Instream Flow Study of the Middle and Lower Brazos River

Draft Study Design

Prepared for

Middle and Lower Brazos River Sub-Basin Study Design Workgroup

Prepared by

TEXAS INSTREAM FLOW PROGRAM
AND BRAZOS RIVER AUTHORITY

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1.0 INTRODUCTION

The Brazos River basin is one of the most diverse river basins in the state, spanning eight distinct ecoregions and rainfall conditions that vary from a mean average of 6 inches per year in headwater areas to more than 50 inches per year near its mouth. The middle and lower Brazos River (portion downstream of Lake Brazos in Waco) reflects much of that diversity as it travels 403 miles through or along the edge of 12 counties in south central and south east Texas. Along the way, the middle and lower Brazos passes through four ecoregions (Gould et al. 1960): a small extent of Cross Timbers and Prairies at the upper end, alternating bands of Blackland Prairie and Post Oak Savannah, and finally Gulf Prairies and Marshes at the lower end. The middle and lower Brazos River supports a diverse ecological community that relies on the quality, quantity, and timing of water moving through the system.

The hydrology of the middle and lower Brazos has been affected by the operation of reservoirs which were constructed in the upper watershed as early as 1941. Typical impacts of reservoir development include a reduction in the magnitude and frequency of large flood events and an increase in the magnitude of low flows. Downstream of Waco, tributaries (Little Brazos River, Little River, Yegua Creek and the Navasota River) and unregulated areas contribute to the river's flow, reducing the impacts of reservoirs. . The flow of the middle and lower Brazos River thus continues to be variable with the seasons and responsive to precipitation patterns within the sub-basin. This portion of the river remains the most hydrologically intact within the basin and is one of the largest, relatively intact floodplain rivers in North America.

The middle and lower Brazos River sub-basin has undergone several transformations over the past century. Native landscapes have given way to agriculture, the primary land use in the sub-basin. Urban areas have developed, including Waco, Bryan/College Station, and suburban areas in Fort Bend and Brazoria counties that are part of the Houston metropolitan area. Mining and industry have developed in areas such as Grimes and Brazoria counties. Dams have been constructed on many of the tributaries. Groundwater resources in the sub-basin, including the Brazos River alluvium aquifer, have been developed. Near its mouth, channelization and levee projects have impacted the river. Along with population and land use patterns, diversions from and return flows to the river have changed over time.

The middle and lower Brazos River is one of the largest, relatively intact floodplain rivers in North America and remains a valuable natural resource for the State of Texas. Nevertheless, transformations within the basin have had a cumulative impact on fish and wildlife dependant on the river. For example, notable changes in fish (Bonner and Runyan 2007) and mussel (Karatayev and Burlakova 2008) assemblages have been documented. Understanding the flow needs of ecosystems dependant on the river provides the rationale behind the Texas Instream Flow Study (TIFP) of the middle and lower Brazos River.

Senate Bill 2, enacted in 2001 by the 77th Texas Legislature, established the TIFP. The purpose of the TIFP is to perform scientific studies to determine flow conditions necessary to support a sound ecological environment in the rivers and streams of Texas. With passage of Senate Bill 3 in 2007, the Texas Legislature restated the importance of maintaining the health and vitality of the State's surface-water resources and further created a stakeholder process that would result in science and policy based environmental flow regime recommendations to protect instream flows and freshwater inflows on a basin-by-basin basis.

Stakeholder involvement has been a key component of the TIFP's middle and lower Brazos River sub-basin study. Through a series of TIFP sponsored meetings, stakeholders were briefed on the TIFP, informed about the available information and current conditions in the sub-basin, and provided a framework from which to define the study goal, objectives, and indicators (described in Section 2.0).

The focus of this Study Design document is to provide:

- an overview (Section 1.0) of
  - available information, results of preliminary analyses and reconnaissance surveys,
  - assessment of current conditions, and
  - a conceptual model of the middle and lower Brazos River sub-basin;
- an overview of the stakeholder process and description of the study goal, objectives, and indicators developed with stakeholders (Section 2.0);
- a description of the proposed technical studies (Section 3.0), including
  - Study Site locations,
  - data collection methods and analysis, and
  - multidisciplinary coordination; and
- an overview of continued stakeholder involvement and future activities (Section 4.0).

Ultimately, the culmination of study efforts will be to characterize the flow-habitat and flow-ecological relationships within the riverine ecosystem supported by the middle and lower Brazos River (Brazos River downstream of Lake Brazos in Waco to the Gulf of Mexico). Results will provide a means of assessing the relevant biological and physical factors associated with various flow regimes. A comprehensive tool will be generated from existing studies and field-gathered data that will provide predictive capabilities necessary to evaluate the ecological significance of the full range of flows (from low, to moderate, to high throughout the annual hydrologic cycle) on the riverine ecosystem of the middle and lower Brazos River.

1.1 Summary of available information and results of preliminary analysis and reconnaissance surveys

The middle and lower Brazos River sub-basin is shown in Figure 1. An inventory of available data and study reports related to the hydrologic, biologic, geomorphic, water quality, and connectivity features of the middle and lower Brazos River sub-basin was completed by the Brazos River Authority (BRA). This effort (BRA 2005) identified more than 300 reports, sources of data, or information related to the study area. Results were then summarized in a database and used to identify gaps in the data (either spatially or temporally). Identification of these gaps by the TIFP and BRA directed specific field surveys and preliminary analysis to better characterize the current condition of the river system. TIFP and BRA staff also conducted surveys of the river in order to familiarize themselves with conditions on the river, and evaluate locations for access and conducting baseline data collection.

A representative example of available information and recent technical studies used to support the Study Design are presented in Table 1. Listing of a study in this table does not imply an endorsement by the TIFP of any conclusions documented in these reports. Rather, these studies are identified because they have collected valuable data related to riverine ecosystems in the middle and lower Brazos River sub-basin. This data will be considered and incorporated along with data collected by TIFP in order to provide a better understanding of the study area.

Figure 1. Map of the Brazos River basin with middle and lower Brazos River sub-basin (study boundary) depicted.

Table 1. Studies of interest to the TIFP study of the middle and lower Brazos River sub-basin.

Type of Study	Name of Study	Author/s	Year
Physical Processes	Brazos River bar: a study in the significance of grain sized parameters	Folk & Ward	1957
Physical Processes	The nature of channel planform change: Brazos River, Texas	Gillespie & Giardino	1997
All Disciplines	Analysis of instream flows for the lower Brazos River – hydrology, hydraulics, and fish habitat utilization	Osting, Mathews, & Austin	2004
All Disciplines	Response of oxbow lake biota to hydrologic exchanges with the Brazos River channel	Winemiller et al.	2004
All Disciplines	Middle and lower Brazos River instream flow study – data summary evaluation and database	BRA	2005
Physical Processes	Morphology and stratigraphy of the late Quaternary lower Brazos valley: Implications for paleo-climate, discharge and sediment delivery	Sylvia & Galloway	2006
Biology	Fish assemblage changes in three western gulf slope drainages	Bonner & Runyan	2007
Biology	Biological data collection – Brazos River study area	BRA	2007
Water Quality	Brazos River basin summary report	BRA	2007
Physical Processes	Field data collection in support of geomorphic classification of the lower Brazos and Navasota Rivers	Phillips	2007
Connectivity, Hydrology	Geologic and hydrogeologic information for a geodatabase for the Brazos River alluvium aquifer, Bosque County to Fort Bend County, Texas	Shah & Houston	2007
Connectivity, Hydrology	Hydrogeologic characterization of the Brazos River alluvium aquifer, Bosque County to Fort Bend County, Texas	Shah, Houston, & Braun	2007
Connectivity, Hydrology	Application of surface geophysical methods, with emphasis on magnetic resonance soundings, to characterize the hydro-stratigraphy of the Brazos River alluvium aquifer, College Station, Texas, July 2006	Shah, Kress, & Anatoly	2007
Connectivity, Hydrology	Base flow (1966-2005) and streamflow gain and loss (2006) of the Brazos River, McLennan County to Fort Bend County, Texas, 2006	Turco, East, & Milburn	2007
Biology	Distributional survey and habitat utilization of freshwater mussels	Karatayev & Burlakova	2008
Hydrology, Physical Processes	Historical channel adjustment and estimates of selected hydraulic values in the lower Sabine River and lower Brazos River basins, Texas and Louisiana	Heitmuller & Greene	2009
Biology	Distributional survey and habitat utilization of freshwater mussels (Family Unionidae) in the lower Brazos and Sabine River basins	Randklev, Kennedy, & Lundeen	2010

The following sections highlight key studies and preliminary results which describe existing hydrology, biology, geomorphology, water quality, and connectivity conditions in the middle and lower Brazos River sub-basin. Please note that throughout this document the terms geomorphology and physical processes will be used interchangeably to refer to the science or field of study related to processes that shape the physical features of a river system.

1.1.1 Hydrology

USGS gage data and flow trends at representative gages

The U.S. Geological Survey (USGS) has maintained a network of streamflow gages in the middle and lower Brazos River sub-basin since 1898. Currently, the USGS operates 38 gages in the sub-basin, including 6 on the mainstem of the Brazos River and 32 on tributaries. Some historical data is also available from an additional five mainstem stream gages that are no longer maintained. Stream gages with daily streamflow data of interest to an instream flow study of the middle and lower Brazos are listed in Table 2.

Observation of the available gage data indicates that flow conditions in the middle and lower Brazos River have changed over time. Figure 2 shows median flow for each day of the year for data collected from USGS gage #08096500, Brazos River at Waco. The first data set, collected from 1898 to 1940, reflects pre-development hydrology of the river at this location. The second data set, collected from 1984 to 2008, reflects current conditions and the combined effects of changes in the basin. As shown in this figure, median flow in late spring (May) has been reduced while flows in late fall through early spring (November through April) and summer (August) have increased. Median flows in June, September, and October are little changed.

Table 2. USGS stream gages with daily streamflow data of interest in the middle and lower Brazos River sub-basin.

Gage #	Gage Name	Earliest Record	Latest Record	Median Flow (cfs)	Drainage Area (mi^2)
08096500	Brazos Rv at Waco, TX	1898	Present	771	29,559
08097500	Brazos Rv nr Marlin, TX	1938	1951	1,060	30,211
08098290	Brazos Rv nr Highbank, TX	1965	Present	1,000	30,436
08106500	Little Rv nr Cameron, TX	1916	Present	500	7,065
08108700	Brazos Rv at SH 21 nr Bryan, TX	1993	Present	1,650	39,049
08109000	Brazos Rv nr Bryan, TX	1899	1993	1,780	39,515
08110000	Yegua Ck nr Somerville, TX	1924	1991	6.4	1,009
08110100	Davidson Ck nr Lyons, TX	1962	Present	2.8	195
08110800	Navasota Rv at OldSpanishRd nr Bryan,TX	1997	Present	68	1,287
08111000	Navasota Rv nr Bryan, TX	1951	1997	54	1,454
08111010	Navasota Rv nr College Station,TX	1977	1985	81	1,809
08110200	Brazos Rv at Washington, TX	1965	1987	2,310	41,192
08111500	Brazos Rv nr Hempstead, TX	1938	Present	2,560	43,880
08111700	Mill Ck nr Bellville, TX	1963	Present	34	376
08114000	Brazos Rv at Richmond, TX	1903	Present	2,940	45,107
08114500	Brazos Rv nr Juliff, TX	1949	1969	1,940	45,189
08115000	Big Ck nr Needville, TX	1947	Present	1.8	42.8
08116650	Brazos Rv nr Rosharon, TX	1967	Present	3,600	45,339
08117290	Brazos Rv at Freeport, TX	2002	2002	NA	45,603

Figure 3 shows the daily gage data for these same time periods displayed as flow duration curves. From this figure, it can be seen that the occurrence of daily flows between 3,000 and 9,000 cfs and in excess of 30,000 cfs have been reduced slightly from the earlier time period. Conversely, the occurrence of flows between 10,000 and 25,000 cfs has increased slightly. The magnitude of lower flows (those that are exceeded more than 40% of the time) has also increased. The hydrologic changes shown in Figures 2 and 3 are typical for rivers that have been impounded in order to provide flood protection and a more stable water supply.

Observation of data from USGS gage 08114000, Brazos River at Richmond, illustrates that the pattern of hydrologic change is not uniform in the sub-basin. Figures 4 and 5 show daily flow data collected at that gage for the same pre-1941 and post-1983 time periods. It should be noted that the gage at this location did not begin operation until 1903 and there is a gap in the data from 1907-1922. Figure 4 shows an increase in November through January median flows from pre-development conditions, but flows remain relatively similar during the rest of the year. Figure 5 shows an increase in magnitude for the entire range of flows exceeded more than 2 percent of the time. The type of change shown in Figure 5 is typical for a basin experiencing increased runoff due to factors such as increased precipitation or increased impervious cover within the basin. The changes may also be a result of reservoir operation for hydropower generation, flood control, or water supply. A hydrologic evaluation of the sub-basin, as described in Section 6.1 of the TIFP Technical Overview (TIFP 2008), will be required in order to investigate these changes fully.

Changes in the hydrology of the middle and lower Brazos River are due to a combination of factors, which include construction of dams and reservoirs, urban growth and other land use change, and changes in precipitation. As shown in Figure 6, average monthly precipitation for Brenham, Texas has been greater in the period since 1984, relative to the period before 1941.

Dams and reservoirs can have a significant impact on hydrology. Although there are no reservoirs on the mainstem of this portion of river, construction and operation of reservoirs in the basin as a whole may have affected the hydrology of the middle and lower Brazos River. There are 15 reservoirs within the Brazos River basin that were designed with flood and/or conservation storage capacities in excess of 100,000 acre-feet (listed in Table 3). Eight of these reservoirs are located upstream of the middle and lower Brazos sub-basin (three on the Brazos River mainstem and the remainder on tributaries). Seven are located on tributaries within the middle and lower Brazos River sub-basin. Construction of these reservoirs was completed between 1941 and 1983.

Land use changes associated with development and a growing human population can also affect hydrology. The human population of the 12 counties the middle and lower Brazos River flows through or along has grown significantly during the past decades. These counties include Austin, Brazoria, Brazos, Burleson, Falls, Fort Bend, Grimes, McLennan, Milam, Robertson, Waller, and Washington counties. According to US Census data, their combined population has grown from less than 400,000 in 1940 to just over 700,000 in 1980 and more than 1.1 million in 2000. The estimated population of these 12 counties was more than 1.4 million in 2008 and is projected to increase to more than 2.8 million by 2060.

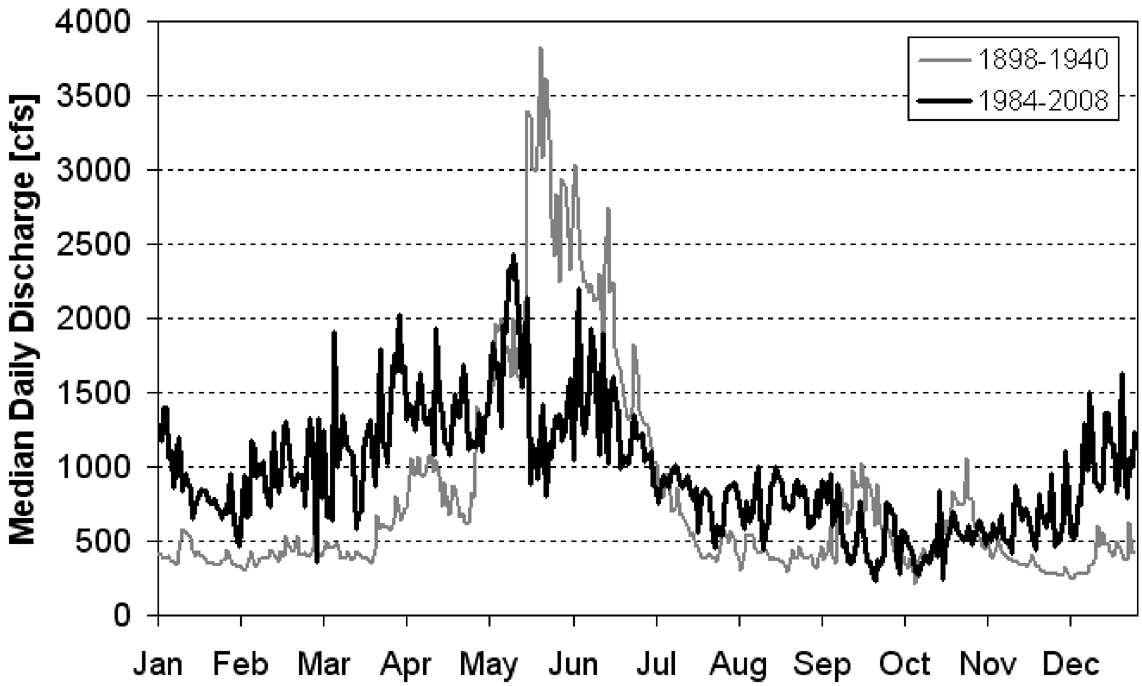

Figure 2. Median of daily streamflow values for USGS gage 08096500, Brazos River at Waco.

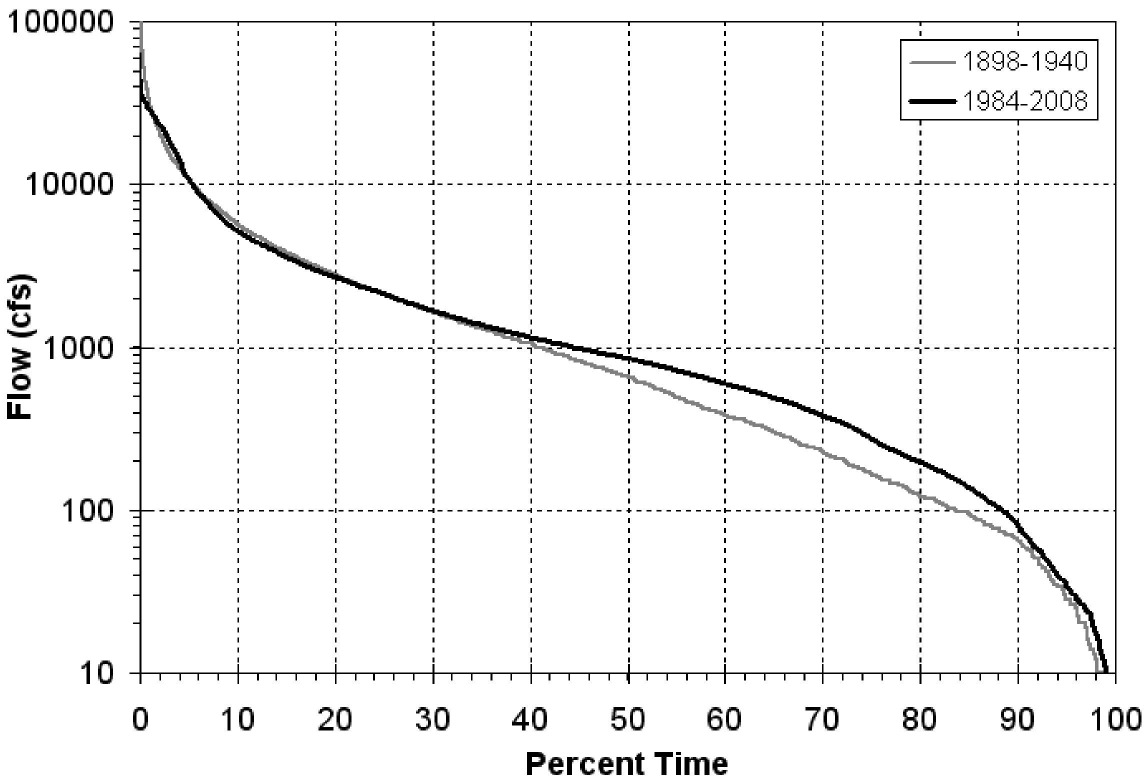

Figure 3. Flow duration curves for daily average flow at USGS gage 08096500, Brazos River at Waco.

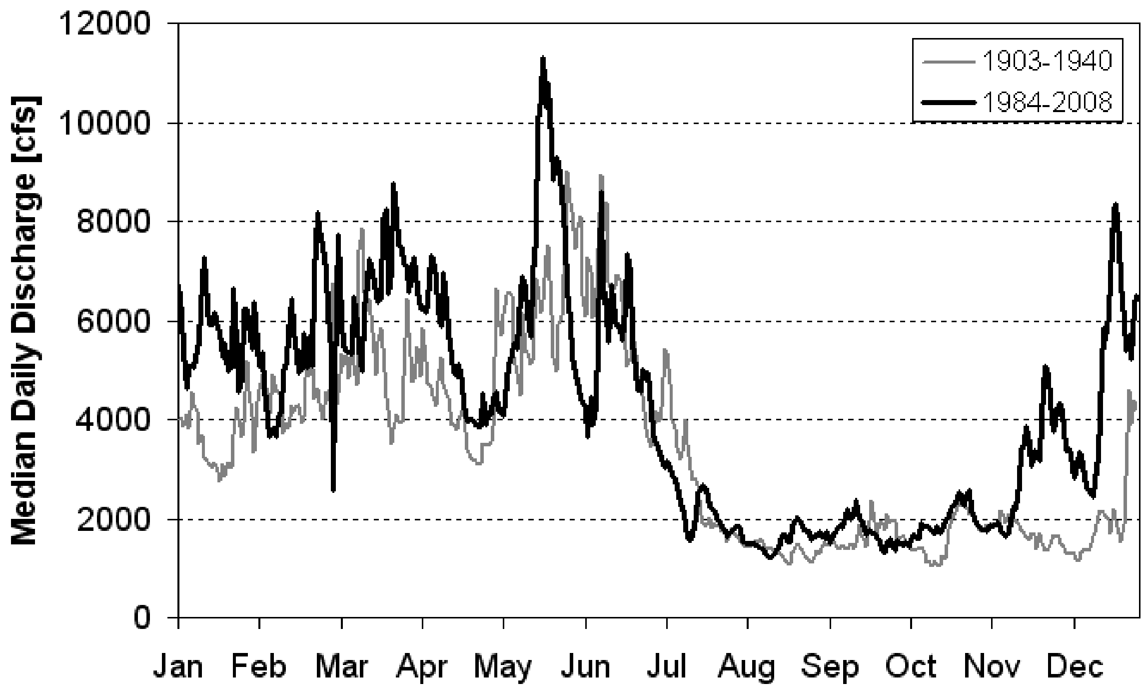

Figure 4. Median of daily streamflow values for USGS gage 0811400, Brazos River at Richmond.

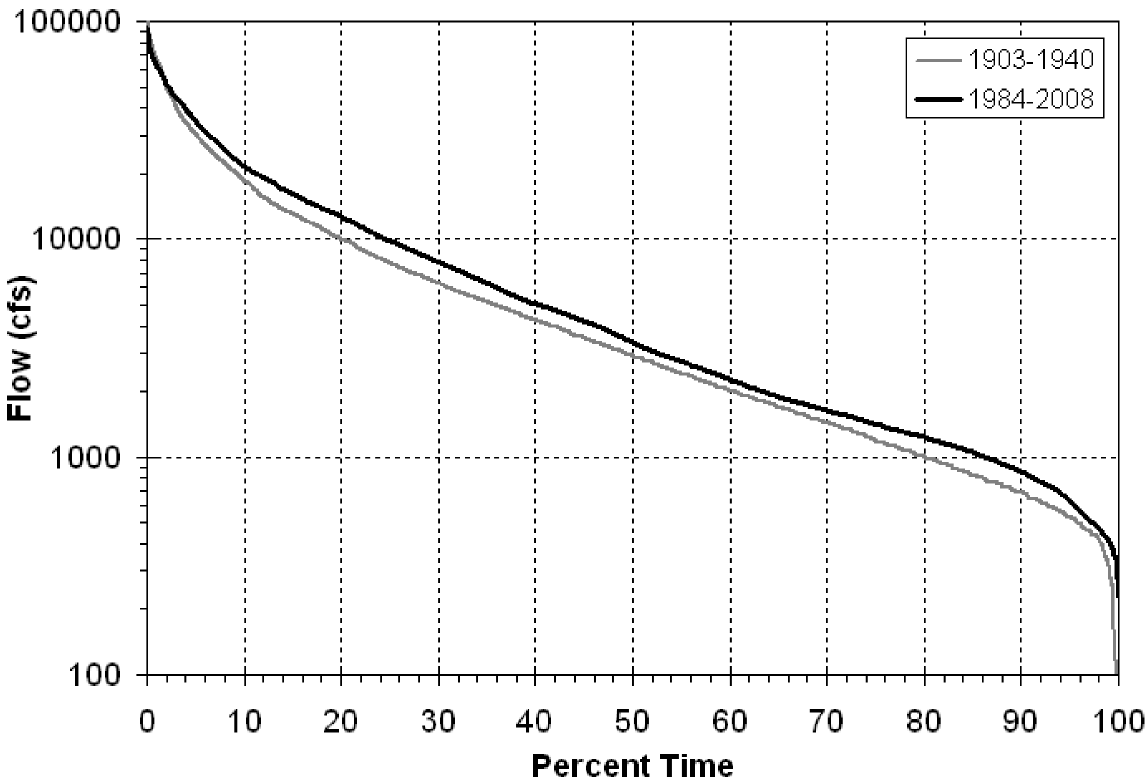

Figure 5. Flow duration curves for daily average flow at USGS gage 0811400, Brazos River at Richmond.

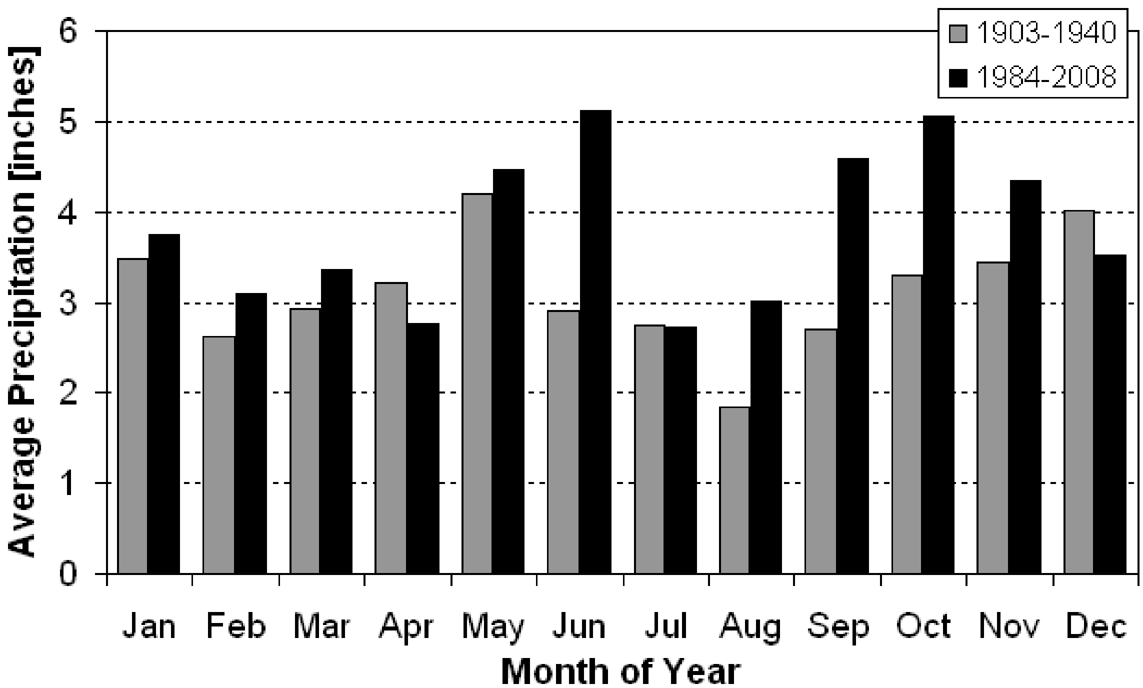

Figure 6. Average monthly precipitation for Brenham, Texas for the periods 1903 to 1940 and 1984 to 2008 (National Climate Data Center data).

Table 3. Brazos River Basin reservoirs with original capacities greater than 100,000 acre-feet.

Location in Brazos Basin	Reservoir Name	Flood Storage† [acre-feet]	Conservation Storage† [acre-feet]	Year Completed
Upper Sub-basin Mainstem	Possum Kingdom Lake		724,464	1941
	Lake Whitney	2,000,204	627,100	1951
	Lake Granbury		155,000	1969
Upper Sub-basin Tributaries	Hubbard Creek Reservoir		317,750	1962
	Lake Waco	722,865	152,500	1965
	Squaw Creek Reservoir		151,047	1977
	Aquilla Lake	146,516	52,400	1983
	Alan Henry Reservoir		115,937	1994
Middle and Lower Sub-basin Tributaries	Belton Lake	1,086,690	457,600	1954
	Proctor Lake	375,294	59,400	1963
	Somerville Lake	507,721	160,100	1967
	Stillhouse Hollow Lake	630,876	235,700	1968
	Lake Limestone		225,400	1978
	Granger Lake	244,620	82,000	1979
	Lake Georgetown	131,517	37,100	1982

†As a result of sedimentation, a reservoir's flood and conservation storage decrease over time. Therefore, these numbers do not reflect current capacities.

Land use changes affect the hydrology of a river in several ways. For example, conversion of land from agriculture to urban areas can increase peak flows and decrease base flows. Land use in the upper portion of the sub-basin is primarily agricultural with two sizeable urban areas, Waco in McLennan County and Bryan/College Station in Brazos County. The lower portion of the sub-basin has many and varied land uses, including agriculture, oil and gas retrieval, chemical industry, mining, and municipalities. The largest urban areas in the lower portion of the sub-basin are in Brazoria and Fort Bend counties and have experienced substantial population growth along with the greater Houston metropolitan area. Table 4 shows population growth and projections for the counties with the largest urban areas near the middle and lower Brazos River.

Surface water diversions and (depending on geology) groundwater extractions can also affect stream hydrology. Irrigated agriculture, dependant on both surface water and groundwater (including the Brazos alluvium aquifer), has historically been the largest user of water in the sub-basin. Water use for agriculture has declined over the past decades, however, and withdrawls for manufacturing and municipal use are now nearly as large as those for agriculture. Surface water diversions in the 12 counties have actually decreased (largely due to decreased agricultural demand) from almost 655,000 acre-feet in 1980 to less than 420,000 acre-feet in 2000. However, groundwater pumping has grown from less than 250,000 acre-feet in 1980 to almost 325,000 acre-feet in 2000.

The Brazos River alluvium aquifer extends along the river from Bosque to Fort Bend counties. Groundwater/surface water interactions between this aquifer and the middle and lower Brazos River may be significant during some flow conditions. Gains or losses to the aquifer may affect subsistence and base flows in the river while high flow pulses and overbank flows may provide significant recharge to the aquifer. Recent studies have estimated streamflow gains and losses and determined characteristics of the Brazos River alluvium aquifer (see Section 1.1.5).

Table 4. Population data for counties with largest urban areas near the middle and lower Brazos River.

		County Population				
County	Urban Areas	1940[a] Census	1980[a] Census	2000[a] Census	2008[b] Estimated	2060[c] Projected
Brazoria	Pearland	27,069	169,587	241,767	301,044	503,894
Brazos	Bryan, College Station	26,977	93,588	152,415	175,122	279,182
Fort Bend	Sugar Land	32,963	130,846	354,452	532,141	1,475,761
McLennan	Waco	101,898	170,755	213,517	230,213	307,378

[a]US census data

[b]US census estimates

[c]TWDB 2006 regional water plan county population projections

1.1.2 Biology

Fisheries data collection results summary

Sixty two native freshwater, 4 marine and two introduced fish species have been reported from the mainstem of the middle and lower Brazos River from collections dating back to 1939 (Table 5). Life history and population information for these species are also provided in Table 5 and are based upon scientific studies (Balon 1975, Balon 1981, Williams et al. 1989, Warren et al. 2000, BRA 2007, Bonner and Runyan 2007, Hubbs et al. 2008). Cyprinidae was the most abundant family, followed by families Centrarchidae, Ictaluridae, Percidae, Catastomidae and Lepisosteidae.

The diversity of fish species reported from the river include representatives from each of the major trophic guilds (piscivore, invertivore, omnivore, and herbivore) and include a number of species with conservation concern such as, smalleye shiner *(Notropis buccula*), sharpnose shiner (*Notropis oxyrhynchus*), pallid shiner (*Hybopsis amnis),* and alligator gar (*Atractosteus spatula)*. A rich variety of reproductive strategies are also represented within the fish assemblage, including broadcast, substrate, and floodplain spawners. In addition, the Ohio river shrimp (*Macrobrachium ohione*) is a catadromous species known to occur in the Brazos River.

Starting in 2006, TIFP and BRA biologists conducted reconnaissance and biological and habitat sampling throughout the middle and lower Brazos River sub-basin. Evaluations of the fish community and habitat assessments were conducted at six sites on the Brazos River, two sites on the Little River, and one site on the Navasota River (Table 6 and Figure 7). Data collected from these sampling efforts provided baseline habitat and fish assemblage data to fill information gaps within the middle and lower Brazos River sub-basin. Collection methods included boat and backpack electrofishing and seining in as many habitat types as possible. Additionally, hoop nets were utilized to supplement collections. Measurements of average habitat depth, dominant substrate, and current velocity were recorded within each habitat type. Individual biological collection efforts were segregated by habitat types from which the samples were collected. Photographs and global positioning system coordinates were recorded from the mid-point of each habitat type. The results from this study are presented in BRA (2007).

Further analysis of the historic species relative abundance levels by Bonner and Runyan (2007) presented some interesting trends. Two endemic species, smalleye shiner (*Notropis buccula*) and sharpnose shiver (*Notropis oxyrhynchus*), along with chub shiner (*Notropis potteri*) and silverband shiner (*Notropis shumardi),* all broadcast spawners, were found to be declining in relative abundance. Conversely, red shiner (*Cyprinella lutrensis*) and bullhead minnow (*Pimephales vigilax*), both substrate spawners, exhibited a significant increase in relative abundance. Relative abundance of blacktail shiner (*Cyprinella venusta*) remained fairly constant in downstream portions of the Brazos River, but increased significantly in upstream reaches.

Mussel data summary

Mussels represent one of the most rapidly declining faunal groups in North America. Life history traits related to their vulnerability include: sensitivity to toxic contaminants, low selectivity of feeding, long life span, size and mobility limitations, low fertilization rates, high juvenile mortality, irregular recruitment, and unique life cycle including an obligate parasitic larval stage (Fuller 1974; Downing et al. 1993; McMahon and Bogan 2001). Other anthropogenic impacts such as dam construction and altered flow regimes have been associated with mussel declines.

Table 5. Life history and population information on fish species collected in the middle and lower Brazos River sub-basin.

Species	Common Name	Population Trend (Brazos River)	Species Status	Resident Status	Trophic Guild	Primary Reproductive Guild	Secondary Reproductive Guild	Tolerance
Atractosteus spatula	alligator gar	-	Vulnerable	N	P	Open Substrate	Phytophil	T
Lepisosteus oculatus	spotted gar	↓	Stable	N	P	Open Substrate	Phytophil	T
Lepisosteus osseus	longnose gar	S	Stable	N	P	Open Substrate	Phytolithophil	T
Amia calva	bowfin	S	Stable	N	P	Nest Spawner	Phytophil	T
Anguilla rostrata	American eel	-	Stable	N	P	Catadromous	Catadromous	-
Alosa chrysochloris	skipjack herring	-	Stable	N	PL	Open Substrate	Phytolithophil	-
Dorosoma cepedianum	gizzard shad	S	Stable	N	H	Open Substrate	Lithopelagophil	T
Dorosoma petenense	threadfin shad	S	Stable	N	PL	Open Substrate	Phytophil	-
Campostoma anomalum	central stoneroller	-	Stable	N	H	Brood Hider	Lithophil	-
Cyprinella lutrensis	red shiner	↑	Stable	N	IF	Brood Hider	Speleophil	T
Cyprinella venusta	blacktail shiner	S	Stable	N	IF	Brood Hider	Speleophil	-
Cyprinus carpio	common carp	S	Stable	I	O	Open Substrate	Phytolithophil	T
Hybognathus nuchalis	Mississippi silvery minnow	S	Stable	N	DT	Open Substrate	Lithopelagophil	T
Hybognathus placitus	plains minnow	-	Stable	N	H	Open Substrate	Pelagophil	T
Hybopsis amnis	pallid shiner	S	Vulnerable	N	IF	Open Substrate	Lithophil	-
Lythrurus fumeus	ribbon shiner	S	Stable	N	IF			-
Macrhybopsis hyostoma	shoal chub	S	Stable	N	IF	Open Substrate	Pelagophil	-
Macrhybopsis storeriana	silver chub	S	Stable	N	IF	Open Substrate	Lithopelagophil	-
Notemigonus crysoleucas	golden shiner	S	Stable	N	IF	Open Substrate	Phytophil	T
Notropis buccula	smalleye shiner	↓	Endangered	N	IF	Open Substrate	Pelagophil	-
Notropis buchanani	ghost shiner	↑	Stable	N	IF	Open Substrate	Pelagophil	-

Population trend (↑ - increasing, S - stable, - - indeterminable, ↓ - decreasing), species status, resident status (N – native to basin, I – introduced to basin), trophic guild (DT – detritivore, H - herbivore, O - omnivore, IF - invertivore, P – piscivore, PL - planktivore), reproductive guild, and tolerance (I – intolerant, - - intermediate, T – tolerant) of fishes reported from the lower Brazos River basin.

Table 5 (cont.). Life history and population information on fish species collected in the middle and lower Brazos River sub-basin.

Species	Common Name	Population Trend (Brazos River)	Species Status	Resident Status	Trophic Guild	Primary Reproductive Guild	Secondary Reproductive Guild	Tolerance
Notropis oxyrhynchus	sharpnose shiner	↓	Threatened	N	IF	Open Substrate	Pelagophil	-
Notropis potteri	chub shiner	↓	Stable	N	P	Open Substrate	Pelagophil	-
Notropis shumardi	silverband shiner	S	Stable	N	IF	Open Substrate	Pelagophil	-
Notropis volucellus	mimic shiner	S	Stable	N	O	Open Substrate	Phytophil	I
Opsopoeodus emiliae	pugnose minnow	S	Stable	N	DT	Nest Spawner	Speleophil	-
Pimephales promelas	fathead minnow	S	Stable	I	O	Nest Spawner	Speleophil	T
Pimephales vigilax	bullhead minnow	↑	Stable	N	O	Nest Spawner	Speleophil	-
Carpiodes carpio	river carpsucker	↓	Stable	N	DT	Open Substrate	Lithopelagophil	T
Ictiobus bubalus	smallmouth buffalo	S	Stable	N	O	Open Substrate	Lithopelagophil	-
Moxostoma congestum	gray redhorse	-	Special concern	N	IF	Open Substrate	Lithophil	-
Ameiurus melas	black bullhead	-	Stable	N	IF	Nest Spawner	Speleophil	T
Ameiurus natalis	yellow bullhead	-	Stable	N	IF	Nest Spawner	Speleophil	-
Ictalurus furcatus	blue catfish	S	Stable	N	P	Nest Spawner	Speleophil	-
Ictalurus punctatus	channel catfish	↓	Stable	N	O	Nest Spawner	Speleophil	T
Noturus gyrinus	freckled madtom	S	Stable	N	IF	Nest Spawner	Speleophil	I
Pylodictis olivaris	flathead catfish	S	Stable	N	IF	Nest Spawner	Speleophil	-
Aphredoderus sayanus	pirate perch	S	Stable	N	IF	Bearer Mouth	brooder	-
Fundulus notatus	blackstripe topminnow	S	Stable	N	H	Open Substrate	Phytophil	-
Fundulus olivaceus	blackspotted topminnow	-	Stable	I	IF	Open Substrate	Phytophil	I
Gambusia affinis	western mosquitofish	↑	Stable	N	IF	Bearer	Viviparous	-
Poecilia latipinna	sailfin molly	-	Stable	N	O	Bearer	Viviparous	T
Labidesthes sicculus	brook silverside	S	Stable	I	IF	Open Substrate	Phytolithophil	I

Population trend (↑ - increasing, S - stable, - - indeterminable, ↓ - decreasing), species status, resident status (N – native to basin, I – introduced to basin), trophic guild (DT – detritivore, H - herbivore, O - omnivore, IF - invertivore, P – piscivore, PL - planktivore), reproductive guild, and tolerance (I – intolerant, - - intermediate, T – tolerant) of fishes reported from the lower Brazos River basin.

Table 5 (cont.). Life history and population information on fish species collected in the middle and lower Brazos River sub-basin.

Species	Common Name	Population Trend (Brazos River)	Species Status	Resident Status	Trophic Guild	Primary Reproductive Guild	Secondary Reproductive Guild	Tolerance
Menidia beryllina	inland silverside	S	Stable	N	IF	Open Substrate	Phytophil	-
Morone chrysops	white bass	S	Stable	I	P	Open Substrate	Phytolithophil	-
Cyprinodon variegatus	sheepshead minnow	-	Stable	N	O	Nest Spawner	Polyphil	T
Lepomis cyanellus	green sunfish	-	Stable	N	IF	Nest Spawner	Polyphil	T
Lepomis gulosus	warmouth	↓	Stable	N	IF	Nest Spawner	Lithophil	T
Lepomis humilis	orangespotted sunfush	S	Stable	N	IF	Nest Spawner	Lithophil	-
Lepomis macrochirus	bluegill	S	Stable	N	IF	Nest Spawner	Polyphil	T
Lepomis marginatus	dollar sunfish	-	Stable	N	IF	Nest Spawner	Polyphil	-
Lepomis megalotis	longear sunfish	S	Stable	N	IF	Nest Spawner	Polyphil	-
Lepomis microlophus	redear sunfish	S	Stable	N	IF	Nest Spawner	Polyphil	-
Lepomis miniatus	redspotted sunfish	-	Stable	N	IF	Nest Spawner	Polyphil	-
Lepomis symmetricus	bantam sunfish	S	Stable	N	IF	Nest Spawner	Polyphil	-
Micropterus punctulatus	spotted bass	S	Stable	N	IF	Nest Spawner	Polyphil	-
Micropterus salmoides	largemouth bass	S	Stable	N	P	Nest Spawner	Polyphil	-
Pomoxis annularis	white crappie	↓	Stable	N	P	Nest Spawner	Phytophil	-
Pomoxis nigromaculatus	black crappie	S	Stable	N	IF	Nest Spawner	Phytophil	-
Etheostoma chlorosoma	bluntnose darter	S	Stable	N	IF	Substratum Chooser	Phytophil	-
Etheostoma gracile	slough darter	S	Stable	N	IF	Substratum Chooser	Phytophil	-
Percina carbonaria	Texas logperch	-	Stable	I	IF	Brood Hider	Lithophil	I
Percina sciera	dusky darter	S	Stable	N	IF	Brood Hider	Lithophil	I

Population trend (↑ - increasing, S - stable, - - indeterminable, ↓ - decreasing), species status, resident status (N – native to basin, I – introduced to basin), trophic guild (DT – detritivore, H - herbivore, O - omnivore, IF - invertivore, P – piscivore, PL - planktivore), reproductive guild, and tolerance (I – intolerant, - - intermediate, T – tolerant) of fishes reported from the lower Brazos River basin.

Table 5 (cont.). Life history and population information on fish species collected in the middle and lower Brazos River sub-basin.

Species	Common Name	Population Trend (Brazos River)	Species Status	Resident Status	Trophic Guild	Primary Reproductive Guild	Secondary Reproductive Guild	Tolerance
Aplodinotus grunniens	freshwater drum	↓	Stable	N	IF	Open Substrate	Pelagophil	T
Oreochromis aureus	blue tilapia	S		I	O	Bearer	Mouth Brooder	T
Agonostomus monticola	mountain mullet	-	Vulnerable	N	O	Catadromous		-
Mugil cephalus	striped mullet	S	Stable	N	DT	Catadromous		-
Mugil curema	white mullet	S		N	O	Catadromous		-

Population trend (↑ - increasing, S - stable, - - indeterminable, ↓ - decreasing), species status, resident status (N – native to basin, I – introduced to basin), trophic guild (DT – detritivore, H - herbivore, O - omnivore, IF - invertivore, P – piscivore, PL - planktivore), reproductive guild, and tolerance (I – intolerant, - - intermediate, T – tolerant) of fishes reported from the lower Brazos River basin.

Table 6. Biological and habitat sample site locations on the middle and lower Brazos River, Little River and Navasota River.

Sample Site Number	Sample Site Description
12020	Brazos River downstream of Highway 159, Washington/Waller Counties
12030	Brazos River upstream of Highway 105, Washington/Brazos Counties
12040	Navasota River West of Piedmont, Navasota/Brazos Counties
12050	Brazos River between Highway 21 and FM 60, Burleson/Brazos Counties
12060	Little River between Highway 486 and Highway 1600, Milam County
12070	Little River downstream of County Road 264, Milam County
12080	Brazos River downstream of Highway 485, Milam/Robertson Counties
12087	Brazos River downstream of Highway 712, Falls County
12090	Brazos River upstream of Highway 7, Falls County

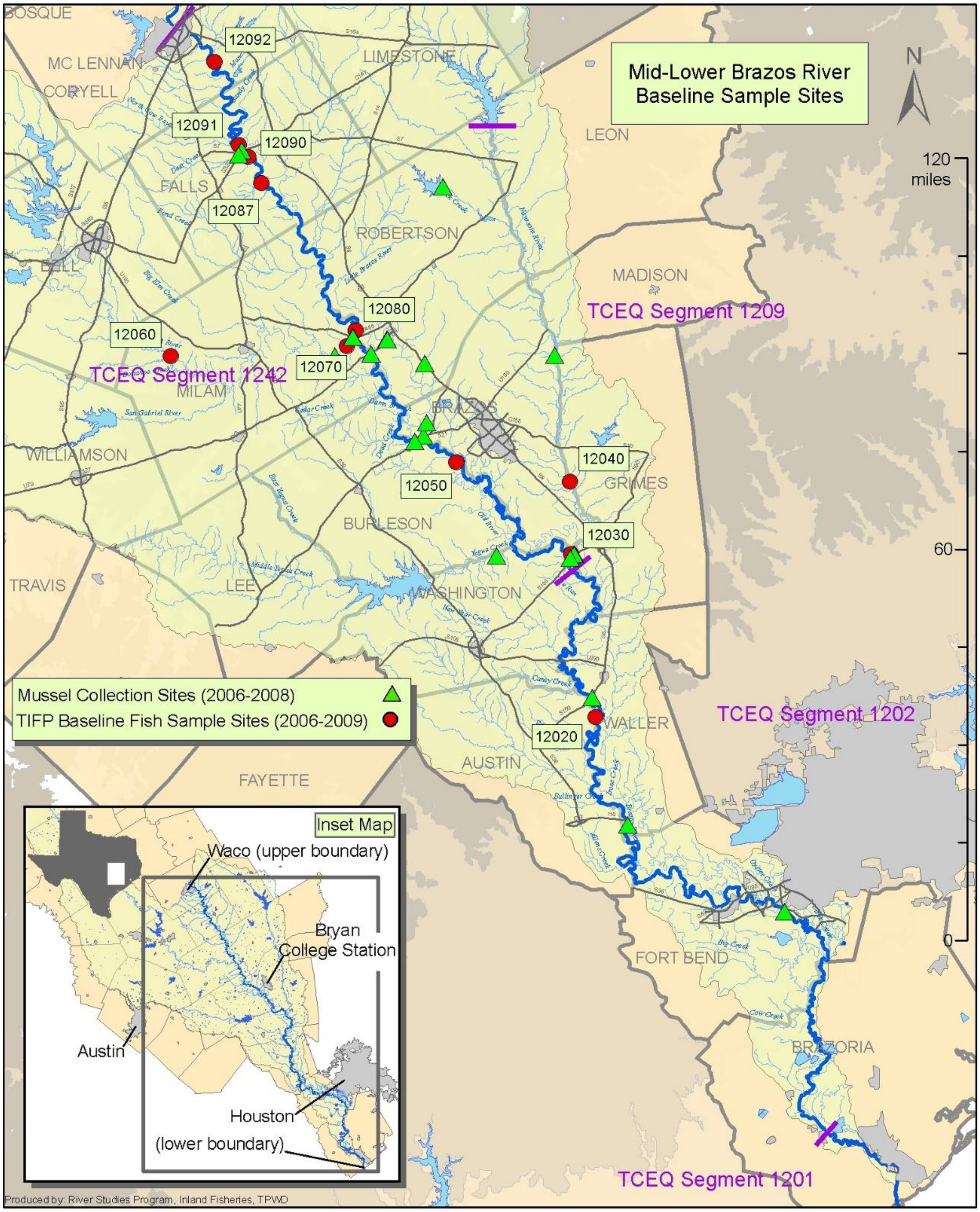

Figure 7. TIFP baseline fish sampling and mussel collection sites in the middle and lower Brazos River sub-basin.

Table 7. Historic occurrence, recent collection, and current status of mussel species in the Brazos River basin.

Mussel Species of Historic Occurrence	Karatayev & Burlakova	Randklev et al.	Current State Status[a]	
			Threatened	Species of Concern
Lilliput (*Toxolasma parvus*)		X		
Texas Lilliput (*Toxolasma texasiensis*)		X		
Texas Fawnsfoot (*Truncilla macrodon*)	X	X	X	X
Tapered Pondhorn (*Uniomerus declivis*)				
Pondhorn (*Uniomerus tetralasmus*)				
Giant Floater (*Pyganodon grandis*)				
Paper Pondshell (*Utterbackia imbecillis*)	X			
Fragile Papershell (*Leptodea fragilis*)	X	X		
Pink Papershell (*Potamilus ohiensis*)	X	X		
Creeper (*Strophitus undulates*)				
Southern Mapleleaf (*Quadrula apiculata*)	X	X		
Golden Orb (*Quadrula aurea*)			X	X
Smooth Pimpleback (*Quadrula houstonensis*)	X	X	X	X
Threeridge (*Amblema plicata*)	X	X		
Rock Pocketbook (*Arcidens confragosus*)	X	X		X
Washboard (*Megalonaias nervosa*)	X	X		
Pistolgrip (*Tritogonia verrucosa*)	X	X		
Tampico Pearlymussel (*Cyrtonaias tampicoensis*)	X	X		
Round Pearlyshell (*Glebula rotundata*)				
Bleufer (*Potamilus purpuratus*)				
Texas Fatmucket (*Lampsilis bracteata*)			X	X
Louisiana Fatmucket (*Lampsilis hydiana*)				
False Spike (*Quincuncina mitchelli*)			X	X
Yellow Sandshell (*Lampsilis teres*)	X	X		
Pond Mussel (*Ligumia subrostrata*)				

[a]TPWD Texas Wildlife Action Plan 2005

Historically, 25 mussel species are known to have occurred in the Brazos River basin. Although mussel distribution and life history information is limited throughout the state (Howells et al. 1996), recent mussel surveys (Figure 7) conducted in the Brazos basin by Karatayev and Burlakova (2008) and Randklev et al. (2010) have documented 14 live mussel species (Table 7). Tributaries of the Brazos River contribute greatly to the diversity of mussels found within the basin, with both studies indicating high densities and high diversity of live mussels in the Navasota River and Yegua Creek. Karatayev and Burlakova (2008) also showed that, in general, mussel abundance was higher in the downstream reaches of the Brazos River.

1.1.3 Physical Processes

Geomorphic processes create the channel characteristics and aquatic habitats of the middle and lower Brazos River. The modern river system exhibits pronounced variability in four dimensions: lateral, vertical, longitudinal and temporal. The physical characteristics of the river channel vary by location as you move downstream as a result of both systematic changes (e.g. increased drainage area and runoff), as well as local effects (e.g. faults and bedrock outcroppings). As the modern channel meanders across the river valley, it is influenced by its geologic history. For example, paleo-channels affect the location of the river and paleo-deposits of coarse grained material affect the composition of the river bed.

A complete understanding of the physical processes that have combined to form the entire length of the modern middle and lower Brazos River is currently unavailable. Obtaining such an understanding would require extensive and lengthy study. What is known about the physical processes that maintain the modern channel is based on a few broad scale studies of the larger river system and a limited number of detailed studies carried out at select locations along the river.

Folk and Ward (1957) completed a study that identifies an important influence of pre-historic conditions on the modern Brazos River. Their study analyzed the material characteristics of a sediment bar in the Brazos River near Calvert, TX and found the grain size distribution to be strongly bimodal, with a gravel fraction composed mostly of material between 4 to 11 millimeters in diameter and a sand fraction with material mostly between 0.15 to 0.45 millimeters in diameter. The absence of intermediate size material implies that the sand size particles are not the products of the physical wearing down of the gravel size particles. After extensive statistical analysis, Folk and Ward concluded that the two fractions were from different sources. Further, they concluded that the gravel mode achieved its sorting elsewhere in a high energy environment. Their findings are consistent with a paleo-deposit source for the gravel fraction of the bar at this location.

The modern middle and lower Brazos River is not powerful enough to transport gravel size material significant distances. The slope of this portion of river is relatively modest, dropping only 350 feet in the roughly 400 river miles from Waco to the coast. Historic stream flows (since late 1890's) combined with this slope are too small to move gravel sized sediments significant distances. However, the pre-historic Brazos River had higher flows. Sylvia and Galloway (2006) estimate a mean annual flow in the late Pleistocene as much as four times greater than that of today. The Pleistocene flow regime succeeded in mobilizing gravel sized material and transporting, sorting, and depositing it in various locations in the river valley. As the modern river meanders across the Pleistocene river valley, bank erosion exposes these ancient gravel deposits and adds this material to the bed of the modern Brazos River. Active channel migration is therefore an important process for supply of gravel to portions of the modern middle and lower Brazos River.

Gillespie and Giardino (1997) investigated the channel migration rate of 156 miles of the Brazos River from near the Falls/Milam/Robertson county lines to near the Washington/Austin county lines. This study, based on aerial photographs taken from 1939 to 1988, found that channel width and migration rate decreased since 1939. From data collected at USGS stream gages in the area, they also noted decreases in both discharge and sediment load during the same time period. These decreases are probably responsible for the changes in the river channel. According to these researchers, the channel was still adjusting to the changes in flow and sediment regime in 1988. This study is currently being updated using more current aerial photography and data.

TIFP has conducted a number of activities to segment the Brazos River based on geomorphic features. These activities include work by Philips (2007) that segmented the river channel from Bryan to the coast based on an adaptation of the River Styles classification scheme of Brierly and Fryirs (2005). This classification provides a useful tool to understand differences in physical processes and habitats along the river. The river was segmented into 30 reaches based on channel and valley characteristics. A description of each reach was provided, including characteristic channel and floodplain features such as cutbanks, point bars, bedrock outcrops, meander cutoffs/oxbows, paleochannels, and sloughs. A similar exercise by TWDB personnel broke the remaining portion of the study area (Brazos River from Waco to Bryan) into 13 reaches, also based on the adaptation of River Styles.

The Brazos River alluvium aquifer extends along the river from Bosque to Fort Bend counties and interacts with surface water bodies and deeper, underlying aquifers. For more information about the alluvium aquifer, please see the summary of connectivity studies (Section 1.1.5).

1.1.4 Water Quality

Clean Rivers program historical water quality trends

TCEQ in cooperation with BRA through the Clean Rivers Program produce the Brazos River Basin Summary Report every five years. The 2007 Basin Summary Report provides an overview of monitoring and assessment activities in the Brazos River basin. The report was prepared by BRA staff in coordination with the TCEQ and in accordance with the State's guidelines. The report presents a ten-year history of the levels of bacteria, nutrients, aquatic life use, and other water quality parameters at over 200 active surface water quality monitoring sites throughout 14 major subwatersheds in the basin, covering the period January 1997 through August 2007. Two major subwatersheds, the Central and Lower watersheds of the Brazos River, and 29 monitoring stations are of greatest interest to the TIFP study of the middle and lower Brazos River. Significant findings of the basin summary report are listed below.

- **Bacteria**

    In the central Brazos (Segment 1242), the current assessment indicates elevated bacteria levels exceeding Water Quality Standards in eight water bodies that have been historically 303(d) listed: Brazos River, Thompsons Creek, Campbells Creek, Mud Creek, Pin Oak Creek, Spring Creek, Tehuacana Creek, and Big Creek. The Brazos River was de-listed on the 2008 303(d) List for elevated bacteria levels.

    Additional water bodies with elevated bacteria levels that have not historically been 303(d) listed are: Cottonwood Branch, Still Creek, Pond Creek, Deer Creek, and Walnut Creek. All but Pond Creek were included on the 2008 303(d) List for elevated bacteria levels. Sources of elevated bacteria levels prevalent through much of the watershed have not been determined. Rangeland runoff may be the main contributor, given the rural nature of most of the drainage area.

    In the lower Brazos (Segment 1202), Allen’s Creek continues to be non-supporting for contact recreation use due to elevated levels of bacteria. Permitted domestic outfalls, row crops, and pastureland are located upstream of the sampling location. Any or all of these could contribute to the bacteria load in Allen’s Creek.

    Upper Oyster Creek was originally listed on the 2000 303(d) List for bacterial impairmentsA TMDL for point and non-point sources of bacteria for this water body was completed and approved in 2007.

- **Dissolved Oxygen**

  In the central Brazos (Segment 1242), Thompson Creek is on the 2008 303(d) List for depressed dissolved oxygen. Additional data and information will be collected before a TMDL is scheduled.

  In the lower Brazos (Segment 1202), Upper Oyster Creek was originally listed on the 2000 303(d) List for dissolved oxygen and remains on the 2008 303(d) List. A TMDL is underway for two sections of Upper Oyster Creek, and a use-attainability analysis (UAA) has been completed for another section.

- **Nutrients**

  Nutrient enrichment concerns are apparent in the Central Brazos for portions of three interconnected, effluent-driven streams near Bryan (Still Creek, Cottonwood Branch, and Thompsons Creek) due to elevated levels of nitrite+nitrate nitrogen, orthophosphate phosphorus, and total phosphorus. Another nutrient enrichment concern exists in the upper end of the watershed, as excessive chlorophyll *a* concentrations have been observed in the lower reaches of Tehuacana Creek.

  In the lower Brazos, Allen's Creek has a concern for orthophosphate phosphorus. The same sources that are contributing to the bacteria load may be the cause of the nutrient load in Allen's Creek.

- **pH**

  The only other standard criteria nonconformance occurred in Pin Oak Creek, where pH levels were sometimes less than the specified range. This is most likely a natural condition related to geology and soil type in the subwatershed.

The full Basin Summary Report can be downloaded from the following website: www.brazos.org/BasinSummary_2007.asp.

Water quality data in the middle and lower Brazos River sub-basin is also collected and analyzed through several other programs and agencies. Table 8 outlines the various sources of water quality data that may be utilized in this study of the middle and lower Brazos River. This table does not attempt to list all water quality data sources, only those that collect and analyze water quality data on a regular basis and make the data readily available and easily accessible.

In order to assess current water quality conditions in the middle and lower Brazos River sub-basin, multiple water quality related stations or locations will be used as data points in this study. These locations include the following:

- Wastewater discharge locations – Discharge of pollutants to Texas surface water is regulated under the Texas Pollutant Discharge Elimination System program administered by the TCEQ. There are approximately 82 major wastewater dischargers in the middle and lower Brazos River sub-basin. Major wastewater dischargers are defined as municipal facilities that are permitted to discharge more than 1 million gallons per day and industrial facilities that are permitted to discharge more than half a million gallons per day. Major wastewater discharge locations in the sub-basin are shown in Figure 8.

- Diversion locations – Water diversions from the middle and lower Brazos River are permitted by the TCEQ through the issuance of water rights permits. Water is withdrawn from the river for domestic and livestock use, irrigation, impoundments, and various other uses. There are approximately 91 permits to withdraw water on the middle and lower Brazos River. Water diversion points are show in Figure 9.
- Surface water quality monitoring sites - The Surface Water Quality Monitoring (SWQM) Program has been evaluating biological, chemical, and physical characteristics of Texas' surface waters since 1967. The Clean Rivers Program and the SWQM program utilize the same monitoring sites to assess water quality data in the middle and lower Brazos River sub-basin. Approximately 28 SWQM monitoring sites are located on the sub-basin, as shown in Figure 10.

Table 8. Water quality data information in the middle and lower Brazos River.

Data Source	Types of Data	Frequency
Clean Rivers Program (TCEQ, BRA)	Chemical, Physical, Biological	Weekly, Monthly, Bimonthly, Quarterly, Annually, Continuous
Surface Water Quality Monitoring	Chemical, Physical, Biological	Quarterly, Continuous
TMDL Implementation	Chemical, Physical, Biological	Specific Studies on the Brazos River
Use Attainability Analysis	Chemical, Physical, Biological	As needed
Receiving Water Assessments	Chemical, Physical, Biological	As needed
USGS	Chemical, Physical, Biological	Continuous

Figure 8. Major wastewater dischargers in the middle and lower Brazos River sub-basin.

Figure 9. Water diversion points on the middle and lower Brazos River.

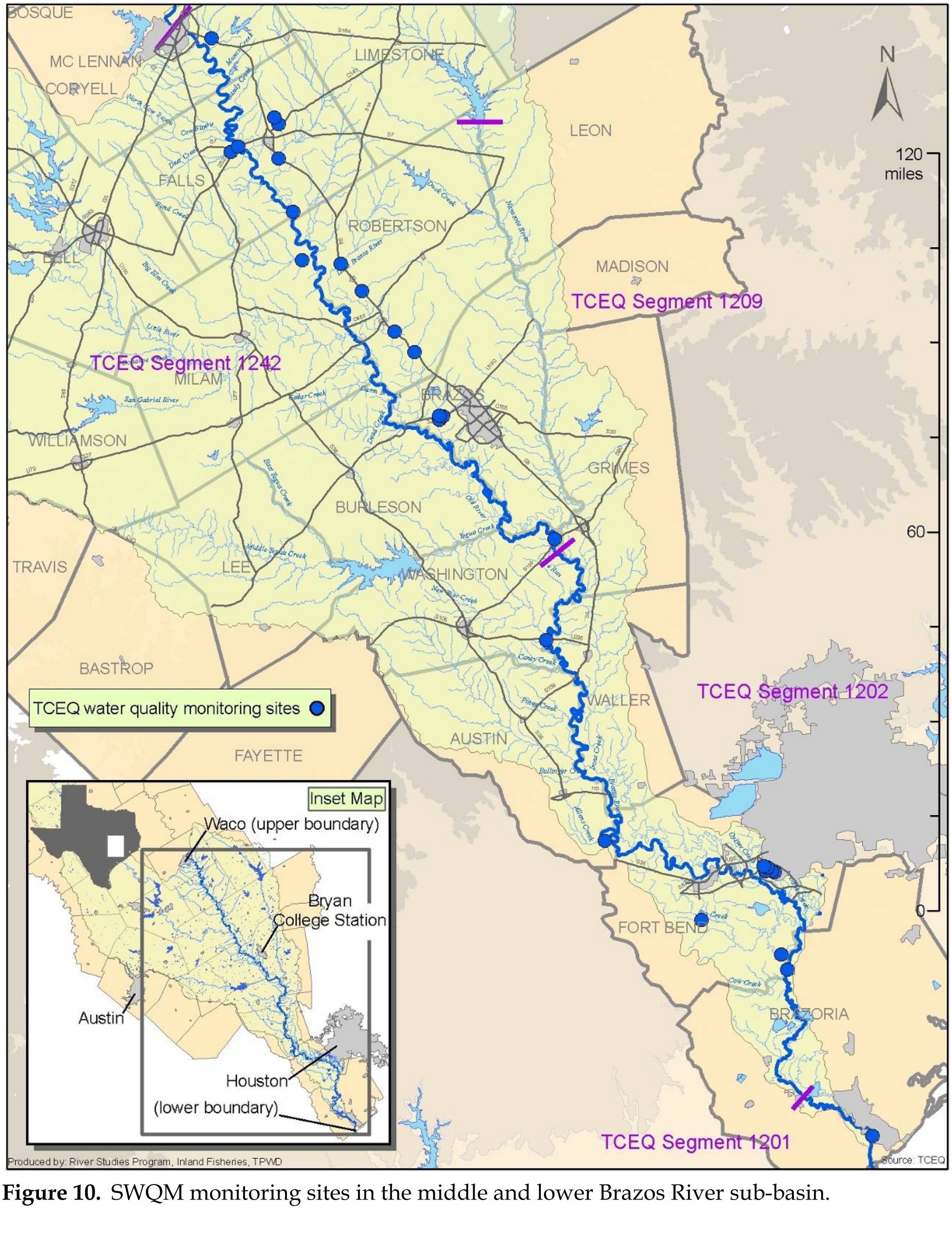

Figure 10. SWQM monitoring sites in the middle and lower Brazos River sub-basin.

1.1.5 Connectivity

Oxbow lakes are an important component of the ecosystem supported by the middle and lower Brazos River. Winemiller et al. (2004) completed a study of the connectivity of six oxbow lakes along the Brazos River from Bryan/College Station to the mouth of the river. Significant differences in the fish assemblage structure of oxbow lakes and the main river channel were identified. Results indicated that during connecting flow events, adult fish migrated from the river channel to oxbow lakes while a greater number of juvenile fish migrated from oxbow lakes to the river channel. Oxbow lakes were found to have different connectivity characteristics according to their age and proximity to the river channel. Researchers concluded that oxbow lakes with a variety of age/connectivity characteristics increased overall fish diversity.

The middle and lower Brazos River is connected to both its alluvium aquifer and underlying aquifers. The Brazos River alluvium aquifer extends along the river from Bosque County to Fort Bend County. Interactions between this aquifer and surface water bodies in the middle and lower Brazos sub-basin may be considerable during some flow conditions. During low flows, gains or losses to the aquifer may affect subsistence or base flow conditions in the river channel. During high flows, high pulse or overbank flows may provide substantial volumes of recharge to the aquifer. The alluvium aquifer also interacts with underlying aquifers, including the Carrizo-Wilcox, Queen City, Sparta, Yegua-Jackson, and Gulf Coast aquifers.

A recent USGS study by Turco et al. (2007) investigated surface water/groundwater connectivity and included a gain/loss study of the Brazos River from McLennan County to Fort Bend County. They divided this portion of the river into segments and took synoptic flow measurements during two time periods, March 1-15, 2006 and August 2-20, 2006. They identified segments of the river that were verifiably gaining or losing, as well as some seasonal variation in this processes. During the March time period, five segments were found to be gaining and none were losing. During the August time period, four segments were gaining and two were losing. The location of underlying aquifers appears to explain some of the variation in gain/loss characteristics along the Brazos River.

USGS studies by Shah and Houston (2007), Shah et al. (2007a), and Shah et al. (2007b) have focused on the characteristics of the Brazos River alluvium aquifer. Those studies determined the location and thickness of the aquifer and hydraulic properties such as specific conductance, transmissivity, and hydraulic conductivity. Additional studies are planned by other state programs in order to obtain data required to develop accurate groundwater models for the area.

1.1.6 Allens Creek Reservoir study

A project specific study was completed by TWDB for a portion of the lower Brazos River (Osting et al. 2004) prior to the initiation of TIFP studies for the entire middle and lower Brazos River. That study focused on the potential impacts of the proposed Allens Creek Reservoir and did not address all of the study components described in the Technical Overview (TIFP 2008). Only subsistence and base flow components were considered. As part of that study, a hydraulic model was developed for a portion of the lower Brazos River downstream of the confluence with Allens Creek. The model was used to analyze the relationship between instream flows and mesohabitats at that location. Another computer model was developed to estimate the effect of instream flows on salinity in portions of the river near its mouth on the Gulf of Mexico. TIFP will evaluate this study and any future studies related to the Allens Creek project and incorporate portions that provide greater understanding of the middle and lower Brazos River.

1.2 *Assessment of Current Conditions*

To assess current conditions in the middle and lower Brazos River sub-basin, available information was acquired and evaluated along with data from TIFP and BRA sampling efforts. Specific data layers included tributaries, human development (roads, bridges, towns, etc.), land use, aerial photography, USGS stream gages, discharge locations, withdrawal locations, water quality monitoring sites and data, historic and recent biological data collections, habitat evaluations (aquatic and riparian), and geomorphic data.

1.2.1 Hydrology

Tributaries of middle and lower Brazos River include the Little, Little Brazos, and Navasota rivers and Yegua, Davidson, Mill, and Big creeks. The most significant tributaries, in terms of their flow contributions to the mainstem river, are the Little and Navasota rivers. At their confluence, the Little River has a median flow of approximately half the median flow of the Brazos River. The Navasota River has a median flow of approximately 5% of that of the Brazos River at their confluence. Under base flow conditions, no other tributaries make as significant a contribution to the flow of the middle and lower Brazos. In the upper portion of the sub-basin, flow in the middle and lower Brazos appears to be affected by the operation of upstream reservoirs. These affects are reduced lower in the sub-basin as more and more unregulated areas contribute to the flow of the river. The river also is connected to its alluvium aquifer, which extends from McLennan to Fort Bend counties. The alluvium aquifer overlies deeper aquifers, including the Carrizo-Wilcox, Queen City, Sparta, Yegua-Jackson, and Gulf Coast aquifers. Flow within the sub-basin remain responsive to precipitation patterns and maintain much of its natural variability. The middle and lower Brazos River remains one of North America's largest relatively intact floodplain rivers.

1.2.2 Biology

In recent TIFP fish collections (2006-2008), over 50 species of fish were collected in the lower Brazos River sub-basin. The diversity of fish species recently collected includes representatives from each of the major trophic guilds (piscivore, invertivore, omnivore, and herbivore). Fish species representing several habitat categories (riffle, shallow run, deep run, deep pool, shallow pool, edge, and backwater) have been observed. Riffle habitat is the most limited within the sub-basin. Species utilizing riffle habitat include red shiner (*Cyprinella lutrensis*), bullhead minnow (*Pimephales vigilax*), shoal chub (*Macrhybopsis hyostoma*), as well as juvenile channel catfish (*Ictalurus punctatus*), flathead catfish (*Pylodictis olivaris*), and river carpsucker (*Carpiodes carpio*). Species collected that are representative of deep run habitat include flathead catfish (*Pylodictis olivaris*), freshwater drum (*Aplodinotus grunniens*), longnose gar (*Lepisosteus osseus*) and gizzard shad (*Dorosoma cepedianum*). A variety of the sunfish species collected are reported to be representative of shallow pool, edge, slow run and backwater habitat. Freshwater drum (*Aplodinotus grunniens*) and three catfish species along with alligator gar (*Atractosteus spatula*) and longnose gar (*Lepisosteus osseus*) may also serve as representatives of deep pool habitat. Several species including silverband shiner (*Notropis shumardi*), ghost shiner (*Notropis buchanani)*, shoal chub (*Macryhbopsis hyostoma*), river carpsucker (*Carpiodes carpio),* and chub shiner (*Notropis potteri*) are representative of shallow and moderately deep run habitats.

Fish habitat use may vary depending on life stage. Some species such as channel catfish (*Ictalurus punctatus*) might be used as indicators for more than one habitat type. Furthermore, there is longitudinal variation in species abundance. Some species may be utilized in the analysis only for downstream reaches where they are more abundant, e.g. blue catfish (*Ictalurus furcatus*) or alligator gar (*Atractosteus spatula*).

Given that there is very limited mussel data throughout the state, trends and current conditions of mussel populations are difficult to discern. Of the 25 mussel species known to occur in the Brazos River basin historically, only 14 species have been recently documented in mussel distribution surveys (Karatayev and Bulakova 2008, Randklev et al. 2010). Six of the 25 species that occurred historically in the basin are listed as species of concern (TPWD 2005): golden orb (*Quadrula aurea*), smooth pimpleback (*Quadrula houstonensis*), rock pocketbook (*Arcidens confragosus*), Texas fatmucket (*Lampsilis bracteata*), Texas fawnsfoot (*Truncilla macrodon*) and false spike (*Quincuncina mitchelli*). Of these six species, five of them were recently listed as state-threatened by TPWD (golden orb, smooth pimpleback, Texas fatmucket, Texas fawnsfoot, and false spike). Smooth pimpleback and Texas fawnsfoot were both collected in the recent mussel surveys by Karatayev and Bulakova (2008) and Randklev et al. (2010), with the smooth pimpleback being very abundant in the Navasota River and Yegua Creek.

Much of the middle and lower Brazos River floodplain has been cleared up to or near the banks for agricultural and ranching purposes, leaving isolated patches of riparian habitat scattered throughout the basin. Riparian habitats vary in width from a few meters to greater than fifty or sixty meters in undisturbed areas. There are only a few areas adjacent to the middle and lower Brazos River covered by dense hardwood canopies, primarily in downstream reaches near Brazos Bend State Park, and lack of these types of areas limits the growth of underlying vegetation. Riparian vegetation along the lower Navasota does offer wide dense hardwood riparian corridors. Along the Brazos, stream canopy is sparse and confined, leaving an open exposed channel throughout. The Little River, Little Brazos and Navasota River provide stream canopy from open to partially and completely closed canopies. Macrophytes have a limited distribution in the middle and lower Brazos River but are abundant in some areas of the Navasota and occur in greater numbers in areas of the stream that are open to direct sunlight and reduced flow. Within the floodplain, wetlands such as oxbows provide critical nursery habitat for many species including floodplain spawning fish. Hydrologic connectivity between oxbow habitat and the main river channel is critical to maintenance of some fish communities. These relationships have been documented by several studies within the middle and lower Brazos sub-basin (Winemiller et al. 2004).

1.2.3 Physical Processes

The middle and lower Brazos River flows across exposed bedrock of Late Cretaceous to Quaternary age, eventually discharging into the Gulf of Mexico. Bedrock formations crop out in bands parallel to the coast and dip towards the Gulf of Mexico. The Cretaceous exposed rock is composed mainly of limestone, marl and shale which do not form any important aquifer in the area. The Tertiary aged rocks consist mainly of shale, clay, and sand and contain some of the major aquifers in the area. Unconsolidated material deposited by the river has created a valley containing an alluvium aquifer. The river is actively migrating across the valley and numerous oxbow lakes occur along its length. The river is predominantly sand bedded, although in some areas, outcroppings of bedrock and gravel deposits provide coarser bed material.

1.2.4 Water Quality

Water quality in the middle and lower Brazos River sub-basin continues to improve (BRA 2007); however, water quality concerns are still experienced throughout the sub-basin for particular constituents. Nutrients are also a concern in portions of the lower and middle Brazos River**.** The sources of the nutrients are varied and depend on the sampling location. Elevated nutrient levels are typically found below wastewater discharge points, but nutrients can also enter the stream system from runoff, discharge of groundwater polluted with nutrients, through natural and manmade sources, and even through the atmosphere. At this time, only Thompson Creek and Upper Oyster Creek are identified as impaired by the TCEQ for low dissolved oxygen levels. The sources of the nutrients are varied and depend on the sampling location.

1.2.5 Connectivity

Although the river is not associated with a major estuary or extensive riparian/wetland areas, connectivity is still an important issue for ecosystems dependent on the middle and lower Brazos River. Remaining riparian areas are sustained by periodic connectivity with the river. Species associated with oxbow lakes and other floodplain habitats also require periodic connectivity. The middle and lower Brazos River does have an extensive alluvium aquifer and is connected to this and deeper aquifers. Flows that connect the river with its floodplain may be an important source of recharge for these aquifers. The main stem of this portion of the river has not been dammed and no issues related to longitudinal connectivity have been identified.

1.3 *Conceptual Model*

As described in the Technical Overview (TIFP 2008), a conceptual model is useful to characterize the current understanding of the riverine ecosystem and develop study designs. A conceptual model incorporates much of the basic understanding of the system at the point of study initiation. As such, it represents a beginning point from which to develop flow/ecology relationships and direct studies to further refine understanding.

A general conceptual model of the middle and lower Brazos River is shown in Figure 11. This model has been adapted from a general model for an unconfined sand bedded stream developed by Stillwater Sciences (2003). It has been tailored for the middle and lower Brazos River by incorporating important findings from previous studies and local knowledge gained from participants during study design workgroup meetings.

Because conditions vary along the river, various aspects of the general conceptual model are of lesser or greater importance depending on location. For example, the significance of riparian areas and floodplain habitats vary along the river. Groundwater/surface water interactions vary depending on the underlying aquifers. Although predominantly sand, the bed material of the channel also varies within the study area. There are limited areas with bed material including larger sediments and bedrock, depending on local conditions. Large woody debris is in limited supply along the middle and lower Brazos River. This factor, in combination with the large size of the channel, acts to limit the impact of large woody debris on the physical shape of the channel.

The expected relationships between flow components and various ecological process of the middle and lower Brazos River sub-basin are shown in Table 9. This table was adapted from the example flow/process relationships shown on page 14 of the Technical Overview (TIFP 2008). All four components of an environmental flow regime are provided in this table, as well

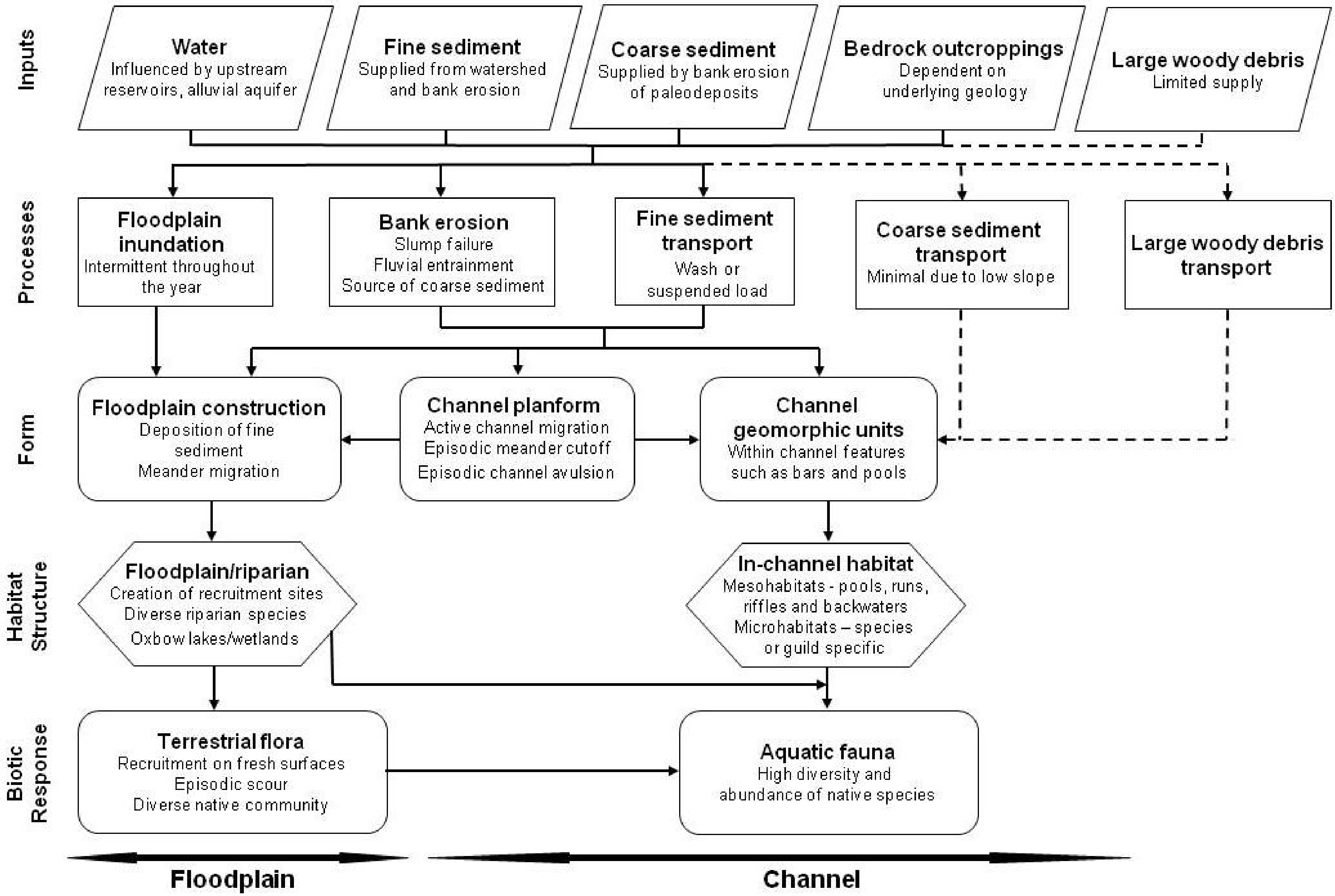

Figure 11. General conceptual model of the riverine ecosystem of the middle and lower Brazos River.

as expected relationships to ecosystem processes. Although processes are categorized by primary discipline, each has linkages across disciplines and must be studied in a multi-disciplinary way.

Table 9. Ecological processes supported by instream flow components of the middle and lower Brazos River.

Component	Hydrology	Geomorphology	Biology	Water Quality	Connectivity
Subsistence flows Infrequent, low flows (typically during summer)		Increase deposition of fine and organic particles	Provide limited aquatic habitat Maintain populations of organisms capable of repopulating system when favorable conditions return	Maintain adequate levels of dissolved oxygen, temperature, and constituent concentrations (particularly nutrients)	Provide limited connectivity along the length of the river May be affected by groundwater/ surface water interactions
Base flows Average flow conditions, including variability	Vary by season and year	Maintain soil moisture and groundwater table in riparian areas Maintain a diversity of habitats	Provide suitable aquatic habitat for all life stages of native species	Provide suitable in-channel water quality	Provide connectivity along the length of the river May be affected by groundwater / surface water interactions
High flow pulses In-channel, short duration, high flows	May be influenced by reservoir operations and land use changes	Maintain channel and substrate characteristics Prevent encroachment of riparian vegetation Play an important role in recovery of channel after flood events	Provide spawning cues for organisms	Restore in-channel water quality after prolonged low flow periods	Provide connectivity to habitats near channel edge
Overbank flows Infrequent, high flows that exceed the channel	Influenced by reservoir operation	Provide lateral channel movement, an important source of coarse material for channel Form new habitats Flush organic material into channel Transport nutrients and sediment to floodplain	Provide spawning cues for organisms Provide access to floodplain habitats Maintain diversity of riparian vegetation	Restore water quality in floodplain water bodies	Provide connectivity to floodplain Recharge the alluvium aquifer Provide large volumes of freshwater to estuary

2.0 STAKEHOLDER INVOLVEMENT AND STUDY DESIGN DEVELOPMENT

2.1 *Stakeholder Involvement*

Stakeholder involvement has been a key component of the TIFP middle and lower Brazos River study, beginning with initial meetings to gain historic and current perspectives on the basin to more recent meetings convened to develop study specific goals and objectives to guide the development of the study design. Throughout the process, stakeholders provided a wealth of local knowledge which complemented historical reports and data. This information was used to identify areas for reconnaissance activities. Preliminary analysis was performed on historical data as well as the data generated in the reconnaissance efforts and results were presented at basin update meetings. Stakeholders and agency personnel developed the study goal, objectives, and indicators at subsequent study design workgroup meetings. Section 4.0 describes the continued stakeholder involvement as the study progresses beyond the design and field sampling components.

2.2 *Study Goal and Objectives*

The overall goal or vision agreed upon by the study design workgroup was for ***"a middle and lower Brazos River that provides for sustainable environmental, economic, and social uses".*** Because of the TIFP's mandate ("sound ecological environment"), expertise (environmental rather than economic and social), and resources (limited), objectives were developed primarily for meeting the environmental aspects of this goal. Planning for the economic (and to some extent social) uses of water is covered primarily by the state's regional water planning process. Objectives for multiple disciplines (hydrology, biology, physical processes, water quality, and connectivity) were developed for this TIFP study with an overriding aim to determine the natural, historic, and current conditions related to each. To evaluate progress made toward meeting the goal and objectives, a set of indicators were selected and are summarized below (more details provided in Section 2.3). It should be noted that the use of sport fish as a biological indicator and bacteria as a water quality indicator does reflect, to some degree, social and economic goals related to recreation.

2.2.1 Hydrology

The hydrologic objective is to identify environmentally important flow components and characteristics that will be of value in focusing study on potential environmental consequences of flow alterations and, ultimately, in developing a flow regime to sustain ecological processes dependant on the middle and lower Brazos River. This objective has three parts, including identification of: flow regime components and characteristics; current, historical, and naturalized patterns of flow; and sources of instream flow and factors which may affect those sources. Indicators selected to characterize flow regime components are frequency, timing, duration, rate of change, and magnitude of overbank, high pulse, base habitat, and subsistence flows. Historical flow patterns will be based upon the above indicators from the older portions of gage records. Current flow patterns will be developed from gage records from the last 20 to 25 years. Gains and losses (the difference in the amount of water entering and leaving specific sections of the river channel) will be used to investigate sources of instream flow.

2.2.2 Biology

The biological objective is to determine and maintain flows necessary to support key aquatic habitats, native species, and biological communities known to occur in the river and riparian zones. Biology was split into three categories for evaluation purposes: instream biological communities, instream habitat, and riparian habitat. Indicators of instream biological communities include native species richness, relative abundance of target species, fish (flow sensitive species, sportfish, prey species, imperiled species, and intolerant species), and other aquatic organisms (such as mussels). Instream habitat indicators are habitat quality and quantity for key species and mesohabitat area and diversity. Riparian habitat indicators include vegetation (age class, richness, diversity, density, and canopy cover), soils, and hydrology (gradient of inundation and base flow levels).

2.2.3 Physical Processes

The physical processes objective is to identify relationships among flows, bank stability, channel maintenance, and alluvial and associated aquifers. Indicators chosen for evaluation of bank stability are the rate of lateral channel migration, channel avulsion, and bank erosion. Observations of in-channel bars and meander pools will provide indicators of channel maintenance. Indicators related to interactions with alluvial and associated aquifers will be total flow gains or losses in particular sections of the river. Flood impact summaries provided at most USGS streamflow gage sites will be used as indicators of flood impacts.

2.2.4 Water Quality

The water quality objective is to identify flow-related water quality in the four flow regime components. Indicators include nitrogen, phosphorus, dissolved oxygen, temperature, total suspended solids (TSS), salinity, and bacteria concentrations.

2.2.5 Connectivity

Objectives for connectivity include identifying how flows influence riparian zones and support lateral and longitudinal connectivity. Connectivity categories selected for evaluation are riparian zone, lateral connectivity, and groundwater/surface water interaction. The area of specific habitat areas and total area inundated by overbank flows of particular magnitudes will be used as the indicator of connectivity to riparian zones. Frequency, duration, and timing of connection of floodplain habitats (oxbow lakes, backwaters, etc) to the river will serve as the indicator for lateral connectivity. Gain or loss in specific sections of the river will be used as the indicator for groundwater/surface water interaction.

2.3 *Study Indicators*

As described in the Technical Overview (TIFP 2008), a list of all practical indicators consistent with the study goal and objectives for the middle and lower Brazos River sub-basin was provided to the study design workgroup. These indicators were then paired down to those ecologically significant indicators that were directly related to components of the flow regime. The following tables (Tables 10 through 13) present the final list of indicators as determined by the stakeholder process for hydrology, biology, physical processes, water quality, and connectivity.

Table 10. List of Hydrology indicators and their importance to the instream flow study.

Hydrology		
Indicators		
Category	*Indicator*	*Explanation*
Flow regime components	Overbank flows (frequency, timing, duration, rate of change, and magnitude)	Infrequent, high magnitude flow events that enter the floodplain • Maintenance of healthy riparian areas • Transport of sediment and nutrients to/from floodplain • Connectivity of riparian and floodplain habitats to the river channel • Recharge alluvium aquifer
	High pulse flows (frequency, timing, duration, rate of change, and magnitude)	Short duration, high magnitude within channel flow events • Maintain sediment transport and physical habitat features of the river channel • Provide longitudinal connectivity along the river corridor for many species (e.g., migratory fish)
	Base habitat flows (frequency, timing, duration, rate of change and magnitudes)	Range of average or "normal" flow conditions • Provide instream habitat quantity and quality needed to maintain the diversity of biological communities • Maintain water table and support/maintain healthy riparian vegetation
	Subsistence flows (frequency, timing, duration, rate of change, and magnitude)	Low flows maintained during times of very dry conditions • Maintain water quality standards • Prevent loss of aquatic organisms • Prevent loss of riparian vegetation
Natural variability	Natural	Determination of the natural variability of the above indicators, based on the older portions of gage records, presumably less impacted by human activity. The exact time period may vary by gage site.
	Current	Variability of the above indicators based on the last 20-25 years of gage records.
Sources of instream flow	Total flow gain or loss in section of river	Difference in the amount of water entering and leaving a specific section of the river channel. Sources of gains include inflow from tributaries, alluvial and deeper aquifers, and discharges to the river. Sources of losses include direct evaporation, transpiration from riparian areas, diversions, and recharge of alluvial and deeper aquifers. Indicator may be influenced by shallow groundwater surface elevation and hydraulic head of deeper aquifers.

Table 11. List of Biology indicators and their importance to the instream flow study.

Biology		
Indicators		
Category	*Indicator*	*Explanation*
Instream Biological Communities	Native Richness	Richness, or the number of species or taxa, is a measure of community health, can be applied at a variety of scales (reach to basin to statewide), and can be related to modifications in flow. May also use proportions such as the proportion of native to non-native species.
	Relative Abundance	The number of organisms of a particular species as a percentage of the total community
	Fish • Flow sensitive species • Sportfish • Prey species • Imperiled species • Intolerant species	Fish are useful indicators because: • they occupy a range of habitats and have a variety of life histories that are generally known • their position at various levels of the aquatic food chain provides an integrative view of the watershed • they are useful for examining both direct toxicity and stressful conditions by looking at indicators such as missing species or depressed growth and reproduction • they are valued by the public There are many species of fish in the river and all of them cannot be studied individually. Those that may warrant study include: flow sensitive species, sportfishes, prey species, imperiled species, and intolerant species.
	Benthic invertebrates • mussels • riparian plants • other vertebrates	These may be appropriate as indicators.
Instream Habitat	Habitat Quality and Quantity for Key Species	Involves relating suitable habitat (microhabitat) and flow for key species. Habitat attributes may include current velocity, depth, substrate and cover; other attributes may be important for some species.
	Mesohabitat Area and Diversity	This indicator stems from the knowledge that diverse habitats support diverse communities. Mesohabitat analysis provides a quantifiable relationship between larger scale habitat (e.g. riffles, runs, pools) area and flow; habitat diversity can be derived from same data. Uses biological data for all species in a community (e.g., fish species) to define the attributes of each mesohabitat.

Table 11 (cont.). List of Biology indicators and their importance to the instream flow study.

Biology		
Indicators		
Category	*Indicator*	*Explanation*
Riparian Habitat	Vegetation • Age class distribution of riparian species • Riparian species richness and diversity • Density • % Canopy cover	These are key components in assessing the diversity, health, and functionality of riparian habitat and ensuring that adequate riparian species are present for recruitment and maintenance of the ecosystem. Riparian plants typically must maintain contact with the water table, so their presence and diversity is an important indicator of soil moisture (water table) characteristics. The listed vegetation parameters can be correlated with important riparian functions, such as stream bank stabilization, temperature dynamics, and nutrient cycling.
	Soils • Riparian soil types	In the absence of riparian vegetative indicators, soil characteristics identified by the soil survey database can be used to determine past or present hydrologic influence and hence historical riparian area extent.
	Hydrology • Gradient of inundation • Base flow levels	Periodic occurrence of flood (overbanking) flows, associated channel dynamics and the preservation of base flows capable of sustaining high floodplain water tables are essential to maintaining the health of riparian ecosystems. Groundwater depths can be sampled and coupled with surface water data to produce a probability of inundation curve. Overbanking flow requirements can be modeled.

The following list of species are proposed as key species based on their abundance in the middle and lower Brazos River, habitat use, life history, sensitivity to change (hydrologic and water quality), and/or sport fish value:

Alligator gar (*Atractosteus spatula*) are the largest of the fish species occurring in Texas, reaching maximum lengths of around 3 m (nearly 10 ft) (Lee and Wiley 1980) and maximum weights of approximately 127 kg (280 lbs) (IGFA 1999). Alligator gar reach sexual maturity at about 14 years of age and are believed to live up to 50 years (Ferrara 2001). Alligator gar utilize pool and backwater habitats of rivers (Suttkus 1963, Gelwick and Morgan 2000). Spawning occurs between April and early June (May and Echelle 1968, Lee and Wiley 1980). Periodic high flow events provide connection to floodplain habitats, such as oxbow lakes, where alligator gar lay adhesive eggs onto plant matter. Oxbow lakes in the Brazos River floodplain are important spawning grounds (Zeug et al. 2005, Robertson et al. 2008). Alligator gar are a popular recreational target for bowfishing and commercial harvesting occurs in some areas (Thomas et al. 2007). This species appears to be declining in most of its range due to habitat alteration, over-fishing and intentional eradication (Jelks et al. 2008). In 2008, TPWD instituted a daily bag limit of one to regulate harvest.

Spotted bass (*Micropterus punctulatus*) are native to Texas including the Brazos River basin (Hubbs et al. 2008) and are regulated by TPWD as a sport fish. Spotted bass are found in large rivers and streams in slow moving pools with structure (Warren 2009). In streams, spotted bass utilize faster flowing water than largemouth bass (*Micropterus salmoides*) (Ross 2001). Spawning occurs from April through June (Vogele 1975); males construct and guard nests in areas of low to moderate current velocity. Spotted bass become sexually mature after about 1 year and have an average life span of about 6 years (Webb and Reeves 1975).

Shoal chub (*Macrhybopsis hyostoma*) occur within the Mississippi River basin and in Texas occur from the Sabine to the Lavaca River (Eisenhour 2004, Hubbs et al. 2008). The species is considered to be stable within the Brazos River basin (Bonner and Runyan 2007), but it has been extirpated from other systems (Luttrell et al. 2002, Eisenhour 2004). Shoal chub occur in medium to large rivers (Eisenhour 2004, Winemiller et al. 2004) and utilize run and riffle habitats up to around 2 m depth (Eisenhour 1997) with clean sand or pea-size gravel substrates and moderate current velocities (20-40 cm/s; Luttrell et al. 2002). In the Brazos River, relative abundance was fairly consistent through the year and weakly associated with peak discharge (Winemiller et al. 2004). Shoal chub are open water spawners; spawning is likely triggered by high flow events (Bottrell et al. 1964, Miller and Robison 2004). Reproductive age is 1 year and specimens live up to 2 years (Starrett 1951).

Silverband shiner (*Notropis shumardi*) occur within the Mississippi River drainage and is considered relatively stable, although declines have been noted in the Brazos basin (Bonner and Runyan 2007). The species is considered a large river fish but can also be found in smaller tributaries and oxbows (Gilbert 1980a, Linam et al. 1994, Winemiller et al. 2004, Li and Gelwick 2005, Zeug et al. 2005). Silverband shiner utilize moderate to swift current velocities and moderate to deep depths and is associated with turbid water over silt, sand, and gravel substrates (Gilbert 1980a, Robison and Buchanan 1988, Cross and Collins 1995). Li (2003) reported that the species to be common along the shallow river-margin of the lower Brazos River during the summer and winter. Edwards (1997) reported the breeding season as extending from May through mid-Fall. Conner (1977) reported spawning behavior over hard sand to fine gravel substrates in water 1-2 m deep in strong current. This species is considered a broadcast spawner. Winemiller et al. (2004) suggested silverband shiner may migrate into tributaries to spawn during high flow conditions in the Brazos River.

Chub shiner (*Notropis potteri*) occur in several river basins in Texas including the Brazos River basin (Hubbs et al. 2008). Within the Brazos River basin this species is considered to be in decline (Bonner and Runyan 2007). Chub shiner prefer large, turbid rivers (Gilbert 1980b) but also occur in smaller tributaries (Hubbs and Bonham 1951). This species is associated with flowing water habitats including shallow runs with moderate velocity and sand substrate (Perkin et al. 2009) and is considered tolerant of high salinities (Echelle et al. 1972, Taylor et al. 1993, Higgins and Wilde 2005). Little is known of the reproductive habitat needs of this species though it is likely a broadcast spawning pelagophil. The spawning season extends from March through September (Perkin et al. 2009). It is presumed they reach sexual maturity by year one and a maximum life span of 2.5 years (Perkin et al. 2009). An opportunistic feeder, chub shiner consume aquatic invertebrates as well as small fish.

Blue, channel, and flathead catfish are native to the Brazos River basin (Hubbs et al. 2008) and have important sport fish value. Because juveniles of these species utilize riffle and shallow run habitat, this life stage will be used to evaluate the relationships between flow and these habitats. Blue catfish (*Ictalurus furcatus*) inhabit large rivers and streams (Hubbs et al. 2008) and utilize swift chutes and pools with current over silt-free sand, gravel and rubble substrates (Glodek 1980a, Pflieger 1997). The spawning season occurs late spring to early summer at water temperatures of 21-25 °C (Sublette et al. 1990). Blue catfish build nests in holes (speleophils) usually in back water areas or pools. Channel catfish (*Ictalurus punctatus*) are associated with medium to large rivers in clear water with swift currents over sand or gravel bottoms (Glodek 1980b). Juveniles are often found in riffles, while adults are more common in pools (Hubbs et al. 1953). Spawning occurs in the late spring and early summer (Ross 2001) when temperatures reach 16-24 °C. Channel catfish are also speleophils. Flathead catfish (*Pylodictis olivaris*) usually inhabit deep holes of medium to large rivers (Glodek 1980c). Young-of-the-year live in rocky riffles until the fish get between 2 to 4 inches in length and then begin to distribute among other river habitats. This random distribution seems the rule in fish ranging from 4 to 12 inches in length. Individuals measuring 12 to 16 inches in length were associated with cover at intermediate depths in the stream, while larger individuals, more then 16 inches in length, almost invariably near more massive logs and drift usually in or near deep holes in the stream bed (Minckley and Deacon 1959). In Texas, the spawning season occurs between late June and July (Hubbs et al. 1953). Flathead catfish are also speleophils; nests are constructed under logs or other concealing cover (Breder and Rosen 1966).

Table 12. List of Physical Processes indicators and their importance to the instream flow study.

Physical Processes		
Indicators		
Category	*Indicators*	*Explanation*
Bank stability	Rate of lateral channel migration	Rate of lateral movement of channel across valley. Some migration of the channel is crucial to support diverse riparian habitats and a healthy ecosystem.
	Rate of channel avulsion	Rate of creation of channel cut-offs. Cut-offs, in the form of oxbow lakes, backwater areas, and abandoned channels, provide distinct and important habitats.
	Rate of bank erosion	The rate at which flows erode the sides of channels. This will vary by bank material and condition of the banks (vegetated, saturated, etc.).
Channel maintenance	In-channel bars (area, configuration, sediment size)	Sediment bars are an important in-channel bed form. Flow across these features provides a diversity of hydraulic conditions. Bar formation, in combination with opposite-bank erosion, is the driving process behind channel migration. As bars age, they gradually create new areas of floodplain and riparian habitat.
	Meander pools (depth)	Meander pools are another important in-channel bed form. Deep pools provide diverse hydraulic conditions and cover for some species. They also provide refuge habitat for many species during low flow periods.
Alluvial and associated aquifers	Flow gain or loss in section of river	Difference in the amount of water entering and leaving a specific section of the river channel. Sources of gains include inflow from tributaries, alluvial and deeper aquifers, and discharges to the river. Sources of losses include evaporation, evapo-transpiration from riparian areas, diversions, and recharge of alluvial and deeper aquifers. Indicator may be influenced by shallow groundwater surface elevation and hydraulic head of deeper aquifers.
Flood impacts	Stage (at USGS gage locations)	The National Weather Service provides flood impact summaries for most USGS streamflow gage sites, based on water surface elevation or "stage." These summaries provide an estimate of negative impacts of overbank flows.

Table 13. List of Water Quality indicators and their importance to the instream flow study.

Water Quality		
Indicators		
Category	*Indicator*	*Explanation*
Nutrients	Nitrogen Nitrate + Nitrite, Ammonia	Nutrient – any substance used by living things to promote growth. In water, the term generally applies to nitrogen and phosphorus. Nitrate-Nitrogen – A nitrogen containing compound that can exist as a dissolved solid in water. Excessive amounts (>10 mg/L) can have harmful effects on humans and animals. Nitrite-Nitrogen – An intermediate oxidation state of the nitrification process (ammonia, nitrite, nitrate). Ammonia-Nitrogen – Ammonia, naturally occurring in surface and wastewaters, is produced by the breakdown of compounds containing organic nitrogen.
	Phosphorus Orthophosphate Total	Orthophosphate – The most important form of inorganic phosphorus, making up 90% of the total. The only form of soluble inorganic phosphorus that can be directly used, it is the least abundant of any nutrient and is commonly the limiting factor. Total Phosphorus – A measure of all forms of phosphorus in water, including soluble and particulate phosphorus.
Oxygen	Dissolved Oxygen	The oxygen freely available in water. Dissolved oxygen is vital to fish and other aquatic life. Traditionally, the level of dissolved oxygen has been accepted as the single most important indicator of a water body's ability to support a desirable aquatic life.
Temperature	Temperature	The temperature of water is an important factor in an aquatic ecosystem because it controls biological activities and chemical processes. Stream systems exhibit *diel* (daily) temperature variations. Most aquatic organisms depend upon the environment to regulate metabolic rates and have adapted to temperature ranges that occur in their habitat. However, alteration of habitat, especially by human activities, can cause temperatures to exceed these ranges.
Water clarity	Total Suspended Solids (TSS)	A measure of the total suspended solids in water, both organic and inorganic.
Salinity	Salinity	The amount of dissolved salts in water, generally expressed in parts per thousand (ppt).
	Specific Conductance	Specific conductance is a measure of salinity in water. Salty water has high specific conductance.
Recreational health (Contact Recreation)	Bacteria	*E.coli* (freshwater) and enterococci (saline waters) are used as indicators of potential waterborne pathogens.

Table 14. List of Connectivity indicators and their importance to the instream flow study.

Connectivity		
Indicators		
Category	*Indicator*	*Explanation*
Riparian zone	Total area inundated	The amount of out of channel area inundated by an overbank flow of a particular magnitude.
	Habitat area inundated	The amount of habitat area of a particular type that is inundated by an overbank flow of a particular magnitude.
Lateral connectivity	Connection to river (frequency, duration, timing)	Periodic connectivity of the river with oxbow lakes, backwaters, and other floodplain habitats is important to maintain the health of these areas and the organisms that depend on them.
Groundwater/ surface water interaction	Total flow gain or loss in section of river	Difference in the amount of water entering and leaving a specific section of the river channel. Sources of gains include inflow from tributaries, alluvial and deeper aquifers, and discharges to the river. Sources of losses include evaporation, transpiration from riparian areas, diversions, and recharge of alluvial and deeper aquifers. Indicator may be influenced by shallow groundwater surface elevation and hydraulic head of deeper aquifers.

3.0 DESCRIPTION OF TECHNICAL STUDIES

In keeping with it's statewide mandate, the TIFP will conduct technical studies of the middle and lower Brazos River in order to determine flow conditions necessary to support "a sound ecological environment" in that system. The goal and objectives developed by the study design workgroup (described in section 2.2) were used to develop study indicators (described in section 2.3). The proposed technical studies will investigate how the flow regime may influence these indicators.

The description of technical studies is divided into two main sections. The first section (3.1) provides the locations (Study Segments, Reaches, and Sites) for proposed activities and the rationale for their selection. The second section (3.2) provides an overview of the proposed studies (essentially, the "What" and "Why") and how the proposed activities address specific objectives and indicators. This section also provides the description of data collection methods, data analysis and modeling, and multidisciplinary coordination. This is essentially "How" the data will be collected and analyzed. The Technical Overview (TIFP 2008) provides substantial detail regarding many of these activities, and thus will be referenced where appropriate.

3.1 *Study Site Selection*

In order to plan study activities, the middle and lower Brazos River was divided into Study Areas, Reaches, and Sites. Throughout the remainder of this document, these specific divisions of the sub-basin will be referred to as "Study Areas," "Study Reaches," and "Study Sites." The more general terms "area," "reach," and "site" will be used to refer to general lengths of river. While broader studies may be conducted across an entire Study Area, other studies will be conducted at particular Study Sites. Localized studies may have a single purpose (e.g., sediment data collection) or may address multiple indicators and involve multiple disciplines (e.g., hydraulic and habitat modeling site). Study Sites were selected in cooperation with the study design workgroup following the process described below. Details like the specific length of each Site will be determined in the field and be dependant upon availability, distribution and abundance of habitat types, as well as study resources.

The TIFP has used a three-tier evaluation to identify proposed Study Sites on the middle and lower Brazos River. Tier 1 evaluation was high-level and based on significant hydrologic features, resulting in the designation of four large-scale Study Areas for the middle and lower Brazos River. These Study Areas were further divided into potential Study Reaches based on major geomorphologic features and conditions. Tier 2 evaluation was more detailed and focused on specific parameters relative to hydrology, biology, geomorphology, and water quality supported within Reaches. This detailed evaluation determined which activities are recommended within the proposed Study Reaches. Tier 3 evaluation examined in finer detail shorter stretches of the river (Study Sites) that would represent the Study Areas and Reaches in general and be of a practical size for the project's resources.

TIER 1

The uppermost project boundary for the TIFP study of the middle and lower Brazos River is Lake Brazos on the Brazos River at Waco while the downstream boundary is the confluence with the Gulf of Mexico (Figure 12). Based on significant hydrologic features, the middle and lower Brazos was segmented into four broad Study Areas (Figure 12). The three points of division are:

- the extent of tidal influence (approximately the State Highway 332 bridge) at River Mile (RM) 25,
- the confluence with the Navasota River at RM 226, and
- the confluence with the Little River at RM 311.

Study Areas were numbered 1 through 4, from downstream to upstream. Study Areas 1 (RM 0 to 25) and 2 (RM 25 to 226) correspond to TCEQ Water Quality Segments 1201 and 1202, respectively. Study Areas 3 (RM 226 to 311) and 4 (RM 311 to 403) combined are equivalent to TCEQ Water Quality Segment 1242.

TIFP has conducted a number of activities to segment the Brazos River based on geomorphic features. These activities include work by Philips (2007) that segmented the river channel from Bryan to the coast into 30 reaches based on the River Styles classification scheme of Brierly and Fryirs (2005). A similar exercise by TWDB personnel broke the Brazos River from Waco to Bryan) into 13 reaches, also based on River Styles. This level of segmentation (a total of 43 river styles) was determined to be too detailed for the purposes of study site selection. Therefore, based on more general geomorphic features, the four Study Areas were segmented into 10 Study Reaches (Figure 12). Distinguishing features of each Reach are provided in Table 15.

Study Area 1 was not divided further and is equivalent to Study Reach 1.

Study Area 2 was divided into Study Reaches 2, 3, and 4. The boundary between Study Reach 2 and 3 is Oyster Creek (RM 110). Downstream of this location the river enters a delta environment (continues to the river's mouth). The boundary between Study Reaches 3 and 4 is roughly the confluence with Clear Creek (RM 176). Downstream of this point, the river is has a high degree of connectivity with its floodplain (continues to river's mouth).

Study Area 3 was divided into Study Reaches 5, 6, and 7. The boundary between Study Reaches 5 and 6 is the confluence with Yegua Creek (RM 241). Downstream of this point, the river has a low degree of connectivity with its floodplain (a condition that prevails until the confluence with Clear Creek at RM 176). The boundary between Study Reaches 6 and 7 is the confluence with the Little Brazos River (RM 284). Upstream of this point, the Brazos River occupies a "new" (on a geologic time scale) channel and the Little Brazos River occupies the older, paleo-channel of the Brazos River.

Study Area 4 was divided into Study Reaches 8, 9, and 10. The boundary between Study Reaches 8 and 9 is in the general location of Farm Road 413 (RM 346). Downstream of this point, the river occupies a newer channel (a condition that occurs until the confluence with the Little Brazos River at RM 284). The boundary between Study Reaches 9 and 10 is the location of a significant change in channel sinuosity that occurs near Highway 7 (RM 364). Upstream of this point the channel is highly sinuous while downstream the channel is considerably straighter.

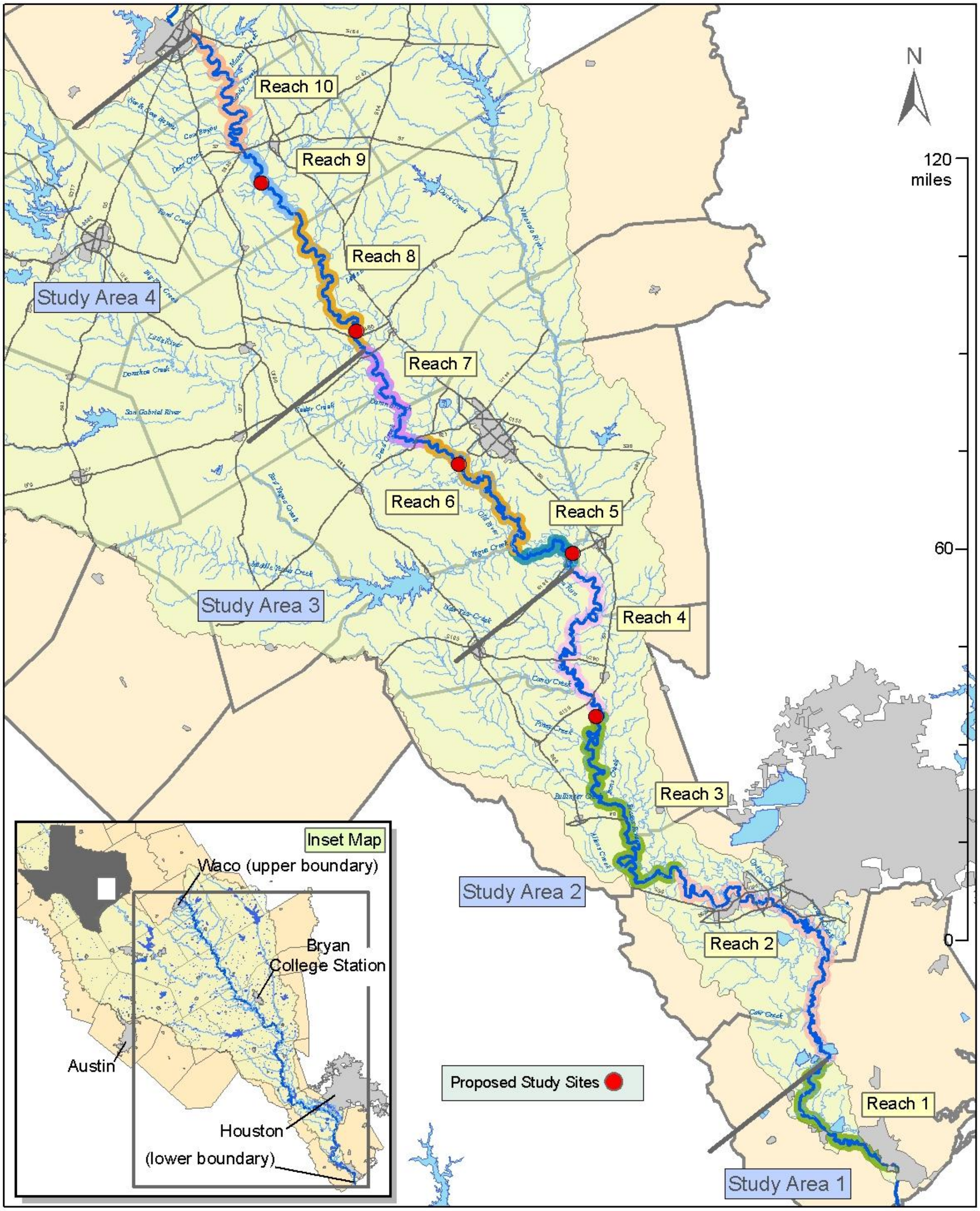

Figure 12. Proposed TIFP Study Areas, Reaches and Sites for the middle and lower Brazos River.

Table 15. Description of proposed TIFP Study Areas and Reaches for the middle and lower Brazos River.

<table>
<tr><th>Proposed Study Areas</th><th>Proposed Study Reaches</th><th>River Mile (USGS)</th><th>Upstream Boundary Landmark</th><th>Floodplain /Channel Connectivity</th><th>Other Geomorphic Features</th><th>TCEQ Segment Number</th></tr>
<tr><td rowspan="3">4</td><td>10</td><td>364-403</td><td>Below Lake Brazos</td><td rowspan="5">Moderate</td><td>High Sinuosity</td><td rowspan="6">1242</td></tr>
<tr><td>9</td><td>346-364</td><td>Highway 7</td><td>Low Sinuosity</td></tr>
<tr><td>8</td><td>311-346</td><td>Farm Road 413</td><td rowspan="2">“New” Channel</td></tr>
<tr><td rowspan="3">3</td><td>7</td><td>284-311</td><td>Little River</td></tr>
<tr><td>6</td><td>241-284</td><td>Little Brazos Rv.</td><td rowspan="5"></td></tr>
<tr><td>5</td><td>226-241</td><td>Yegua Creek</td><td rowspan="2">Low</td></tr>
<tr><td rowspan="3">2</td><td>4</td><td>176-226</td><td>Navasota River</td><td rowspan="3">1202</td></tr>
<tr><td>3</td><td>110-176</td><td>Clear Creek</td><td rowspan="3">High</td></tr>
<tr><td>2</td><td>25-110</td><td>Oyster Creek</td></tr>
<tr><td>1</td><td>1</td><td>0-25</td><td>St. Highway 332</td><td>Tidal</td><td>1201</td></tr>
</table>

TIER 2

Tier 2 involved evaluating each of the Study Reaches in more detail to determine what activities should be conducted within each Reach. To accomplish this task, existing data (USGS gages, diversions, fish and mussel data, aerial photography, geomorphic data, water quality sampling stations) was considered.

Data from recent fish collection efforts in the middle and lower Brazos (BRA, TPWD, Bonner and Winemiller samples from years 2000 to 2009) was used to evaluate fish assemblage structure across Study Reaches. Cluster analysis revealed three significant groupings for the nine Reaches with available data (Reach 1 had no data). Reaches 2, 3, 4, and 5 were found to share a similar fish assemblage structure, as did Reaches 6, 7, 8 and 9. Reach 10 had a distinct fish assemblage structure, which may be attributed to the small number of data sets available for this Reach and the proximity of the samples to the dam at Lake Brazos (which forms a barrier to fish movement). Preliminary analysis of additional data collected in 2009 indicated that the fish assemblage structure of Reach 10 was similar to that of Reach 9.

Evaluation of potential mussel Study Sites relied on data from recent activities in the middle and lower Brazos River, including Karatayev and Burlakova (2008) and Randklev et al. (2010).

The proposed Reaches, a summary of key characteristics and study activities proposed for each Reach are provided below:

- **Middle and Lower Brazos River (MLBR)**
  - **MLBR TIFP Study Area 1**
    - Reach 1 – Gulf of Mexico Confluence to State Highway 332 (RM 0 to 25)
      - This reach has been highly modified by levees and channelization, changing the connectivity between the channel and surrounding land areas from its natural condition and thereby reducing the potential to manage flows to benefit riparian areas. It is highly probable that the presence of estuarine and marine species makes the fish assemblage in this reach different from the rest of the sub-basin. In addition, this area is tidally influenced, considerably adding to the complexity of instream habitat models. Therefore, at this time, <u>no Reach specific activities are proposed</u>.
  - **MLBR TIFP Study Area 2**
    - Reach 2 – State Highway 332 to Oyster Creek (RM 25-110)
      - Reaches 2 and 3 are well connected with floodplain areas and are within the Gulf Prairies and Marshes ecoregion. Brazos Bend State Park (RM 59) has a fairly intact riparian area with good access via the state park. However, few biological studies have been conducted in Reach 2, limiting the amount of available baseline data. Therefore, <u>no Reach specific activities are planned at this time.</u>
    - Reach 3 – Oyster Creek to Clear Creek confluence (RM 110-176)
      - This Reach is characteristic of conditions in Study Area 2. A future reservoir is planned in the lower portion of the Reach (Allens Creek at RM 125). Baseline fish data and some mussel data are available, with the most recent data being collected at the upper end of this Reach (RM 175). Wildcat Bend (RM 170) has the potential to form an oxbow and contains relatively intact riparian habitat. Therefore, <u>hydraulic and habitat modeling (fish and possibly mussels), a baseline riparian assessment, and associated instream flow sampling activities are proposed for a Site between RM 170 and 175.</u>
    - Reach 4 – Clear Creek confluence to Navasota River confluence (RM 176-226)
      - This Reach has low connectivity between the channel and surrounding land areas. The fish assemblage is similar to that in surrounding Reaches. Therefore, at this time, <u>no Reach specific activities are proposed</u>.
  - **MLBR TIFP Study Area 3**
    - Reach 5 – Navasota River confluence to Yegua Creek confluence (RM 226-241)
      - Substantial recent and historical fish and mussel data sets exist within this Reach. Although the fish assemblage is similar to that in Reaches 2 and 3, physical differences in the channel in this Reach may affect the way habitat is utilized. A narrow corridor of riparian habitat exists within the Reach, as well as the potential for lateral connectivity with the Navasota River. <u>Hydraulic and habitat modeling (for fish and mussels), baseline riparian assessment, and associated instream flow sampling activities are proposed for a Site upstream of Highway 105 (RM 229).</u>
    - Reach 6–Yegua Creek confluence to Little Brazos River confluence(RM 241-284)
      - This Reach has moderate connectivity between the channel and surrounding land areas and lies within the Post Oak Savannah ecoregion

but riparian areas are limited throughout the Reach. Mussel Shoals (RM 275) is located within the Reach and consists of a unique, large rocky shoal. A significant amount of historical fish data exists for this location. The fish assemblage is characteristic of that found in Reaches 6 through 9. Hydraulic and habitat modeling (fish and mussel) and associated instream flow sampling activities are proposed for this reach.

- Reach 7 – Little Brazos River confluence to Little River confluence (RM 284-311)
  - This reach has similar channel connectivity characteristics, lies in the same ecoregion, and has a similar fish assemblage to Reach 6. Therefore, at this time, no Reach specific activities are proposed.

- **MLBR TIFP Study Area 4**
  - Reach 8 - Little River confluence to Farm Road 413 (RM 311-346)
    - This reach contains a high diversity of fish and mussel habitat. Although the fish assemblage is similar to that in Reach 9, physical differences in the channel may affect habitat utilization. Riparian habitat is limited. Therefore, at this time, only hydraulic and habitat modeling (fish and mussel) and associated instream flow sampling activities are proposed for this reach.
  - Reach 9 – Farm Road 413 to Highway 7 (RM 346-364)
    - This Reach is characteristic of conditions in Study Area 4 and contains a high diversity of fish and mussel habitat. The fish assemblage is characteristic of that found in Reaches 6 through 9. Baseline fish data has been collected at a site in this reach (RM 356). This Reach has moderate connectivity between the channel and surrounding land areas and lies within the Blackland Prairie ecoregion. Riparian habitats can be described as intact for portions of the reach while other areas are substantially disturbed. While these conditions may not be ideal for a riparian habitat assessment, these areas are representative of the Study Area. Hydraulic and habitat modeling (fish and mussel), baseline riparian assessment, and associated instream flow sampling activities are proposed for this Reach.
  - Reach 10 –Highway 7 to immediately downstream of Lake Brazos(RM 364-403)
    - This Reach has moderate connectivity between the channel and surrounding land areas and lies within the same ecoregion as Reach 9. There is limited biological baseline data for this reach, but preliminary analysis of data collected in 2009 indicates that this Reach is similar to Reach 9 in fish assemblage structure. Therefore, at this time, no Reach specific activities are proposed.

TIER 3

As it is not economically feasible to study an entire Study Reach, representative Study Sites within Reaches are selected. Instream and riparian habitats were evaluated based on the aerial photography and data presented in the Tier 2 assessment were evaluated in detail. Tier 3 assessment was done to locate representative Study Sites within each selected Reach. Study Sites proposed along the middle and lower Brazos River are depicted in Figure 12. At this time, the exact upper and lower boundary of each Study Site is not defined. The exact placement of a Study Site will be determined by evaluating the reach scale habitat mapping (described below in Section 3.2.2) and selecting an area with mesohabitats in similar proportion as the overall reach. These Sites will typically range from 0.5 to 2 river miles in length (determined by a minimum of 40 times the mean wetted width or a maximum of one full meander wavelength) with a goal of being representative of the Study Reach. An important additional criterion is property access. Although the majority of work will take place within the river channel, control points/targets for surveying will need to be located at distances away from the channel. Additionally, the riparian assessment will need to be performed while traversing the banks.

3.2 *Study Components*

The Technical Overview (TIFP 2008) outlines four major study components including hydrology and hydraulics, biology, physical processes, and water quality (TIFP 2008; Chapters 6, 7, 8, and 9). Additionally, the Technical Overview (TIFP 2008) discusses connectivity, dimension, and scale in stream systems (TIFP 2008; Section 3.3). As such, specific objectives and indicators for connectivity were developed during the series of stakeholder workshops (Section 2.3). This section describes the proposed study activities, proposed locations, and methods for each of the five components relative to the indicator categories established by the stakeholder process. The multi-disciplinary roles necessary to perform an instream flow study inherently cause overlap when presenting methods for the five major study components. However, to remain consistent with the Technical Overview and previous sections, each of the five components will again be discussed by section with interactions between components highlighted.

3.2.1 Hydrology and Hydraulics

The ecosystems dependant upon the middle and lower Brazos River have evolved in response to the inter- and intra-annual variability in flow that includes cycles of overbank flows, high flow pulses and subsistence flows with intervening periods of base flows. This variability in the cycling of flow is typically referred to as the flow regime. An evaluation of the flow regime will address several of the hydrological indicators including natural variability, current variability, and gain or loss in river flow. A number of long-term flow gaging stations exist in the basin (Table 2) allowing characterization of flow variability, i.e., how the flow regime changes spatially (moving downstream towards the coast) and temporally (comparing early periods to later periods).

Natural variability / flow regime components

Natural variability includes typical fluctuations in base flow, limited periods of very low or subsistence flow, and high flows including within-channel pulse events and overbank flow events. The long period of stream flow records (beginning in late 1800's to early 1900's at some locations) allow comparisons between early periods that may represent a more natural condition to later periods reflecting reservoir operations, current land use, water usage, and other conditions affected by human's use of water and the landscape. Statistics derived from a hydrologic evaluation (described in section 6.1 of the Technical Overview) will be used to characterize the flow record and evaluate ranges for the four main instream flow components: subsistence flow, base flow, high flow pulses, and overbank flow. Existing flow analysis tools may be used to evaluate these components (e.g., Indicators of Hydrological Assessment [IHA], Hydrology-based Environmental Flow Regime [HEFR], Texas Hydrological Analysis Tools [TxHAT]) or alternatively, standard statistical methods may be used including non-parametric statistics (e.g., 5^{th} percentile flow). Any statistical characterization of flows will be complementary to field studies and physical assessments that identify flow levels beneficial to the existing natural ecology of the middle and lower Brazos River.

Hydraulic and habitat models

In addition to statistical analysis of the flow record at existing gages, site-specific field studies will focus on development of two-dimensional (2D) hydraulic and habitat models. A 2D hydraulic model provides simulated flow conditions for a given stretch of river (habitat study site). The simulated flow conditions are then run through a GIS-based physical habitat model to predict habitat conditions within that habitat study site. For each simulated flow, the spatial availability of suitable habitat can then be queried using habitat suitability criteria for habitat guilds and key species. For each guild and key species, streamflow to habitat relationships are developed. The general process of hydraulic modeling in support of habitat modeling is described in sections 6.2, 7.3, and 10.2 of the Technical Overview.

For the TIFP study of the middle and lower Brazos River, 2D hydraulic and habitat models will be developed to evaluate changes in microhabitat across a range of flow rates. This analysis will specifically aid the development of subsistence and base flow components and will therefore focus on flow rates from about the median to the 10 percentile flow as described in section 6.1.3 of the Technical Overview (TIFP 2008). Hydraulic and habitat modeling will be conducted within Reaches 3, 5, 6, 8, and 9 on the middle and lower Brazos (Figure 12, Section 3.1). These models will characterize existing habitat conditions across a range of flow rates. Specific habitat types will be characterized based upon habitat utilization data recorded in the middle and lower Brazos River sub-basin relevant to the aquatic organisms present in the area. The collection of the biological data is described in the Biological Section (Section 3.2.2) below. Identifying breakpoints or sharp changes in habitat availability provides insight into flow rates relevant to river ecology. Relevant flow ranges identified by the habitat modeling will be compared to the frequency of those flows exhibited in historical and current flow records. Instream flow guidelines for achievement of particular flows may be recommended on the basis of both physical habitat requirements and upon historical frequency of occurrence. Other analyses, including development of a habitat time series, may be conducted to consider both habitat and flow frequency.

Development of hydraulic and habitat models is one of the more resource intensive tasks involved in a typical instream flow study. Model development represents a multi-stage, multi-disciplinary process that includes (1) biological data collection to characterize relevant habitat, (2) physical data collection to characterize the river channel, (3) data processing to integrate points into a cohesive map of the river system, (4) hydraulic model development, calibration and validation, (5) habitat model development, including the integration of habitat utilization data, (6) analysis of habitat model results and, finally, (7) evaluation of results leading to development of flow guidelines.

To characterize velocity and depth patterns at a level suitable for use in evaluating microhabitat, the model developed at each habitat Study Site needs input data at a sufficiently high resolution. In particular, detailed maps of bathymetry (elevation of the channel bed) and substrate (materials comprising the channel bed) are required as well as water surface elevation data. At the same time, flow rate, depth and velocity will be collected.

Topography, water surface elevation and discharge

At each model Study Site, complete channel and near-channel floodplain Digital Terrain Models (DTMs) will be created using a combination of survey-grade GPS equipment and conventional surveying equipment coupled with hydro-acoustic depth/velocity sounding data. Survey data will be reviewed for completeness (missing data, holes in the topography, etc.) on a daily basis using ArcView software, and supplementary topographic surveying will be conducted to ensure complete coverage of each intensive Study Site.

Once the model Study Sites are established, low-altitude, high-resolution color aerial photography will be flown at each of the five habitat modeling Study Sites at relatively low flows. Capturing images of the terrain at low flows will help to increase the amount of channel topography that can be generated from the aerial photos. The film negative from the flight mission will be handled and stored to meet National Map Accuracy Standards (NMAS). All negatives will be scanned. Scanned images will be manually georeferenced using distinct features in common with available black and white imagery. The aerial photography will be used to the degree practicable to fill in potential gaps in difficult to survey areas for the completion of the DTM. The DTM will be used to characterize the channel in both the 2D hydraulic and habitat models.

The color aerial photography will also be used to assist in substrate mapping, riparian mapping, water's edge description, mesohabitat mapping, and woody debris assessment. Results of mapping of geomorphic features (described in section 3.2.2) will also be used to complete substrate and large woody debris maps required for habitat modeling.

Model calibration, validation and sensitivity analysis

Calibration is the process whereby a model's input parameters are tuned to maximize measures of model performance using measured field data. To assess the ability of the model to predict real-world conditions, the model is then validated against additional field data using the calibrated ("tuned") parameter values.

The minimum calibration data required for hydraulic modeling consists of a stage-discharge relationship at the upstream and downstream end of each habitat Study Site. Development of a stage-discharge relationship requires a minimum of three flow measurements, during high, medium, and low flow conditions. Additional calibration data will be collected in the form or water surface elevations measured throughout the Site during the same flow conditions (high, medium, and low). Water surface elevations will be measured with survey grade GPS (centimeter accuracy) or conventional surveying equipment to adequately characterize changes in edge of water and water surface slope throughout the Site. During data collection, a temporary staff gage or pressure transducer will be installed at the downstream end of the Study Site to document any changes in stage.

Each time stage-discharge data for the development of rating curves is collected (a minimum of 3 flows at each Site), additional depth/velocity point measurements for calibration and validation will be collected. Velocity data (consisting of average column velocity and direction) will be collected using acoustic doppler profilers or other velocity measurement devices. Elevation contour maps and a random point generator will be used to produce a quasi-random set of calibration/validation point locations. Half of the velocity and depth data will be used to calibrate the roughness and viscosity parameters in the 2D hydraulic model and the other half to validate the model results and report uncertainty. Additional data to validate the accuracy of 2D hydraulic models will be collected and will consist of the length and width of any large recirculation zones observed during high, medium, and low flow conditions.

Substrate roughness and eddy viscosity are two parameters commonly used to calibrate hydraulic models. The 2D hydraulic model will be calibrated to at least three measured water surfaces (high, medium, and low flow) by adjusting substrate roughness and eddy viscosity parameters. To adjust substrate roughness, substrate maps at each Study Site will include an estimated hydraulic roughness height based on the size of the largest particle in each substrate category. During the calibration phase of the hydraulic modeling, the roughness heights across all substrate types will be increased or decreased by a constant percentage until the modeled water surface matches the measured water surface. This will first be done at the moderate calibration flow. A check that the calibrated roughness performs accurately at the high and low calibration flows will be performed. If necessary an equivalent roughness height modifier regression will be used to scale roughness height over the range of modeled flows. A similar procedure will be used to calibrate the viscosity parameters, which are used by the model to calculate viscosity at each node based upon local velocity. Since viscosity parameters are assigned as constants for all areas of the model, a modifier regression may be used to scale the parameters over the range of flows. When roughness height and viscosity adjustments are obtained that generate accurate modeled water surface elevations for all three flows, the hydraulics model will be assumed to be calibrated. All subsequent hydraulics modeling of the various flows for habitat modeling will be completed using calibrated channel roughness heights and viscosity parameter adjustments. A range of flows will be modeled at each Study Site. This flow range covers the majority of median monthly flows in the historical range including temporary pulse flow events, but not including flood flow conditions. The focus of this range is in-channel aquatic habitat conditions.

Uncertainty in environmental models exists and can, to some degree, be characterized. A riverine model uses generalized parameters to describe and simulate the physical characteristics of the river. These generalized parameters have uncertainty bounds associated with them, which leads to model uncertainty. Calibration of a hydraulic model aids in reducing but not totally eliminating model uncertainty. The sensitivity of hydraulic model results to changes in calibrated parameters will be investigated. If the model is found to be highly sensitive to a parameter, efforts will be made to reduce the parameter uncertainty through further data analysis, calibration and/or acquisition of additional data.

Groundwater/ surface water interaction

As described in Section 1.1.6, the USGS has conducted several studies related to groundwater/ surface water interactions along the middle and lower Brazos River. A gain/loss study for the Brazos River from McLennan to Fort Bend counties was completed in 2007. Several studies have characterized the Brazos River alluvium aquifer and studies related to developing a Groundwater Availability Model for the area are ongoing. The TIFP will continue to monitor the results of these studies to assess their relevance to objectives related to groundwater/ surface water interaction.

3.2.2 Biology

Detailed biological studies at representative reaches of the middle and lower Brazos River are required in order to understand the relationship between biology and flow conditions and address the overall biological objective to: "Identify flow regimes: (1) for the benefit of the native ecosystem (i.e. habitat, flora, and fauna); (2) to maintain a diverse aquatic community and prevent the extinction of native species; and (3) to preserve/protect and restore/improve key habitat features for native species in river and riparian zones." Instream biological community and species level indicators will be used to measure how the study methodologies discussed below will address the biological objective. Biological surveys, riparian assessments and models, and instream habitat models will play a substantial role in identifying flow conditions needed to meet the goal and objectives set forth for the middle and lower Brazos River. Many of the methods and analyses described in this section correspond directly with guidance provided in Chapter 7 of the Technical Overview (TIFP 2008).

Reach scale habitat mapping

Information collected during the aerial reconnaissance in combination with existing information and data layers (geomorphic reaches, aerial photos, geology, etc.), and meso-scale physical habitat types will be mapped in GIS using the following characteristics:

- Pool - flat surface, slow current; usually relatively deep
- Backwater - flat surface, very slow or no current
- Run/Glide - low slope, smooth, unbroken surface
- Riffle - moderate slope, broken surface
- Rapid - moderate to high slope, very turbulent (e.g. boulder field)
- Chute - very high velocities in confined channel

Ground truthing will be conducted by boat, kayak, and/or walking depending on specific conditions of the river or stream; these surveys should be performed when flows are at or below median conditions when habitat features are relatively easy to evaluate. Field notes and drawings will be digitized and incorporated into a GIS layer that can be used to query the amount and location of various habitat types. Riparian vegetation categories will also be delineated on the photos, digitized and incorporated into a GIS layer. This information can be used to determine appropriate Study Sites within select Reaches that represent habitat found in larger areas. The channel reach maps may also be used to evaluate how modeled habitat at a Study Site scales up to total habitat available within a Reach or Study Area, if necessary, and to assist in designing stratified sampling protocols.

Instream biological communities - fish and mussel surveys

Assessing the current condition of fish and mussel communities and their relationship to instream flows is an important step in focusing detailed studies (e.g., microhabitat use), evaluating and validating models developed from those studies and in long-term monitoring programs. As discussed in Section 1.1.2, baseline fish sampling throughout the lower Brazos River has been performed between 2006 and 2008 with the goal of collecting representative samples of fish species present in their current relative abundance. Baseline mussel surveys were conducted between 2006 and 2007 in order to determine present and historical species richness and distribution (Karatayev and Burlakova 2008). Given the level of detail performed during these sampling efforts (see baseline fish survey methodology), baseline data will be useful in evaluating and validating the models developed from the detailed microhabitat studies. Baseline fish sampling will also be used to help address the indicators of species richness and relative abundance of native, sport, and prey fishes in the middle and lower Brazos River.

Fish surveys

Fish will be collected in each identifiable mesohabitat within a Study Site (consisting of a minimum length of river 40 times the mean wetted width or a maximum of one full meander wavelength) using multiple gear types (seines and electrofishers). In most cases, each mesohabitat will be sampled by one pass sampling effort using the gear type most appropriate for the conditions. If unable to employ multiple gear types, the reason will be indicated and effort increased with the gear type able to be utilized at that mesohabitat. Physical measurements will be made in association with each sampling event (e.g., each seine haul) and will include current velocity, depth, substrate composition and embeddedness, and instream cover (large woody debris, boulders, undercut banks, macrophytes, velocity shelters, etc.). Notes on climatic conditions and mesohabitat typing will also be recorded. Released fish will be identified, measured, photo-documented, and examined for disease and other anomalies. Voucher specimens will be preserved in 10% formalin. In all cases, fish sampling will continue as long as additional species are being collected.

Electrofishing (900 seconds minimum total combined trigger time) will be conducted using either boat or backpack electrofishing dependent on the habitats being sampled. Boat electrofishing will occur in habitats too deep or swift for effective backpack or seine sampling (e.g., pools, fast runs), and backpack electrofishing will focus on areas shallow enough for effective sampling by wading (e.g., riffles, shallow runs). Seines may be placed downstream of the areas sampled by the backpack electrofishing crew to assist in fish collection, if necessary. After a particular habitat type has been thoroughly sampled, collected fishes will be processed independently and fish abundance, electrofishing time, site information, personnel, and output settings can be recorded for each sampling event.

Seining (minimum 10 effective seine hauls) will be conducted in various habitats using a variety of seines sizes and seining techniques (e.g., riffles kicks) in order to complement electrofishing efforts. It should be noted that a seine haul where zero fish are collected is considered an effective seine haul if the haul was not impeded (i.e. snagged), allowing fish to escape. Examples of commonly used seines include a 9.1 m x 1.8 m x 7.6 cm (30′ x 6′ x 1/4″) mesh seine for sampling pools and open runs and a 4.6 m x 1.8 m x 5.7 cm (15′ x 6′ x 3/16″) mesh seine for sampling riffles, runs, and small pools. All seines will be constructed of delta weave mesh with double lead weights on the bottom line. Seine size used, seine haul length, site information, and personnel will be recorded. Fishes collected from each seine haul will be processed independently.

Mussel surveys

To determine abundance, distribution, and habitat utilization of mussels within Study Sites, a systematic sampling approach will be employed (Strayer and Smith 2003). In this method, a sampling area consisting of a length of channel two times the wetted width of each identifiable mesohabitat within the Study Site will be sampled. Using a 0.25 m^2 quadrat, a minimum of 20 samples will be collected, each spaced equidistance from at least three random starting points. Strayer and Smith (2003) provide a formula to calculate distance between systematically selected units:

$$d = \sqrt{\frac{L \cdot W}{n / k}}$$

Where d is the distance between units, L and W are the length and width of the sampling area, n is the total number of quadrats, and k is the number of random starts. Given that a 0.25 m^2 quadrat will be employed, distance between sampling units calculated using the formula can be rounded down to the nearest half meter. In each of the sample quadrats, mussel species will be identified and enumerated. Physical measurements such as depth, current velocity, and substrate type will be recorded for each sample for use in habitat suitability criteria development. Pooler and Smith (2005) found systematic sampling approaches with greater than two random starts more accurate at estimating abundance than simple random sampling, 0.25 m^2 quadrats more accurate and precise in estimating abundance than 1 m^2 quadrats, and systematic sampling estimates more accurate when distance between sampling units across the stream are less than or equal to the distance between sampling units along the stream (hence the two times the wetted width sampling area).

Live mussels collected within the sampling quadrats will be identified, counted, and photo-vouchered. Dead mussels and valves will also be identified and counted. Shell lengths will be recorded for live mussels to determine size structure and will provide a surrogate for age class determination. Within each sampling quadrat, random substrate cores (10) will be collected to determine sediment particle size (using sieve fractionation plots), current velocity measured near the surface and near the bed, and channel slope at the study site. These data will be used to calculate hydraulic variables (Reynolds number, Froude number, sheer stress, etc.) which have been shown to be important in characterizing mussel beds (Morales et al. 2006, Randklev et al. 2010) and in being able to predict effects of flow regimes on mussel distribution and density (Steuer et al. 2008).

Instream habitat surveys and habitat modeling

For several flow regime components, instream flow recommendations depend on assessments of how instream habitat changes with variations in streamflow. This study will address these habitat-flow relationships using two complementary approaches. The first is an assessment of the area and diversity of intermediate scale habitats, referred to as mesohabitats (e.g., riffles, runs, and pools) in relationship to streamflow. Habitat diversity is a primary factor affecting the richness and abundance of fishes and other aquatic organisms and can be assessed by using mesohabitat criteria. Those criteria can be derived either from biological (habitat guild approach) or hydraulic variable data coupled with a hydraulic model that describes the distribution and magnitudes of depth and current velocity at different streamflow rates. This approach addresses the indicator of mesohabitat area and mesohabitat diversity and is a valuable approach in species-rich ecosystems such as the middle and lower Brazos River.

The second layer of assessment addresses the habitat quality and quantity for key species (microhabitat) to ensure that their habitat and life history needs are specifically addressed. In this approach, habitat suitability criteria for the life stage of a particular species are developed and used in the habitat model (as above) to develop microhabitat-flow relationships. Specific sampling strategies may need to be developed to ensure adequate sampling of particular species (e.g. alligator gar).

For each Study Site where habitat modeling will be conducted, GPS units will be used to delineate mesohabitats according to the following characteristics:

- Pool - flat surface, slow current; usually relatively deep
- Backwater - flat surface, very slow or no current
- Shallow Run/Glide - low slope, smooth, unbroken surface
- Deep run - low slope, smooth, unbroken surface
- Riffle - moderate slope, broken surface
- Rapid - moderate to high slope, very turbulent (e.g. boulder field chutes)

If the mesohabitat can be further discriminated, it will be assigned a qualifier for relative current speed and depth using 'fast' or 'slow' for current velocity and 'shallow' or 'deep' for depth. Notes on location and density of woody debris and other instream cover, unique habitat features (e.g., a unique outcrop) and substrate composition will be taken. Measurements of current velocity and depth will be taken to facilitate development of objective criteria to define mesohabitat types in the middle and lower Brazos River. These mesohabitat surveys should be performed when flows are at or below median conditions when habitat features are relatively easy to evaluate. Standardized field guides and sampling protocols will be provided to field crews in order to maximize the accuracy and repeatability of habitat data collection.

Fish microhabitat utilization and biological validation surveys

Because native fish and mussel communities in the middle and lower Brazos River have evolved life history strategies and patterns of habitat utilization that correspond to natural flow regimes, they represent ideal taxa to assess the relationship between biology and streamflow conditions. Detailed studies on fish and mussel habitat use will be needed to develop habitat suitability criteria. Key species (described in Section 2.3), anticipated for microhabitat modeling include alligator gar, shoal chub, silverband shiner, chub shiver, juvenile sport catfish, and spotted bass. Those criteria can then be used in conjunction with instream habitat modeling (discussed below) to develop an index of suitable habitat (e.g. weighted usable area [WUA]) to support fish and mussel populations at various flow levels. These types of studies will help identify flow requirements necessary to conserve flow-sensitive, intolerant, and imperiled fish and mussel species, as well as key aquatic habitats that support those species.

Determining habitat utilization for use in developing habitat suitability criteria (HSC) will be done by sampling fishes using a stratified random design consisting of mesohabitat and substrate categories. Given these combinations and the total number of sites and flow rates to be sampled, the minimum number of samples can be determined. It is important to recognize that the primary role of these categories in fish sampling is as an analog for depth and velocity; pools tend to be slow and deep and riffles tend to be fast and shallow, for example. Stratifying sample locations by mesohabitat helps ensure a wide range of depths and velocities are sampled. Further, each site will be sampled four times from low to high base flow conditions, but only when diverse habitat conditions exist and sampling efficiency is not compromised. A minimum number of HSC samples will be collected from each combination of mesohabitat and substrate categories at each study site under each of the four flow rates. This minimum number may be as low as three but will be calculated once the total number of combinations at each study site is determined. For example, three samples per strata/site/flow was used on the Lower San Antonio River Instream Flow Study which had five habitat categories, eight substrate categories, five sites, and four flow rates.

The first step is to generate substrate and mesohabitat maps so that the number of combinations can be determined. To map substrate, cross-sections will be established every 10–20 meters throughout each study site. Shorter cross-section intervals may be needed to map sites that have complex substrate patches while longer intervals can be used at sites that exhibit fairly homogeneous distributions of fine substrates (such as sand). At each transect, 3-10 evenly spaced substrate grabs will be made across the width of the river and classified using the modified Wentworth Scale (TIFP 2008). A greater number of substrate grabs (up to 10) may be needed in sites or habitats with complex combinations of substrate. Where differences among substrate grabs are noted, more detailed sampling will be conducted to establish exact location of substrate changes. GPS receivers capable of sub-meter accuracy will then be used to map polygon areas of similar substrate. Coordinate data will be processed to create detailed maps of substrate for each study site. Substrate/cover data may be grouped into fewer categories in order to facilitate distribution of samples in the stratified-random design.

Based on the reach scale maps (see *Reach scale habitat mapping* above) of mesohabitats and the substrate maps generated at each site; an initial allocation of sample points can be made across the combinations of mesohabitat and substrate, study sites and flow rates. This initial allocation may need to be adjusted (using detailed site maps described below) to ensure all habitat types can be sampled to meet design criteria. Although substrate conditions are typically assumed to be constant in instream flow modeling (and thus, will be mapped only once), hydraulic habitat conditions (depth and velocity) change considerably with flow rate. Therefore, more detailed habitat mapping will be conducted immediately prior to, and at a similar flow rate to, each HSC-related fish sampling event.

To create detailed mesohabitat site maps, the river will be divided into mesohabitat categories (as defined above). Current velocity and depth will be measured to guide the mapping. A GPS unit will then be used to delineate each mesohabitat, with detailed site maps being generated.

The detailed mesohabitat site map and substrate map will be merged to form one map and then used to spatially locate the allocated random samples at a given site for a given flow rate. The sampling locations generated are simply meant as a general guide to aid field biologists in selection of appropriate areas. They are not meant to identify exact sampling locations, but rather, to approximate general areas of interest. Field biologists are responsible for picking an area near the suggested sample point of sufficient size to capture resident fish, with relatively consistent depths and velocities. For example, points that fall along or within transition zones (where conditions begin to change) will be dropped and the next random point located. This will ensure that data accurately describe instream conditions for each mesohabitat type.

Once a location is found in the field, a sampling area consistent in depth, velocity, and substrate characteristics will be delineated. The size of the sampling area will depend on considerations such as mesohabitat type and gear limitations. Although effective size of the sampled area will vary among mesohabitat types, an effort will be made to establish an approximate effective size for each type. Additionally, variation in size of sampling areas can be accounted for by determining the size of each sample area and using fish density (# fish/m^2) instead of raw abundance during calculation of habitat suitability.

At the sampling area, fish will be collected using seines, backpack and/or boat electrofishers or combinations thereof, as appropriate. Collected fish will be identified, enumerated and length range measured prior to release or preservation. Voucher specimens will be kept and large specimens photographed following TIFP protocols. Mesohabitat fish sampling will include both daytime and nightime efforts to properly identify diurnal differences in habitat use by species and age class.

Physical characteristics of the sampled area will also be measured. Parameters will include current velocity, water depth, substrate types (dominant and subdominant) and cover characteristics. These characteristics will be used to develop habitat suitability indices for modeling purposes. Further, instantaneous water quality readings (DO, pH, temperature and conductivity) will be measured from the sampled area.

Similar sampling procedures have been used in development of fish habitat use data for instream flow assessments in Texas (BIO-WEST 2008).

Biological data analysis

The goal of analyzing biological data is to develop a conceptual model of biological assemblage dynamics and health and habitat utilization. By evaluating and modeling habitat use over a range of hydrologic conditions, we can develop quantitative instream flow recommendations that support the study objectives as well as the overall objective of a sound ecological environment. Among the goals for analysis are to evaluate temporal and longitudinal trends in assemblage structure and seek to relate those trends to broad-scale habitat conditions within the system. That may include both in-channel and riparian influences as well as tributary and other inputs. This approach will undoubtedly include using multivariate statistics (e.g. detrended correspondence analysis or other tools) to examine such trends and the effects of physicochemical variables. Diversity, richness, and relative abundance along with other derived information such as biotic integrity indices will also be assessed to provide indicators of ecosystem condition.

To determine the relationship between biology and streamflow conditions, habitat utilization data for fishes and mussels will be developed to evaluate a variety of habitat factors such as depth, substrate, mean column velocity, bed velocity, cover, etc. That information will result in habitat suitability criteria, which can then be integrated with simulations of instream habitat modeling (see 2D hydraulic models above) to develop an index of habitat availability for various flow conditions. The development of habitat suitability criteria for fishes in the middle and lower Brazos River may require the approach of grouping fishes into guilds (e.g. habitat guilds) using multivariate techniques in conjunction with supplemental life history information. A guild approach would simplify assessments (over 60 species historically collected in the middle and lower Brazos River sub-basin), but maintain an assemblage-based approach for addressing instream flow requirements and can be used in a complementary assessment of habitat suitability for individual key species. A GIS-based physical habitat model will be used to assess habitat versus flow relationships, including mesohabitat diversity.

Across a range of flow rates, habitat models will be used to characterize suitability of aquatic habitat for key species or groups of species. The biological validation data collected will be used during habitat modeling to validate or to modify the habitat modeling procedures. Flow ranges, typically at the subsistence and base flow levels, will then be identified that are appropriate to maintain the health and function of the aquatic ecosystem.

Riparian habitat - baseline surveys and evaluation

The health of riparian ecosystems is linked to the periodic occurrence of overbank high flow pulses, associated channel dynamics, and the preservation of base flows capable of sustaining high floodplain water tables (Busch and Scott 1995). Because of the importance of maintaining connectivity of riparian vegetation to hydrology, assessing the condition of riparian vegetative communities is an important component in determining ecosystem health. In order to determine baseline riparian vegetative conditions, detailed studies that characterize the riparian habitat will be conducted within representative study areas. Key riparian vegetative indicators to be assessed are: age class distribution, richness and diversity, density, and % canopy cover. This information will then be linked back to overbanking and base flow requirements for the maintenance of a healthy riparian ecosystem.

The purpose of characterizing riparian habitat within the study area is to identify the extent and condition of existing riparian habitats as well as the surrounding land use. Extent and distribution of riparian communities will be assessed using the TPWD/NatureServe Vegetation Classification System database, which utilizes vegetation types, soils, and topography parameters. To verify accuracy, classify small changes to the TPWD/NatureServe Classification System, and gather specific riparian community composition and structure data, riparian habitats within the five habitat modeling Study Sites will be assessed during field visits being conducted for physical or biological data collection.

Riparian habitat will be characterized by establishing 50m transects in a stratified random approach at the Study Sites along the middle and lower Brazos River. In general, transects will typically be placed perpendicular to the river channel, and the number of transects run will be determined by the size of the Study Site selected. Information will be collected to determine density, dominance, and frequency of riparian plant species, land use, and adjacent land use.

Tree strata will be sampled within a 10m x 50m area whose center line corresponds to the 50 m line transect established. All single trunked, woody, perennial vegetation (trees) with a diameter at breast height (dbh) of greater than 5 cm within the sample area will be measured and recorded by species into one of the following size class categories: 5-15cm, 16-25 cm, 26-35 cm, 36-45cm, 46-55cm, 56-65cm, 66-75cm, 76-85 cm, 86-95 cm and greater than 95cm. Measurement will be to closest cm, rounded as appropriate. Canopy closure will be estimated using spherical densiometers at the 10m, 20m, 30m and 40m intervals on center transect line. The mean of the 4 densiometer measurements will be calculated.

Shrub composition and relative abundance will be calculated using a line intercept method. Shrubs are all multi-trunked, woody perennial vegetation and also all single trunked woody perennial vegetation less than 5cm dbh. The linear distance, to the nearest cm, that each species intersects the line will be recorded. Percent coverage of each species will be calculated by dividing the total linear distance of each species by 5000cm. Overlapping canopy of different species will be recorded according to distance each species intersects the line transect. Total distance with no shrub canopy will also be recorded. Total percent shrub canopy cover will be calculated according to the following formula: 1 – (no shrub linear intercept distance / 5000).

Herbaceous vegetation composition will be determined using a line point intercept methodology. A 1 meter long 1/8 inch diameter "pin" will be set vertically every 1 meter along the 50 meter line, starting at 0. All species of herbaceous vegetation, woody vines and woody seedlings that touch the pin will be recorded. Relative abundance of each species will be calculated using the formula: # pins touched by species / 51.

The line intercept for shrubs is along center transect line. Point line intercept for herbaceous vegetation is at 1 meter intervals along the center 50-meter transect. All trees within 5 meters on either side of the 50-meter line are recorded in 10-cm size categories.

Data obtained from transect surveys will be assumed to be representative of the entire stand of vegetation. Measurements collected during the first sampling effort will be used to establish existing, or baseline, conditions within the riparian zone. Measurements collected in subsequent sampling events can be used to compare against baseline conditions to assess changes in species composition and structure over time.

The recurrence interval of inundation is important to riparian and wetland areas. HEC-RAS models and LiDAR data will be used to evaluate how different riparian areas are affected by high flow pulses and overbank flows, and how riparian areas may transition (spatially) according to differences in wetting and drying characteristics. Results of HEC-RAS overbanking studies will include quantifiable area (acres) inundated for each reach. Overlaying inundation areas with existing land use maps (National Land Cover Dataset) or with interpreted riparian area maps allows assessments of frequency of habitat inundation. As with flow information, the most comprehensive source of river stage information is from the USGS gauging station network. Changes in flow-stage rating curves over time can be evaluated and the stage data will be used to validate HEC-RAS overbanking models. For further description of the use of HEC-RAS models, please see Section 3.2.5.

3.2.3 Physical Processes

The objective of the physical processes component is to identify the interrelationships between flows and bank stability, channel maintenance, and alluvial and associated aquifers. Geomorphic activities will focus on four areas: (1) analysis of available aerial photographs as a source of historical geomorphic data, (2) evaluation of sediment dynamics in active channel areas, (3) detailed mapping of geomorphic features, and (4) evaluation of the impacts of overbank flows. The first activity will be carried out along the length of the middle and lower Brazos River and build on work previously completed by Gillespie and Giardino (1997). The second will be carried out at the scale of the length of the middle and lower Brazos River and at select field sites in order to evaluate processes that operate at these different levels. The third activity will be carried out only at select field study sites. The fourth will rely on data from USGS gage locations on the main stem of the middle and lower Brazos River. No activities are proposed in order to evaluate surface water/groundwater interactions. TIFP will rely on the results of studies completed by other parties (including USGS) in order to address indictors related to this topic.

Analysis of aerial photos

Available aerial photographs will be analyzed and historical rates of bank erosion, lateral channel migration, and channel avulsion will be estimated. Available photo coverage for the middle and lower Brazos River begins as early as the 1930's (Gillespie and Giardino 1997). By comparing changes over time, estimates will be made for historical decadal rates of bank erosion, lateral channel migration, and channel avulsion development. The possibility of estimating flow thresholds necessary to initiate these processes by comparing changes in aerial photos with hydrologic flow records will be explored.

Evaluation of sediment dynamics

Sediment dynamics in the study area will be evaluated based on a combination of sediment budgeting for active channel and floodplain areas. Sediment budgeting is the analysis of particular matter, organic or mineral, which is depositing and moving through the fluvial system. Sediment budgeting will be completed at two scales: (1) sediment sampling at USGS gage sites: (Example: to identify size of material being moved) and (2) sediment budgeting at select sites: (Example: to identify source of coarse sediment found in a particular bar).

At the first scale, the entire middle and lower Brazos River will be segmented based on USGS gage locations. Sediment budgets for the active channel area of each segment will be completed, including estimates of sediment input to the segment from the upstream channel, tributaries, and banks. At the second scale, sediment budgets will be studied to see how the deposition and transport processes work and differ between sections of the river. The stability of deposit and residence time of particles will be determined for specific size classes of material (for example, sand between 0.1 and 2 millimeters in diameter or gravel between 4 to 10 millimeters in diameter).

In order to support the objective of evaluating sediment dynamics, sediment modeling will be conducted at two scales. First, a one-dimensional model will be used to investigate sediment dynamics through different reaches of interest within the middle and lower Brazos River sub-basin. Reaches will be selected to represent the variety of different morphology and sediment characteristics in the study area and will be the equivalent of a few meander wavelengths. A sediment transport model will be coupled with a standard one-dimensional hydraulic model (such as HEC-RAS) to estimate the magnitude of flows that perform various geomorphic processes within each reach, such as floodplain deposition, meander migration, or bar maintenance. The models will be modified to incorporate several mechanisms, including bimodal surface particle transport and river morphodynamics. Stream power patterns will be analyzed in order to understand specific fluvial process such as the movement of particular sediment sizes through the reach, deposition on the floodplain, and bed aggradation or degradation. Field data will be collected in order to compare with model results.

Second, two-dimensional hydraulic and sediment transport models will be used to estimate finer scale processes at work in pools or bars of interest. A number of sites representing the range of different morphologies, facies patterns, and fluvial characteristics on the middle and lower Brazos River will be modeled. Sites will be approximately one meander wavelength in length, but the reaction at each bar and pool will be of interest. Processes such as deposition patterns on bar surfaces and maintenance of pool depths will be modeled. Stream power patterns and sediment movement thresholds required to accomplish channel scale process goals will be estimated and compared to independent empirical data.

Mapping of geomorphic features

Geomorphic mapping of channel scale morphology will be completed at field study sites, including habitat modeling Sites. As part of this mapping, channel morphology features (such as thalweg location, bank shape, and bar size) will be mapped. Geomorphic mapping will extend up the banks to the beginning of the active flood plain (approximately the area inundated by the 2-year return interval flood). Bed and bank sediment material, as well as large woody debris, will also be mapped. Sediment material will be sieved in order to determine grain sizes and sorting pattern. Work will be conducted in a manner consistent with finer scales associated with River Styles (Brierley and Fryirs 2005), which includes mapping of channel and hydraulic units. The detailed geomorphic map will be of value for determining substrate material, associated roughness for hydraulic modeling, and the physical features of biological habitat. The data collected during the detailed geomorphic mapping will be in a format allowing the extraction of more general mesohabitat and substrate maps for analysis of fish habitat utilization (see Section 3.2.2).

Overbank flows

The range of overbank flows of interest to the TIFP study of the middle and lower Brazos River will range from events that have historically occurred more than once per year to those that occur only once every few years. The impacts of such flows can be estimated based on flood impact summaries provided by the National Weather Service for most USGS streamflow gage sites. In addition, the HEC-RAS models described in Section 3.2.5 will provide an estimation of the extent of area inundated by overbank flows, providing another measure of their impact.

3.2.4 Water Quality

Maintaining adequate water quality is an essential part of managing a river ecosystem, so evaluating water quality along with hydrology, biology and physical processes is an essential part of the lower and middle Brazos River study. To a large degree, appropriate water quality is monitored and regulated through the EPA and TCEQ in processes like the CRP, National Pollutant Discharge Elimination System, Total Maximum Daily Load (TMDL) program and others. BRA actively participates in and manages portions of these processes. Generally, existing water quality programs (e.g., CRP) will be used to evaluate water quality. Any new data will be collected according to water quality protocols that already exist for those programs. Water quality issues will be evaluated and will consider results of on-going or completed BRA studies (basin nutrient loading study, bacteria Watershed Protection Plans, previous water quality models, etc.) and state-wide efforts (nutrient criteria development). However, existing studies do not provide sufficient detail to assist in the development of instream flow recommendations that address water quality concern. In particular, dissolved oxygen (DO) is a primary parameter of concern since low levels can have detrimental effect on aquatic organisms. Unfortunately, relationships between flow, nutrients, and DO in the lower and middle Brazos sub-basin are not well quantified at this time.

Nutrients, dissolved oxygen, and temperature

Despite the somewhat comprehensive set of water quality programs already in place, the tools used in those programs to promote good water quality have thus far been applied for specific programmatic purposes. The tools may not yet have been applied for a range of scenarios necessary to evaluate instream flows. At least one of these tools, the QualTX water quality model, is developed for some reaches within the middle and lower Brazos River sub-basin. However, it is anticipated updates and revisions to the existing QualTX models or development of new models will be necessary to analyze effects relative to various flow regimes. Currently, QualTX can be used to evaluate steady-state water quality conditions across a range of low to moderate flows. The primary output is DO concentration based upon inputs including flow, nutrient concentration, temperature and other physical and kinematic parameters.

Refinements or development of these models will require data accumulation and manipulation. Data needs include but are not limited to current: (1) water balance (volume and location of inflows, discharges, and diversions), (2) loading from tributaries and contributing watershed, (3) treatment plant discharges (both volume and loading), (4) literature values for modeling parameters and/or (5) collection of additional field data (travel time, diurnal variations, etc.). Interaction with BRA and other entities will be necessary, particularly as related to understanding the middle and lower Brazos River sub-basin and development of modeling scenarios. Calibration of model parameters will be conducted, as will model sensitivity analyses. The calibrated model will be validated using a set of known conditions if sufficient data is available. Once calibrated and validated, the model will be a useful tool for understanding and estimating water quality impacts for different instream flow scenarios. The model will also be useful for understanding potential future conditions.

Rather than use the model as a starting place to identify flows, the model will be used to check and adjust flow rates determined to be beneficial to the river ecology. It is anticipated that if QualTX is used, it will be to evaluate low flows, consistent with the subsistence or base flow levels. The greatest potential for low DO to occur is during low-flow, high-temperature conditions, when potential for aeration is reduced and DO saturation is low. However, following rain events DO concentration in creeks and rivers can be affected by an influx of organic matter from the watershed, so understanding the response to these events may also be important. Since this represents a more dynamic process, analysis tools in addition to the steady-state QualTX model may need to be developed. Assessing water quality is complex. The concentration of DO depends on a number of factors including temperature, nutrient concentration, organic matter, organisms present and rates of decay. Each of those factors needs to be quantified in a way that is relevant to each flow scenario to be evaluated.

A number of flow scenarios will be evaluated and compared. The baseline for comparison will need to be agreed-upon and could either be representative of current conditions or could be the TCEQ's current model that evaluates the water body's capacity to assimilate all permitted discharges. Potential scenarios to compare include the current level of discharges with lower base flows, fully permitted discharges with lower base flows, a reduced discharge level (coinciding to a reuse scenario) against lower base flows, or other potential future conditions.

At most Study Sites, measurements of the standard water quality parameters will be made during each site visit. Standard parameters include temperature, conductivity, pH, and DO. These measurements are complementary to existing programs (e.g., CRP) where these parameters and others continue to be measured and recorded at regular intervals at regular stations for long periods of time.

Recreational health

Due to excessive concentrations of bacteria, portions of the lower and middle Brazos River have been placed on the EPA 303(d) list of impaired water bodies. The TCEQ has performed Total Maximum Daily Load assessments on the impaired reaches of the lower and middle Brazos River (TCEQ 2008) to determine the desired bacterial load reductions that may be required to bring the Brazos River in compliance with State surface water quality standards. In response to the TCEQ TMDL reports, BRA initiated the development of a series of Watershed Protection Plans (WPPs) designed to address water quality impairments and attain load reductions determined by TCEQ TMDL studies. In addition to the WPPs, the TCEQ has contracted with BRA to develop Implementation Plans (IP) that will provide a detailed list of identified Best Management Practices (BMPs) and a schedule for their implementation. BRA will initiate the development of a WPP for the lower and middle Brazos River when funds become available.

3.2.5 Connectivity

The objective of the Connectivity component is to identify the interrelationships between flow and connectivity between the main channel and other ecosystems supported by the middle and lower Brazos River. The primary focus of activities related to this discipline will be on understanding connectivity between the river and riparian areas and floodplain habitats. A broad scale model will be developed to estimate the extent of inundation caused by high flow pulses and overbank flows. TIFP will rely on the results of previous studies (by TIFP, USGS, and others) to address connectivity with oxbow lakes and groundwater/ surface water interactions.

Inundation modeling

A one-dimensional hydraulic model (HEC-RAS) will be used to model the extent of inundation along the length of the river for a range of high flow pulses and overbank flows. Differences in interval between inundation events will be evaluated spatially along the length of the river to identify breakpoints or to identify areas where frequent inundation may have significant impact on riparian condition. The area of various habitat types inundated by flows will be evaluated, along with the total of all areas inundated. Flows to be evaluated will have recurrence intervals ranging from less than one year (high pulse flows) to 10 years (overbank flows). Given the small magnitude of these flows, i.e., much lower magnitude than typically analyzed for flood studies (e.g., 100-year flood), in-channel bathymetry may become an important factor. Detailed cross-sectional information may need to be developed for select reaches of the river where it is not currently known. This information may be developed from a combination of new survey data, high-resolution LIDAR data, and statistical relationships that result in synthetic in-channel cross-sections.

Inundation modeling at the broad scale describe above is ineffective for evaluating connectivity between the river and oxbow lakes. Relatively fine scale topographic features control connectivity with these off-channel water bodies, making direct measurements a more accurate means of evaluation. Earlier studies funded by TIFP (Winemiller et al. 2004, described in Section 1.3.5) have determined the flow conditions required to connect the river with six oxbow lakes. These lakes, of varying age and connectivity frequency, were located along the Brazos River between College Station and the Gulf of Mexico. TIFP will rely on the results of this study in order to evaluate connectivity between the river and oxbow lakes along the middle and lower Brazos River and does not plan additional activities related to this topic.

Groundwater/ surface water interaction

A number of recent studies have focused on characteristics on groundwater/surface water interactions along the middle and lower Brazos River (see Section 1.1.5). Other state programs may conduct additional studies of this type in order to develop groundwater models for the area. TIFP will monitor the results of these studies, but does not plan to conduct additional studies related to this topic.

4.0 CONTINUED STAKEHOLDER INVOLVMENT AND FUTURE ACTIVITIES

Stakeholder involvement has been and will continue to be an integral part of the entire TIFP process (Figure 13). This study design document will be reviewed by the study design workgroup and subsequently submitted for peer review. Annual presentations will be made to the stakeholder group in order to provide technical updates of study progress, including data collection, analysis, and modeling activities. As the instream flow study moves forward as briefly outlined below, stakeholder input will continue to be vital for successful completion and implementation.

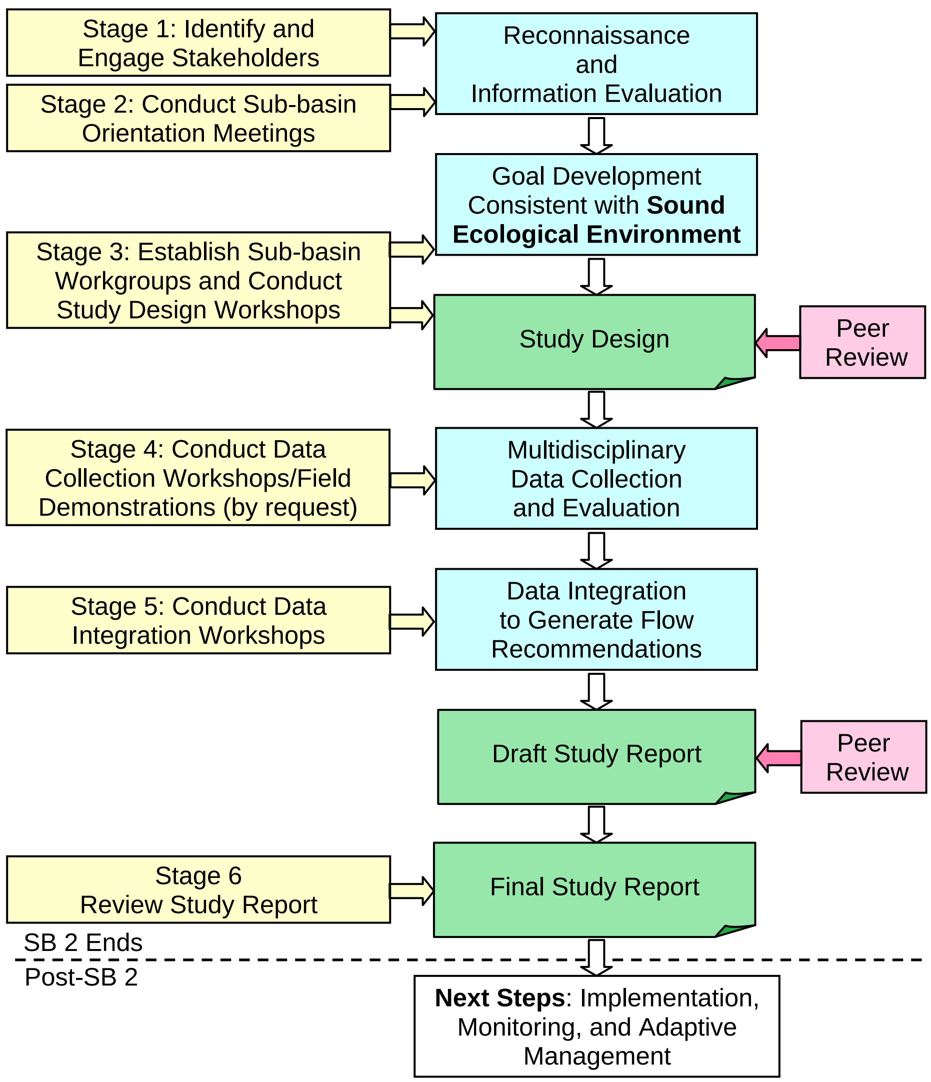

Figure 13. Stages of stakeholder participation in the TIFP study of the middle and lower Brazos River.

As described in the Technical Overview (TIFP 2008; Chapter 10), data integration to generate flow recommendations is an integral component of the overall study. Descriptions of flow recommendations will include four components of the hydrologic regime: subsistence flows, base flows, high flow pulses, and overbank flows (Table 10-1, TIFP 2008).

- **Subsistence Flows** - The primary objective of subsistence flow recommendations will be to maintain water quality criteria. Secondary objectives for the middle and lower Brazos River will include providing habitat that ensures a population is able to recolonize the river system once normal, base flow rates return.
- **Base Flows** - The primary objective of base flow recommendations will be to ensure adequate habitat conditions, including variability, to support the natural biological community of the middle and lower Brazos River sub-basin. These habitat conditions are expected to vary from day to day, seasons to season, and year to year. This variability is essential in order to balance the distinct habitat requirements of the various key species of the sub-basin.
- **High Flow Pulses** – The primary objectives of high flow pulse recommendations will be to maintain important physical habitat features and longitudinal connectivity along the river channel. Many physical features of the middle and lower Brazos River provide important habitat during base flow conditions that cannot be maintained without suitable high flow pulses.
- **Overbank Flows** – The primary objectives of overbank flow recommendations will be to maintain riparian areas, provide lateral connectivity between the river channel and active floodplains, and recharge the alluvium aquifer. Secondary objectives for overbank flows are to move organic debris to the main channel, providing life cycle cues for various species, and maintaining the balance of species in aquatic and riparian communities.

Chapter 11 of the Technical Overview (TIFP 2008) documents several steps that need to be performed after Study Design development and multidisciplinary data collection and evaluation for the middle and lower Brazos River study. In conjunction with continued stakeholder involvement, these major steps include the preparation of Draft and Final Study Reports and Implementation, Monitoring, and Adaptive Management. As outlined above, and discussed in Chapter 11 (TIFP 2008), the product of Senate Bill 2 is a series of instream flow recommendations that will achieve a sound ecological environment, in this case for the middle and lower Brazos River.

After study reports are completed, the additional steps (Implementation, Monitoring, and Adaptive Management) will be necessary to translate recommendations into action. Following up on Senate Bill 2, Senate Bill 3 creates a process to generate regulatory environmental flow standards based on the "the best available science." That legislation ensures that the development of management strategies to meet instream flow recommendations will be ongoing and adaptive and will consider and address local issues. Management strategies will outline steps or policies requiring adoption by state agencies, stakeholders, and possibly the legislature to implement new flow regimes. The strategies will also include recommendations related to monitoring and adaptively managing the aquatic environment through periodic review and refinement of flow recommendations.

Specifics regarding these activities are not described in this Study Design document but will be presented as the study progresses. However, these activities are important to note to best put this Study Design document into context within the overall middle and lower Brazos River study and directives from Senate Bills 2 and 3.

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6.0 APPENDIX

Comment 1 (Page 5, paragraph 2) – Suggested the following change: "The hydrology of the middle and lower Brazos has been affected by the operation of **flood storage reservoirs in the watershed since 1951**."

Response 1 – Changed wording to reflect when large reservoirs were built (beginning in 1941), not when they may have begun to affect hydrology of the middle and lower Brazos River.

Comment 2 (page 5, paragraph 2) - The middle and lower Brazos are largely uncontrolled and marginally influenced by reservoirs. Federal flood storage, primarily located on tributary rivers, reduce flood peaks and increase the subsistence and base flow regimes. However, the lower Brazos River is one of North America's relatively intact flood plain rivers.

Response 2 – Added text stating that the middle and lower Brazos is one of the largest relatively intact floodplain rivers in North America.

Comment 3 (page 10, paragraph 2) - It should be noted from Fig. 3 that the reduction in flows at the Waco gage greater than 30,000 cfs represent less than 1 percent of the time. And that flows that have been reduced between 3000 cfs and 9000 cfs represents less than 12 percent of the time. These variances are so slight that impacts are barely noticeable on the graph. If these slight reductions are to be explained in the text, it should also be noted that the flows between 10,000 and 25,000 cfs have increased.

Response 3 – Added text to note the increase in flows between 10,000 and 25,000 cfs.

Comment 4 (page 10, paragraph 3,4) - The increase in flows at the Richmond gage can also be explained by hydrogeneration from Lake Whitney, extended releases from Federal reservoirs to evacuate flood storage, and releases from water supply to honor downstream contractual commitments.

Response 4 – Added text clarifying that changes in flow at the Richmond gage could also be caused by reservoir operation to meet various objectives.

Comment 5 (page 10, paragraph 5) – Suggested the following change: " … construction and operation of reservoirs in the basin as a whole may have affected the hydrology of the middle and lower Brazos River **primarily by increasing base and subsistence flows**."

Response 5 – Although it appears likely that base and subsistence flows of the middle and lower Brazos River have increased due to reservoir operation, other changes in the flow regime may be as or more important. Also, reservoirs may not be responsible for all of the hydrologic changes in the sub-basin. After completing the instream flow study, which will include a hydrologic evaluation, we will be in a better position to evaluate the effects of reservoirs on the sub-basin. Therefore, no change was made to the text at this time.

Comment 6 (page 13, table 3) - Original capacities shown are not representative of current capacities, recent TWDB volumetric surveys indicate a reduced conservation storage as a result of sediment deposits over time.

Response 6 – Added a footnote explaining that due to sedimentation, original storage capacity estimates may not be reflective of current capacities.

Comment 7 (page 14, paragraph 3) - There appears to be an issue with water demands between 1980 and 2000. The total water diversion from surface and ground water is shown to be 905,000 af in 1980. The total water diversion from surface and ground water in 2000 is shown as 745,000. There is no explanation for the 160,000 af decrease in total demand between years 1980 and 2000.

Response 7 – As mentioned earlier in this paragraph, "Water use for agriculture has declined over the past decades…" Decreasing demand from this sector is predominantly responsible for the decrease in total water diversion in the 12 county area. Parenthetic statement to this effect added to text.

Comment 8 (page 15, paragraph 1) States that 62 fish species have been reported from the mainstem of the middle and lower Brazos River, and references Table 5. Table 5 contradicts this statement, as 68 species are listed.

Response 8 – Added text to paragraph to explain that sixty two freshwater native, 4 marine, and two introduced fish species have been reported from the mainstem of the middle and lower Brazos River.

Comment 9 (page 15, paragraph 4) - "*Notropis Shumardi* " is misspelled – should be "*Notropis shumardi.*"

Response 9 – Spelling corrected in text.

Comment 10 (page 18, table 5) - "*Percina carbonia* " is misspelled – should be "*Percina carbonaria.*"

Response 10 – Spelling corrected in text.

Comment 11 (page 29, paragraph 1) - The Allens Creek study did not investigate flows in the range of subsistence. The Allens Creek study used 7Q2 as the lower limit of the analysis and concentrated on base conditions. Subsistence flows in the lower basin are less than 7Q2.

Response 11 – As mentioned in the paragraph, the Allens Creek study "developed a computer model to estimate the effect of instream flows on salinity in portions of the Brazos River near its mouth…" Flow conditions investigated included a continuous flow of 734 cfs (equivalent to the 7Q2 flow calculated for USGS gage number 08111500 near Hempstead). Other conditions investigated were based on resutls from Run 3 of TCEQ's Water Availability Model for the Brazos River. This WAM Run assumes surface water withdrawals up to the fully authorized amount and no returns flows to the river (somewhat of a "worst case" scenario in terms of the magnitude of flows in the river). Of the 58 years (1940-1997) of WAM model results, three years were selected for investigation with the computer model of river salinity. The years evaluated included the driest year (1956), a year with annual flow equal to the median of all years (1994), and the wettest year (1992). Constant daily flows for each month of each year were developed by taking monthly WAM results and dividing by the number days in the month. The flows modeled for these three years dipped well below 700 cfs.

Comment 12 (page 29, paragraph 3) – See Comment 2.

Response 12 – Added text noting that the middle and lower Brazos River is one of North America's largest relatively intact floodplain rivers.

Comment 13 (page 32, figure 11) - Include woody debris in the conceptual model as an input along with fine and coarse sediment. Woody debris is recognized as contributing to input to habitat modeling (p 51, 54, 56 and 60).

Resonse 13 – Added "Large woody debris" to figure and additional text noting that large woody debris has a limited impact on the characteristics of the middle and lower Brazos River.

Comment 14 (page 32, figure 11) - Consider changing the description of the Water input in the conceptual model. "Influenced by upstream reservoirs" See Comment 2.

Response 14 – It seems relatively probable that upstream reservoirs have some influence on the hydrology of the middle and lower Brazos River. The magnitude of this impact is not described in the figure but will be determined as part of the instream flow study.

Comment 15 (page 35, paragraph 2) - It should be noted that sport fish used as indicator species incorporate economic and social components of the overall goal or vision originally agreed upon by the study design workgroup. Bacteria used as an indicator of recreational health of the waterbody also addresses social and potentially economic goals.

Response 15 – TIFP agrees and the text has been altered to reflect this comment.

Comment 16 (pages 38-39, table 11) - **Consider the following key species as indicators:** White-faced Ibis, Interior Least Tern, Houston toad, Alligator snapping turtle. A description with justification is listed below.

White-faced Ibis, State Listed Threatened; potential or known presence within Brazoria. Fort Bend, Waller, Austin, Washington, Grimes Counties; prefers freshwater marshes, sloughs, and irrigated rice fields, but will attend brackish and saltwater habitats; nests in marshes, in low trees, on the ground in bulrushes or reeds, or on floating mats; could be linked to HFP and overbank flow regimes in riparian areas.

Interior Least Tern, Federally Listed Endangered, State Listed Endangered; potential or known presence in McLennan, Falls, Milam, Robertson, Burleson, Brazos, Washington, Grimes, Waller, Austin, Fort Bend and Brazoria Counties; nests along sand and gravel bars within braided streams, rivers; also known to nest on man-made structures (inland beaches, wastewater treatment plants, gravel mines, etc); eats small fish and crustaceans, when breeding forages within a few hundred feet of colony; could be linked to HFP and overbank flow conditions.

Houston toad, Federally Listed Endangered, State Listed Endangered; potential or known presence in Milam, Robertson, Burleson, Brazos, Washington, Waller, Austin, and Fort Bend Counties; endemic; sandy substrate, water in pools, ephemeral pools, stock tanks; breeds in spring especially after rains; burrows in soil of adjacent uplands when inactive; breeds February-June; associated with soils of the Sparta, Carrizo, Goliad, Queen City, Recklaw, Weches, and Willis geologic formations; could be linked to overbank flow conditions in riparian areas.

Alligator snapping turtle, State Listed Threatened; potential or known presence in Falls, Milam, Robertson, Burleson, Brazos, Washington, Grimes, Waller, Austin, Fort Bend and Brazoria Counties; perennial water bodies; deep water of rivers, canals, lakes, and oxbows; also swamps, bayous, and ponds near deep running water; sometimes enters brackish coastal waters; usually in water with mud bottom and abundant aquatic vegetation; may migrate several miles along rivers; active March-October; breeds April-October.

Response 16 – While the **White-faced Ibis** will frequent marshes, swamps, ponds, and rivers, its preferred habitat is freshwater marshes. In Texas, they breed and winter along the Gulf Coast and may occur as migrants in the Panhandle and West Texas. Since this is a migratory species, it may utilize the Brazos River and associated habitats on occasion while migrating, however, this species is not considered to be river flow dependent. Therefore, TIFP staff do not believe it would be suitable as a target indicator species for the Brazos River instream flow study.

In Texas, the **Interior Least Tern** is known to breed at three reservoirs along the Rio Grande River, on the Canadian River, and throughout the Red River basin. As wintering habitat, interior least tern may utilize the Texas Gulf Coast including possibly around the Brazos River. While it does require bare or sparely vegetated sand, shell, and gravel beaches, sandbars, islands, and salt flats associated with rivers and reservoirs for nesting, TPWD biologists responsible for conducting surveys throughout the State have not found any nesting colonies along the middle and lower Brazos River. Therefore, TIFP staff do not think it would be a reasonable use of resources to consider the interior least tern as a target species for the Brazos River instream flow study.

While the **Houston toad** has historically occurred in several counties within the Brazos River basin (Burleson, Milam, Robertson, Leon, Lee, Austin), the only critical habitat designated by U.S. Fish and Wildlife Service within the Brazos River basin is a small area (one mile radius around the entrance to Lake Woodrow) in Burleson County. The nearest known locale to the Brazos River is Sealy, TX - nearly four miles from the main channel of the Brazos. Typical breeding habitat for the Houston toad is small ponds and ephemeral pools; along upland tributaries with deep, sandy soils. To our knowledge, they have never been observed along large rivers or their riparian corridors (i.e. within the floodplain of a large river). Consequently, TIFP staff do not think it would be a reasonable use of resources to expend time and energy considering the Houston toad as a target species for the Brazos River instream flow study.

Alligator snapping turtles inhabit freshwater river systems and associated habitats such as lakes, canals, oxbows, swamps, ponds, and bayous throughout the Mississippi River basin. They also occur in the rivers and associated habitats of several drainage basins that flow into the Gulf of Mexico, from the Suwanee River, Florida, in the east to the western limits of the species' range in Texas. They prefer deep water bodies with muddy bottoms and abundant vegetation. Based on information from the U.S. Fish and Wildlife Service, the alligator snapping turtle is declining throughout its range as a consequence of several known factors. Two of the leading factors contributing to loss of the species' native habitat are commercial and agricultural development of former bottomland hardwood forest and associated freshwater streams, as well as river and bankside modifications that alter or eliminate crucial nesting sites. Another major threat is over-collection of live adult turtles from the wild for human consumption and for export of live animals destined for the pet trade. Alligator snapping turtle hatchlings are sold in the domestic and international pet trade, whereas adult specimens are harvested for local human consumption and for use in the specialty meat trade within the United States (Reed et al. 2002). Since the threats to alligator snapping turtles do not appear to be directly linked to changes in flow regimes in the middle and lower Brazos River, TIFP staff do not believe it would be suitable as a target indicator species for the Brazos River instream flow study.

Reed, R.N., J. Congdon, and J.W. Gibbons. 2002. The alligator snapping turtle (*Macroclemys* [=*Macrochelys*] *temminckii*): A review of ecology, life history, and conservation, including demographic analyses of the sustainability of take from wild populations. Report to the Division of Scientific Authority, U.S. Fish and Wildlife Service.

Comment 17 (page 39, table 11) - No mention in report of specific riparian plant species as indicator.

Response 17 – Available literature and local knowledge provided at the study design workgroup meetings did not suggest any candidate riparian plant species. Baseline surveys and evaluations of riparian habitat that will be completed by this study will be useful to determine riparian plant species that may be used as indicators for future work.

Comment 18 (page 39, paragraph 1) - The concept of using fish species that are imperiled, vulnerable, or decreasing in abundance as key species in the analysis seems tenuous. It would be problematic trying to relate their presence, absence, or relative abundance directly to instream flow, since the chances of collecting them at all would be low due to their rareness. As such, they would not seem to be reliable indicators of instream flow suitability. Two of the "key species" listed at the bottom of p. 39 fall into this category - chub shiner (*Notropis potteri*) and alligator gar (*Atractosteus spatula*).

Response 18 – Species that are declining in number may be especially good candidates for indicators as they may be sensitive to changes in flow conditions. None of the fish species or groups of fish species proposed as indicators are considered threatened, endangered, or so few in number that they would be difficult to use as indicators. All five of the proposed fish species and members of the group of species (juvenile sport catfishes) were collected during baseline fish surveys conducted in the sub-basin in the summer of 2006 (BRA 2007). Only one individual alligator gar was collected, but this was probably due to gear type not well suited for collecting this species. Use of gear and sampling methodology specifically targeting alligator gar should result in collection of many more individuals. Only ten individual chub shiners were collected, but again, it should be possible to increase this number by targeted sampling for this species. The remaining species or groups of species proposed for use as indicators were relatively abundant (at least 40 individuals collected) during the baseline survey.

Comment 19 (page 48, paragraph 6) - Tier 3 assessment to locate representative Study Sites within each selected reach lacks detail. The map that is referenced does not give a specific description of the area or the extent of the study area. We recommend labeling the map with the name of the study site and include a description of the proposed selected area and the reason for the selection.

Response 19 – Added text to the paragraph to further describe the Study Site selection process.

Comment 20 (page 56, paragraph 2) - The list of key species presented here doesn't match the list at the bottom of p. 39. Burrhead chub (*Macrhybopsis marconis*) doesn't occur in the Brazos Basin (Table 5; Thomas, Bonner, & Whiteside 2007).

Response 20 – Text corrected to list appropriate key species.

Comment 21 (page 57, paragraph 2) - "San Antonio River" should be "Brazos River". It appears that portions of this section were cut and pasted from a report for the San Antonio River basin.

Response 21 – Text corrected.

Comment 22 (page 60, paragraph 2) - "San Antonio River" should be "Brazos River". It appears that portions of this section were cut and pasted from a report for the San Antonio River basin.

Response 22 – Text corrected.