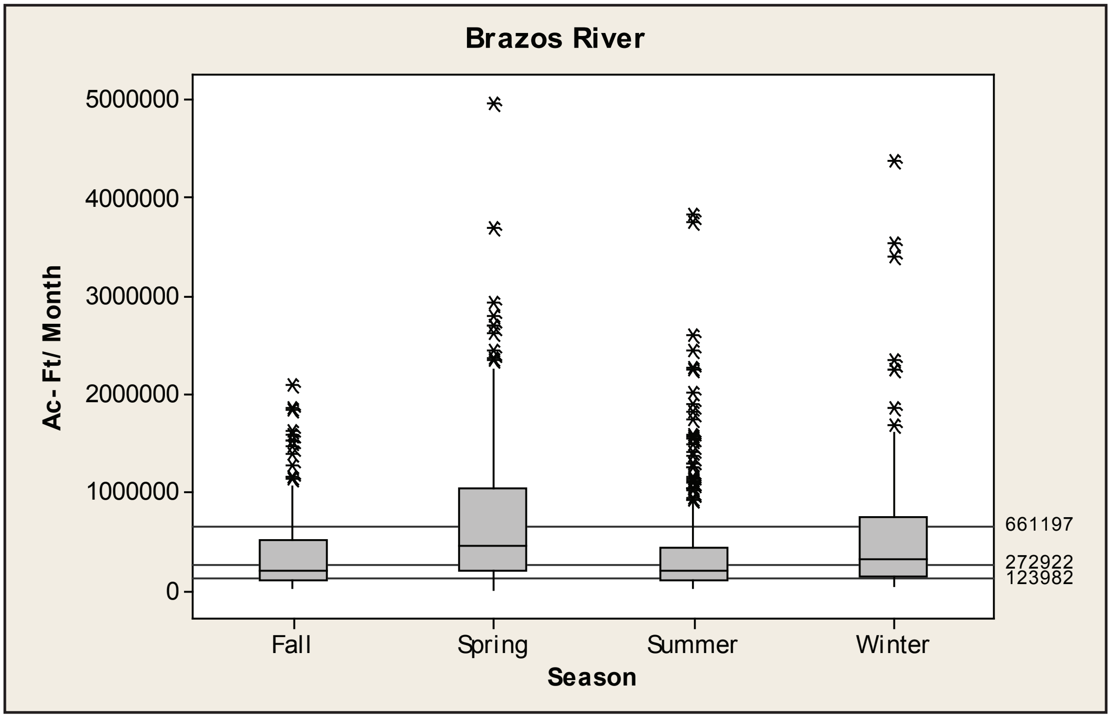


Figure 7.23. Estimated monthly Brazos estuary freshwater inflow by season based on TWDB estimated flows generated from Richmond gage and TWDB inflow estimate regression model (Period of record October 1944–September 2010). Fall (Oct-Nov); Winter (Dec-Feb); Spring (Mar-May); Summer (Jun-Sep). Numbers on the right vertical axis denotes overall upper and lower quartile and median. Note: Seasonal periods were defined based on biological criteria (Day et al. 1989; Monaco et al. 1989) and do not reflect the BBEST definition of seasons related to instream flow recommendations. (http://midgewater.twdb.texas.gov/bays_estuaries/hydrologypage.html)

nature of the estuary. Reduction in active delta formation may have negative implications for long-term coastal community and ecosystem protection given projected sea level rise scenarios (Davis 2011; Montagna et al. 2011). Additionally, one of the areas most sensitive to sea level rise due to a deficit of sand material is reportedly the Brazos River mouth (Davis 2011).

Since long-term spatially intense salinity monitoring data are not available, we were not able to evaluate how this would affect salinity levels. Most likely, since the alternative scenarios do not seem to differ significantly from historical conditions, the salinity may be elevated during some time periods but probably not for extended times. During the recent years, there has been concern by the U.S. Coast Guard of increasing salinities in the area around Freeport, which is located adjacent to and is hydrologically connected to the Brazos River via the Intercoastal Waterway (Guthrie 2011). After examining data from various monitoring agencies over the period of 1991 to 2010, the Coast Guard concluded that mean salinity in the vicinity of all monitoring sites had increased only slightly or not at all. This is substantiated by observed hydrology and predicted inflow data obtained form from the TWDB and USGS (Figure 7.19).

Orlando et al. (1993) conducted an analysis of salinity at the Brazos River during both low flow and high flow periods. For their analysis they evaluated two periods, including a high flow period (April–June 1975) and low flow period (August–October 1975). During the high flow period, monthly average flows at the Richmond gage 811400 and projected monthly freshwater inflow ranged between 10,280 and 22,820 cfs or 676,913 to 1,478,948 acre-feet (Fig-

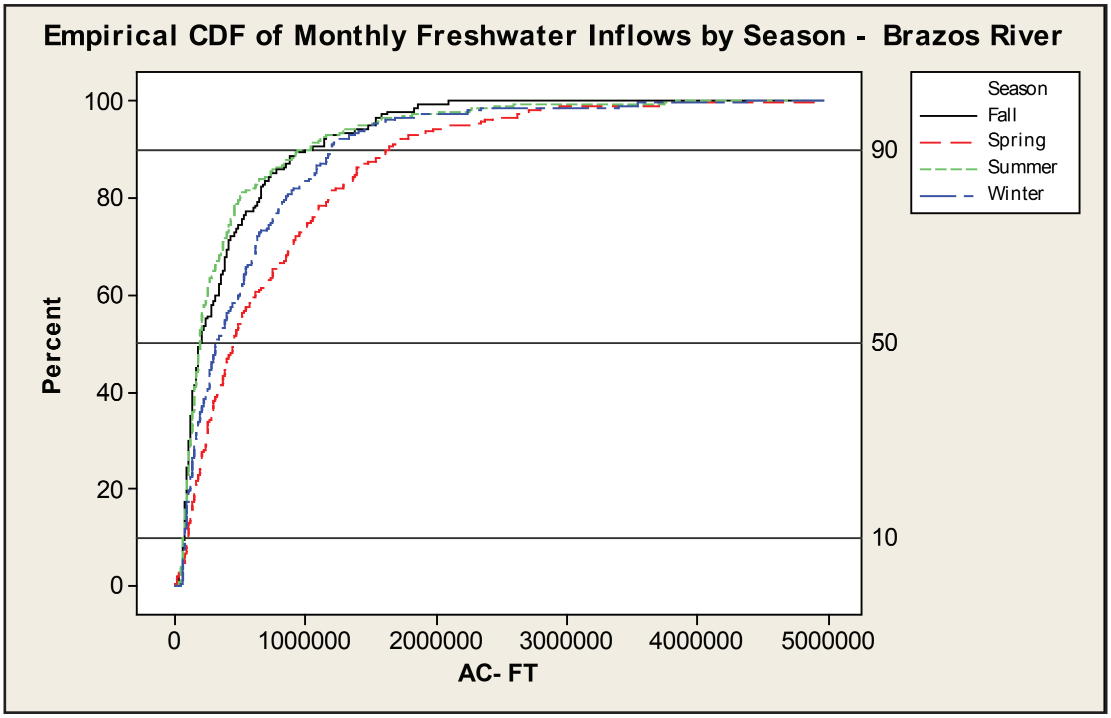


Figure 7.24. Estimated monthly Brazos estuary freshwater inflow by season based on TWDB estimated flows generated from Richmond gage and TWDB inflow estimate regression model. (Period of record October 1944–September 2010). Fall (Oct-Nov); Winter (Dec-Feb); Spring (Mar-May); Summer (Jun-Sep). Note: Seasonal periods were defined based on biological criteria (Day et al. 1989; Monaco et al. 1989) and do not reflect the BBEST definition of seasons related to instream flow recommendations. (http://midgewater.twdb.texas.gov/bays_estuaries/hydrologypage.html)

ure 7.29). In contrast, during the low flow period (August–October 1975) monthly average flows at the Richmond gage 811400 and projected monthly freshwater inflow ranged between 1,741 and 4,225 cfs or 130,775 to 289,657 acre-feet. The resulting salinity regime at surface and bottom showed a direct response with increasing levels moving further upstream. A distinct salinity wedge was always present regardless of flows encountered during this period.

Due to the lack of a paired time series of biological, water quality, and hydrological data, it is difficult to propose any specific recommendations regarding maintenance of freshwater inflows from the Brazos River to the Gulf of Mexico. Obviously, the current conditions at the mouth of the Brazos River reflect the historical record of inflows, which has resulted in a steady progressive development of a river delta that includes associated wetlands. However, without sufficient long-term biological and physical data to define more specifically what those conditions are, the effects of any variation of salinity, sediment, and nutrient supply from what has occurred historically will be difficult to predict for purposes of proposing any recommended inflow regime.

For purposes of this analysis, the Brazos BBEST assumes that the instream flow regime recommendations for the Brazos River at Richmond gage will provide sufficient inflows to support a sound environment at the mouth of the Brazos River. This recommendation is based on the riverine nature of this estuary and the use of the lower portion of the

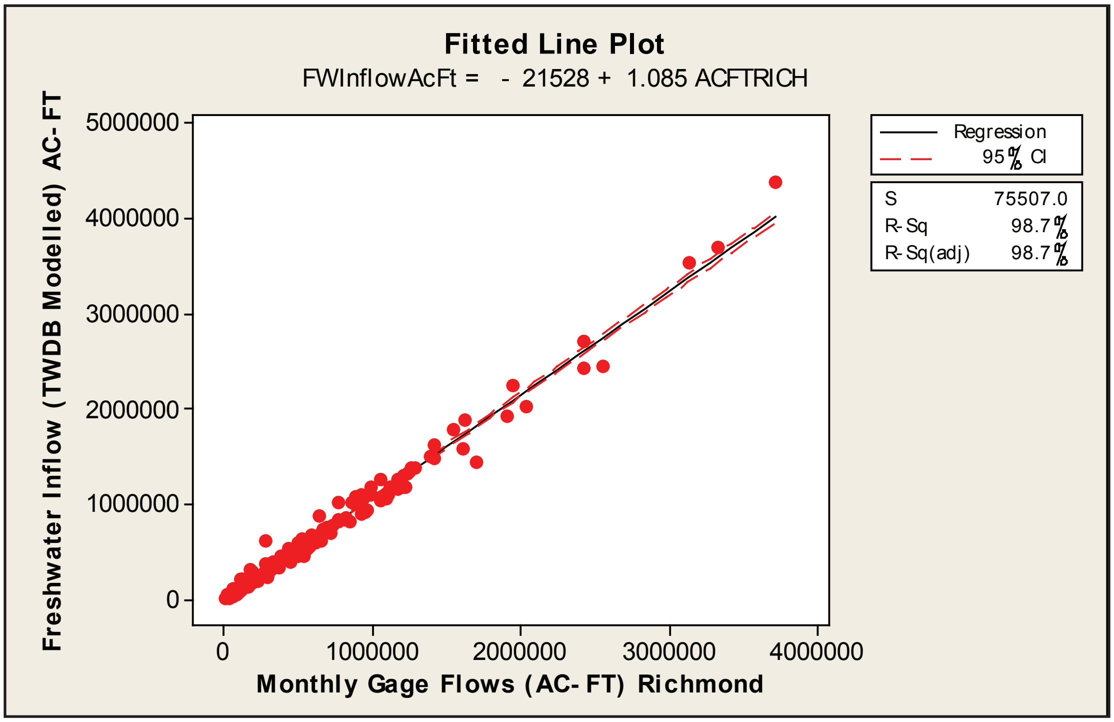


Figure 7.25. Empirical relationship between estimated freshwater inflows to the Brazos River estuary based on TWDB estimates and monthly total flow at the USGS Richmond gage 811400 (Period of record January 1940–December 1997).
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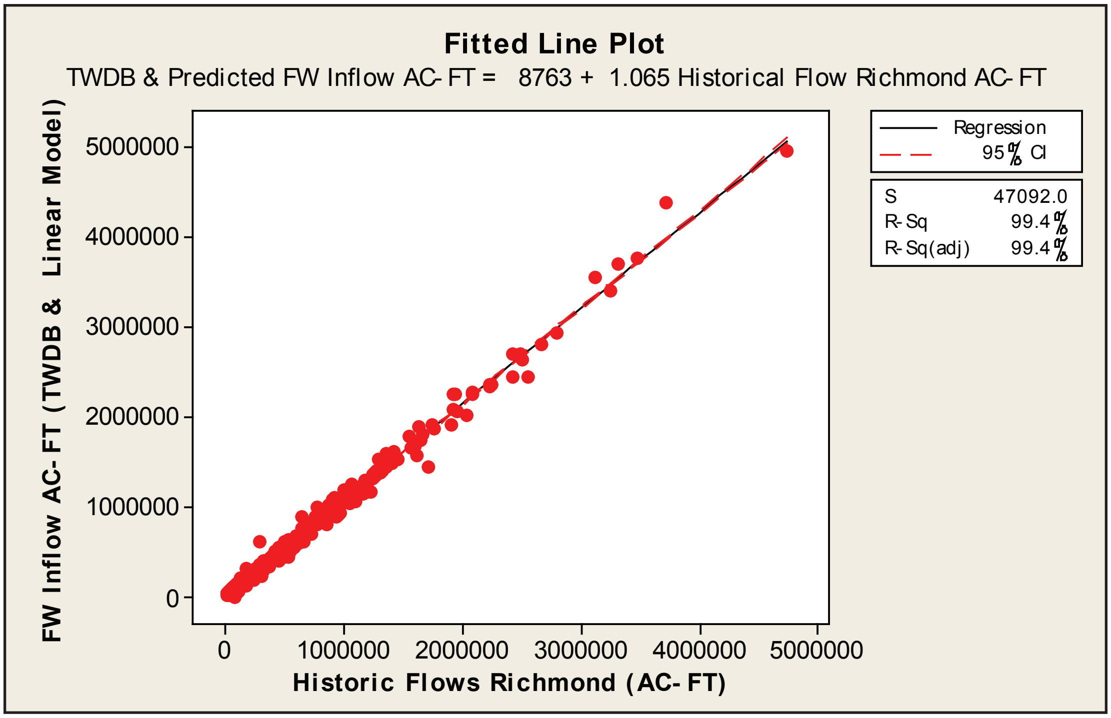

Figure 7.26. Empirical relationship between estimated freshwater inflows to the Brazos River estuary based on TWDB estimates and additional regression model estimates and monthly total flow at the USGS Richmond gage 811400 (Period of record January 1940–December 1997).
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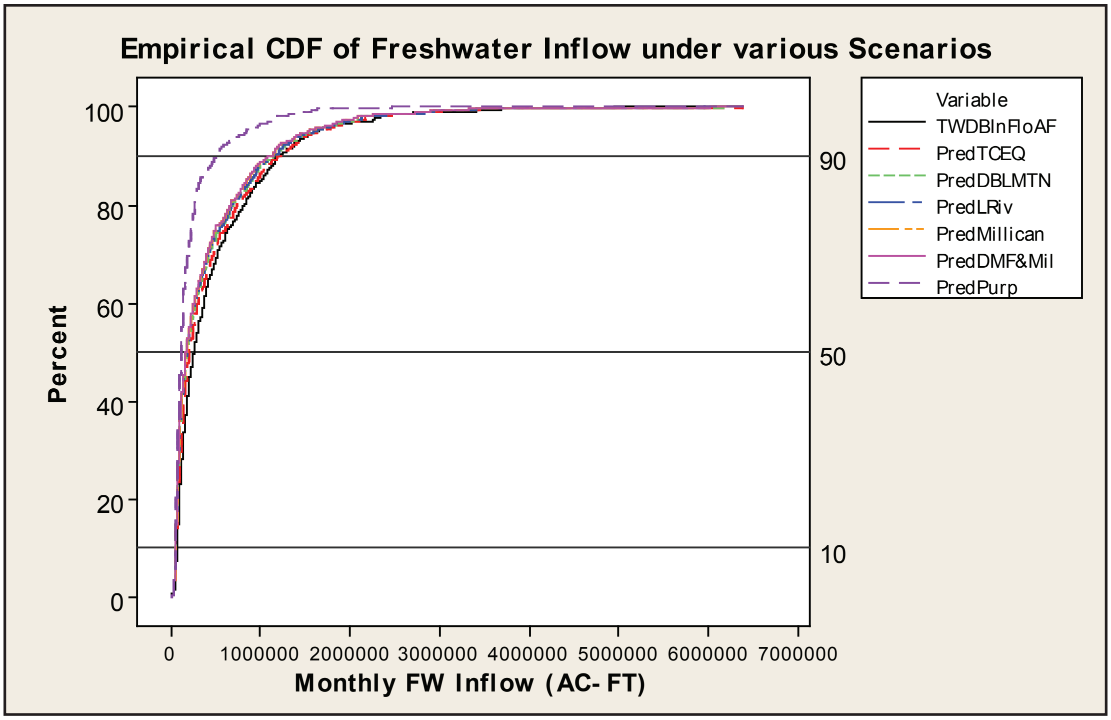

Figure 7.27. Comparison of cumulative distribution of resulting freshwater (FW) inflows to the Brazos River estuary under various project alternatives using TWDB estimates (1/77–12/09) and regression model-predicted freshwater inflows (FW) for pre-1977 and post-2009. Estimates were derived using data from January 1940–September 2010. Changes in Richmond gage monthly flows (acre-feet) were used to evaluate various scenarios considered using the period of record extending from January 1940–December 1997. TWDBInFloAF = predicted FW inflows using historical gage data; Pred TCEQ = FW inflow under current conditions (TCEQ Run 8); PredDBLMTN = with Double Mountain Fork constructed; PreLRiv = with Little River Reservoir constructed; PredMillican = with Millican-Panther Creek Reservoir constructed; PredDMF&Mil = with DMF and Millican Reservoirs constructed; PredPurp = purple curve (*E- flows only* scenario). All units in acre-feet per month.

river and upper reaches of the estuarine zone by both freshwater and estuarine organisms (Purtlebaugh 2010; Stevens et al. 2010). Here we assume that flows supporting instream functions in the lower river will provide many of the same services for the lower estuarine zone, including a flow regime that supports delivery of sediments and nutrients as well as a variable salinity regime.

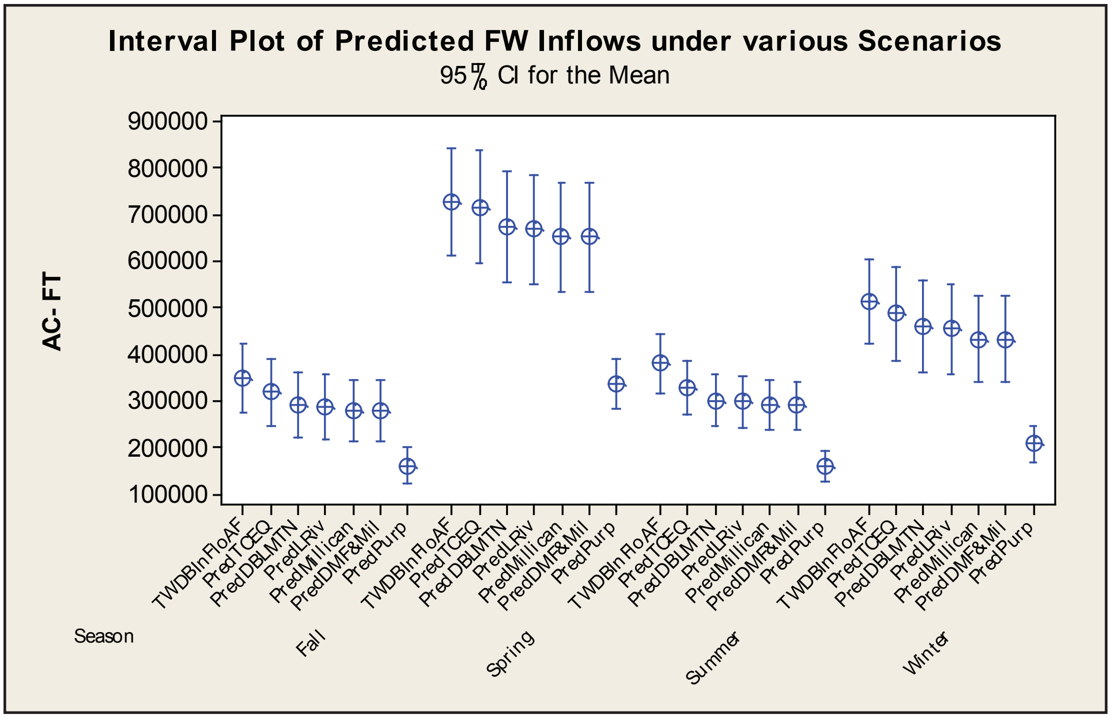

Figure 7.28. Comparison of average predicted freshwater (FW) inflows to the Brazos River estuary under various project alternatives using TWDB estimates (January 1977–December 2009) and regression model-predicted FW inflows for pre-1977 and post-2009. Estimates were derived using data from January 1940–September 2010. Changes in Richmond gage monthly flows (acre-feet) were used to evaluate various scenarios considered using the period of record extending from January 1940 –December 1997. TWDBInFloAF = predicted FW inflows using historical gage data; Pred TCEQ = FW inflow under current conditions (TCEQ Run 8); PredDBLMTN = with Double Mountain Fork constructed; PreLRiv = with Little River Reservoir constructed; PredMillican = with Millican-Panther Creek Reservoir constructed; PredDMF&Mil = with DMF and Millican Reservoirs constructed; PredPurp = *E- flows only* scenario. All units in acre-feet per month.

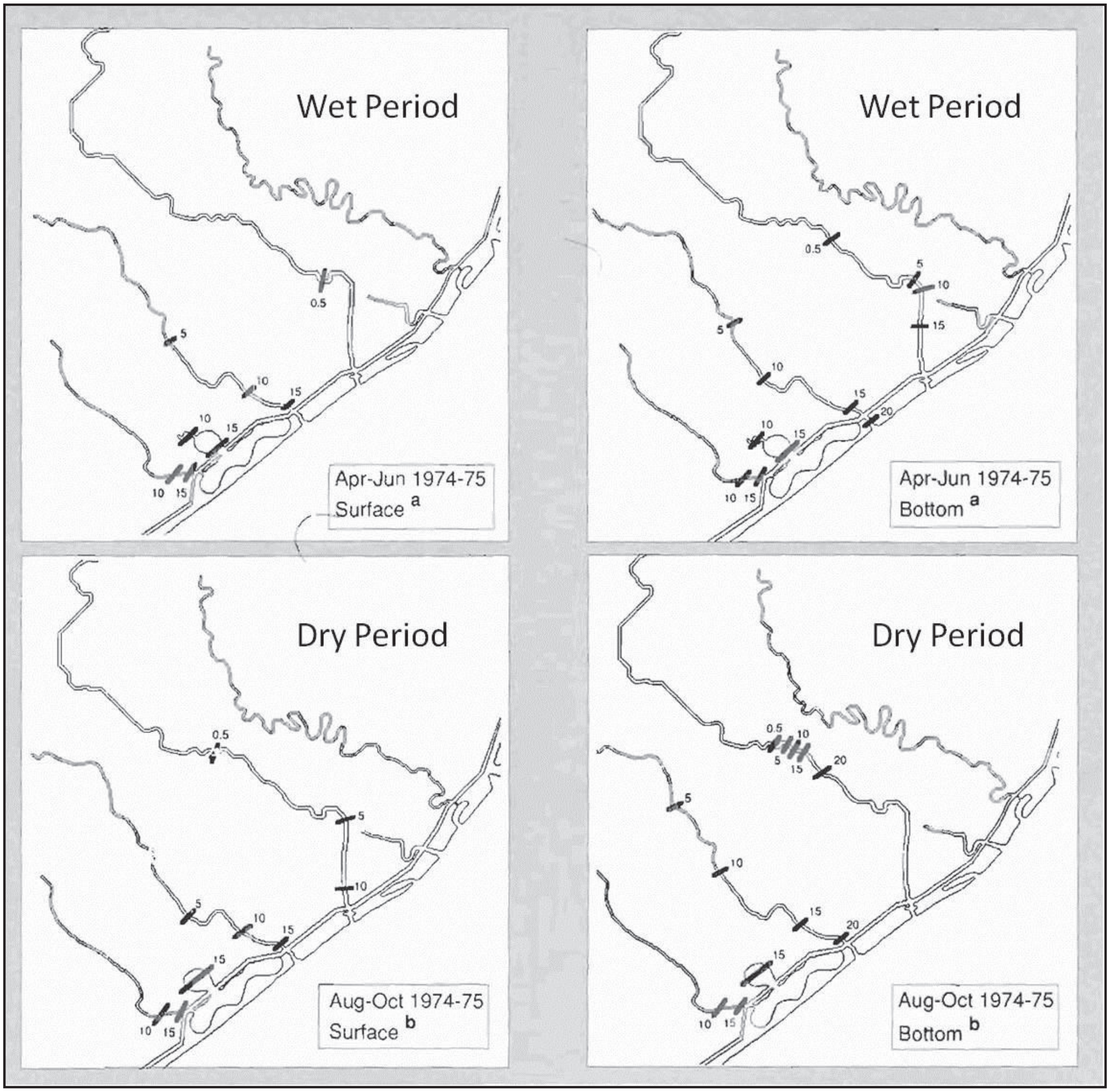

Figure 7.29. Surface and bottom salinities during April–June 1975 and August–October 1975 for the Brazos River and April–June 1974 and August–October 1974 for San Bernard River. Figure from Orlando et al. (1993). Original data sources cited in Orlando et al. (1993): a. Armstrong and Goldstein (1975) and b. Johnson (1977). Salinity expressed in units of parts per thousand.

7.4 Estuarine Inflows from the San Bernard River Basin

The San Bernard River is a small coastal river that discharges directly into the Intracoastal Waterway and then opens out to the Gulf of Mexico. The San Bernard River/Cedar Lakes estuary extends from the head of tide at the salt barrier approximately 2 kilometers upstream of State Highway 35 to its terminus with the Gulf (Orlando 1993). The estuary encompasses the area west of the Brazos River, including the associated marshes interspersed with tidal creeks. Cedar Lakes and Cowtrap Lake, located west of the San Bernard River, are the two largest areas of open water within this estuary. Most exchange with the Gulf of Mexico has occurred through the mouth of the San Bernard River. In recent times, due to longshore currents, the mouth of the river has often closed. Recently, the mouth has been dredged open. As with the Brazos River, we used the TWDB estimates and the upstream Boling gage average monthly flows to attempt to develop a predictive model to extend the time series (Figure 7.27). However, unlike the Brazos River, the model indicated that the gaged flows were not highly correlated with TWDB estimates and should not be used to estimate flows.

Historical flow probabilities are depicted based on the TWDB period of record (Figure 7.28 and 7.29). No specific alternate scenarios were evaluated as in the case of the Brazos River. Based on our analysis, freshwater inflows in the San Bernard estuary are extremely variable and often drop to low levels (<50,000 acre-feet per year). The lowest seasonal monthly flows generally occur during the month of August (Figure 7.30). Interestingly, higher monthly mean flows occur during the months of September and October versus higher flows observed during spring months in the Brazos River. However, little variation in seasonal median flows was noted (Figure 7.31).

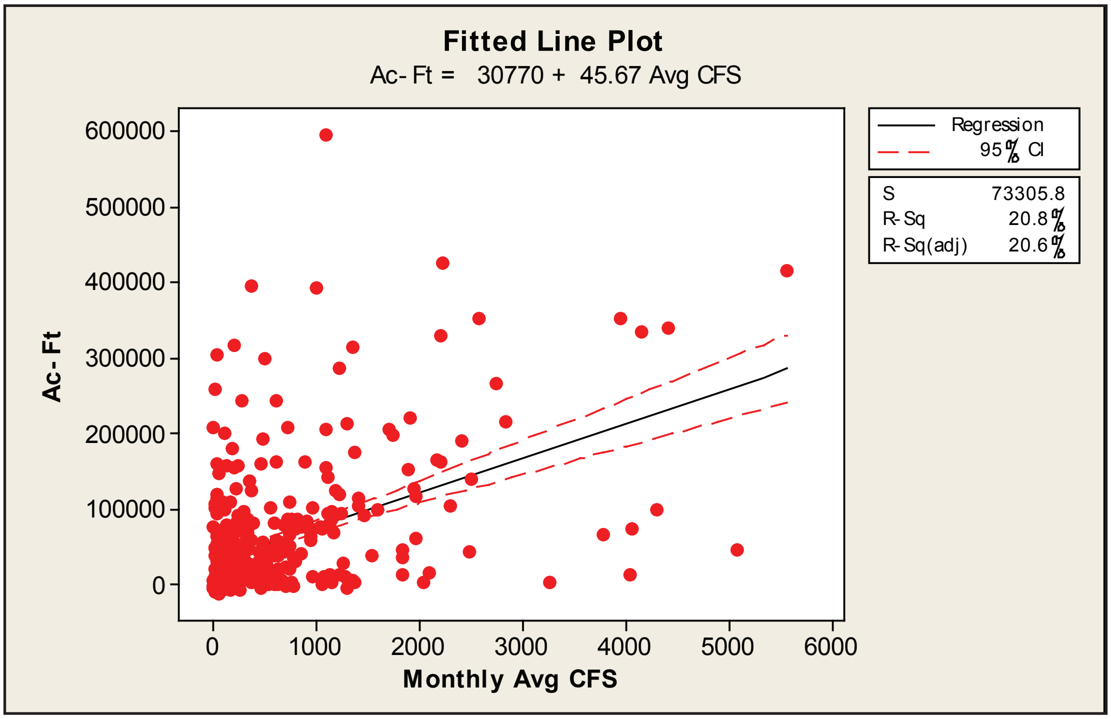

Figure 7.30. Empirical relationship between estimated freshwater inflows to the San Bernard River estuary based on TWDB estimates and average monthly daily flow at the USGS Boling gage 08117500 (Period of record January 1977–December 2009). (http://midgewater.twdb.texas.gov/bays_estuaries/hydrologypage.html)

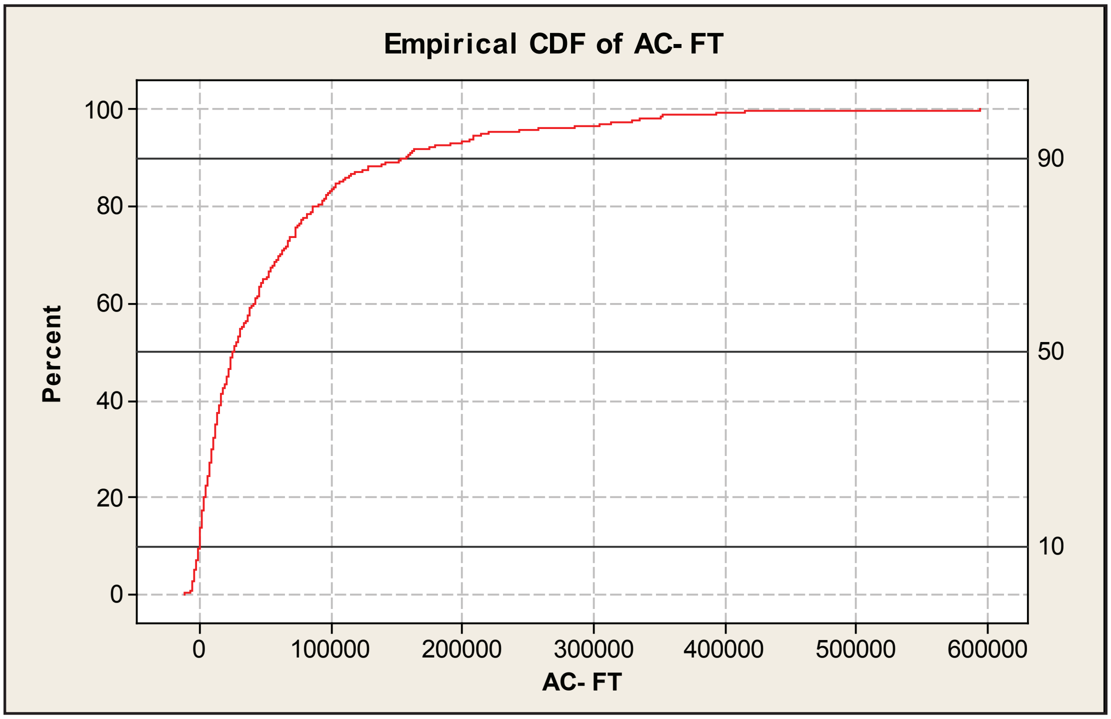

Figure 7.31. Comparison of cumulative distribution of resulting freshwater (FW) inflows to the San Bernard River estuary using TWDB estmates (January 1977–December 2009). (http://midgewater.twdb.texas.gov/bays_estuaries/hydrologypage.html)

Orlando et al. (1993) conducted an analysis of salinity at the San Bernard River during both low flow and high flow periods. For their analysis they evaluated two periods: a high flow period (April–June 1974) and low flow period (August–October 1974). No freshwater inflow estimates are available for this period from the TWDB. However, Orlando et al. (1993) stated that "freshwater inflow was 45 percent above the average flow during the wet period while it was approximately 30 percent below average for the dry period." The resulting salinity regime at surface and bottom showed a less dramatic response to the reduction in flow than the Brazos River (Figure 7.29). Evaluation of the Boling gage data, however, showed a more equivalent discharge volume during these two periods. A distinct salinity wedge was always present regardless of flows encountered during these periods.

Due to the lack of paired long-term biological, water quality, and hydrological data, it is difficult to propose any specific recommendations regarding maintenance of freshwater inflows from the San Bernard River to the Gulf of Mexico. Obviously, current conditions at the mouth of the San Bernard River reflect the historical record of inflows. However, without sufficient long-term biological, water quality, and physical data to define more specifically what those conditions are, the effects of any variation of salinity, sediment, and nutrient supply from what has occurred historically will be difficult, if not impossible, to predict for purposes of proposing any recommended inflow regime.

For purposes of this analysis, the Brazos BBEST will assume that the instream flow regime recommendations for the San Bernard River at the Boling Gage (USGS Gage No. 19552010) will provide sufficient inflows to support a sound environment at the mouth of the San Bernard River. This recommendation is based on the riverine nature of this estuary and the continuum that exists in the lower portion of the river and upper reaches of the estuarine zone, which

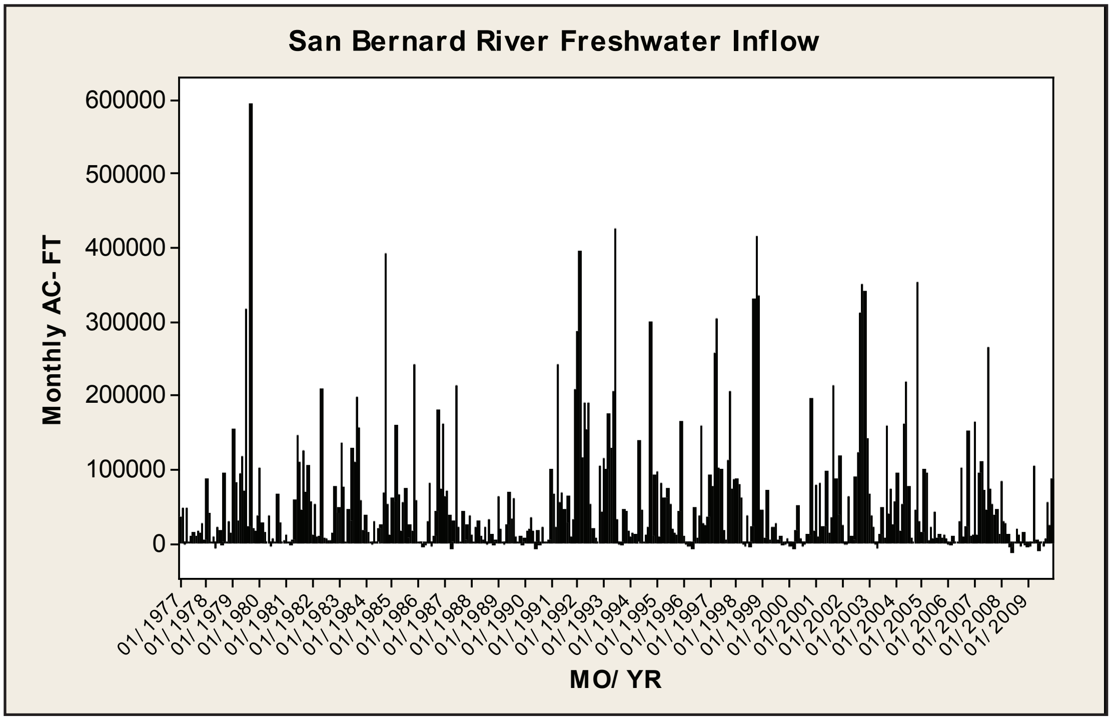

Figure 7.32. Estimated monthly freshwater inflows to the lower San Bernard River estuary and Gulf of Mexico (January 1977–December 2009) based on TWDB estimates. (http://midgewater.twdb.texas.gov/bays_estuaries/hydrologypage.html)

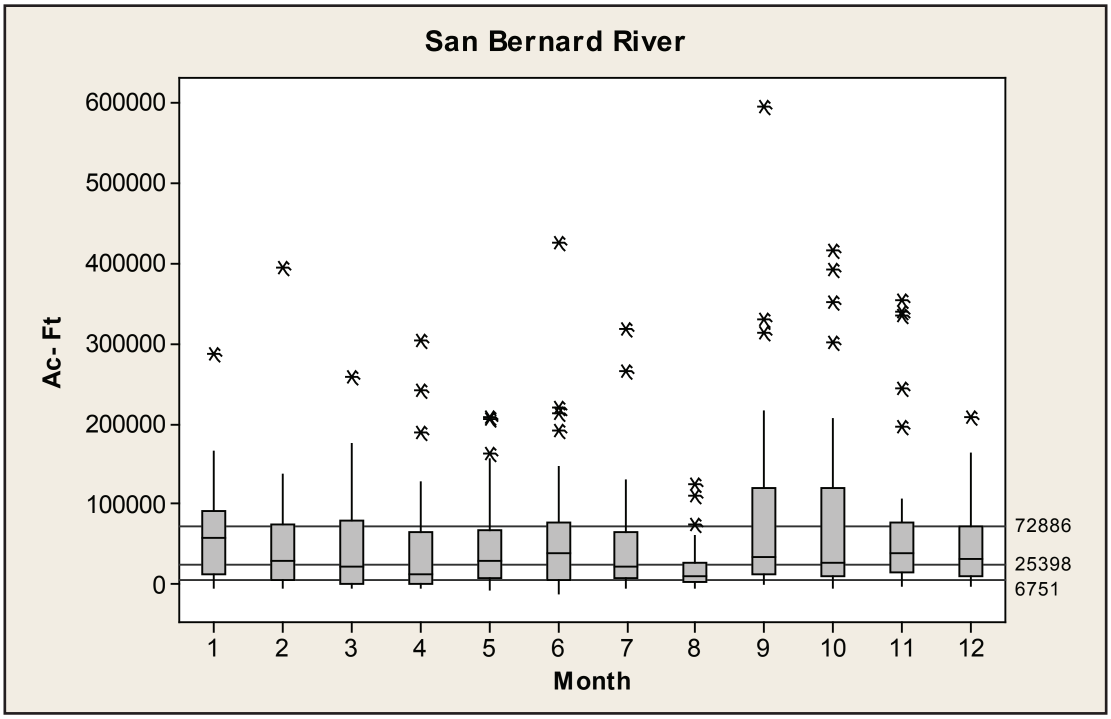

Figure 7.33. Comparison of monthly median predicted freshwater (FW) inflows to the San Bernard River estuary using TWDBestimates (January 1977–December 2009) data. Numbers on right vertical axis denote overall upper and lower quartile and median.

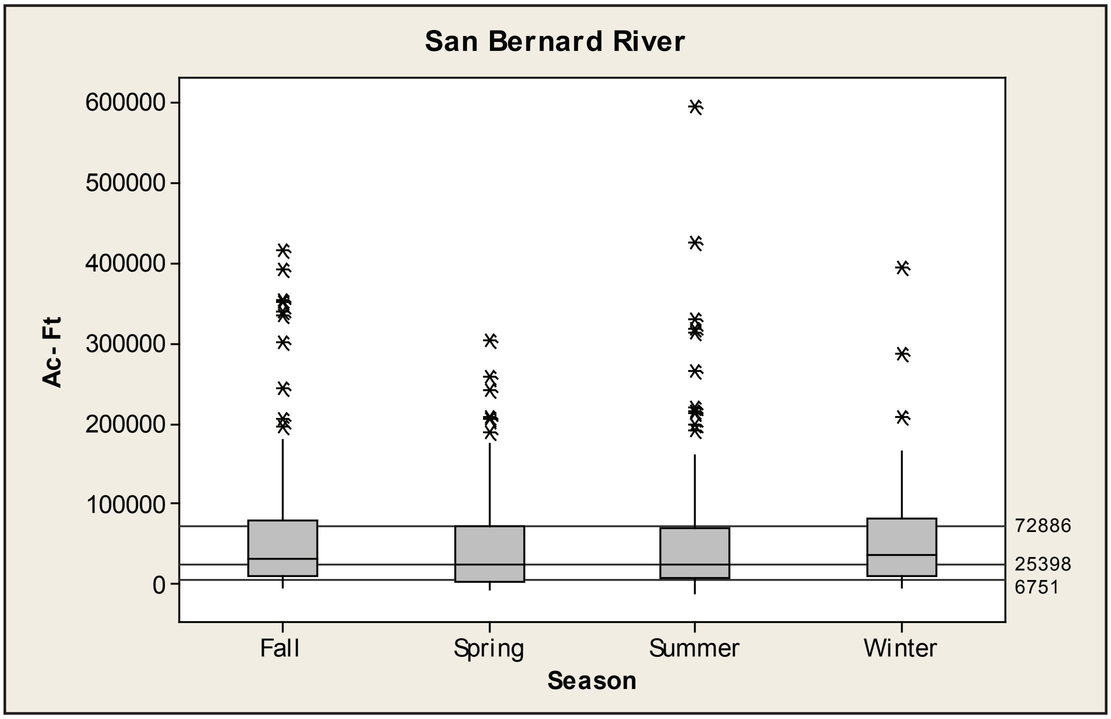

Figure 7.34. Estimated monthly San Bernard estuary freshwater inflow by season based on TWDB estimates (Period of record January 1977–December 2009). Numbers on right vertical axis denotes overall upper and lower quartile and median. Fall (Oct-Nov); Winter (Dec-Feb); Spring (Mar-May); Summer (Jun-Sep). Note: Seasonal periods were defined based on biological criteria (Day et al. 1989; Monaco et al. 1989) and do not reflect the BBEST definition of seasons related to instream flow recommendations. (http://midgewater.twdb.texas.gov/bays_estuaries/hydrologypage.html)

are inhabited by freshwater and estuarine organisms (Purtlebaugh 2010; Stevens et al. 2010). Thus, we assume here that flows that support instream ecological needs in the lower most river reach will provide many of the same functions for the estuarine zone, including varying flows that support a suitable salinity regime and delivery of sediments and nutrients.

8 Adaptive Management

The Brazos BBEST developed its recommended flow regimes based on available information and state-of-the-art analytical methods. Within the Brazos BBEST study area, site-specific data and analyses were limited and, in some instances, lacking for certain ecosystem components and regions. Our instream flow recommendations were developed over 12 consecutive months and relied on the professional judgment of the BBEST members with important data and technical inputs from staff members from agencies involved in the Texas Instream Flow Program (TIFP) created under SB2.

Adaptive management is an important component of the SB3 process. Under the adaptive management directive, the flow regime recommended here will be reassessed periodically and, where appropriate, adjusted in light of new data and improved understanding. Thus, the Brazos River and Associated Bay and Estuary System Stakeholder Committee (BBASC) should endeavor to understand sources of uncertainty associated with these recommendations and propose actions to evaluate and, where warranted, adjust our recommendations.

Below we provide recommendations for monitoring and research that will provide information and data for the periodic reviews of our environmental flows recommendations. A successful adaptive management process includes four basic steps: 1) identify data gaps and what studies are necessary to fill the data gaps; 2) secure funding and resources to implement research and monitoring; 3) conduct research and monitoring and assess results in relation to the environmental flow regime; and 4) develop mechanisms to refine the flow regime and associated implementation strategies.

The following research priorities and monitoring recommendations are broadly categorized by subject matter and provided for the BBASC to consider during preparation of its work plan.

8.1 Research Priorities, Data Collection, and Monitoring Recommendations

8.1.1 Hydrology

8.1.1.1

Texas Water Development Board (TWDB), Brazos River Authority (BRA), and US Army Corps of Engineers (USCOE) annually enter into a cooperative funding agreement with the U.S. Geological Survey (USGS) to support the annual operation and maintenance of streamflow gages in the Brazos Basin. It is recommended that cooperative funding agreements and gaging stations be continued into the future, especially for the 20 focal reaches evaluated in this report.

8.1.1.2

Some water rights holders are not currently diverting to the maximum amount allowable in their water right; assessment of the status of usage patterns by water rights holders could provide information useful for modifying environmental flow regimes and implementation guidelines.

8.1.1.3

Brazos Basin reservoirs are slowly accumulating sediment from upstream catchments. Sediment deposition reduces water storage capacity of reservoirs and water availability. Sediment accumulation has been faster in some reservoirs of the basin (e.g. Lake Granger and Lake Aquilla) and is slower than anticipated by dam engineers in other reservoirs (e.g. Lake Georgetown). The TWDB's Hydrographic Survey Program was authorized by the state legislature in 1991. The Texas Water Code authorizes the TWDB to perform surveys to determine reservoir storage capacity, sedimentation levels, rates of sedimentation, and projected water supply availability. In the Brazos Basin, reservoirs are surveyed approximately every ten years. It is recommended that support for these surveys be continued and that the latest reservoir capacity information be evaluated during the adaptive management review process.

8.1.1.4

Clearly, demand for water will increase in the near future. This increased demand has the potential to impact flows in support of the state's diverse ecological systems. Our BBEST did not attempt to address changes in future supplies because of our SB3 directive as well as basin-specific water availability estimates are lacking under climate-change scenarios. The BBEST recommends that studies be performed to assess future water supplies in terms of new water conservation practices, alternative water supplies, relationships between groundwater and surface waters, desalination potential, and other methods to maintain water, both for human use and for instream and riparian needs to maintain a sound environment.

8.1.2 Geomorphology and Sediment Dynamics

8.1.2.1

Collection of total suspended sediment (TSS) concentration is currently a part of routine water quality monitoring conducted by the Texas Commission on Environmental Quality (TCEQ), BRA, and Houston-Galveston Area Council (HGAC). Continuing data collection of this parameter will allow comparison to historical data. We recommend that TSS data collection be continued at routine water quality monitoring locations that coincide with the locations of the recommended flow regimes.

8.1.2.2

Collection of additional sediment parameters (such as suspended bed material load, bedload, and bed material gradations) should also be added at our focal gaging stations in the basin. Unfortunately, these additional parameters cannot be easily incorporated into routine water quality sampling activities, and it is cost prohibitive to collect these parameters near all of the gaging stations in the basin. In 2007, the TWDB contracted with a consulting firm to perform this type of data collection and analysis in the Brazos River reach downstream from the Navasota River confluence. The BBEST recommends that five stations, one in the San Bernard Basin and four in the Brazos Basin above College Station, should be selected for a special sediment data collection effort. This will allow comparison with historical records.

8.1.2.3

The BBEST recommends a monitoring program to evaluate channel evolution in the lower Brazos River in response to water management following provisions of the new environmental flow regimes. Monitoring should include surveying at the sites selected for recommendation 8.1.2.2, which would be permanently monumented and resurveyed at a prescribed time interval. For example, surveying a specific site annually during the winter (when sight obstruction by vegetation is minimized) is one way to collect data that may, over time, allow development of an understanding of the scour-fill cycle of the stream. Data collected at each site should allow for analysis of changes in cross-section and thalweg shape, berm formation, bank failure, and vegetation changes. Photo documentation should be part of the data set. Each segment-assessed site should be a minimum of one meander wavelength in length and cross sections should be taken along the entire length of the site at an interval of 5 to 10 channel widths apart. This will allow for identification of changes in the characteristics of channel geomorphology and riparian vegetation at the selected sites.

8.1.3 Water Quality

8.1.3.1

Per Senate Bill 818 and under contract with the TCEQ, BRA and HGAC administer and execute the Clean Rivers Program (CRP) for their respective basins. The program has been in place since 1991 and is designed to monitor general water quality, compile a long-term comprehensive database, detect trends, identify pollutant sources, and aid in water quality planning and watershed management. Additionally, the TCEQ's Surface Water Quality Monitoring (SWQM) Program performs routine water quality monitoring at specified sites throughout both river basins. Currently, water quality monitoring stations are established at or near all of the locations where the BBEST has recommended an instream flow regime. Physico-chemical data are gathered on a regular basis at each location. The routine water quality monitoring should be continued at locations that coincide with of the focal reaches for the recommended flow regimes.

8.1.3.2

During periods of extended drought, water temperature, dissolved oxygen, and pH should be recorded hourly (i.e., ever hour over a 24-hr period) whenever flows fall below subsistence flow levels and especially if a reach becomes is reduced to disconnected pools (typically a situation encountered in the upper basin). This would facilitate assessment of effects of extended periods of subsistence flows on water quality and aquatic life use criteria.

8.1.4 Aquatic Fauna, Habitat, Reproductive Ecology

8.1.4.1

BBEST flow recommendations are hypotheses and need to be validated with properly designed and replicated studies. Therefore, we recommend testing community and population responses to components of environmental flow regimes. For example, population-level responses of biota (i.e., population indices, nutrient uptake, growth, condition, reproductive success, and habitat use and selection) would be assessed during and after subsistence, dry/normal/wet base flows, high flow, and overbank flow events. Specific questions should be directed at assumptions of the natural flow paradigm, such as "do recommended subsistence flows sufficiently ensuring survival for transient periods?" and "what are the ecological benefits of high flow pulses, as recommended, to the biological community?"

8.1.4.2

Ecological soundness of stream reaches was based primarily on fish community analyses. Historical and current community analyses should be conducted on other taxonomic groups, especially mussels and aquatic insects, to gain a better understanding of current ecological soundness and to determine legacy effects that might constrain environmental flow recommendations. Some portions of Brazos Basin have diverse mussel communities with at least two of the documented species currently on the Federal Endangered Species Candidate List. Very little is known about mussel ecology and the relationship of various life stages to flows. Some mussel species depend on particular species of fish to complete the parasitic life stage.

8.1.4.3

Biomonitoring protocols for macroinvertebrates and fishes should be developed prior to the implementation of the environmental flow recommendations. Biological Condition Gradient (BCG; Davies and Jackson 2006) is the recommended model for biomonitoring, but the model needs to be developed for the Brazos River Basin.

Currently, the BRA and TCEQ's SWQM staff conducts aquatic life monitoring (ALM), which consists of fish and benthic macroinvertebrate collections and basic habitat assessment. This ALM is conducted in accordance with TCEQ's *Surface Water Quality Monitoring Procedures, Volume 2: Methods for Collecting and Analyzing Biological Assemblage and Habitat Data* and provides TCEQ baseline data on environmental conditions and data to determine if aquatic life use criteria are being attained. Although these data meet the data quality requirements for their intended use and were useful for our effort, there are some limitations in the collection methodology that limit their suitability for instream flow evaluations.

Specifically, the SWQM ALM procedure has insufficient documentation of instream habitat, substrate types, and associated species for development of habitat suitability criteria for fish and invertebrate species and/or habitat guilds. The BBEST recommends that TCEQ's SWQM Program consider incorporating increased habitat and species use documentation into Volume 2 as an optional task for ALM procedures. These optional procedures would only be used when ALM assessments are conducted at or near sites where flow regime recommendations have been developed. This would provide increased flexibility to the ALM data collected as part of the CRP by allowing it to be used for refinement of instream flow recommendations yet still meet the SWQM Program's needs for data to establish baselines and to assess attainment of aquatic life use criteria.

8.1.4.4

When ALM assessments are going to be performed at, or near, locations where the BBEST has recommended an instream flow regime, expanded data on habitat types and species use should be included in the assessment process.

8.1.4.5

No ALM assessments have been performed in the Salt Fork of the Brazos, the Double Mountain Fork of the Brazos, the Clear Fork of the Brazos, or the Brazos River upstream from Possum Kingdom Reservoir. The BBEST recommends that ALM monitoring with expanded habitat data collection be performed in these reaches.

8.1.4.6

Currently, the TIFP is using a multi-disciplinary approach to generate habitat suitability criteria and to determine flow regimes that support a sound environment for the middle and lower Brazos. The TIFP's efforts have involved state agencies (TCEQ, TWDB, Texas Parks and Wildlife Department (TPWD)), BRA, private consultants, and universities to achieve biological, riparian, water quality, geomorphological, hydrological, and hydraulics studies. Data generated by these studies will be used to identify relationships between flow and ecological processes and to generate flow recommendations. Instead of TIFP developing flow recommendations independent of this BBEST, we encourage TIFP to use the hypotheses generated herein, which will be a more efficient and cost-effective method of validating and refining our flow regime recommendations. Consequently, TIFP efforts merit continued support and funding by the state and its participating agencies.

8.1.4.7

The BBEST was unable to identify any documentation of the location, composition, or quantity of mussel beds in the San Bernard Basin. The BBEST recommends a comprehensive mussel survey in the San Bernard Basin.

8.1.5 Riparian Vegetation Monitoring

8.1.5.1

Relationships among riparian plants and their responses to flow regimes were necessarily based on the application of fundamental understanding of responses to pulse and overbank flows, which are based on the extensive scientific literature on the subject. Site-specific studies assessing the composition, coverage, and status of the riparian corridors in the Brazos and San Bernard River basins were generally lacking. The SB2 TIFP Riparian Monitoring Protocol implements a comprehensive, standardized data collection process within riparian corridors. The BBEST recommends extending the TIFP riparian assessments to include assessments near our 20 focal reaches associated with gage stations. These data could then be used as a baseline to track future changes in riparian communities and their relations to flow regime alterations.

The BBEST further recommends that these riparian corridors be assessed every 10 years to evaluate the degree to which recommended flow regimes and implementation strategies maintain riparian vegetation communities characteristic of a sound ecological environment.

8.1.5.2

Given the large amount of disturbance experienced by riparian vegetation communities in the basins of the Study Area (see Temporary Erosion and Sedimentation Control Plan (TESCP)), it is recommended that a survey of both the Brazos and San Bernard rivers and their major tributaries be performed to quantify the locations and extent of damage. This information could then be provided to federal and state agencies and non-profit organizations that educate, sponsor, and/or conduct riparian enhancement and reforestation projects.

8.1.5.3

Portions of the Brazos River Basin are being overrun by the non-native, invasive shrub saltcedar (*Tamarix* spp.) that is outcompeting native riparian vegetation in many areas. Saltcedar now dominates the riparian community in the upper Brazos floodplain and has been identified in other parts of the Brazos Basin. Currently, there is not a thorough accounting of the extent of saltcedar encroachment in the basin. The BBEST recommends working with USGS to complete a study to locate and quantify saltcedar encroachments into the Brazos River riparian corridor and to identify changes in channel morphology associated with saltcedar encroachment.

Based on the results of a saltcedar survey, the BBASC may choose, during a subsequent adaptive management review, to recommend a control strategy for situations in which saltcedar is causing impairment to the native vegetation, degradation to the river channel, and reduction in available surface water (Chew 2009; Shafroth et al. 2008; Stromberg et al. 2009).

8.1.5.4

Currently, not all portions of the Brazos are covered by the TESCP project. The BBEST recommends that as additional phases of the TESCP are completed, the portions of the Brazos not currently covered be mapped and assessed following the protocol documented in Section 4.4 Riparian Vegetation Communities.

8.1.6 Estuarine Monitoring

8.1.6.1

Sediments transported from the river system to the estuary reduce erosion and land subsidence in coastal zones; however, this process may be lessened in the Brazos River Basin by sediment capture in upstream reservoirs. The BBEST recommends that sediment discharge loads carried by freshwater inflows should be calculated in relation to flow regimes to determine the contribution of these sediments in moderating erosion and accretion rates along the coast.

8.1.6.2

Marine dead zones can be caused by an increase in dissolved and particulate nutrient delivery (particularly nitrogen and phosphorus) in river discharge. These nutrients can lead to increases in the density of certain types of phytoplankton and subsequent hypoxia caused by both respiration and decomposition. In 2007 high rainfall resulted in twice the average discharge of the Brazos River into the Gulf of Mexico as normal. This stormwater carried a high nutrient load from urban and rural runoff. The rapid influx of nutrients into the Gulf of Mexico created a temporary dead zone. Currently, the CRP collects nutrient samples in freshwater throughout the Brazos and San Bernard basins. The BBEST believes it would be beneficial to also routinely monitor the Brazos and San Bernard estuaries and adjacent coastal wetlands for nutrient concentrations, which would permit evaluation of nutrient dynamics in relation to flows.

8.2 Scheduling, Funding, and Entities Involved

8.2.1 Schedule

The schedule for implementation of recommended research and monitoring is to be determined based on prioritization of work plan activities by the BBASC; hence, any dates or priorities specified in this section are for illustrative purposes only. The schedule may change based on availability of resources and revised needs for information. Most projects are scheduled to be completed by 2021 to allow review and revision of reports and development of BBASC recommendations to the TCEQ. By 2022, the BBASC may provide the TCEQ and the Environmental Flows Advisory Group a report validating and/or revising instream flow regime recommendations and suggestions for future monitoring, studies, and activities.

In some cases, monitoring, research, and modeling activities may continue past 2021. For example, it may take decades to fully assess the relationship of various life history strategies of different species with instream flow regime components and validate the instream flow regime's suitability for protecting ecological soundness.

The research/monitoring timeline proposed in Table 1 is hypothetical and will most likely need to be adjusted following BBASC selection and prioritization of work plan activities. Actual initiation of many of the recommended research and monitoring projects will depend on securing appropriate resources, and the proposed timeline may also need to be adjusted based on the availability of funding for different types of projects. While it is not anticipated that the proposed timeline will strictly follow the order of priorities, it is anticipated that the priorities will be used as a guide to identifying funding opportunities for measures having the best value in terms of filling data gaps to better refine flow regime recommendations.

8.2.2 Entities Involved

Organizations expected to contribute to the work described include state agencies: principally the TWDB, TCEQ, and TPWD, with possible support by the Texas General Land Office, Texas State Soil and Water Conservation Board, and the Texas Department of Agriculture.

Federal agencies that may help include the USGS, U.S. Environmental Protection Agency (U.S. EPA), U.S. Fish and

Wildlife Service (USFWS), U.S. Department of Agriculture's Natural Resource Conservation Service, U.S. Bureau of Land Management, National Oceanic and Atmospheric Administration, and USCOE.

River authorities, local councils of government, municipalities, water suppliers, and water users may also be involved. Colleges, universities, and their associated research consortiums across the state engage in research and monitoring that may produce the types of information sought in the work plan. In this basin, particularly important academic institutions include Texas Sea Grant, Texas AgriLife Research, Texas AgriLife Extension Service, Texas Water Resources Institute, Texas A&M Institute of Renewable Natural Resources within the Texas A&M University System; Texas State University; Texas Tech University; the Environmental Institute of Houston at the University of Houston-Clear Lake, the Center for Reservoir and Aquatic Systems Research at Baylor University, and the Texas Institute for Applied Environmental Research at Tarleton State University.

Some nonprofit organizations, including the National Fish and Wildlife Foundation, Houston Endowment, The Nature Conservancy of Texas, local chapters of Ducks Unlimited, and local chapters of Texas Master Naturalists, may collect data relating to environmental health, document the composition of riparian communities, and engage in riparian restoration projects. This is a preliminary list of organizations involved; this list should be updated as responsibilities, key personnel, and funding priorities of different organizations change with time.

8.2.3 Funding and Resource Availability

Funding and resource availability are expected to be significant hindrances to completing the research priorities and data collection efforts recommended above. While the federal and state agencies and local governments identified in 8.2.2 have the technical resources to perform many of the recommended tasks, the availability of those resources is significantly limited. Most of the government staff have workloads and pre-existing obligations exceeding their critical maxima. Some of the recommended items may be able to be absorbed by government staff over the next ten years. Completion of the majority of the tasks before the next adaptive management review will most likely require help from universities, research institutes, and consulting firms. Participation by universities and research institutes will be necessary to complete recommended life history-flow regime validation.

As dire as the resource availability situation appears, funding availability will be an even larger obstacle to overcome. The federal government and state government are both presently in a state of budget crisis, direct funding for research and monitoring has vanished, and grant funding is on a steady decline. Historically, the CRP may have been able to absorb some of the recommended tasks that fall within the bounds of their legislatively defined intent, but the program has been tasked with increasingly more duties by TCEQ since the legislature created it in 1991. Despite increasing reliance on the program for the majority of the state's surface water quality data collection, the CRP has not received a funding increase since its inception. Additionally, the program's budget was subject to a 10 percent cut in FY 2011. CRP partners in most river basins are contributing an additional 30-40 percent of the program cost from their water system budget just to meet the core objectives of the CRP for their basins. Further confounding the funding issue is the federal government's trend towards favoring implementation projects to remedy defined problems over research and data collection projects to characterize problems or further general knowledge.

While the task of obtaining funding is daunting, it is not insurmountable. The BBEST has compiled a list of potential funding sources and programs that may be pursued by the BBASC to fund some or all of the recommended data collection and research efforts (Table 8.2). In some instances, the BBASC may need to be flexible with the specifics of individual tasks and be willing to modify tasks as appropriate to access funding sources not directly intended to support the SB3 process. Additionally, the BBASC will need to be willing to be moderately adaptable once tasks have been prioritized and scheduled. Flexibility will allow the BBASC to access funds that would not be available if a rigid adherence to the priority list is maintained (e.g. pursuing a grant that would fund task 5 even though tasks 1-4 have yet to be funded).

One avenue of funding where there is much promise will require the BBASC to appeal to universities, research institutions, and non-profit organizations. There are many research grants available to these groups that are not available to state or local governments, and the grants might fund some of the recommended assessments and research. Additionally, there are many grants available to university students, from undergraduate to post-doctoral, to fund the study of the environment.

The BBASC is responsible for developing the work plan with assistance, if desired, from the BBEST. Some of the recommended projects will require the creation of multi-agency and/or multi-disciplinary teams and will require a clear leadership structure for each project. Perhaps the most important question not addressed by SB3 is who will ultimately guide accomplishment of work plan tasks and who will be responsible for ensuring that funding is obtained. The TWDB is expected to have a prominent role because of its responsibilities for managing water supplies and its funding of water-related research. The TCEQ and TPWD are expected to be included because of their extensive roles and experience in maintaining ecological health of streams and estuaries, and also might share responsibility for ensuring the projects in this work plan are implemented.

8.3 Potential Issues for Adaptive Management

Many issues exist that are currently in the early phases of understanding that may impact current assumptions of the relationships between flow and the ecological health of streams and bays. The BBEST has compiled a list of issues to be examined for potential impact on instream flows and ecological soundness during the future adaptive management reviews; a brief discussion of each issue is presented below.

Texas Instream Flow Program Recommendations

SB2, enacted in 2001 by the Texas Legislature, established the Texas Instream Flow Program. The TIFP is administered by the TCEQ, TWDB, and TPWD. The purpose of the program is for the three agencies to perform scientific and engineering studies to determine flow conditions necessary for supporting a sound ecological environment in the river basins of Texas. Then the three agencies must develop instream flow recommendations for each river basin studied. It is anticipated that TIFP studies will be complete by 2016. With two separate but conjunctive processes developing instream recommendations, it is possible for the SB2 and SB3 recommendations to be contradictory. It is not clear in the legislation exactly how TCEQ is expected to handle two sets of recommendations when developing its regulations for instream flows.

The SB2 study area for the Brazos Basin included the Brazos River below Waco, the Navasota River, and the Little River. The studies being conducted for this portion of the Brazos will be of incalculable value for the BBEST during first adaptive management reviews. The study results will fill many data gaps for the lower portion of the Brazos Basin and allow the BBEST to refine flow regime recommendations for this portion of the basin. The BBEST has recommended that similar data collection efforts and studies be expanded to cover the remainder of the Brazos Basin and be started in the San Bernard Basin. It is unlikely that such studies will be complete for the first adaptive management review, but they might be available to inform future reviews.

New Water Storage Projects

Many potential, new reservoir projects exist for the Brazos River Basin in the regional water plans. It is noted in the plans that new reservoir projects are an important option for the development of future water supplies. While most of the potential reservoirs are not likely to be developed in the near term, there are a few that may come to fruition in the next several decades. The regional water plans acknowledge that the impact of new reservoirs will be lower variability and reductions in quantity of median monthly flows and that there will be impacts on the biological community in the immediate, downstream vicinity of the project site. While the plans conclude that no single project is likely to have a substantial influence on total discharge in the Brazos River or to freshwater inflows to the Gulf of Mexico, it is acknowledged that the cumulative impact of multiple potential reservoirs may reduce freshwater inflows to the Gulf of Mexico. Completion of new water storage projects will dictate a review of recommended flow regimes downstream of the projects to ensure the flow regime is providing adequate flow to maintain a sound environment in the affected river segments and to ensure sufficient water is reaching the Gulf of Mexico.

Off-Channel Reservoirs

Implementation of off-channel reservoirs is becoming more common as increasing environmental constraints limit the development of major on-channel reservoirs. The concept of the off-channel reservoir is to divert water from a primary stream during high flows to storage in a reservoir constructed off of the stream channel. Off-channel reservoirs have the advantage of providing a firm supply during time of drought when run-of-the-river diversions are not available. However, the entire schematic of an off-channel reservoir relies upon scalping high flow events that may have an impact on the ecological soundness of the stream. Any new off-channel reservoirs authorized will be subject to instream flow regulations adopted by TCEQ so their impact to the recommended flow regime should be limited.

Wastewater Reuse

Wastewater reuse is becoming a popular water supply option for many communities. Treated wastewater effluent, instead of potable water, is used for a variety of non-consumptive purposes including irrigation of public and recreational lands, cooling tower water for power generation, and other specific industrial uses. Reuse is classified into two forms: direct and indirect. Direct reuse is piped directly from the wastewater treatment plant to the point of use, while indirect reuse discharges treated wastewater to a stream for subsequent diversion downstream.

Increased pressure on water suppliers will result in an increased emphasis on reuse, and reuse quantities may eventually approach the quality of effluent generated. The impact of reuse projects on streamflows in the study area has not been well documented.

Future indirect reuse authorizations and their amounts will be subject to both instream flow regulations and the doctrine of prior appropriation. Any remaining reuse flows after instream flow needs are met and downstream water rights holders with priority needs are met could be permitted for indirect reuse. Increasing wastewater reuse has the potential to improve water quality through reducing the anthropogenic nutrient load to the aquatic environment. However, uncertainties regarding the overall impact on instream flows, especially in effluent dominated systems, will necessitate assessment of the impacts of increased reuse on instream flows during an adaptive management review.

Nutrient Standards for Streams

The U.S. EPA has mandated that states incorporate numerical nutrient criteria in their water quality standards. In June 2010, TCEQ adopted new numerical nutrient criteria for 75 reservoirs and completed new procedures to evaluate and control potential nutrient impacts from proposed wastewater discharge permits. TCEQ is now conducting additional studies and evaluations to develop potential numerical nutrient criteria for selected streams, rivers, and estuaries in Texas. TCEQ is forecasting that it will complete the draft version and public input process for these new standards by 2013.

Nutrient concerns in water are generally a result of poor land management practices, direct discharge of wastewater treatment plant and industrial effluents, and, in a few isolated areas, underlying geology. The nutrients are either directly discharged into the stream or are washed in by stormwater runoff. Nutrient inputs into streams are not going to be ameliorated by the adoption of instream flow regime recommendations. Instituting better land management practices and removing nutrients from permitted discharges will help to ameliorate negative impacts on streams from nutrients. TCEQ's development of instream nutrient criteria will provide it the regulatory base needed to address nutrient issues in the waters of Texas.

While nutrient concerns are unlikely to be diminished by establishing instream flow regimes, excess nutrient loads can impair the environmental soundness of the aquatic ecosystem. An ongoing BRA evaluation of the lower Brazos has revealed elevated nutrient loading, excessive primary production, and potentially associated aquatic life effects. In addition, a potential for Gulf of Mexico dead zones exists at the mouth of the Brazos, as discussed in Section 8.1.6.2 and would be magnified by further increases in Brazos River nutrient loading. Nutrient standards should be adopted by TCEQ by the time the adaptive management review process begins. The newly adopted criteria should be reviewed by the BBEST and BBASC to determine how the criteria will contribute to improving environmental soundness.

Saltwater Barrier

During low flow periods on the Brazos and San Bernard rivers, saltwater moves upstream beneath overlying freshwater layers. This "salt wedge" at times reaches the water intakes for industrial and municipal users. In low concentrations, saltwater is corrosive, damaging to industrial processes, and more expensive to treat; it also does not meet drinking water standards. In higher concentrations, the water cannot be used at all. To prevent this problem in other river basins, such as the Neches, Trinity, San Antonio, and Guadalupe rivers, saltwater barriers have been constructed.

In the Brazos Basin, freshwater is sometimes released from upstream reservoirs to prevent saltwater intrusion during dry periods. Historically this has occurred infrequently; though when it has occurred, the volumes of water were significant. If a saltwater barrier were present, reservoir releases for saltwater intrusion control would no longer be necessary, which would conserve freshwater for environmental flow or consumptive needs.

The Region H Water Planning Group conducted a preliminary analysis of constructing a saltwater barrier on the Brazos River. The analysis indicated that more detailed study and data collection is warranted and a saltwater barrier for the Brazos River is a recommended strategy in the 2011 Region H Water Plan. A saltwater barrier on the Brazos River could have a positive impact on upstream water availability and habitats. Additionally, most of the existing saltwater barrier permits have a minimum pass-through flow requirement. If this project comes to fruition, it will need to be reviewed by both the BBEST and BBASC to determine if the project is improving water quality in the lower Brazos River, allowing sufficient flows to the Gulf of Mexico, increasing water available for instream flows above the barrier, and whether recommended flow regimes need to revised.

Desalination

Given the Brazos River mainstem's elevated chloride and total dissolved solids concentrations from brine springs in the upper basin and brackish groundwater in many of the aquifers in the basin, desalination is becoming a more attractive, affordable, and relied-upon option for potable water for municipalities and industries. However, increasing reliance on desalination could have some negative implications. Desalination technology provides many more options for access to water supply that traditionally would have been unsuitable for human consumption or industrial process. Access to additional waters may result in areas not currently subject to diversion or areas of very low diversion seeing increased rates of diversion and, thus, reduced instream flows.

Desalination generates a highly concentrated brine by-product that must be disposed. The current method of disposal for the brine is discharge back to the nearest body of surface water or deep well injection. Existing, permitted brine disposal rates into the Brazos are *de minimis* and do not appear to be having a negative effect on water quality at this time; however only four permitted discharges currently exist in the upper portion of the Brazos. The cumulative effects of multiple, additional brine disposal permits is uncertain. Increased brine would affect the aquatic ecology of small streams, alter the chemical composition of water bodies over an extended period, and exacerbate an already troublesome natural condition.

Groundwater/Surface Water Conjunctive Use

Some regional water planning groups have recommended conjunctive use of surface water and groundwater resources. Surface water would be relied on primarily during wet and normal periods and groundwater during drought. During drought, the firm yield of surface water supplies can be nonexistent or very limited. During these dry times, groundwater supplies could be tapped to augment the surface water supply and create a meaningful firm yield. If a conjunctive use project is developed in either the Brazos or San Bernard basins, potential effects should be evaluated during adaptive management reviews to determine if there are impacts on surface water quality or changes in instream flow during periods of subsistence or dry-baseline flows. If there are impacts of these types, the recommended flow regime may need to be adjusted accordingly.

Changes to Classifications on Federal and State Threatened and Endangered Species Lists

Currently, there is only one species on the Federal Endangered Species list that may be affected by instream flow in the study area, the Houston toad (*Bufo hustonensis*). The species, which occurs in the Brazos and San Bernard basins, lives primarily on land but does require still or slow-flowing water that persists for at least 30 days for breeding and tadpole development.

Critical habitat has been established for the Houston toad at one location within the Brazos Basin, a one-mile radius around Woodrow Lake in Burleson County. This location is over four miles from the Brazos River and its riparian corridor. Subsequent population surveys have identified more populations since listing. Several habitat restoration and habitat conservation projects are currently in progress.

Four other species known to occur in the Brazos Basin are on the federal candidate species list, including two fishes, smalleye shiner (*Notropis buccula*) and sharpnose shiner (*Notropis oxyrhynchus*), and two mussels, the Texas fawnsfoot (*Truncilla macrodon*) and smooth pimpleback (*Quadrula houstonensis*). Candidate species are those for which the USFWS has determined that there is sufficient evidence on biological vulnerability and threats to support a proposed rule to list but issuance of the proposed rule is precluded by other listing actions. In addition to the aforementioned species, the Brazos water snake (*Nerodia harteri*) is currently on the state's threatened list due to its limited range in the middle reaches of the Brazos River.

All of these species are affected by instream flows and water availability at some point in their life history, if not totally dependent. Both the federal and state threatened and endangered lists should be reviewed during the adaptive management review process to determine if amendments to critical habitat designations for federal endangered species have occurred, or whether or not any candidate species have been elevated to threatened or endangered status. Changes to species threatened and endangered status could influence flow regime recommendations in reaches inhabited by the species.

Zebra Mussels

Zebra mussels are spreading rapidly across the North America with strong infestations in reservoirs and streams in Oklahoma, Arkansas, and Louisiana. Mussels have now been found in Lake Texoma and Lake Lavon watershed in the Trinity Basin north of the Dallas/Ft. Worth metroplex. While it was once thought that water temperatures in the southern United States were too warm to support zebra mussels, this exotic mussel seems to be highly adaptive. Temperature tolerance of zebra mussels can shift in a just a few generations. Zebra mussels alter the ecology of lakes and rivers, render lakes more susceptible to harmful algae blooms, degrade recreational aesthetics, and clog intakes, trash racks and pipelines. Efforts to stem the expansion of the zebra mussel range across the United States have been ineffective. TPWD is currently mounting an aggressive public outreach campaign to educate the boating public about the mussels and how to prevent their spread.

Climate Variability

The scientific community has documented a global warming trend (IPCC 2007), and there is much debate about the relative contributions of human actions and natural processes to this pattern. If the warming trend continues, this obviously will impact the hydrological cycle in the Brazos Basin just as in other regions of the planet.

Sea Level Rise

Estuaries are the most productive ecosystem in the state and provide a variety of valuable ecosystem services. They provide rich habitat for numerous bird species; are nurseries for saltwater fish, crabs, shrimp, and shellfish; provide erosion control and storm surge protection; regulate the atmosphere through carbon sequestration; and trap nutrients and sediment that are carried from the land by rivers and from the ocean by tides. Additionally, Texas' estuaries play a strong role in the state's economy by providing inland navigation channels, vast resources including minerals and seafood, and recreational opportunities. Texas estuaries contribute billions of dollars to the state's economy annually. Texas' open-water bays, intertidal mudflats, and fringing marshes are being impacted by reduced freshwater inflows, pollution, increasing temperatures, saltwater intrusion, and seawater acidification.

Sea level is rising along most of the U.S. coast and around the world. It is anticipated to continue to increase during the 21st century, although the magnitude of this increase cannot be projected with precision. The world's oceans have been absorbing most of the excess heat generated by climate change; this has led to expanding ocean water, melting mountain glaciers and small ice caps, and melting portions of Greenland and the Antarctic ice sheets. All of these changes have contributed to the observed rise in sea levels.

Depending on the location of water intake structures for drinking water plants and industry and the degree to which the saltwater pushes inland, sea level rise may also have a direct impact on human use. Sea level projections can be informative to instream flow recommendations and sound environment determinations for the lower part of the Brazos Basin and the entire San Bernard Basin.

Carbon-Cycling and Ocean and Estuary Acidification

In addition to increased global temperature and increased sea levels, increased acidification of ocean and estuary waters is being observed. The world's waters absorb carbon dioxide (CO_2) from the atmosphere. The rate of CO_2 emitted to the atmosphere has been on a steady rise since the industrial revolution. The world's water is now absorbing more CO_2 than ever before. When the CO_2 is dissolved into the water, it creates carbonic acid and reduces the water's pH.

An increase in the acidity of ocean and estuarine waters can have direct impacts on marine organisms by reducing the amount of calcium carbonate ($CaCO_3$) available in the water. $CaCO_3$ is a key structural element for many marine organisms including corals, mollusks, and shellfish. Declines in these organisms will reduce the overall productivity of marine and estuarine ecosystems.

One potential contributor to increased acidification of marine and estuarine waters may be freshwater ecosystems. While certain roles of freshwater systems in the carbon cycle are well understood, many questions remain to be answered.

CO_2 is more soluble in freshwater than in saltwater and the degree of solubility is determined by the pH and mineral composition of the receiving water. In systems with carbonate minerals present, dissolved CO_2 and $CaCO_3$ are generally in equilibrium and a change in pH will cause either the release of CO_2 to the atmosphere or the absorption of CO_2 from the atmosphere. Additionally, in waters with cations present, CO_2 will react with the cations and form insoluble carbonates, which precipitate out of the water, thus reducing dissolved CO_2 levels in the water and creating a carbon sink in the sediments of lakes and rivers.

While freshwaters can be a sink for large quantities of carbon, they can also release large quantities of CO_2 to the atmosphere. Recent research suggests that freshwater may release almost as much CO_2 into the atmosphere as terrestrial ecosystems (Butman and Raymond 2011). While freshwater systems clearly have a role in the natural carbon cycle, the exact nature and degree of their contribution is not well understood.

Table 8.1. Proposed research priorities and timelines.

Number	Recommendation	BBEST Recommended Priority	Current Funding	Agencies/ Organizations	Status	Start Date	End Date	Dependent on Specific Climatological Conditions
8.1.1.1	Maintenance of USGS gages	1	Y	USGS, USCOE, TWDB, BRA, HGAC	O			N
8.1.1.3	Reservoir Volumetric Surveys	1	Y	TWDB, BRA	O			N
8.1.3.1	Routine water quality monitoring	1	Y	TCEQ, BRA, HGAC	O			N
8.1.2.1	TSS data collection	1	Y	TCEQ, BRA, HGAC	O			N
8.1.4.2	ALM Assessments with expanded habitat data collection near selected gages	1	Y	TCEQ, BRA	O	2012	2020	N
8.1.1.2	Review water diversion rates from existing water rights holders	1	N	TCEQ, TWDB, TPWD, BBEST, BBASC	R	2020	2020	N
8.1.4.1	Revision of SWQM Procedures, Vol. 2	2	Y	TCEQ	R	2016	2017	N
8.1.4.6	Develop life histories/flow regime components linkages of fish and macroinvertebrates	2	N	TPWD, Universities	R	2013	2020+	N
8.1.4.7	Mussel survey of San Bernard Basin	2	N	TPWD, HGAC	R	2014	2015	N
8.1.2.2	Expanded sediment data collection	2	N	TCEQ, TWDB, TPWD	R	2014	2015	N
8.1.4.3a	ALM Assessment in the Clear Fork of the Brazos	2	N	TCEQ, BRA	R	2014	2015	Y
8.1.4.3b	ALM Assessment in the Brazos above Possum Kingdom	2	N	TCEQ, BRA	R	2015	2016	Y
8.1.4.3c	ALM Assessment in the Double Mountain Fork of the Brazos	2	N	TCEQ, BRA	R	2016	2017	Y
8.1.4.3d	ALM Assessment in the Salt Fork of the Brazos	2	N	TCEQ, BRA	R	2017	2018	Y

Table 8.1. (Continued).

Number	Recommendation	BBEST Recommended Priority	Current Funding	Agencies/ Organizations	Status	Start Date	End Date	Dependent on Specific Climatological Conditions
8.1.5.4	Riparian mapping and assessment using TESCP coverages	2	N	TPWD, BRA	R	2014	2020	N
8.1.4.4	Extension of TIFP instream assessments to both basins	3	N	TPWD, TCEQ, TWDB, BRA, HGAC*	R	2015	2020+	N
8.1.5.2	Riparian Damage Assessment	3	N	TPWD, TCEQ, TWDB, BRA, HGAC*	R	2013	2020	N
8.1.6.1	Sediment loading to estuary	3	N	TWDB, Universities	R	2013	2015	N
8.1.3.2	Subsistence water quality monitoring	4	N	TCEQ, BRA, HGAC, Universities	R	2012	2020	Y
8.1.4.5	Fish sampling at subsistence flows	4	N	TPWD, TCEQ, BRA, HGAC	R	2013	2020	Y
8.1.5.1	TIFP riparian assessment at gaging stations	4	N	TPWD, TCEQ, TWDB, BRA, HGAC*	R	2015	2020+	N
8.1.2.3	Channel response surveys	4	N	TWDB	R	2014	2020	N
8.1.4.8	Develop life histories/flow regime components linkages for mussels	4	N	TPWD, Universities	R	2013	2020+	N
8.1.6.2	Nutrient sampling of estuary and loading calculations	4	N	TPWD, TCEQ	R	2015	2020	N
8.1.5.3	Saltcedar encroachment	5	N	USGS, TPWD, TCEQ, TWDB, BRA	R	2017	2020	N
8.1.1.4	Climate Change-Water Availability Research	5	N	USGS, TPWD, TCEQ, TWDB	R	2017	2020	N

* Time to complete task could be greatly reduced if funding for outside assistance obtained

O - ongoing task that will most likely continue to be performed by respective agencies in perpetuity

R - recommended task dependent on funding and/or agency staff availability

Table 8.2. Potential funding sources.

Program Name	Primary Focus	Funding Type	Funding Organization Type	Eligible Applicants	Potential Limited to a Specific Watershed or Recommendation
USCOE- Project Modifications for Improvement of the Environments	Ecosystem restoration with emphasis on fish and wildlife where a COE Project has contributed to degradation	Cost-Share	F	State or Local Government	Little River
USCOE - Aquatic Ecosystem Restoration	Aquatic ecosystem restoration	Cost-share	F	State or Local Government	
USEPA - Greater Research Opportunities Fellowships for Undergraduate Environmental Study	Environmental Study	Cost-share	F	Undergraduate Students	
USEPA - Science to Achieve Results Fellowships for Graduate Environmental Study	Environmental Study	Cost-share	F	Graduate Level Students	
USFWS - Cooperative Endangered Species Conservation Fund	Conservation projects for candidate, proposed, and listed species	Cost-share	F	State	mussels, smalleye shiner, sharpnose shiner, Brazos water snake
USFWS - Fisheries Conservation Management	Evaluating water quality, assessment of in-stream and riparian habitat, introduced species	Cost-share	F	State, Local Government, Non-profits, Universities	
USNSF - Doctoral Dissertation Research	Environmental sciences	Grants	F	Universities	Life history investigations
USNSF - Exploratory Research	Exploratory work on untested, but potentially transformative, research ideas or approaches; must involve radically different approaches, apply new expertise or engage interdisciplinary perspectives	Grants	F	State, Local Government, Universities, Scientists	
USNSF - Hydrologic Science Grant	Aqueous geochemistry, physical, chemical, and biological processes within water bodies	Cost-share	F	Not specified	Sediment and Channel response assessment
USNSF - Long-term Research in Environmental Biology	Generating long time series of biological and environmental data that address particular ecological and evolutionary processes	Grants	F	Universities	Life history investigations

Table 8.2. (Continued).

Program Name	Primary Focus	Funding Type	Funding Organization Type	Eligible Applicants	Potential Limited to a Specific Watershed or Recommendation
USNSF - Science, Engineering and Education Sustainability Fellows	Investigation that cross traditional disciplinary boundaries and address issues of sustainability through a systems approach	Grants	F	Post-Doctoral Fellow	
NOAA - Sea Grant Community Climate Adaptation Initiative	Climate adaptation efforts to enhance climate adaptation in coastal communities	Grants	F	Sea Grant College Programs - Texas A&M	Lower Brazos, San Bernard
TCEQ - Supplemental Environmental Project Program	Investing penalty dollars towards environmentally beneficial uses; must define a project and have accepted into program	Grants	S	Local Government, NPOs	
TCEQ - Clean River Program	Water quality monitoring, ALM and data assessment; current funding inadequate to cover Brazos Basin	Contract	S	BRA, HGAC	
Texas Sea Grant	Sustainable coastal communities, ecosystems, and habitats	Grants	S	Marine Researchers	Lower Brazos, San Bernard
TWDB - TIFP Studies	Supports data collection and modeling efforts required by SB2	Contract	S	TPWD, TCEQ, BRA, Researchers	SB2 Study Area
BRA - Water Quality Initiatives	Augments TCEQ's CRP funding to meet the requirements of the CRP for the entire basin	Self-funded	S	NA	
Doris Duke Charitable Foundation	Wildlife conservation, climate change, land stewardship and sustainability	Grants	NPO	Not specified	
Ducks Unlimited	Wildlife and habitat conservation; also runs projects directly	Grants	NPO	Not specified	
National Fish and Wildlife Foundation	Fish conservation, wildlife and habitat conservation	Grants	NPO	Not specified	
Turner Foundation	Biodiversity, protect functioning ecosystems, create buffer zones and wildlife corridors	Grants	NPO	Not specified	
The Nature Conservancy	Conservation, restoration, and sustainable development practices; runs projects directly		NPO	NA	Lower Brazos, San Bernard

Table 8.2. (Continued).

Program Name	Primary Focus	Funding Type	Funding Organization Type	Eligible Applicants	Potential Limited to a Specific Watershed or Recommendation
North American Native Fishes Association Conservation Research Grant	Research on vulnerable North American fish species	Grants	NPO	Student, Researcher, Conservation Group	Smallnose and/or sharpnose shiners
FishAmerica Fisheries Research Grant	Research projects to further the Nation Fish Habitat Plan	Grants	NPO	Government, Local Communities	Brazos Below Waco, Navasota, Little River, San Bernard
ALCOA Foundation - Advancing Sustainability Research Initiative	Natural resource management, sustainable design, environmental economics	Grants	C	Universities, NPOs	
Sea World & Busch Gardens Conservation Fund	Species research, habitat protection, animal rescue and rehabilitation	Grants	C	NPOs, Government, Universities, Research Centers	
Shell Oil Company	Threatened wildlife and/or habitats, water quality research, ecosystems restoration	Grants	C	NPOs	

F - Federal Government, S - State Government, NPO - Non-profit Organization, C - Corporate

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