Instream Flow Study of the Middle and Lower Brazos River

Prepared by

TEXAS INSTREAM FLOW PROGRAM

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EXECUTIVE SUMMARY

Senate Bill 2, enacted in 2001 by the 77th Texas Legislature, established the Texas Instream Flow Program (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. These studies consist of multi-disciplinary assessments of biology, hydrology, water quality, geomorphology, and connectivity (where possible). Flow conditions are framed in the form of flow regimes comprising several components: subsistence, base flows, high flow pulses, and overbanking flows. Table ES-1 provides basic definitions of flow components and examples of riverine processes supported by each.

Table ES-1. 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	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 Maintain longitudinal connectivity
Base flows	Average flow conditions, including intra- and inter-annual variability	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 channel corridor

Table ES-1 (cont). Ecological processes supported by instream flow components of the middle and lower Brazos River.

Component	Hydrology	Geomorphology	Biology	Water Quality	Connectivity
High flow pulses	In-channel, short duration, high flows	Maintain channel and substrate characteristics Prevent encroachment of riparian vegetation	Provide spawning cues for some species	Restore normal water quality conditions after prolonged subsistence or low base flows	Provide connectivity to near-channel water bodies Maintain water table levels in floodplain and soil moisture for plants
Overbank flows	Infrequent, high flows that exceed the channel	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 and estuary	Provide migration and spawning cues for some species Provide access to floodplain habitats Maintain diversity of riparian vegetation	Restore water quality in floodplain water bodies	Provide connectivity to floodplain and estuary

The Brazos River Basin is one of the largest river basins in Texas, spanning six ecoregions as it flows from its headwaters in New Mexico to its outlet at the Gulf of Mexico. The TIFP study area of the middle and lower Brazos River remains unimpounded; however, river flows in the study area are regulated by upstream and tributary reservoirs which supply water to municipal and industrial users, generate hydropower, provide flood control, and create recreation opportunities for the public. The middle and lower Brazos River supports a rich ecological community that relies on the quality, quantity, and timing of water moving through the system.

Stakeholder involvement was integral in the planning of the TIFP study. The overall goal or vision agreed upon by stakeholders was for the sub-basin to be ***"a middle and lower Brazos River that provides for sustainable environmental, economic, and social uses".*** Through a series of public meetings, the TIFP developed study specific objectives, indicators, and a study design. The TIFP study of the middle and lower Brazos River includes activities related to the five major disciplines: biology, hydrology, water quality, geomorphology, and connectivity. Appendices provide information on each discipline and TIFP responses to stakeholder comments.

> A high quality, natural environment is essential for conserving the quality of life Texans, future generations of Texans, and visitors to this state enjoy. Intact and functioning ecosystems are also critical for maintaining a strong state economy. Healthy aquatic systems that maintain biological integrity are essential to conserve the state's natural biodiversity, as well as support tourism, recreational pursuits, commercial and recreational fisheries, and a myriad of other industries.
>
> TIFP, 2002

Study activities were carried out to identify flow-ecology relationships related to a flow regime supportive of a sound ecological environment. Results from completed and ongoing study and data collection efforts related to the middle and lower Brazos River were utilized to the extent possible. Subsistence flow recommendations were based on aquatic habitat, water quality, and temperature. Base flow recommendations were based on aquatic habitat versus flow relationships developed from six intensive study sites and the water quality analysis related to mussel recruitment. Pulse and overbank flow recommendations were based on riparian flow ecology relationships identified at six field sites. Timing and duration of pulse and overbank flow recommendations were informed by life history requirements of focal riparian species, floodplain spawning fish, and flows necessary to support oxbow connectivity. Based on analysis at the most downstream study site (Allens Creek), flow recommendations were also made to support sediment transport processes that maintain the river channel and instream habitats, assuming a geomorphically stable channel exists or could be achieved in the near future. It is important to note that the current channel of the lower Brazos River is not geomorphically stable but is incising at a rate of more than a foot per decade near Richmond and Rosharon. The cause of this ongoing incision does not appear to be alteration of the flow regime or the impact of upstream reservoirs. Rather, the source appears to be more recent (since 1980) with impacts emanating from the lower portion of the river. Identifying the cause or causes of this incision is beyond the scope of this study. However, if the ongoing incision is not reduced or eliminated, it will have an adverse impact on the environmental benefit of the recommended flow regime. Left unchecked, the ongoing incision will reduce or negate the environmental benefit of flows intended to benefit instream habitats, riparian areas and/or provide connectivity to oxbow lakes and other floodplain habitats.

Final flow recommendations are provided for six sites (Figure 65–Figure 70). Flow regime recommendations were generally consistent with modern and historical flow records (pre-reservoir) but in some cases the recommended flows occur less frequently in the more recent period than they occurred in the past. However, if these flow levels occur in the lower and middle Brazos River, the predicted ecological benefits, such as those outlined in Table ES-1 will be supported. Further, a monitoring program is recommended to evaluate the effectiveness of these recommendations and may provide additional information that could result in modifications or revisions to these flow regime recommendations.

1 INTRODUCTION

The Brazos River basin is one of the most diverse river basins in the state, spanning six ecoregions; rainfall conditions that vary from a mean average of six inches per year in headwater areas to more than 50 inches per year near its mouth (HDR 2001). The Brazos River flows for 1,280 miles (2,060 km) (Kammerer 1990) southeast and discharges into the Gulf of Mexico at Freeport, Texas. The Brazos River ranks second only to the Mississippi River in terms of sediment load delivered to the Gulf of Mexico, where it forms a wave-dominated delta (Carlin 2013). The Brazos River main stem and tributaries have been altered by construction of 17 major reservoirs for flood control and water supply (Brazos BBEST 2012). Although the middle and lower Brazos River remains unimpounded, flows are regulated by these upstream and tributary reservoirs. 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. Historical discharge records indicate highest flows generally occur during winter and spring (Zeug and Winemiller 2008a); however, unpredictable rainstorms can generate high flow pulses and overbanking flows during any time of year.

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 1920. 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), unregulated areas, and water supply operations contribute to the river's flow, reducing the impacts of reservoirs. The flow of the middle and lower Brazos River continues to be variable with the seasons and responsive to precipitation patterns within the sub-basin.

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.

Senate Bill 2, enacted in 2001 by the 77th Texas Legislature, established the Texas Instream Flow Program (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 (TIFP 2008). With passage of Senate Bill 3 (SB3) 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. Instream flow studies function to provide scientific information that can be utilized during the adaptive management process within SB3 to inform environmental flow recommendations. As part of the TIFP process, the agency partners identified the middle and lower Brazos River as a priority sub-basin study area.

Stakeholder involvement has been a key component of the TIFP middle and lower Brazos River 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. From that foundation, a Study Design document was prepared in 2010 for the middle and lower Brazos River (TIFP/BRA 2010). This Study Design was peer reviewed by stakeholders and the U.S. Geological Survey (USGS) and subsequently modified based on comments received.

A wealth of hydrological, biological, geomorphological, and water quality information was collected and analyzed in support of the SB2 instream flow study. This information has been condensed and compiled to generate this report. As will be evident throughout this report, the culmination of study efforts to date have resulted in a characterization of the flow-habitat and flow-ecological relationships associated with the riverine environment within the middle and lower Brazos River (Waco, Texas to the Coast).

1.1 *Stakeholder Involvement and Study Design*

The middle and lower Brazos River sub-basin is shown in Figure 1. As previously stated, stakeholder involvement was integral in the development of the Study Design for the TIFP middle and lower Brazos River sub-basin study. This involvement started with initial meetings to gain historic and current perspectives on the basin, which then led to a series of meetings designed to develop study specific goals and objectives to guide the development of the study design. Throughout the study design process, stakeholders provided a wealth of local and technical knowledge which complemented historical reports and available data. 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. The Study Design (TIFP/BRA 2010) focused on:

- An overview (Section 1 of the Study Design) 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 of the Study Design);
- A description of the proposed technical studies (Section 3 of the Study Design), including
    - Study site locations,
    - Data collection methods and analysis, and
    - Multidisciplinary coordination; and
- An overview of continued stakeholder involvement and future activities (Section 4 of the Study Design).

The contents of the Study Design document will not be repeated in this document but are referenced as they constitute a wealth of background information regarding historical and current-day perspective and study activities.

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

1.2 *Study Goals and Objectives*

The overall goal or vision agreed upon by the stakeholders 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 and will, therefore, not be addressed in this report. 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. 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.

The objectives for each component were defined as follows:

- **Hydrology**
  - Identify flow regime components and their characteristics
  - Identify/define current, historical, and naturalized patterns of flows to determine potential environmental consequences of changing from these patterns
  - Identify all sources of instream flow and factors which may affect those sources
- **Biology**
  - Identify flow regimes:
    - for the benefit of the native ecosystem (*i.e.,* habitat, flora, and fauna)
    - to maintain a diverse aquatic community and prevent the extinction of native species
    - to preserve/protect and restore/improve key habitat features for native species in river and riparian zones
- **Physical Processes/Geomorphology**
  - Identify interrelationships among flows, bank stability, channel maintenance, and alluvial and associated aquifers
- **Water Quality**
  - Identify flow-related water quality in the four flow regime components.
- **Connectivity**
  - Identify how flow influences riparian zones integrity and connectivity with the river
  - Identify flows that support lateral connectivity (*i.e.,* oxbows and backwaters)
  - Identify flows that support longitudinal connectivity

The following objectives (separate from a discipline) were agreed to by the group:

- Define/determine current, historical and natural conditions in each flow regime component (overarching objective)
- Evaluate relationships between flow regimes and economic and social uses, including recreational use
- Consider how water planning studies and instream flow studies will impact and interact

Tables 1 - 4 list discipline specific indicators identified during the stakeholder process.

Table 1. 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 earliest gage records, which are 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 2. 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 2 (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.

Table 3. 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 4. 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 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.

2 METHODS AND ANALYSIS

2.1 *Study Site Selection and Study Components*

To plan study activities, the middle and lower Brazos River sub-basin was divided into study areas, reaches, and sites using a three-level approach (TIFP/BRA 2010) (Figure 2). The evaluation of study areas 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. Study areas were numbered 1 through 4, from downstream to upstream. Study Areas 1 (river mile [RM] 0 to 25) and 2 (RM 25 to 226) are within TCEQ Classified Segments 1201 and 1202, respectively. Study Areas 3 (RM 226 to 311) and 4 (RM 311 to 403) combined are within TCEQ Classified Segment 1242. These four study areas were then further divided into 10 study reaches based on geomorphologic conditions such as floodplain/channel connectivity and sinuosity (see Phillips 2007 and Table 15 in TIFP/BRA 2010). Unless otherwise noted, river mileages referenced in this document represent the distance along the Brazos River from the confluence with the Gulf of Mexico as measured from the National Hydrology Dataset (NHDPlus dataset, 2006 version).

The evaluation of study reaches was more detailed and focused on specific parameters relative to hydrology (*e.g.*, USGS data and diversions), biology (fish and mussel assemblage data), geomorphology, and water quality data within the ten reaches (TIFP/BRA 2010). This detailed evaluation determined which activities were appropriate within the study reaches and which study reaches no study activities were proposed (see page 48 and 49 of TIFP/BRA 2010).

As it is not economically feasible to study an entire Study Reach, representative study sites within reaches were selected. Instream and riparian habitats were evaluated based on the aerial photography and data presented in the study reach assessment were evaluated in detail. The study site assessment was done to locate representative study sites within each selected Study Reach.

Coordinates for each specific study site are shown in Table 5 and locations are mapped in Figure 3. Upper and lower boundaries for each site were selected in accordance with guidance from TIFP (2008). All study sites encompass at least one meander wavelength of river channel, ensuring a variety of channel structures and bed forms are included. During high flow events, many dynamic geomorphic processes that adjust channel shape occur. While the flow is rising, flow may scour the bed and outer edge of meander bends. As flow recedes, deposition may occur on the bed and along the inner edge of meander bends. The processes of scour and deposition may not balance exactly for individual high flow events, but geomorphically stable systems will maintain their physical characteristics (such as channel width and bed forms) over time. Including at least one meander wavelength of river channel in the study site reduces the impact of small variations in channel shape or configuration on study results. Boundary locations were also selected to accommodate accurate hydraulic modeling.

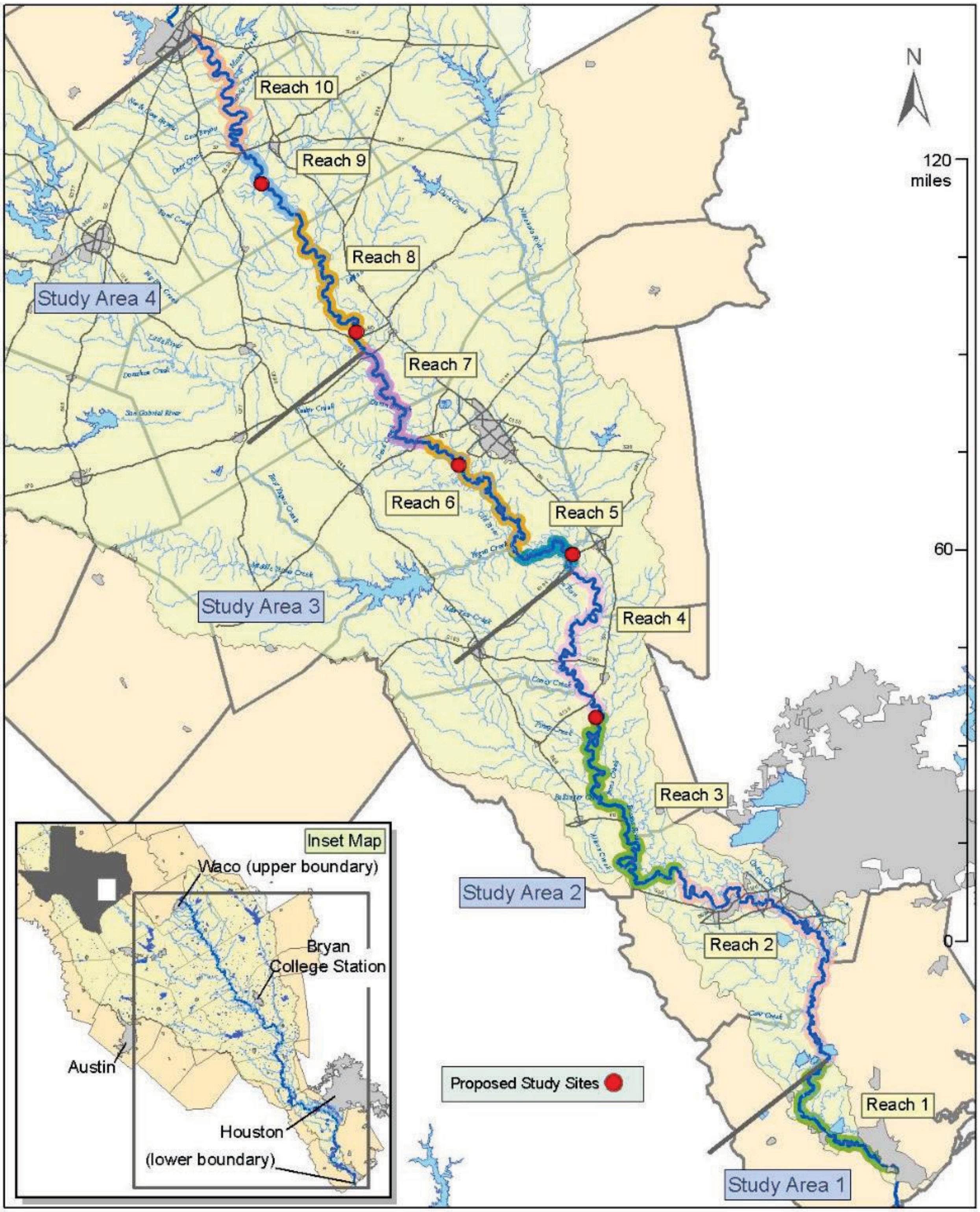


Figure 2. Texas Instream Flow Program study areas, reaches and sites for the middle and lower Brazos River.

Table 5. Coordinates of upper and lower boundaries for each study location.

Site	County	Study Site Number	Upper Boundary °N	Upper Boundary °W	Lower Boundary °N	Lower Boundary °W
Marlin	Falls	12087	31.243236	96.919853	31.201947	96.900800
Hearne	Robertson	12080	30.897217	96.691778	30.879925	96.691264
Mussel Shoals	Brazos	12050	30.602775	96.465244	30.576458	96.426422
Navasota	Brazos	12030	30.384058	96.174397	30.371067	96.151217
Wildcat Bend	Waller	12020	29.959083	96.106908	29.938789	96.108706
Allens Creek	Fort Bend	12010	29.648706	96.022969	29.633708	95.990539

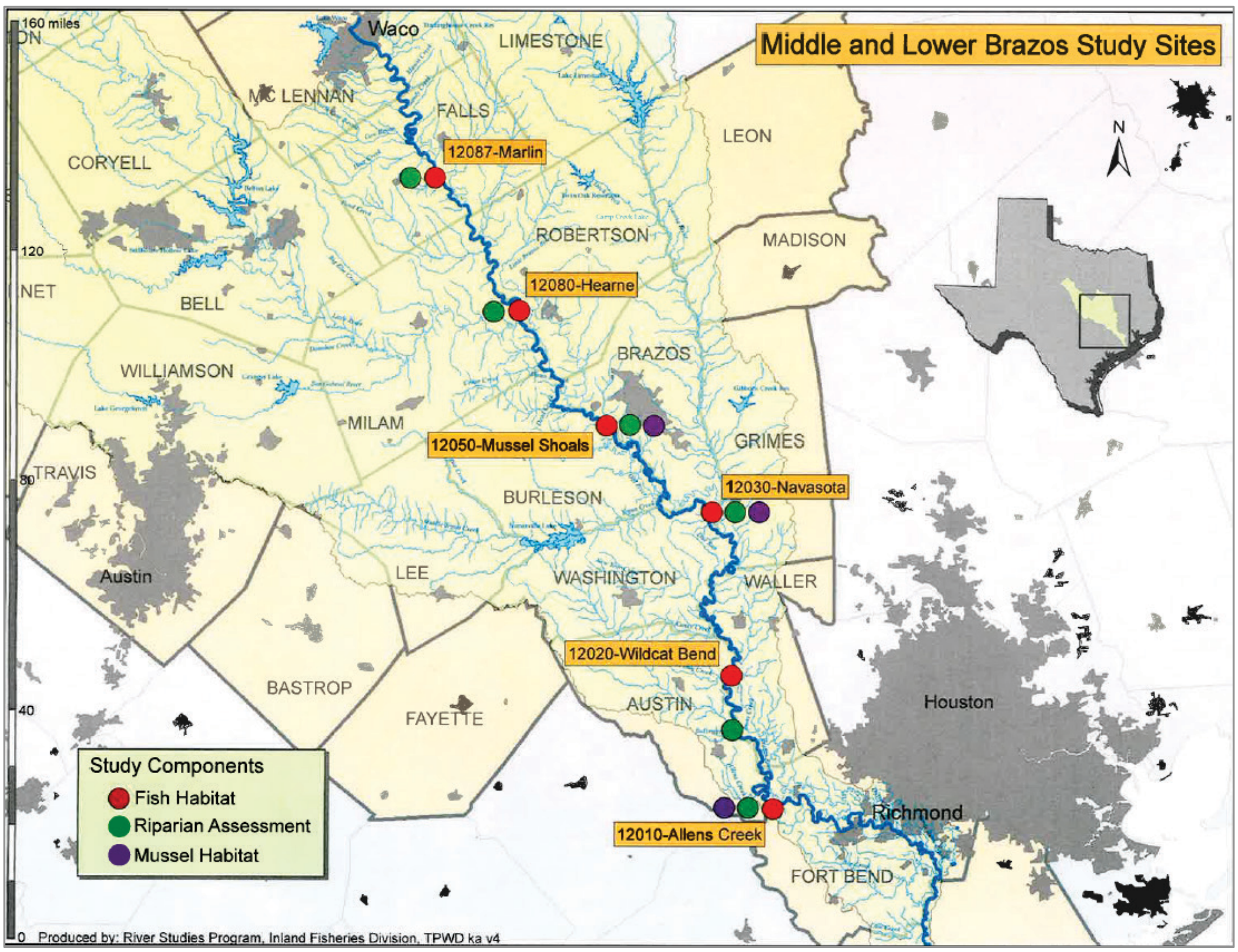


Figure 3. Map of six study sites located along the middle and lower Brazos River.

The Technical Overview (TIFP 2008) and Study Design (TIFP/BRA 2010) outlines four major study components including hydrology and hydraulics, biology, physical processes, and water quality. Sections 2.2 through 2.5 provide a brief overview of existing conditions and data collected, and then describe the study activities, locations, and methods for each of the four components relative to the indicator categories established by the stakeholder process.

2.1.1 *Brazos River at Marlin (Site 12087)*

The study site, Brazos River at Marlin (site 12087 in Figure 3), located within Falls County, is approximately 3.4 river miles (5.5 kilometers [km]) downstream of Farm-to-Market 406 near the city of Marlin, TX. The study site is 5.5 river miles (8.9 km) in length between RM 367.2 and 361.7. Mesohabitats at the Marlin study site are dominated by run habitats; however, backwater, pool, and riffle mesohabitats are all well represented within the study site. Substrates at the Marlin study site are dominated by gravel and sand with considerable amounts of silt as well. Patches of large rock and clay are present but in lesser amounts. Near the middle of the study site the river channel splits and creates a large riffle complex.

2.1.2 *Brazos River at Hearne (Site 12080)*

The study site, Brazos River at Hearne (site 12080 in Figure 3), is located along the Milam/Robertson County border approximately 3.0 river miles (4.8 km) upstream of Farm-to-Market 485 near the town of Hearne, TX. The study site is 3.1 river miles (4.99 km) in length between RM 323.2 and 320.1. Mesohabitats at the Hearne study site are dominated by run habitats; however, backwater and pool habitats were also abundant at the sampled flow levels. Riffle habitats are present but to a much lesser extent. Substrates are primarily sand and gravel with considerable amounts of silt substrate as well. Immediately downstream of the study site are at least two large boulder fields in the river channel.

2.1.3 *Brazos River at Mussel Shoals (Site 12050)*

The study site, Brazos River at Mussel Shoals (site 12050 in Figure 3), is located along the Burleson/Brazos County border approximately 8.6 river miles (13.8 km) downstream of Highway 21 near the city of Bryan, TX. The study site is 2.6 river miles (4.2 km) in length between RM 284.6 282.0. Mesohabitats at the Mussel Shoals study site are dominated by run habitats; however, riffle habitats are present near the upstream and downstream ends of the study site. The large riffle complex at the upstream end of the study site is littered with fossilized large woody debris. Substrates are primarily sand and gravel with considerable amounts of boulder and bedrock substrates as well. Small patches of silt and clay are also present.

2.1.4 *Brazos River at Navasota (Site 12030)*

The study site, Brazos River at Navasota (site 12030 in Figure 3), is located along the Washington/Brazos County border approximately 1.6 river miles (2.6 km) upstream of Highway 105 near the city of Navasota, TX. The study site is 2.6 river miles (4.18 km) in length between RM 237.4 and 234.8. Just upstream of the study site, there are remnants of an old lock and dam structure built circa 1910[1]. Mesohabitats at the Navasota study site are dominated by run habitats; however, backwater, pool, and riffle mesohabitats are all well represented within the study site. Substrates at the Navasota study site are dominated by sand and gravel with considerable amounts of cobble and boulder substrates as well. Patches of silt and clay are present but in lesser amounts.

[1] http://us.geoview.info/lock_and_dam_on_brazos_river_washington_county_circa_1910,41973733p

2.1.5 *Brazos River at Wildcat Bend (Site 12020)*

The study site, Brazos River at Wildcat Bend (site 12020 in Figure 3), is located along the Austin/Waller County border approximately six river miles (9.7 km) upstream of FM 529 near the town of Burleigh, TX. The study site is 4.7 river miles (7.56 km) in length between RM 176.5 and 171.8. Mesohabitats at Wildcat Bend consist mostly of run habitat with considerable amount of backwater at all three flow levels sampled. Some of the pools measured were 12-14 feet (3.6-4.3 meters) deep. At low flow levels, a large riffle complex is exposed near the downstream end of the study site. Substrates at the study site are primarily sand and silt with small patches of clay and gravel. Much of the study site contains patches of large woody debris that provide habitat for fish as well as adds roughness to the channel.

2.1.6 *Brazos River at Allens Creek (Site 12010)*

The study site, Brazos River at Allens Creek (site 12010 in Figure 3), located along the Austin/Fort Bend/Harris County border, is 3.7 river miles (5.9 km) long between RM 129.5 and 125.8. The Allens Creek study site was selected to complement previous work performed at this location (Osting *et al.* 2004, Li and Gelwick 2005). During a reconnaissance trip in May 2013, a large sand and gravel dredging operation was operating at the study site of the previous work. In an effort to distance our efforts away from sand and gravel operations, the study site was relocated approximately three river miles downstream of the FM 1093 bridge near the town of Wallis, TX. The study site is dominated by run and pool mesohabitats with the exception of a unique riffle feature that is prominent at flows of approximately 3,000 cubic feet per second (cfs). Substrates at the study site are primarily sand and silt with small patches of clay and gravel.

2.2 *Hydrology and Hydraulics*

To characterize the flow-habitat and flow-ecology relationships within the riverine ecosystem supported by the middle and lower Brazos River, hydrology and hydraulics studies focused on hydrologic analysis, hydraulic modeling in support of instream habitat modeling, and evaluation of high flow pulse and overbank flows. During the stakeholder process, indicators for hydrology were identified (TIFP/BRA 2010) including characteristics of flow regime components (including variability of those characteristics) and sources of instream flow. Flow characteristics are discussed in Sections 2.2.1 and 2.2.3. Hydraulic modeling in support of other disciplines is discussed in Sections 2.2.2 and 2.2.3.

2.2.1 *Hydrologic Analysis*

The middle and lower Brazos River ecosystem has 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 flow is typically referred to as the flow regime. An evaluation of the flow regime was conducted to assess hydrological indicators including natural variability, current variability, and gain or loss in river flow. The USGS) has maintained a network of streamflow gages in the middle and lower Brazos River sub-basin since the late nineteenth century. Currently, nine streamflow gages are operational on the main stem of the Brazos River downstream of the City of Waco, with additional gages on many tributaries. This network allows characterization of spatial changes in the flow regime (moving upstream or downstream).

However, the ability to characterize how the flow regime has changed temporally (from early periods to later periods) is limited as only three gages on the Brazos River (USGS Gage Nos. 08096500 at Waco, 08109000 near Bryan, and 08114000 at Richmond) have continuous records going back prior to 1960. Even data from these three gages is not entirely free of human influence. As early as 1936, flows at USGS Gage No. 08096500 on the Brazos River at Waco were regulated by the original Lake Waco (constructed upstream in 1929) and low flows were affected by numerous small diversions (Grover *et al.* 1937). An accurate and accepted estimate of what daily flows in the basin would look like without human influences (referred to as daily "naturalized flows") is under development (Wurbs and Zhang 2016), but is still considered to be developmental.

Data from gages in the middle and lower Brazos River sub-basin with long flow records (shown in Table 6) were analyzed to provide an estimate of human impacts on the hydrology of the sub-basin. USGS Gage Nos. 08108700 (Brazos River at State Highway 21 near Bryan) and 08109000 (Brazos River near Bryan) were included because they are relatively close together (five river miles) and, as a pair, they provide a long period of record for this part of the Brazos River. Based on the data from these gages, comparisons were made between contemporary flows in the Brazos River and flows from earlier time periods when human influence was much less.

Table 6. Unites States Geological Survey stream gages in the middle and lower Brazos River with long periods of record.

USGS Gage No.	**USGS Gage Name**	**Continuous Record Begins**	**Ends**	**River Mile***	**Drainage Area (mi²)**
08096500	Brazos River at Waco	1898	Present	401	29,559
08108700	Brazos River at SH 21 near Bryan	1993	Present	286	39,049
08109000	Brazos River near Bryan	1918	1993	281	39,489
08114000	Brazos River at Richmond	1922	Present	92	45,107

*River mileage measured from confluence with Gulf of Mexico as reported in Turco *et al.* (2007).

When comparing flow statistics from different time periods, it is important to be aware of the role that natural climate variability may play in any differences that may appear in the statistics. Through history, the Brazos basin has experienced periods of both severe drought and extreme wet conditions. That variation can be seen in annual precipitation records of the North Central Texas Climate Region, which covers a large portion of the Brazos basin (Figure 4). Comparing statistics from long time periods (such as 20 years) dampens some of the effect of including extremely wet or dry years in the analysis; however, comparisons may still reflect some natural differences in meteorology. In addition, the Brazos basin is quite large, including portions of seven of the ten climate regions in Texas. As a result, part of the basin can be in drought while wet conditions prevail in other portions of the basin.

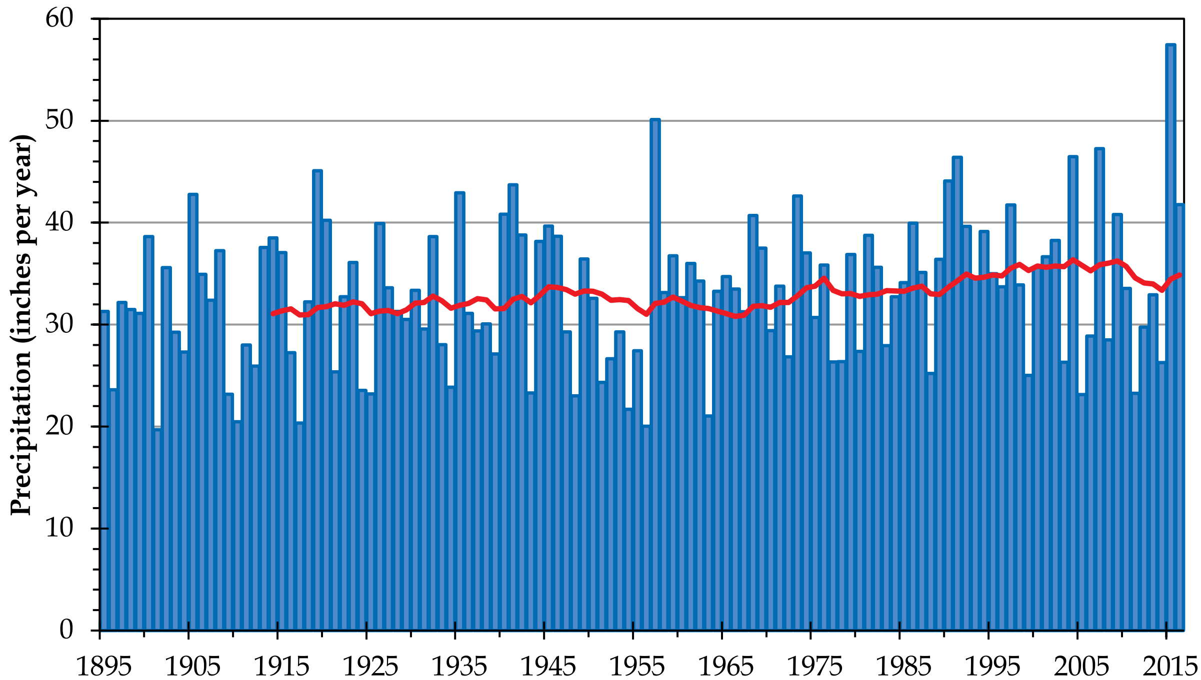


Figure 4. Annual precipitation for the North Central Texas climate region with 20-year moving average (red line) (data from NCEI 2017).

Authorized water rights in the entire Brazos basin total more than 2.9 million acre-feet per year (TCEQ 2017). Actual diversion amounts from 2000 to 2014 have averaged about 922,000 acre-feet per year (TCEQ 2017). For comparison purposes, the average annual flow of the Brazos River, as measured by USGS Gage No. 08116650 near Rosharon, is slightly more than six million acre-feet per year.

Relatively large reservoirs were present in the Brazos basin as early as the 1920's. The largest of these was the original Lake Waco (replaced with a larger version in 1965), which was completed in 1929 and had an original storage capacity of about 39,400 acre-feet. Other lakes present in this time period were the original Lake Mineral Wells (completed in 1920), original Lake Cisco (completed in 1923), and Lake Kirby (completed in 1927). All of these reservoirs were located on tributaries of the upper Brazos River and (with the exception of the original Lake Waco) all had storage capacities of less than 10,000 acre-feet. The first reservoir in the basin with a storage volume greater than 50,000 acre-feet was Possum Kingdom Lake, completed in 1941. As shown in Table 7, 17 reservoirs with storage capacities greater than 50,000 acre-feet are now present in the basin.

There are no reservoirs located on the main stem of the middle and lower Brazos River downstream of Waco. However, there are a total of 43 reservoirs in the Brazos basin with individual capacities greater than 5,000 acre-feet located on the upper Brazos River and on tributaries throughout the basin. These reservoirs have a number of purposes, including flood control, water supply, hydropower, and industrial cooling. Total reservoir storage in the basin is about 7.7 million acre-feet including almost 4 million acre-feet of flood storage.

Table 7. Brazos River basin reservoirs with original storage capacities greater than 50,000 acre-feet.

Location	Name	Original Storage* (acre-feet)	Year Completed
Main Stem	Possum Kingdom Lake	725,000	1941
	Lake Whitney	2,000,000	1951
	Lake Granbury	154,000	1969
Tributaries	Lake Stamford	58,000	1953
	Belton Lake	1,100,000	1954
	Lake Graham	53,700	1958
	Hubbard Creek Reservoir	318,000	1962
	Proctor Lake	374,000	1963
	Lake Waco**	726,000	1965
	Somerville Lake	508,000	1967
	Stillhouse Hollow Lake	630,000	1968
	Squaw Creek Reservoir	151,000	1977
	Lake Limestone	225,000	1978
	Granger Lake	244,000	1980
	Lake Georgetown	131,000	1982
	Aquilla Lake	146,000	1983
	Alan Henry Reservoir	116,000	1994

*Original storage (conservation storage plus flood storage, if applicable) information compiled from TWDB (2017) and USACE (2017). As a result of sedimentation, a reservoir's storage decreases over time. Therefore, these numbers do not reflect current capacities.

** Conservation pool raised by seven feet in 2003 but combined (flood and conservation) storage not altered by this change.

There is only one stream gage in the basin with a long enough period of record to evaluate the potential impact of the earliest reservoirs in the basin, USGS Gage No. 08096500 Brazos River at Waco. Continuous gaging began at this location in 1898, providing more than 20 years of data prior to the construction of the original Lake Waco in 1929 on the Bosque River, a tributary of the Brazos River. This gage is a few miles downstream of the location of that reservoir. Lake Possum Kingdom was completed in 1941, but is more than 280 miles upstream. Lake Whitney, on the main stem of the Brazos River about 40 miles upstream of the gage, was completed in 1951. Time periods from before the old Lake Waco (pre-1929), between the old Lake Waco and Lake Whitney (1929 to 1950), and after construction of the last major reservoirs in the basin (post 1983) were selected for analysis. Twenty years of continuous data were used from each time-period. To minimize the impact of different climate conditions on results, the starting year of the 20-year periods were adjusted to align average annual flow volume during the three time-periods as closely as possible. The three 20-year periods selected for comparison were 1905-1924, 1929-1948, and 1989-2008. Average annual flow volumes for these three periods differ by less than six percent. Other factors that could impact hydrology within and between the time periods, such as reallocation of storage between flood and conservation pools for Lake Waco or changes in hydropower operation for Lake Whitney and Possum Kingdom Lake, could not be accounted for with the available gaged data. Nevertheless, these time periods broadly represent three different hydrologic periods in the history of this gage.

Annual peak flows for USGS Gage No. 08096500 Brazos River at Waco were examined and are shown in Figure 5. Prior to 1950, annual peak flows are highly variable but do not show a strong trend over time. This implies that the old Lake Waco did not impact annual peak flows at the Waco gage significantly. Application of a Kruskal-Wallis test (Helsel and Hirsch 2002) does not detect a difference in annual peak flows between 1905-1924 and 1929-1948 time periods. After 1950, Figure 5 shows a marked reduction in annual peak flows, implying that reservoir construction from 1950 to 1965 did impact annual peak flows at the Waco gage. Application of a Kruskal-Wallis test (Helsel and Hirsch 2002) confirms a statistically significant difference in annual peak flows between the 1989-2008 time period and the two earlier time periods.

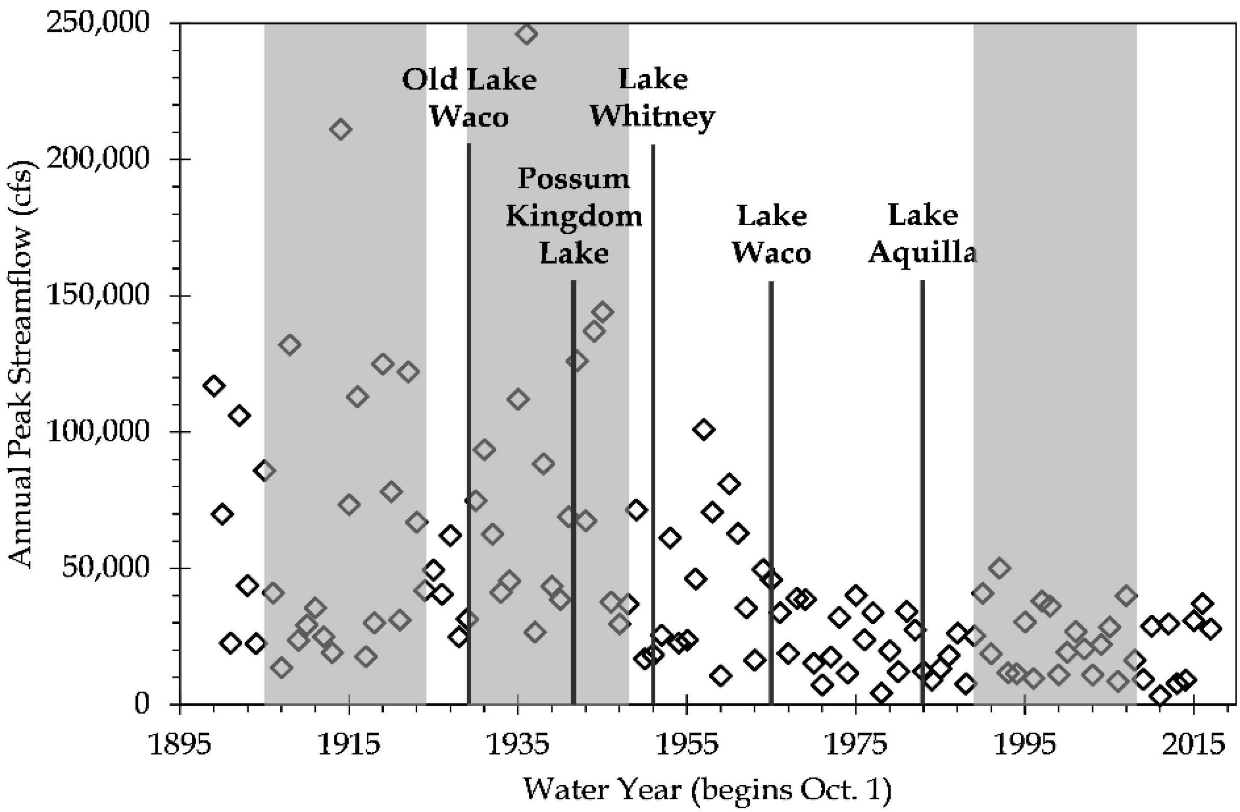


Figure 5. Annual peak streamflow at United States Geological Survey Gage No. 08096500 Brazos River at Waco, Texas and construction dates for select reservoirs. Time periods for analysis shown in gray.

Flow duration curves for USGS Gage No. 08096500 Brazos River at Waco for the three time periods are shown in Figure 6 and Figure 7 and the data is also displayed in Table 8. As shown in Table 8 and Figure 6, high flows (exceeded 5% or less of the time) are different during the three time periods. During the middle (1929-1948) time period, the largest flows and those exceeded five percent of the time were little changed from the earliest time period (1905-1924). However, flows between these two values were reduced. For example, the flow exceeded one percent of the time decreased from almost 37,000 cfs in 1905-1924 to about 31,000 cfs in 1929-1948. In the late time period (1989-2008) flows exceeded less than one percent of the time were reduced relative to the two earlier time periods, while flows exceeded between two and five percent of the time were elevated relative to the earlier time periods. Figure 7 and Table 8 show how the entire range of flows fared during these three time periods. In the middle time period, flows exceeded 50 percent of the time or more are elevated relative to the earlier time period. For example, the median flow goes from 665 cfs in the early time period to 866 cfs in the middle time period. The flow exceeded 90 percent of the time goes from almost 40 cfs in the early time period to more than 110 cfs in the middle time period. Changes in lower flows are much less dramatic from the middle to late (1989-2008) time period. For example, the median and 90 percent exceedance flows change modestly from the middle to the late period, growing to 869 and dropping to 91 cfs, respectively. Application of a Kruskal-Wallis test (Helsel and Hirsch 2002) confirms that the data from the three time periods are different.

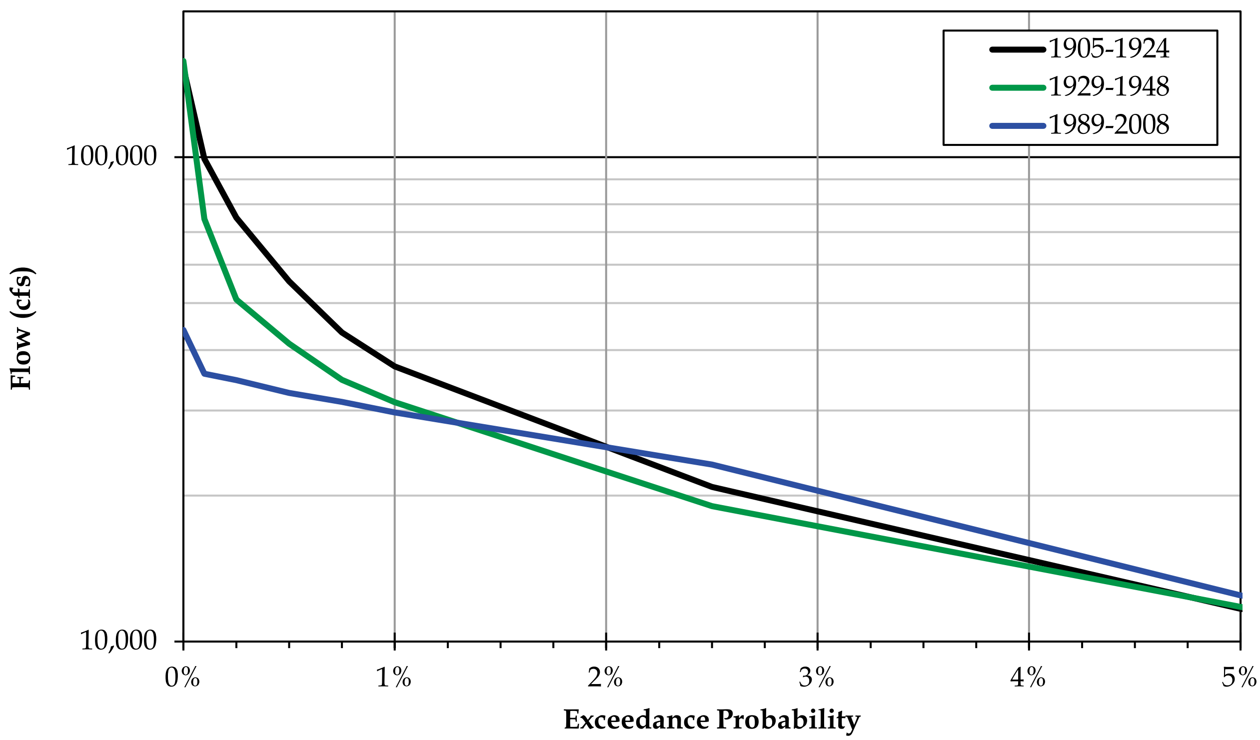


Figure 6. Occurrence of high flows at United States Geological Survey Gage No. 08096500 Brazos River at Waco for three time periods (1905-1924, 1929-1948, and 1989-2008).

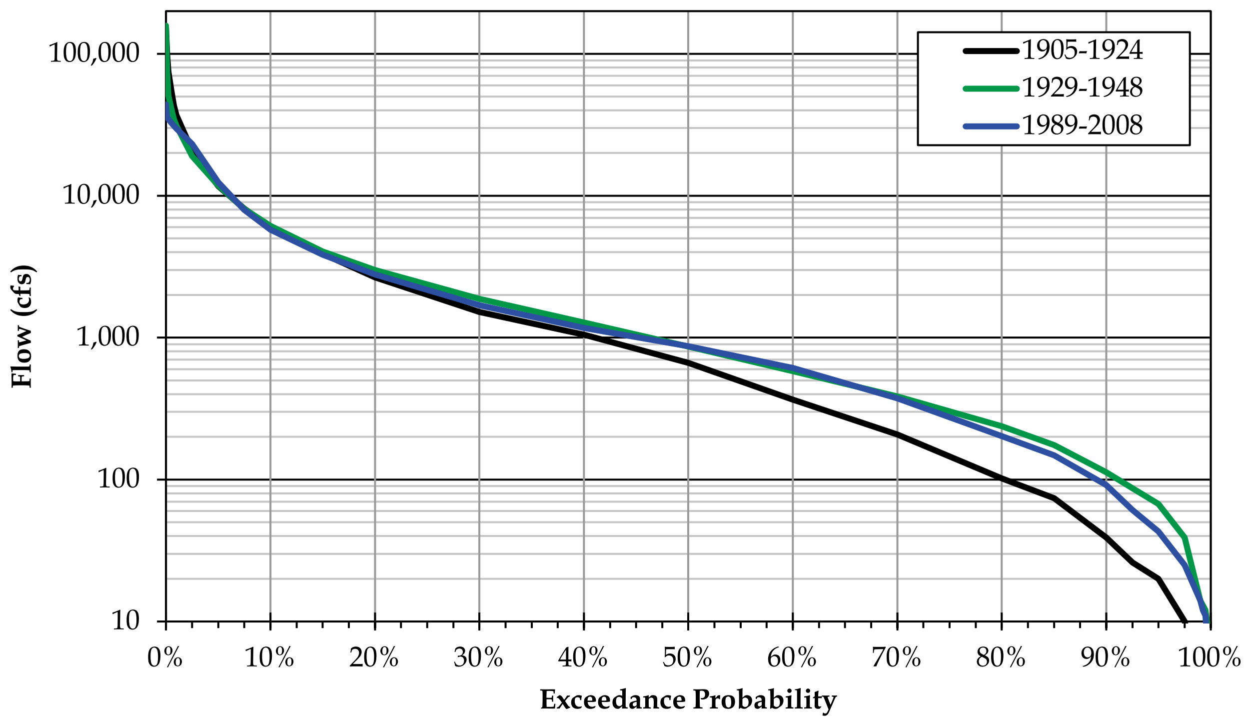


Figure 7. Flow duration curves for United States Geological Survey Gage No. 08096500 Brazos River at Waco for three time periods (1905-1924, 1929-1948, and 1989-2008).

The seasonality of flows at USGS Gage No. 08096500 Brazos River at Waco has also changed over time. Figure 8 shows average monthly flows for the three time periods examined. The two earlier time periods (1905-1924 and 1929-1948) show peaks of average monthly flow in May, with flows in April and June also relatively large in comparison to flows in the rest of the year. In the latest time period (1989-2008), the peak monthly flow occurs in March, with a secondary peak in June.

Table 8. Flow exceedance statistics for United States Geological Survey Gage No. 08096500 Brazos River at Waco for three time periods (1905-1924, 1929-1948, and 1989-2008).

Exceedance Probability (%)	1/1/1905 to 12/31/1924 (cfs)	1/1/1929 to 12/31/1948 (cfs)	Time Period 1/1/1989 to 12/31/2008 (cfs)
0.0	153,000	158,000	44,000
0.1	99,192	74,540	35,709
0.25	74,970	50,818	34,674
0. 5	55,440	41,192	32,600
0. 75	43,444	34,722	31,222
1.0	36,996	31,192	29,696
2.5	20,840	19,040	23,200
5.0	11,680	11,800	12,460
7.5	8,100	8,060	7,972
10.0	5,980	6,136	5,756
15.0	3,900	4,060	3,850
20.0	2,660	2,990	2,790
30.0	1,520	1,880	1,690
40.0	1,050	1,280	1,170
50.0	665	866	869
60.0	365	580	612
70.0	208	386	373
80.0	102	238	202
85.0	74	175	149
90.0	39	112	91
92.5	26	87	61
95.0	20	67	43
97.5	10	39	25
99.0	3	14	14
99.25	3	13	12
99.5	1	12	11
99.75	0	9	6
99.9	0	8	3
100.0	0	6	0.5
Average Annual Flow Volume (ac-ft/yr)	1,999,346	2,003,474	1,895,944

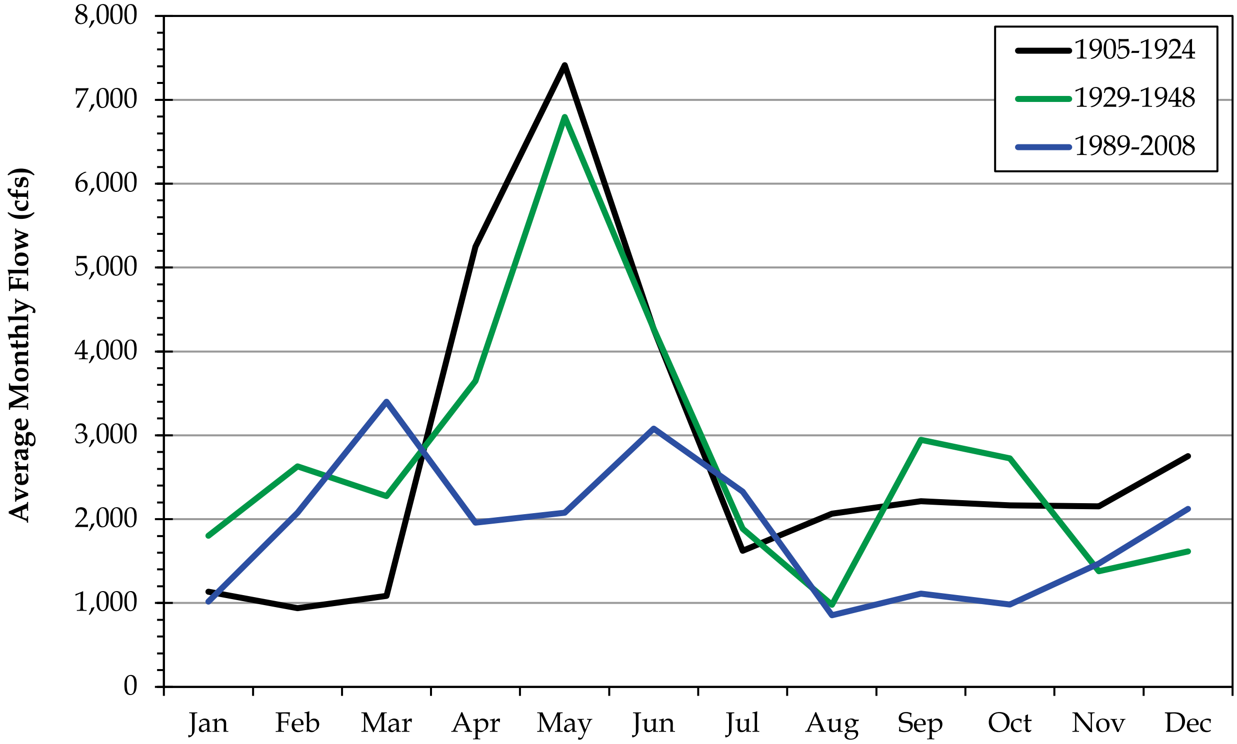


Figure 8. Average monthly flows for United States Geological Survey Gage No. 08096500 Brazos River at Waco for three time periods (1905-1924, 1929-1948, and 1989-2008).

The comparison of data from USGS Gage No. 08096500 Brazos River at Waco for the three time periods (1905-1924, 1929-1948, 1989-2008) reveals some interesting clues about how reservoir construction, land use, and agricultural, industrial, and household use have impacted the hydrology of the middle and lower Brazos River. First, average annual flow volume appears little changed. As shown in

Table 8, average annual flow volume between the three time periods varies by less than six percent.

Second, peak flows have been altered significantly from historical values. As shown in Figure 5, annual peak flows were not changed early in the gage record (1905-1924 to 1929-1948), but have changed later in the record (1929-1948 to 1989-2008). It appears that the original Lake Waco, constructed in 1929 on a tributary of the Brazos River upstream of the gage location, had little impact on peak flows of the Brazos at Waco. However, annual peak flows are significantly different in the later time period (1989-2008). Between 1948 and 1989, several large dams were constructed upstream of Waco, including Lake Whitney in 1951 on the main stem of the Brazos River and the current Lake Waco in 1965 on a tributary of the Brazos River. Both these lakes have large flood control pools.

Third, large flows less than peak flows have also been changed, but not always decreased. Figure 6 shows that flows exceeded less than one percent of the time were reduced in the later time period (1989-2008) relative to the earlier time periods (1905-1924 and 1929-1948). However, flows exceeded from two to five percent of the time were larger in the later time period. The operation of large flood control reservoirs is the most likely cause of this change in hydrology. As part of their regular operation, flood control reservoirs remove larger flows from the system by storing them temporarily. Later, stored water is released at a reduced flow rate. TIFP notes that although operation of flood control storage can alter the hydrologic function of a river, flood control reservoirs provide important benefits to society by mitigating destructive, life-threatening flooding. Fourth, low flows have increased over time. As shown in Figure 7 and Table 8, flows exceeded 20 percent of the time or more are increased from the earliest time period (1905-1924) to the later time period (1989-2008). For example, the median flow increased from 665 cfs to 869 cfs for these two time periods. It's worth noting, however, that this change in lower flows was already present in flow records from the middle time period (1929-1948). Operation of water supply reservoirs, which moderate flow conditions by storing water during times of excess and releasing water during low flow conditions, is the most likely cause of the increase in lower flows.

Fifth, the seasonality of flows has been altered over time. As shown in Figure 8, monthly average flows in earlier time periods (1905-1924 and 1929-1948) showed pronounced seasonality, with a large peak in May and relatively high flows in April and June as well. Intra-annual flow variability is much reduced in the recent time period (1989-2008), with the peak flow month being March with a secondary peak in June. Moderation of intra-annual flow variability and shifting of seasonal peaks is a common feature of hydrologic systems impacted by reservoirs.

Hydrologic analysis for additional gage locations on the main stem of the Brazos River was conducted and is available in Appendix A. Although these additional gages do not have as long a period of record as was available for the gage at Waco, results show how hydrologic conditions vary along the length of the middle and lower Brazos River. For comparison purposes, two 20-year time periods were selected for analysis, 1921-1940 and 1996-2015. These time periods represent, respectively, a time before and after large reservoir construction in the basin. Twenty year time periods that account for other factors that may affect hydrology, such as changes in reservoir operation and construction of smaller reservoirs, could not be identified with the available gaged data. Flow duration curves for the three locations for the two time periods are shown in Figure 9 and Figure 10 and Table 9.

As shown in Table 9, average annual flows at each location for the two-time periods are within 23%, 5%, and 4%, respectively, for Waco, Bryan, and Richmond. The large difference in average annual flow at Waco compared to the other two locations may be due to a larger impact of drought on the Brazos Basin upstream of Waco during the more recent time period.

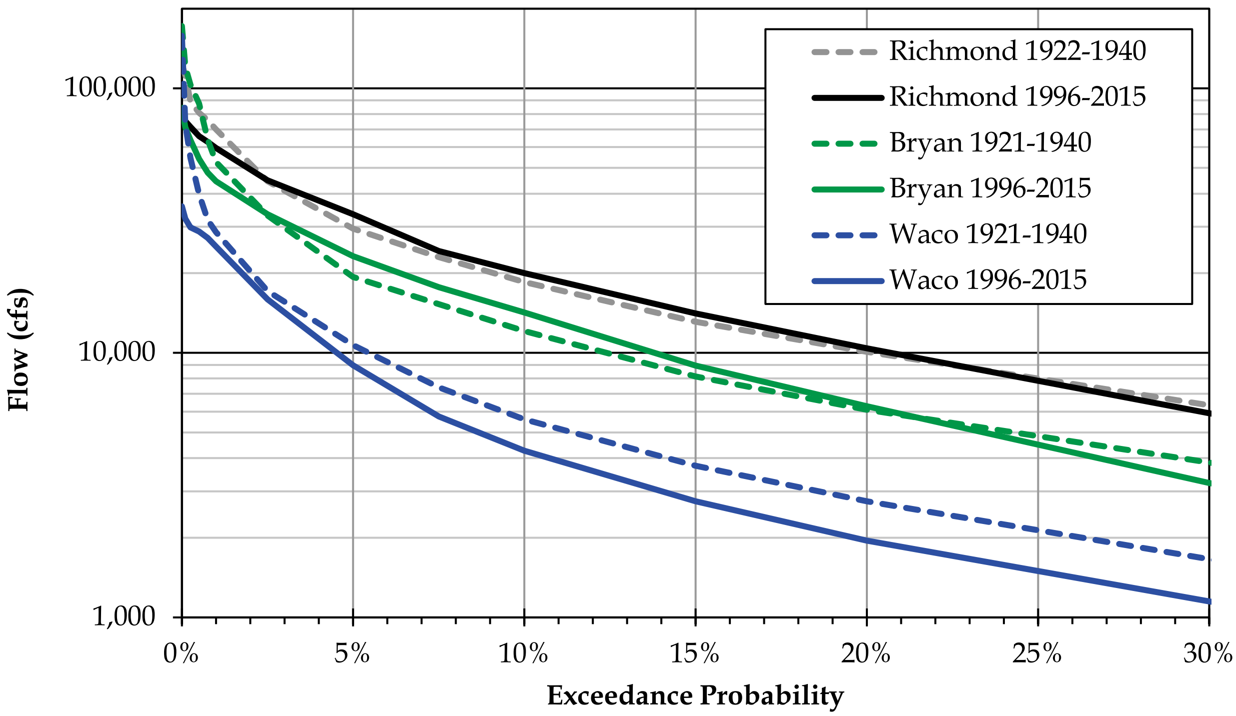


Figure 9. Occurrence of high flows for Brazos River at Waco, Bryan, and Richmond for two time periods (1921-1940 and 1996-2015). Data from 1/1/1926 to 6/30/1926 unavailable at Bryan. Data from 1/1/1929 to 9/30/1922 unavailable at Richmond.

Table 9. Flow exceedance statistics for Brazos River at Waco, Bryan, and Richmond for the two time periods (1921-1940 and 1996-2015).

Exceedance Probability (%)	**Waco**		**Bryan**		**Richmond**	
	1921-1940 Flow (cfs)	**1996-2015 Flow (cfs)**	**1921-1940* Flow (cfs)**	**1996-2015 Flow (cfs)**	**1921-1940** Flow (cfs)**	**1996-2015 Flow (cfs)**
0.0	158,000	35,800	172,000	84,400	123,000	79,600
0.1	73,287	32,109	120,631	71,344	112,334	75,200
0.25	54,496	29,800	103,193	63,850	89,001	71,575
0.5	39,828	28,748	87,616	54,148	80,900	65,951
0.75	31,822	27,222	63,920	48,066	75,702	62,800
1.0	28,588	25,196	52,570	44,500	69,936	59,502
2.5	17,140	15,940	33,093	33,440	44,540	44,900
5.0	10,700	8,988	19,385	23,200	29,500	33,400
7.5	7,400	5,750	15,300	17,700	23,000	24,258
10.0	5,614	4,270	12,100	14,200	18,500	20,000
15.0	3,740	2,750	8,140	8,944	13,100	14,100
20.0	2,750	1,950	6,100	6,284	10,100	10,400
30.0	1,660	1,150	3,850	3,220	6,340	5,913
40.0	985	755	2,540	1,884	4,200	3,570
50.0	590	465	1,640	1,220	2,840	2,260
60.0	342	293	1,080	918	1,910	1,560
70.0	207	183	694	690	1,330	1,090
80.0	125	111	477	512	930	775
85.0	98	79	400	438	760	645
90.0	74	56	314	360	640	533
92.5	62	47	270	321	565	480
95.0	46	37	224	285	500	423
97.5	28	26	167	228	425	343
99.0	13	14	134	181	301	277
99.25	12	12	125	167	264	260
99.5	9	11	114	153	159	246
99.75	3	8	103	141	103	220
99.9	3	5	95	132	53	200
100.0	3	3	89	120	35	182
Average Annual Flow Volume (acre-feet per year)	1,761,286	1,355,510	3,694,881	3,529,001	5,408,980	5,200,329

*Data unavailable from 1/1/1926 to 6/30/1926.
**Data unavailable from 1/1/1921 to 9/30/1922.

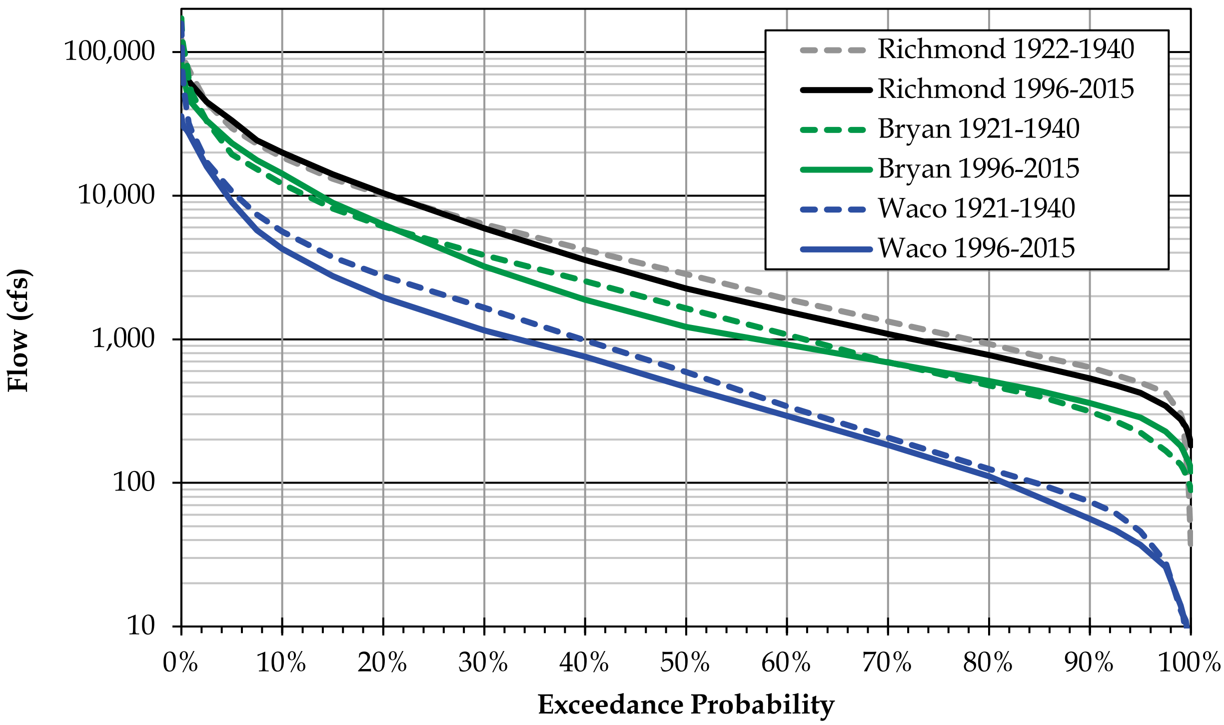


Figure 10. Flow duration curves for Brazos River at Waco, Bryan, and Richmond for two time periods (1921-1940 and 1996-2015). Data from 1/1/1926 to 6/30/1926 unavailable at Bryan. Data from 1/1/1929 to 9/30/1922 unavailable at Richmond.

Monthly median flows were calculated for the Waco, Bryan, and Richmond study sites for early and current time periods. For that analysis, an older time period of 1923 to 1942 was used to have 20 years of data for each month (the Bryan and Richmond gages are missing a few months of data in the earlier 1921 to 1940 time period). Results are shown in Figure 11.

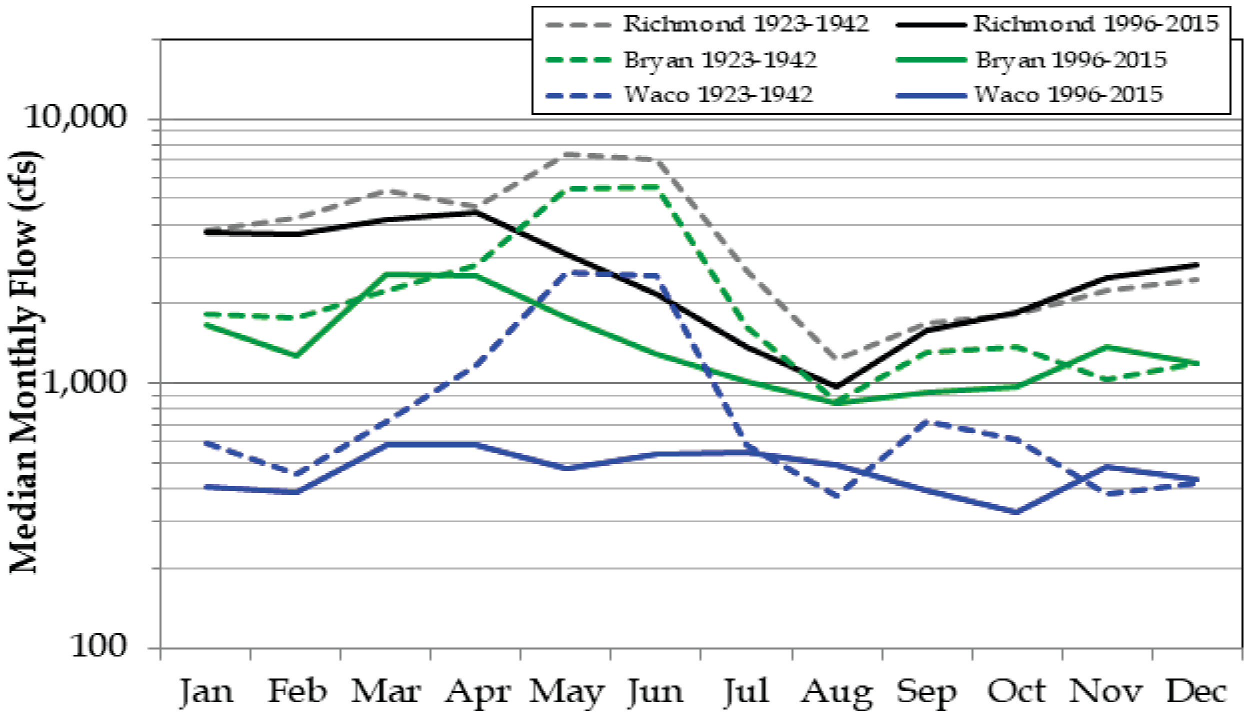


Figure 11. Median monthly flows for Waco, Bryan, and Richmond for two-time periods (1923-1942 and 1996-2015).

2.2.2 *Hydraulic and Habitat Models*

In addition to statistical analysis of the flow record at existing gages, site-specific field studies focused on the development of two-dimensional (2D) hydraulic and habitat models for base flow conditions at each of the six modeling sites.

The 2D hydraulic model utilized for this project was Adaptive Hydraulics Modeling system (ADH) (Berger *et al.* 2011). ADH is an unstructured finite element computer software package capable of modeling 2D and three-dimensional (3D) shallow water equations, 3D Navier-Stokes equations, groundwater equations and groundwater-surface water interactions. ADH solves the hydraulic and sediment transport equations while dynamically adapting the mesh so that a coarse mesh can give results as accurate as a mesh with finer resolution (Berger *et al.* 2011) (see Figure 12).

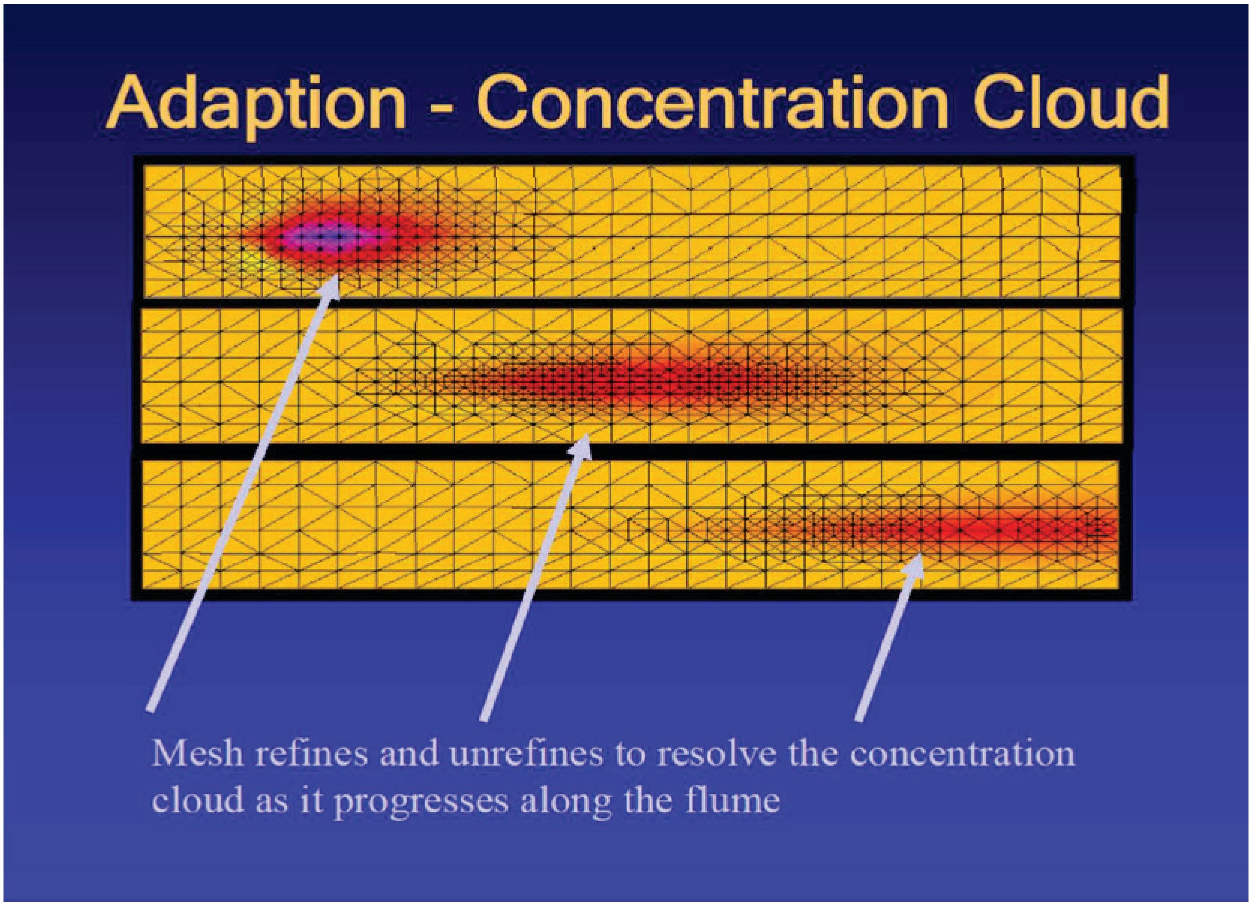


Figure 12. Example of the dynamically adaptive mesh of Adaptive Hydraulics Modeling showing how the mesh characteristics change over time (top, middle, bottom panels) as a sediment plume moving downstream (left to right) is modeled (from Berger *et al.* 2011).

ADH contains other useful features such as wetting and drying and completely coupled cohesive and non-cohesive sediment transport. The User's Manual for Adaptive Hydraulics Modeling system provides additional information on the hydrodynamic modeling capabilities of ADH (Berger *et al.* 2011).

Field data necessary to construct an ADH model include the following:

- Topography/bathymetry,
- Water surface elevations,
- Discharge,
- Substrate, and
- Instream cover.

At each model study site, complete channel and near-channel floodplain Digital Terrain Models (DTM) were created using a combination of conventional survey equipment and survey grade Global Positioning System (GPS) equipment (centimeter accuracy) coupled with a hydro-acoustic depth sounder.

Calibration data for 2D hydraulic modeling consisted of measurements to develop a stage-discharge relationship at the upstream and downstream end of each habitat study site. Water surface elevations were measured throughout the study site at a minimum of three different discharges. Detailed water surface elevations were measured with survey grade GPS and/or conventional surveying equipment at a minimum of three flows (across a range of flows from the 40 to 80 percent exceedance flows) to adequately characterize changes in edge of water and water surface slope throughout the study site (see Table A-5 in Appendix A). Water level measurements were referenced to onsite benchmarks installed at study site boundaries (upstream and downstream) and at intermediate transition points (mid-site or at grade controls). Elevations for each benchmark were determined using post-processed survey-grade GPS linked to the nearest available, established National Geodetic Survey (NGS) Continuously Operating Reference Stations (CORS).

Substrates were mapped at each study site based on dominant and subdominant particle sizes (see Figure 13 for an example). In areas too deep for visual characterization, sampling with an Ekman dredge (or equivalent sediment sampler) or sounding was used to characterize the substrate.

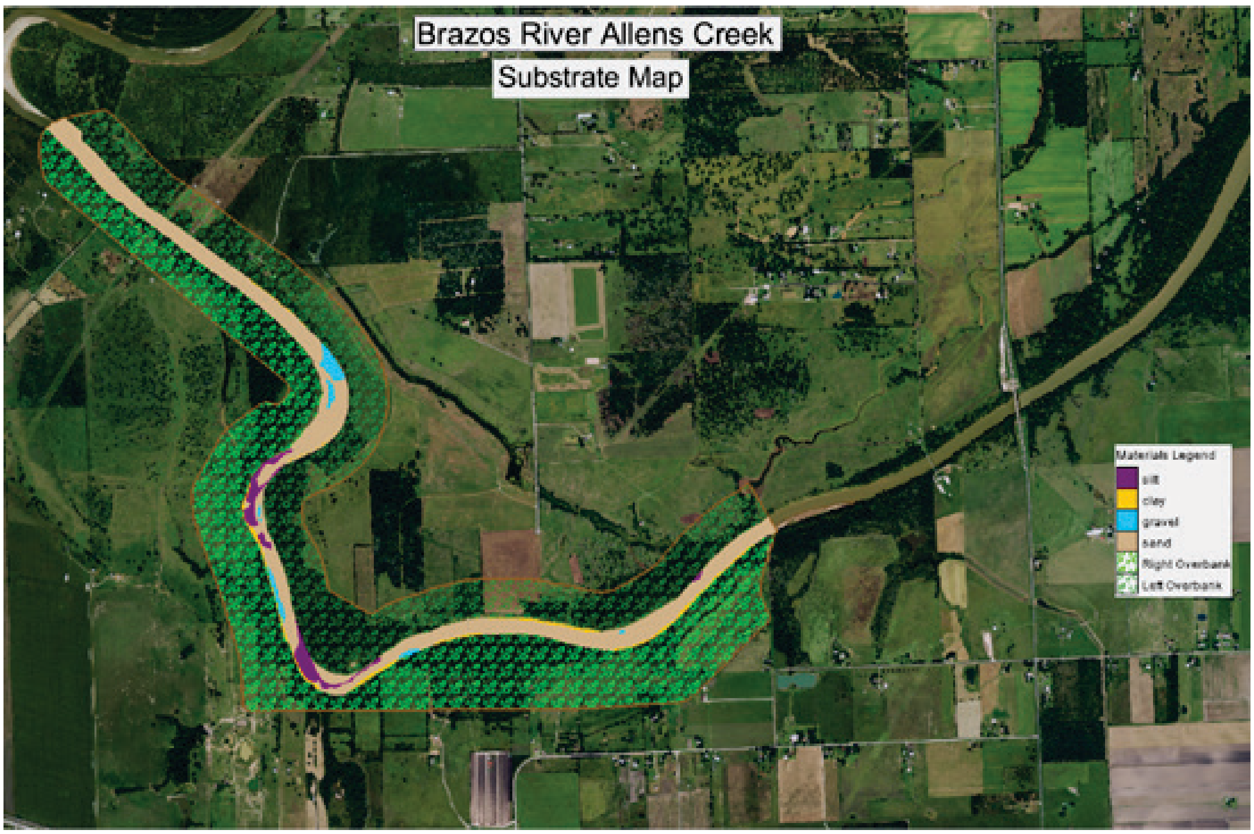


Figure 13. Substrate characterization at the Allens Creek study site.

DTM were generated for each study site using all available topographic and elevation data (*e.g.,* Figure 14). The hydraulic model mesh geometry was created from the DTM. Mesh refinement involved localized geometry refinement and application of substrate roughness. Calibration of model output at all study sites considered all available elevation, flow, velocity, and depth measurements.

Spatially-explicit 2D hydraulic model output was used to determine the area of available habitat for all six study sites for a range of in-channel flows (see Section 2.3.8). This range represented flows exceeded in the daily flow record from 40 to more than 80 percent of the time (for example, 250 cfs to nearly 4,000 cfs at the Allens Creek study site). See Table A-5 in Appendix A for a complete list of modeled flows and their corresponding percent exceedance values.

Figure 14. Digital terrain model for the Brazos River at the Allens Creek study site.

Model calibration was completed for at least three flow rates at each study site. The range of calibrated flows covered the low, moderate, and higher flow conditions relative to the range of all flows evaluated (250 to 4,000 cfs). To model additional intermediate flow rates, rating curves relating flow rate to water surface elevation were developed at each study site to determine boundary conditions. At each study site, a uniform, triangular, finite element mesh with approximately 5- to 25-foot spacing between nodes (vertices), depending on study site geometry, was used (Figure 15). Based upon field data, the model mesh included channel areas both upstream and downstream of study site boundaries. Habitat was not considered in these "extra" upstream and downstream areas located outside the study site boundaries. The model included these extra areas to ensure depth and velocity fields inside the study site boundaries were not influenced by spurious numerical effects that have the potential to occur at upstream and downstream boundaries. Similarly, the model mesh included near-channel floodplain area on both sides of the channel to ensure wetted water edges along the banks did not extend to the edge of the model. At each study site, the same geometric mesh was used for all modeled flow rates. Adjustments to the mesh made at a particular steady-state flow rate were carried through to each of the other flow rates at the same study site.

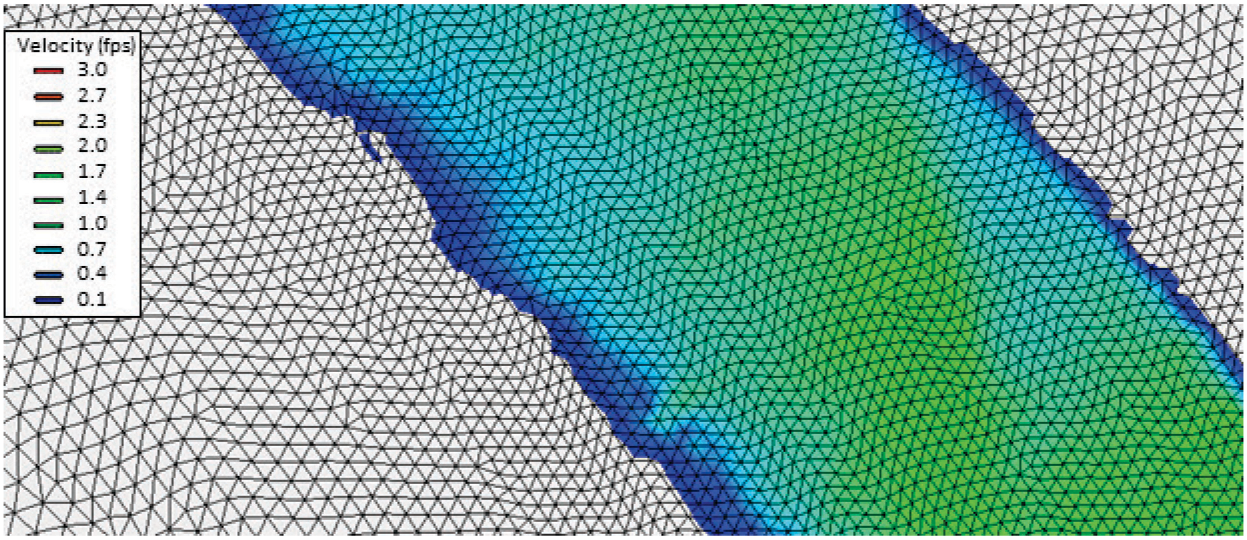


Figure 15. Adaptive Hydraulics Modeling 2-D model mesh for the Brazos River at the Allens Creek study site.

Calibration proceeded by adjusting model inputs so that model predictions of water surface elevation tracked field observations. Calibration was accomplished primarily by adjusting roughness values. Bathymetry and downstream water surface elevation boundary conditions were also adjusted in some cases. In ADH, the Manning "n" roughness is assigned by elements and was based on substrate material.

Water surface elevation was the primary indicator used for calibration, with some consideration of point measurements of depth and velocity as well. Adjustments to model inputs were made until model predictions for water surface elevation matched field data near the downstream benchmark, near the upstream benchmark, and at intermediate locations where field data were available. Predicted depth and velocity were matched as nearly as possible at discrete points where observations were available. In limited areas exhibiting abrupt, localized changes in water surface elevation, bathymetric complexities (*e.g.*, areas with rock outcrops or ridges forming water surface steps) were incorporated into the mesh where bathymetric, photographic, and/or water surface elevation data were available. Based upon professional judgment, additional changes to bathymetry were made in localized areas (*e.g.*, within secondary channels or within constricted areas of the main channel during very low flow) to ensure predicted flow rate, wetted width, water edge, and/or water surface elevations matched observations.

For most calibrated models the predicted water surface elevation profile matched observations within 0.1 feet. Very seldom did the models computed water surface differ from observed measurements by more than 0.15 feet. Validation measures included water surface elevation measurements at upstream and mid-reach locations, field maps of water's edge, and comparison to velocity and depth point measurements. The ADH model results were used to quantify relationships between streamflow and instream habitat (see Section 2.3.8). Calibration flows and modeled flows for each study site are listed in Table A-5 in Appendix A.

2.2.3 *High Flow Pulse and Overbank Assessment*

The characteristics of high flow pulse and overbank flows were evaluated using the available USGS stream gage data described in Section 2.2.1. Characteristics examined included peak flow, duration, and time of year of events. Results for the USGS Gage No. 08096500 Brazos River at Waco are shown in Figures 16 and 17. The two time periods shown in these figures are the oldest 20 years of continuous data for this gage (1889-1918) and a recent 20-year period (1991-2010). These time periods were selected because their average annual flow volume is similar (1.76 million acre-feet for 1889-1918 and 1.77 million acre-feet for 1991-2010) and they represent the least altered hydrologic conditions (1899-1918) and the current operation of reservoirs in the basin (1991-2010). Similar results for additional gages are included in Appendix A.

Figure 16 shows the relationship between magnitude and duration of pulse and overbank flow events as measured at the USGS Gage No. 08096500 Brazos River at Waco. In this figure, the peak flow is not the instantaneous peak, but rather the largest average daily flow observed for the event. Instantaneous peak flows would be expected to be higher. The duration of the event is the number of days that the average daily flow was 5,000 cfs or greater. A flow of 5,000 cfs was selected as being representative of low magnitude pulse events (exceeded about 10 percent of the time in the daily flow records for both the 1889-1918 and 1991-2010 time periods).

Data from the USGS gage at Waco shows a dramatic difference in the hydrology of pulse flows from the early to contemporary time period (Figure 16). In the early time period, average daily peak flow magnitudes were much larger than in the contemporary period. This is consistent with the reduction in annual instantaneous peak flows shown in Figure 4 of Section 2.2.1. The duration of high flow events increased dramatically from the early to the contemporary time period. Both the decrease in event peaks and the increase in event durations can be attributed to the operation of large reservoirs upstream of this gage.

TIFP notes that although reservoir operations in the Brazos River Basin can alter the hydrologic function of the river, these reservoirs provide important benefits to society by mitigating destructive, life-threatening flooding and ensuring water supply for growing populations. Regarding overbank flow events, flood control reservoirs reduce these events by storing them in their flood control pools and then releasing that stored volume at a reduced flow rate over a longer period of time. The U.S. Army Corps of Engineers (USACE) owns and operates many of the basin's reservoirs. The USACE has established control discharges (downstream flow targets) that are maintained to the extent possible during large rainfall events to mitigate flooding and the resultant threats to human health, safety and property. Water supply reservoirs have similar impact on high flow pulses as they capture those events to replenish their conservation pools. Reservoir operations, including releases for downstream use and hydropower generation, may also affect high pulse and overbank flows. The focus of TIFP studies is the environmental aspect of streamflow; at the present time, the system of reservoirs in the basin reduces the peaks and increases the duration of high pulse and overbank flow events. This alteration of pulse events is less pronounced at gage locations downstream of Waco.

Data from the USGS gage at Waco also show how the timing of high pulse and overbank flows throughout the year has changed over time (Figure 17). Again, data for all flow events greater that 5,000 cfs in the time periods 1899-1918 and 1991-2010 are displayed. The day of the calendar year that events begin (*i.e.,* first day flow is 5,000 cfs or greater) is plotted on the x-axis and the cumulative percentage of events with a start day less than or equal to this value is plotted on the y-axis. There are a couple of noteworthy differences between the plots from the two time periods.

In the early time period (1899-1918), only about 14% of events began before May 1 (day 121), about 35% of events began in May and June (days 121 to 181), and about 25% of events began in July, August, and September (days 182-273). In the recent time period (1991-2010), about 45% of events began before May 1 (day 121), about 25% of events began in May and June (days 121 to 181), and only about 7% of events began in July, August, and September (days 182-273).

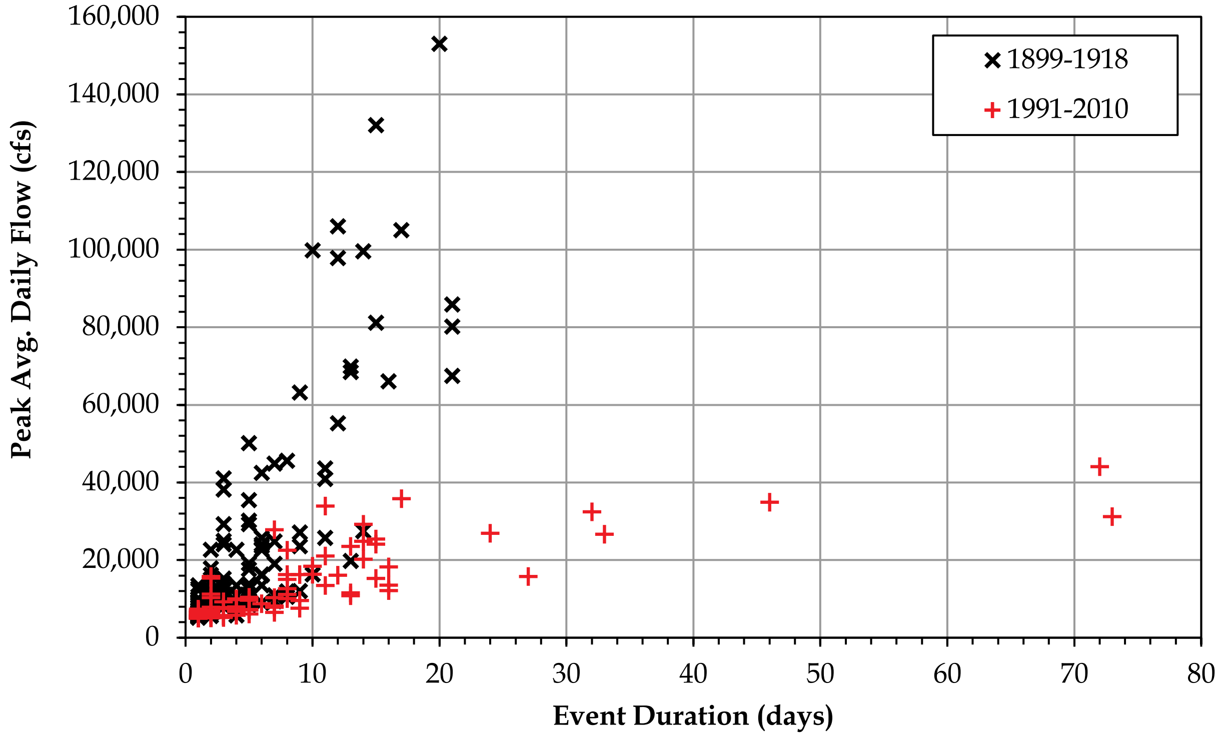


Figure 16. Peak and duration for flow events greater than 5,000 cubic feet per second at United States Geological Survey Gage No. 08096500 Brazos River at Waco.

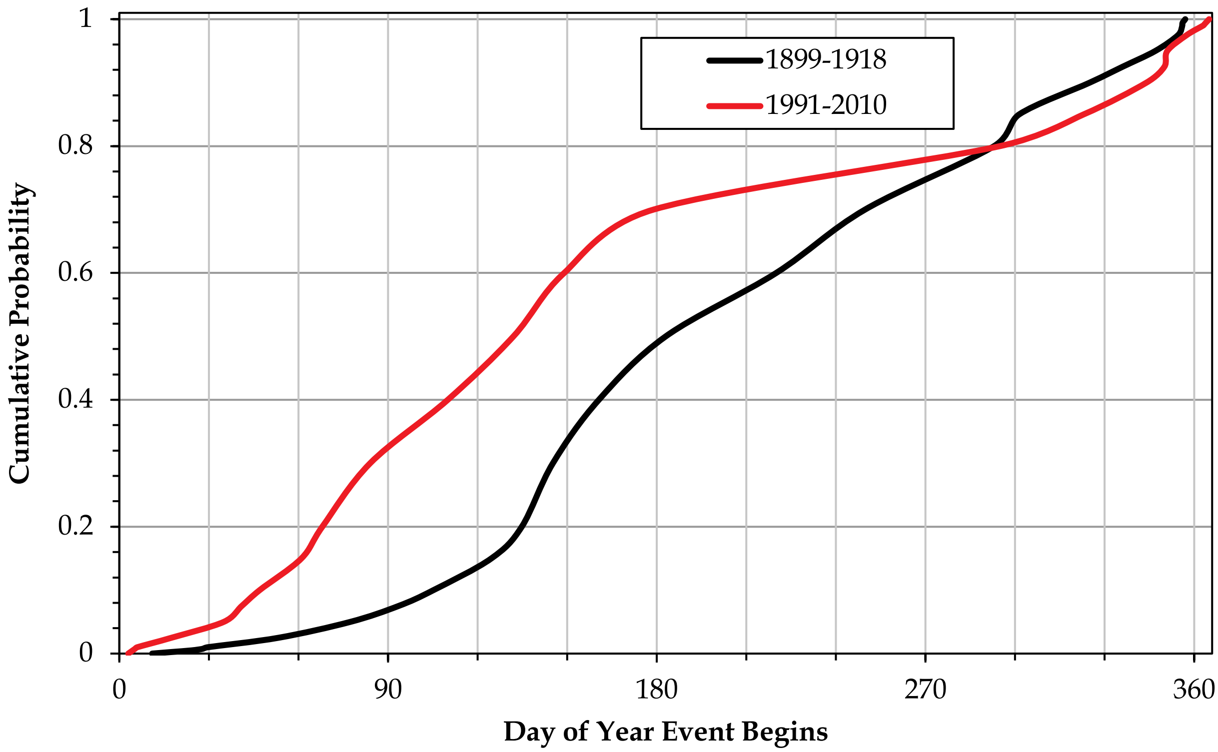


Figure 17. Distribution of days flow events greater than 5,000 cfs begin for Unites States Geological Survey Gage No. 08096500 Brazos River at Waco.

To consider the needs of riparian areas (see Sections 2.3.14 and 3.3.1), a linear interpolation model was developed to estimate water surface elevations of pulse and overbank flows at riparian study sites along the middle and lower Brazos River (Figure 18 and Table A-4 in Appendix A). This model made use of rating curves from the seven active USGS stream gages on the main stem of the Brazos River between Waco and the coast to estimate water surface elevations for a range of flows of interest to riparian studies (4,000 to 80,000 cfs). Rating curves tor the five farthest downstream gages covered a range of flows up to 80,000 cfs. Rating curves for the gages at Waco and near Highbank covered a range of flows up to 42,000 and 53,000 cfs respectively. For the Waco and Highbank gages, rating curves were extended to include flows as large as 80,000 cfs (see Appendix A). For locations between gages, values of water surface elevation were interpolated from the nearest gages.

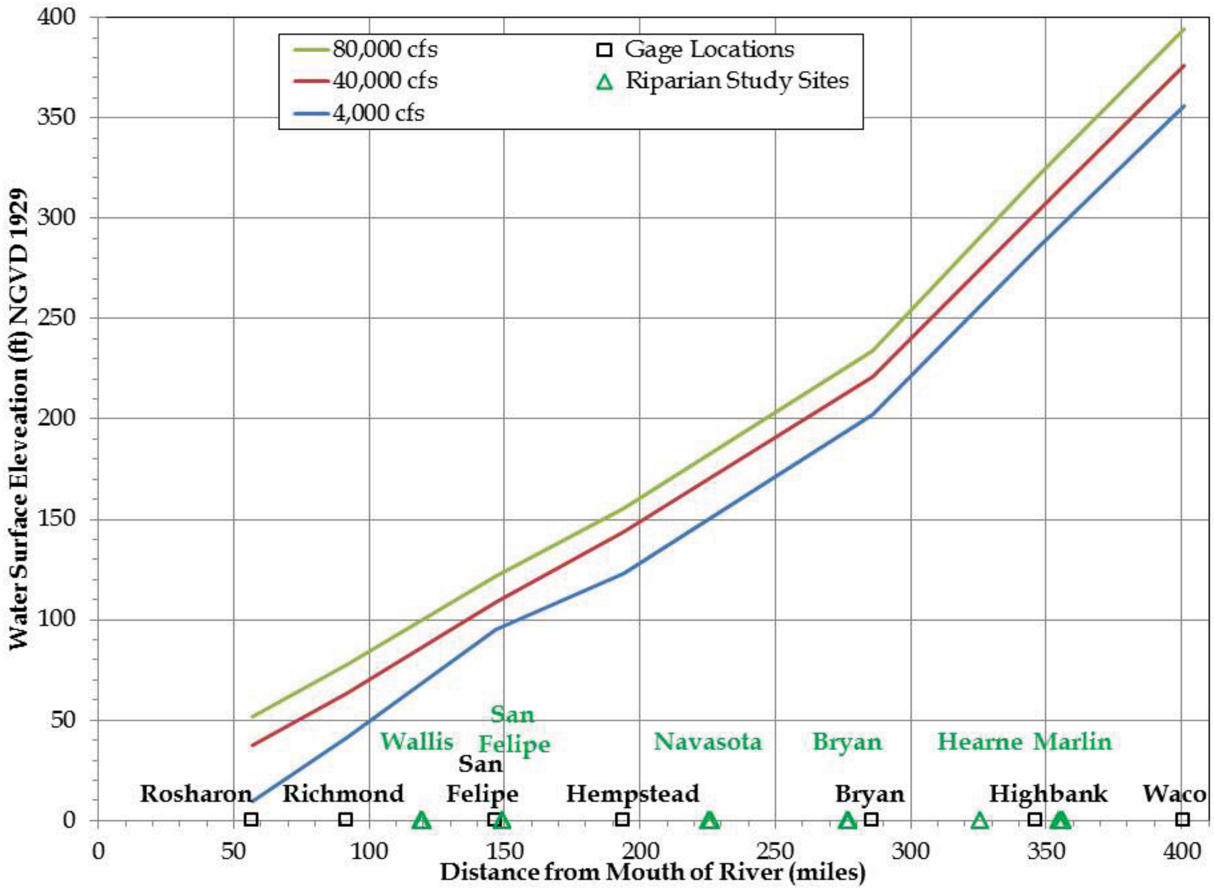


Figure 18. Interpolated water surface elevations along the length of the middle and lower Brazos River (river miles as reported by Turco *et al.* 2007) for three flow rates. Location of riparian study areas and Unites States Geological Survey gages are shown along the X axis.

2.3 *Biology*

To characterize the flow-habitat and flow-ecology relationships within the riverine ecosystem supported by the middle and lower Brazos River, biological studies focused on fish, mussels, and riparian areas. During the stakeholder process, indicators for biologic communities were identified (TIFP/BRA 2010) including biological communities (*e.g.*, native richness and relative abundance of fishes and benthic invertebrates including mussels), instream habitat including habitat quality and quantity for key species and mesohabitat area and diversity (*e.g.*, fish habitat guilds), and riparian areas including vegetation characteristics, riparian soil types, and relationships to hydrology such as the gradient of inundation. Species identified as key species include Alligator Gar *Atractosteus spatula*, Spotted Bass *Micropterus punctulatus*, Shoal Chub *Macrhybopsis hyostoma*, Silverband Shiner *Notropis shumardi*, Chub Shiner *N. potteri*, juveniles of Blue Catfish *Ictalurus furcatus*, Channel Catfish *I. punctatus*, and Flathead Catfish *Pylodictis olivaris* (TIFP/BRA 2010).

2.3.1 *Fisheries*

Sixty-two native freshwater, four estuarine/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. 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 *Notropis amnis*, and Alligator Gar. A rich variety of reproductive strategies are also represented within the fish assemblage, including broadcast, substrate, and floodplain spawners. Further analysis of the historic species relative abundance levels by Bonner and Runyan (2007) presented some interesting trends. Two endemic species, Smalleye Shiner and Sharpnose Shiner, along with Chub Shiner and Silverband Shiner, 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. Fishes were the primary taxa of interest for instream habitat modeling as described in the study design (TIFP/BRA 2010) and summarized in the following sections.

2.3.2 *Habitat Suitability Criteria (HSC) Development for Fish*

Habitat suitability criteria (HSC) development is a critical component of instream habitat analysis and is a multi-stage process: (1) substrate and mesohabitat mapping; (2) fish microhabitat sampling and habitat data collection to quantify habitat utilization; (3) evaluation of the suitability of integrating supplemental fish data; (4) data analysis to generate habitat guilds; and (5) development of habitat suitability criteria for Brazos River fish habitat guilds (Botros *et al.* 2016). To generate a robust and unbiased dataset for development of habitat suitability criteria for fish, a sampling matrix of 400 habitat areas was generated for the six Brazos River study sites using substrate-mesohabitat combinations consisting of four coarse mesohabitat types (backwater, pool, riffle, and run) and five substrate types (clay, silt, sand, gravel, and large rock). This sample allocation was based on habitat data collected during baseline fish sampling conducted by TIFP and the Brazos River Authority (BRA 2007). These 400 samples were then allocated across the study sites and three target base flow ranges (low, medium, and high); base flow ranges were provided by TWDB (Table 10) based on percentiles (low – 5-15th percentile; medium – 15-35th percentile; and high – 25th to 50th percentile). This initial matrix was used to guide HSC sampling efforts (Table B-1 in Appendix B) with a goal of at least 300 habitat areas sampled for fish; adjustments were made due to substrate-habitat combination availability at the time of sampling and tracked in the matrix (see Section 2.3.4).

Table 10. Target base flow ranges for field sampling efforts.

USGS Gage Station Locations	Low	Medium	High
Highbank	100-275	275-650	650-975
Bryan	275-550	550-1025	1025-1475
Hempstead	450-850	850-1550	1550-2500
Richmond	500-900	900-1700	1700-2900

2.3.3 *Substrate and Mesohabitat Mapping*

Substrate and mesohabitat mapping is used to generate a map of substrate and habitat combinations to support a stratified random sampling design for HSC development. Substrate areas were mapped at each study site using a Trimble XT Global Positioning System (GPS), and substrates were classified into the following categories: clay, silt, sand, gravel, or large rock. Raw GPS data was imported into a map layer or shapefile using Geographic Information System (GIS) software, ERSI ArcMap 10.x. Mesohabitat areas (*i.e.,* backwater, pool, run, or riffle) were visually mapped by biologists using a Trimble XT GPS unit on the day prior to fish-habitat data collections. Next, a mesohabitat shapefile was created from the GPS field data and intersected with the substrate shapefile in ESRI ArcMap 10.x to randomly select the appropriate mesohabitat-substrate polygons following the sampling matrix.

2.3.4 *Fish-Habitat Data Collection*

The sampling matrix was used to track total number of mesohabitat-substrate combinations or habitat areas sampled across study sites on the Brazos River. The mesohabitat-substrate combination maps (Section 2.3.3) were used to randomly place sampling locations based on the distribution of points in the sampling matrix. The randomly selected sampling habitats were located using a GPS and marked by a weighted buoy, and left undisturbed for 30 minutes before fish collection to minimize the effects of disturbance. Fish were then sampled using the most appropriate sampling gear (*i.e.,* seine, boat or barge electrofishing). Boat electrofishing was conducted using a Smith-Root 5.0 Generator Powered Pulsator (GPP) electrofisher and 8-amp generator. Generally, electrofishing was conducted within the range of 60-70 pulses per second direct current. Usually two electrofishing boat passes were conducted through the habitat area of interest while netters would collect all stunned fish to the maximum extent possible. For wadable habitat areas, straight seines of 15 or 30 feet in width and 3/16 and 3/8-inch mesh sizes respectively were utilized to collect fish. For wadable areas with dense vegetation and other cover, barge electrofishing was utilized using a similar set up as the boat electrofishing, however a wand and 300-foot cord were utilized to pulse electricity into the water. Where appropriate, a combination of these gear types was used to effectively sample each selected mesohabitat considering the challenges in fish sampling fish in large, turbid rivers. Biological (*e.g.,* fish behavior, species, body length), environmental (*e.g.*, conductivity, turbidity, depth, current velocity), and technical (*e.g.,* electrofishing control unit) influence fish sampling gear capture efficiency, and the composition of fish samples (Bayley and Dowling 1990, Bonar *et al.* 2009, Price and Peterson 2010). Each fish sampling gear has inherent limitations/biases which must be considered when interpreting data. For example, fast moving shallow waters (*e.g.,* riffles) make seining and backpack electrofishing difficult, as the current can carry the seine faster than the samplers are able to safely walk, and fishes can be swept out of the electrical field before being captured (Bonar *et al.* 2009). In deep fast flowing waters boat electrofishing is generally considered an effective and efficient means to sample fish. However, capture efficiency decreases with depth and velocity (Casselman *et al.* 1990), as fish may not be stunned as easily (*i.e.*, avoid the electrical field), temporarily immobilized but quickly displaced outside the electrical field, or if stunned and immobilized not observed by netters (Bonar *et al.* 2009). High turbidity, which was frequently encountered during fish sampling in the Brazos River, likely further decreased our ability to observe and collect fish in deep fast flowing water. While the sampling gear(s) best suited to the conditions (*i.e.*, depth and velocity) was used to collect fish habitat suitability data in the Brazos River (TIFP 2008), sampling gear limitations in deep, fast moving, and turbid water likely negatively influenced abundance and richness estimates for these samples. Stream fish managers are acutely aware of, and consider sampling limitations/biases in their analysis of fish assemblage data (Bonar *et al.* 2009, Price and Peterson 2010), as should readers of this report.

Sampled habitat areas were then delineated into a rectangular polygon and habitat measurements taken at five points, A-E (Figure 19). Depth (in feet) and velocity (in feet per second) were measured using a Marsh-McBirney Flowmate 2000 current velocity meter and top-setting wading rod (4, 6, or 10-foot wading rod). Primary and secondary substrate calls were made using a sounding pole and/or scoop for deeper sites or by hand at wadable locations. Substrate size was classified according to the modified Wentworth scale (TIFP 2008). At point C of each habitat area sampled, one water quality measurement for temperature (in °C), dissolved oxygen (in milligrams per liter), conductivity (in micro-siemens per centimeter), and hydrogen ion concentration (pH) was taken using a calibrated multiprobe instrument. At point C, other field parameters recorded included channel position (edge or mid-channel) as well as instream cover type and percentage.

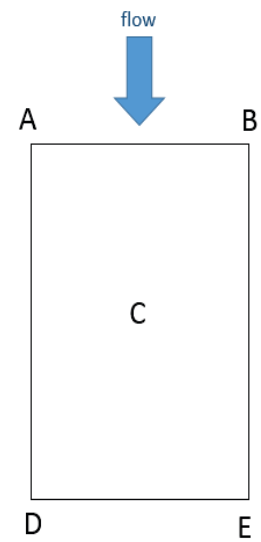


Figure 19. Orientation of points A-E in each habitat area sampled

Table B-2 (Appendix B) provides the final tally of sampled habitat areas across study sites and base flow conditions for each of 13 fish-habitat sampling events. A sampling event typically consisted of one day mapping mesohabitats followed by two days of fish sampling and habitat measurements. Not all base flow conditions were sampled at each study site due to the timing of drought and flood conditions that occurred during the study period. For example, to avoid biases in habitat suitability data collection, fish-habitat samples were not collected during periods of extreme low flows when diverse habitat conditions were not present (see Botros *et al.* 2016). High flow conditions also precluded efficient and safe sampling. Diverse hydraulic (i.e., depth and current velocity) habitat conditions were available during each of the 13 fish-habitat sampling events. In summary, between August 2010 and September 2014, 327 habitat areas were sampled for fish across all of the Brazos River study sites and base flow conditions (Table 11); 302 of these samples contained fish. At three study sites, all base flow conditions were sampled, while only two flow conditions were sampled at Marlin and Hearne, and only one flow condition was sampled at the Allens Creek study site. While the majority of sampling events were conducted at low base flow conditions, a substantial number of sampling events occurred at average and high flow conditions (Table 11) ensuring that biases towards very low or very high base flow conditions were minimized.

Table 11. Fish-habitat sampling efforts across all study sites and base flow condition.

Base Flow Condition	Marlin	Hearne	Mussel Shoals	Navasota	Wildcat Bend	Allens Creek	Totals
Low	28	26	23	24	26		**127**
Average	20		24	26	27		**97**
High		28		18	17	15	**78**
Totals	**48**	**54**	**47**	**68**	**70**	**15**	**302**

During HSC sampling, a total of 52,208 fish (49 species) were collected (Table 12). Red Shiner (N= 29,518) and Bullhead Minnow (N=15,502) were the most abundant species collected and were nearly ubiquitous.

Table 12. Fishes included in the Brazos River habitat suitability criteria field collections, 2010-2014 (N=302 samples).

Common Name	Abundance	Occurrences	Common Name	Abundance	Occurrences
Red Shiner (large)	16899	262	Channel Catfish (large)	12	12
Bullhead Minnow	15502	210	Tadpole Madtom	12	8
Red Shiner (small)	12619	254	Smallmouth Buffalo	11	9
Channel Catfish (small)	1636	106	*Chub Shiner	10	2
Ghost Shiner	1021	46	Inland Silverside	10	9
Western Mosquitofish	1005	58	Slough Darter	10	5
Shoal Chub (large)	639	45	Mississippi Silvery Minnow	9	5
Longear Sunfish (large)	604	87	White Bass	9	8
Gizzard Shad (small)	432	45	Largemouth Bass	8	6
River Carpsucker (small)	347	58	*Redear Sunfish	7	2
Silverband Shiner	221	26	*Blacktail Shiner (large)	6	4
Longear Sunfish (small)	165	41	Spotted Bass (large)	5	5
Blue Catfish	163	40	*Warmouth	5	3
Flathead Catfish	129	49	*Silver Chub	3	2
River Carpsucker (large)	125	55	*Bigscale Logperch	2	2
Orangespotted Sunfish	84	17	*Blackstripe Topminnow	2	2
Bluegill	56	22	*Freshwater Drum	2	2
Green Sunfish	56	30	*Ribbon Shiner	2	1
Blacktail Shiner (small)	53	5	*Yellow Bullhead	2	2
Longnose Gar	45	29	*Alligator Gar	1	1
White Crappie	45	12	*Bluntnose Darter	1	1
Striped Mullet	44	29	*Brook Silverside	1	1
Dusky Darter	41	17	*Central Stoneroller	1	1
Spotted Bass (small)	39	21	*Gray Redhorse	1	1
Shoal Chub (small)	29	15	*Sailfin Molly	1	1
Spotted Gar	22	20	*Spotted Sucker	1	1
Gizzard Shad (large)	20	17	*Striped Basses (*Morone*)	1	1
Threadfin Shad	16	9	*Texas Logperch	1	1
Pugnose Minnow	15	9			

*removed from analysis due to low sample sizes (<5 samples)

2.3.5 *Fish Sample Processing*

Fish were processed independently for each mesohabitat-substrate area sampled. Larger fishes were identified in the field, measured (total length), examined for anomalies, photographed, and released. Retained fishes were preserved in 10% formalin and returned to the laboratory. In the laboratory, fish samples were processed for curation (transferred to 70% ethanol), sorted by species, identified, enumerated, and selected species measured. Many fishes utilize different habitats as they grow and mature. Eight species were split into two life stages (large or small) based on Mayes *et al.* (2013) and see TIFP/SARA (2011). Fishes that were measured and their respective size thresholds are provided in Table 13. Initial identifications were confirmed and vouchered specimens permanently housed at the University of Texas Biodiversity Collections Facility in Austin, Texas. Data from all fish and habitat samples were entered into the GoFish database maintained by TPWD Inland Fisheries.

Table 13. Fish species measured and separated into large and small classes for habitat guilding analysis.

Species	Common Name	Size Threshold
Carpiodes carpio	River Carpsucker	100 mm
Cyprinella lutrensis	Red Shiner	35 mm
Cyprinella venusta	Blacktail Shiner	35 mm
Dorosoma cepedianum	Gizzard Shad	150 mm
Ictalurus punctatus	Channel Catfish	200 mm
Lepomis megalotis	Longear Sunfish	35 mm
Macrhybopsis hyostoma	Shoal Chub	35 mm
Micropterus punctulatus	Spotted Bass	125 mm

2.3.6 *Data Analysis to Generate Fish Habitat Guilds*

Generating HSC for nearly 60 individual species/size class categories would complicate interpretation of study results, yet basing flow recommendations on the needs of a few species may be detrimental to other species. Therefore, a fish habitat guild approach was used to best represent the habitat needs of the entire fish community. A habitat guild is defined as a group of species that use similar habitat. Grouping species based on similar habitat use, and creating HSC for each resulting habitat guild simplifies interpretation of study results while still representing the flow requirements of the entire fish community. The habitat guild approach is often used for instream flow studies on warm water streams with high species richness (TIFP/SARA 2011, Persinger *et al.* 2010, BIO-WEST 2008) such as the Brazos River.

To create guilds, habitat conditions were characterized for each sample area (N=302) by calculating the mean of the depth and velocity data for the five individual measurements taken at each sampling area. Mean depth and current velocity, and dominant substrate were combined with abundance data from each species/life stage and summarized in a Canonical Correspondence Analysis, or CCA (Ter Braak and Šmilauer 2012). For habitat guilding, Red Shiner and Bullhead Minnow were removed from the analysis since these two species made up more than 90% of the relative abundance of the overall assemblage and were found in all habitat types thus confounding habitat associations of other fish species. Furthermore, species collected in less than five occurrences were also removed from the guilding analysis due to insufficient replicates (species indicated by an asterisk in Table 12) including two key species, Alligator Gar and Chub Shiner.

With Red Shiner, Bullhead Minnow, and species with low occurrences excluded, relative abundances were recalculated and the CCA rerun. Based on the resulting CCA ordination plot, fish species were visually grouped into six habitat guilds (Figure 20). Where a particular species/life stage category fell in close proximity to guild boundaries, habitat descriptions from the literature and professional judgment were used to make final guild determination. The species/life stage categories and total number of each species collected within each of the resulting habitat guilds are presented in Table 14.

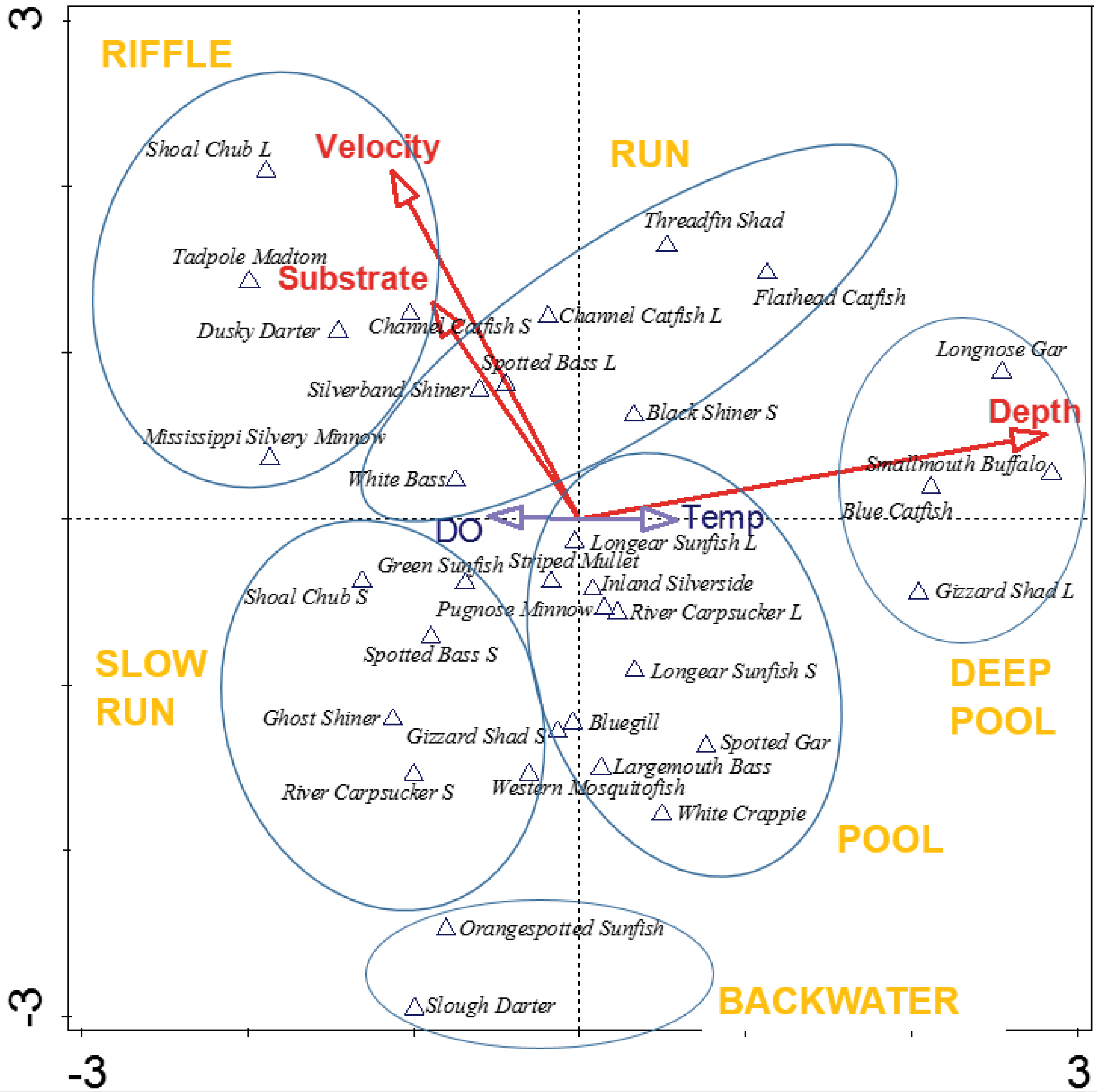


Figure 20. Canonical correspondence analysis ordination plot with six fish habitat guilds for the middle and lower Brazos River (blue ovals) and associated name.

Table 14. Number of individuals and locations observed for each habitat guild and their component species (size category). Key species are indicated by an asterisk.

Habitat Guild	Common Name	Species	Total Number Observed	Number of Locations Observed
	River Carpsucker (large)	*Carpiodes carpio (≥100 mm)*	125	55
	Gizzard Shad (small)	*Dorosoma cepedianum (<100 mm)*	423	45
	Spotted Gar	*Lepisosteus oculatus*	22	20
	Bluegill	*Lepomis macrochirus*	56	22
	Longear sunfish (large)	*Lepomis megalotis (≥45 mm)*	604	87
Pool	Longear Sunfish (small)	*Lepomis megalotis (<45 mm)*	157	41
	Inland Silverside	*Menidia beryllina*	10	9
	Largemouth Bass	*Micropterus salmoides*	8	6
	Striped Mullet	*Mugil cephalus*	44	29
	Pugnose Minnow	*Opsopoeodus emiliae*	15	9
	White Crappie	*Pomoxis annularis*	46	12
	Guild Total		**1510**	**335**
	Orangespotted Sunfish	*Lepomis humilis*	85	18
Backwater	Slough Darter	*Etheostoma gracile*	10	5
	Guild Total		**95**	**23**
	Ghost Shiner	*Notropis buchanani*	1021	46
	Green Sunfish	*Lepomis cyanellus*	56	30
	River Carpsucker (small)	*Carpiodes carpio (<100 mm)*	347	58
Slow Run	Shoal Chub (small)	*Macrhybopsis hyostoma (<35mm)**	29	15
	Spotted Bass (small)	*Micropterus punctulatus (<125mm)**	39	21
	Western Mosquitofish	*Gambusia affinis*	1008	58
	Guild Total		**2500**	**228**
	Blacktail Shiner (small)	*Cyprinella venusta (<35mm)*	53	5
	Channel Catfish (large)	*Ictalurus punctatus (≥200mm)*	12	12
	Flathead Catfish	*Pylodictis olivaris**	129	48
Run	Silverband Shiner	*Notropis shumardi**	221	24
	Spotted Bass (large)	*Micropterus punctulatus (≥125mm)**	5	5
	Threadfin Shad	*Dorosoma petenense*	16	8
	White Bass	*Morone chrysops*	9	8
	Guild Total		**445**	**110**
	Blue Catfish	*Ictalurus furcatus**	163	46
	Gizzard Shad (large)	*Dorosoma cepedianum (≥100 mm)*	20	17
Deep Pool	Longnose Gar	*Lepisosteus osseus*	45	29
	Smallmouth Buffalo	*Ictiobus bubalus*	11	9
	Guild Total		**239**	**101**
	Channel Catfish (small)	*Ictalurus punctatus (<200mm)*	1636	114
	Dusky Darter	*Percina sciera**	41	35
Riffle	Mississippi Silvery Minnow	*Hybognathus nuchalis*	9	9
	Shoal Chub (large)	*Macrhybopsis hyostoma (≥35mm)**	639	75
	Tadpole Madtom	*Noturus gyrinus*	12	12
	Totals		**2337**	**245**

Key species that were not collected in sufficient numbers for guild analysis include: Alligator Gar and Chub Shiner. The Pool habitat guild did not include any of the key species. Of the three catfish key species, only Channel Catfish were parsed out into small (juvenile) and large (adult) size classes. In this study, Blue Catfish was classified in the Deep Pool habitat guild while Flathead Catfish was placed in the Run habitat guild.

2.3.7 *Data Analysis to Generate Habitat Suitability Criteria*

Habitat data (depth, velocity, and substrate) from species/life stage categories within a particular guild were combined to generate frequency histograms for the continuous variables depth and velocity. Data were binned using 0.25-foot increments for depth and 0.1 fps increments for velocity. Suitability criteria were then generated using nonparametric tolerance limits (NPTL) based on the central 50%, 75%, 90%, and 95% of the data (Bovee 1986) using custom software produced by Dr. Thom Hardy (Texas State University). Tolerance limits for the central 50% of the data were used as boundaries for the most selected habitat and the range of data between these two points was assigned a suitability of 1.0. Data between the 50% tolerance limits and the 75% tolerance limits were assigned a suitability of 0.5. Data between the 75% tolerance limits and the 90% tolerance limits were assigned a suitability of 0.2. And data between the 90% tolerance limits and the 95% tolerance limits received a suitability of 0.1. Data beyond the 95% tolerance limits were considered unsuitable and given a suitability of zero.

Resulting HSC for depth and velocity for each habitat guild are depicted in Figure 21 and Figure 22. HSC for the categorical variable substrate were developed using normalized frequencies. The substrate with the highest frequency (most utilized) received a suitability value of 1.0. All other substrates received a lower suitability dependent on their relative frequency (Figure 23). Since sand (green bars in Figure 23) seemed to drive suitability for all the habitat guilds (with the exception of Deep Pool) and because substrate was closely aligned with the velocity vector in the CCA guild analysis (Figure 23), substrate suitability criteria were not utilized further in the analysis.

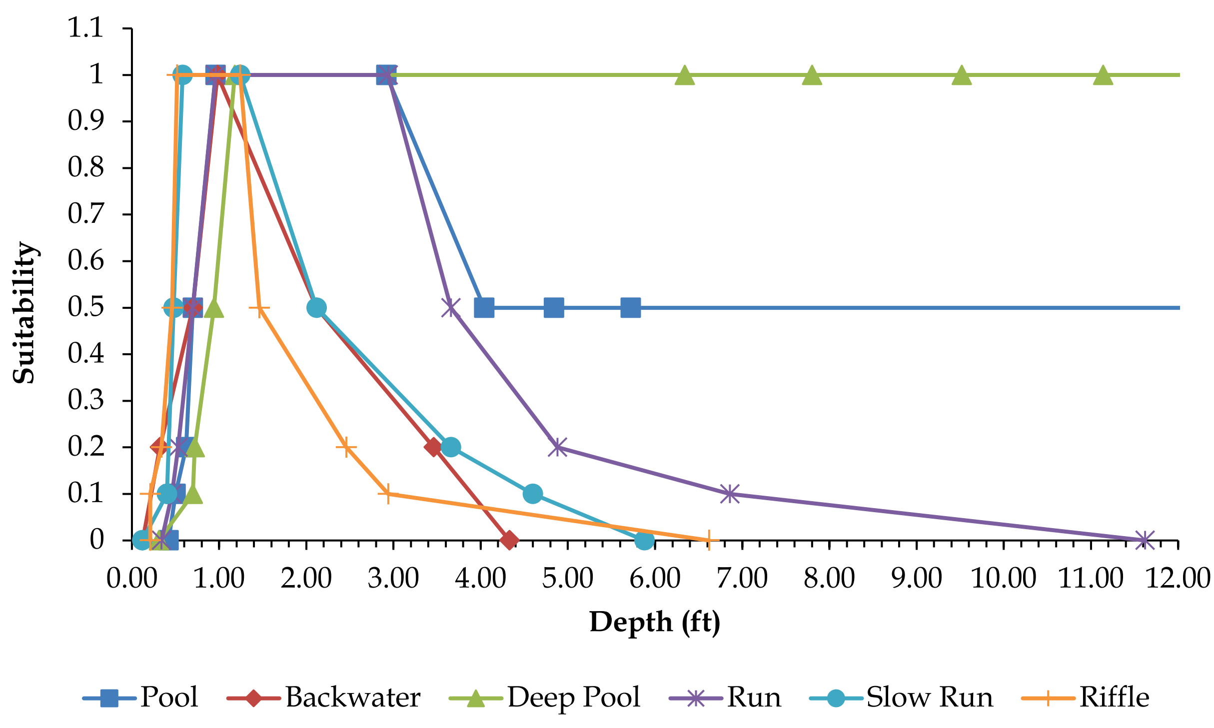


Figure 21. Habitat suitability curves for depth of six fish habitat guilds.

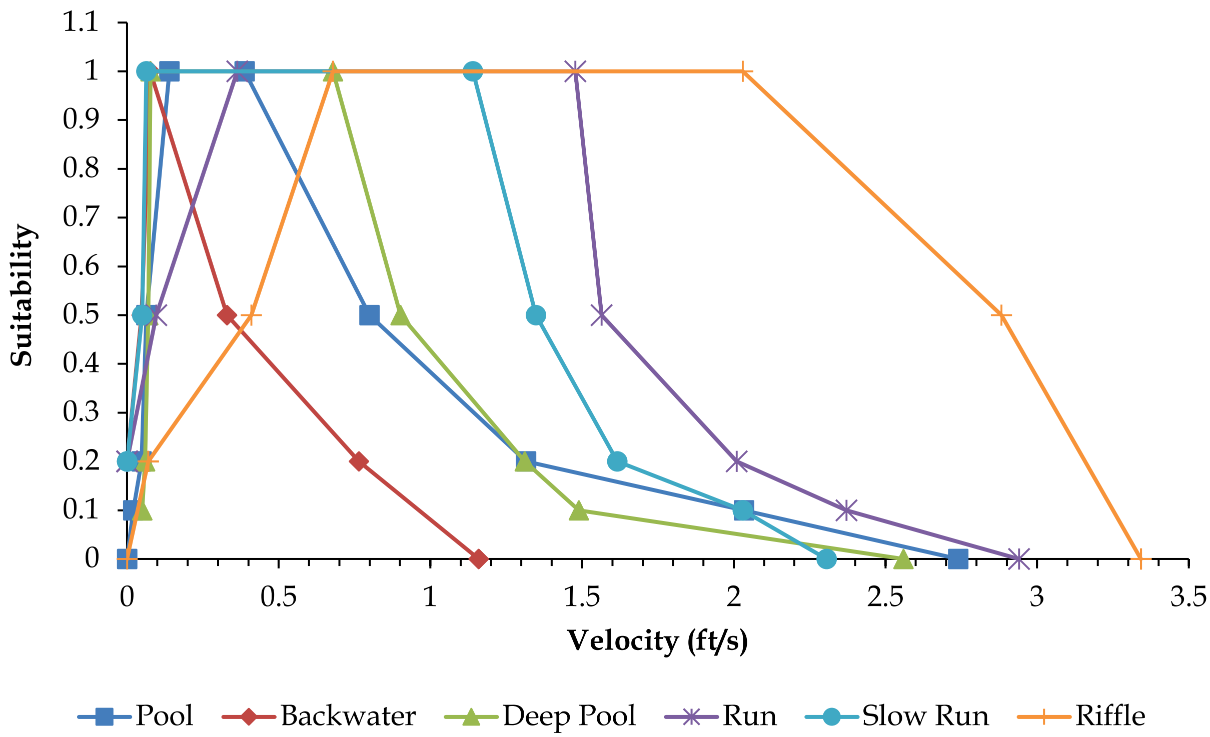


Figure 22. Habitat suitability curves for current velocity of all six fish habitat guilds.

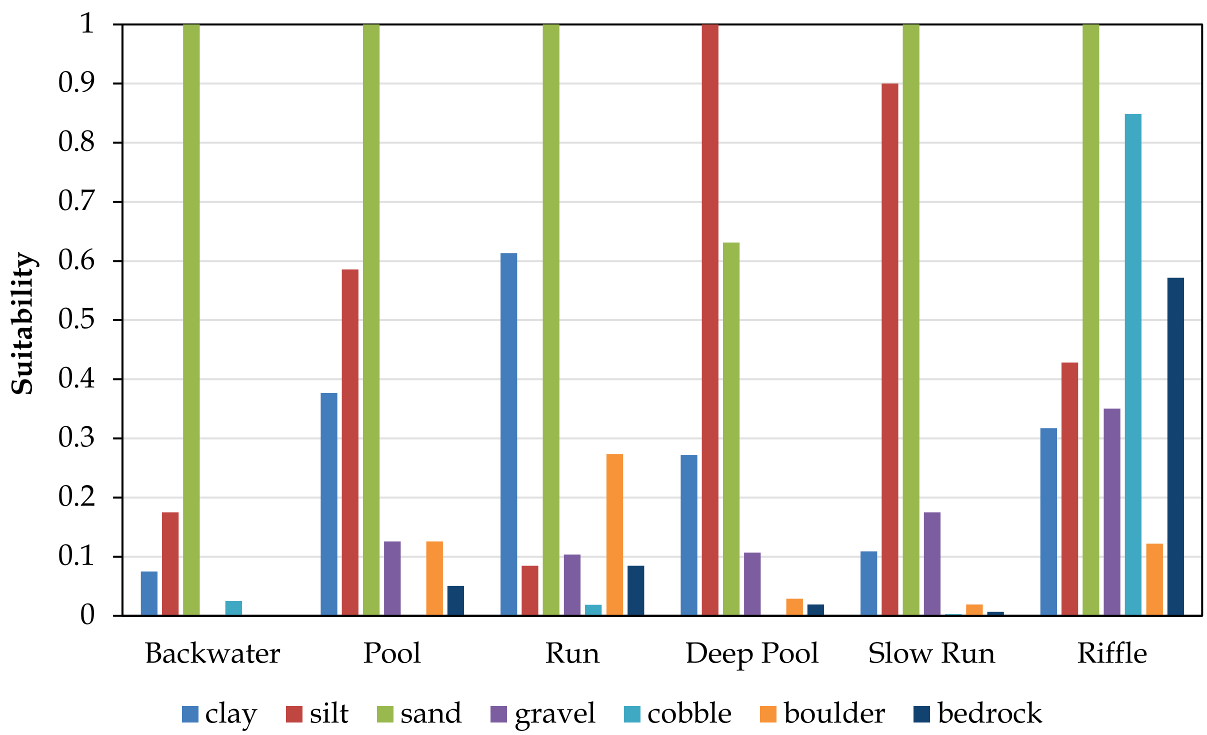


Figure 23. Categorical substrate suitability for each of the six fish habitat guilds.

Depth HSC were modified based on the professional judgment and previous experience of the study team as follows. Given the known reduction in electrofishing capture efficiency at depths greater than approximately six feet (1.8 m), reductions in suitability for the Deep Pool and Pool guilds at depths greater than approximately six feet (1.8 m) were more likely a result of sampling limitations rather than a pattern in habitat utilization. Fishes of the Deep Pool guild (adult Gizzard Shad, for example) are known to commonly inhabit areas considerably deeper than those from which they were captured in this study. As a result, the depth HSC curve for Deep Pool was modified to exhibit a suitability of 1.0 for all depths of approximately 3.0 feet (0.9 meters) or greater. Similarly, to account for sampling limitations, the tail of the Pool HSC curve was also extended at a suitability of 0.5 (Figure 21).

2.3.8 *Calculating Weighted Usable Area*

Final HSC curves for each habitat guild were then applied to hydraulic model output to generate Weighted Usable Area (WUA) to streamflow curves. To do this, a Composite Suitability Index (CSI) was calculated for each habitat guild at each node in a given hydraulic model run (*e.g.*, 1,000 cfs). The CSI was calculated by taking the geometric mean of the suitability for depth (DepthSI) and velocity (VelocitySI) as follows:

$$CSI = (VelocitySI * DepthSI)^{1/2}$$

The CSI for each node was then multiplied by the area of that node to generate a WUA, and these values were summed for each habitat guild at each flow rate for each study site. As noted previously, for the Brazos River, substrate HSC were not used to generate the composite index and did not influence WUA output. The total WUAs for each habitat guild at each modeled flow rate were then compiled to create WUA-streamflow relationships (Figure 24). To assess all habitat types and to identify streamflows that provide maximum areas among all habitat guilds, graphs were also created to depict percent of maximum WUA versus discharge for each habitat guild (Figure 25).

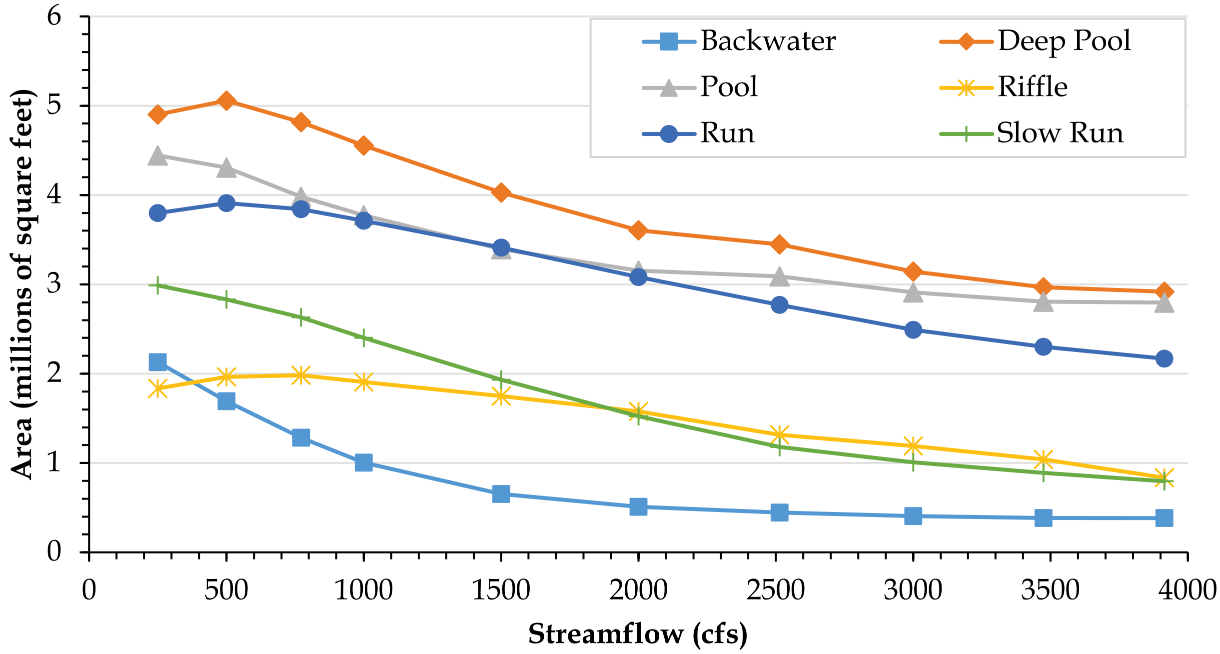


Figure 24. Total weighted usable area versus modeled streamflow at the Brazos River Allens Creek study site.

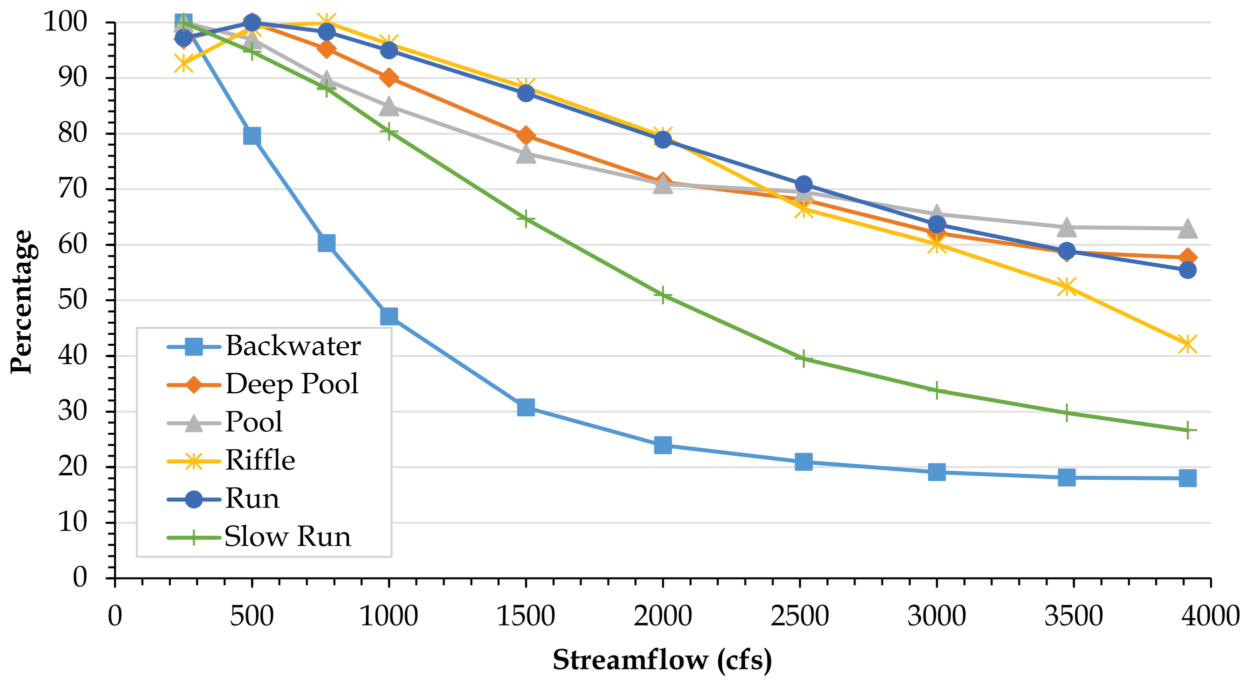


Figure 25. Percent of maximum total weighted usable area versus simulated streamflow at the Brazos River Allens Creek study site.

Another consideration when examining WUA is habitat quality. Total WUA uses suitability indices from 0.1 to 1.0, which includes low and high quality habitat. However, at a particular flow rate, it is possible that large amounts of low quality habitat (CSI <0.5) contribute substantially, and little high quality habitat exists. To examine habitat quality, high quality (CSI

≥ 0.8) and moderate quality (CSI ≥ 0.5) habitat WUAs were calculated at each modeled flow rate. The levels of quality (0.8 for high and 0.5 for moderate) for this assessment were based on professional judgment of and consensus by the study team. Figure 26 and Figure 27 show this analysis for each guild at the Allens Creek study site. All WUA curves are presented for each study site in Appendix B.

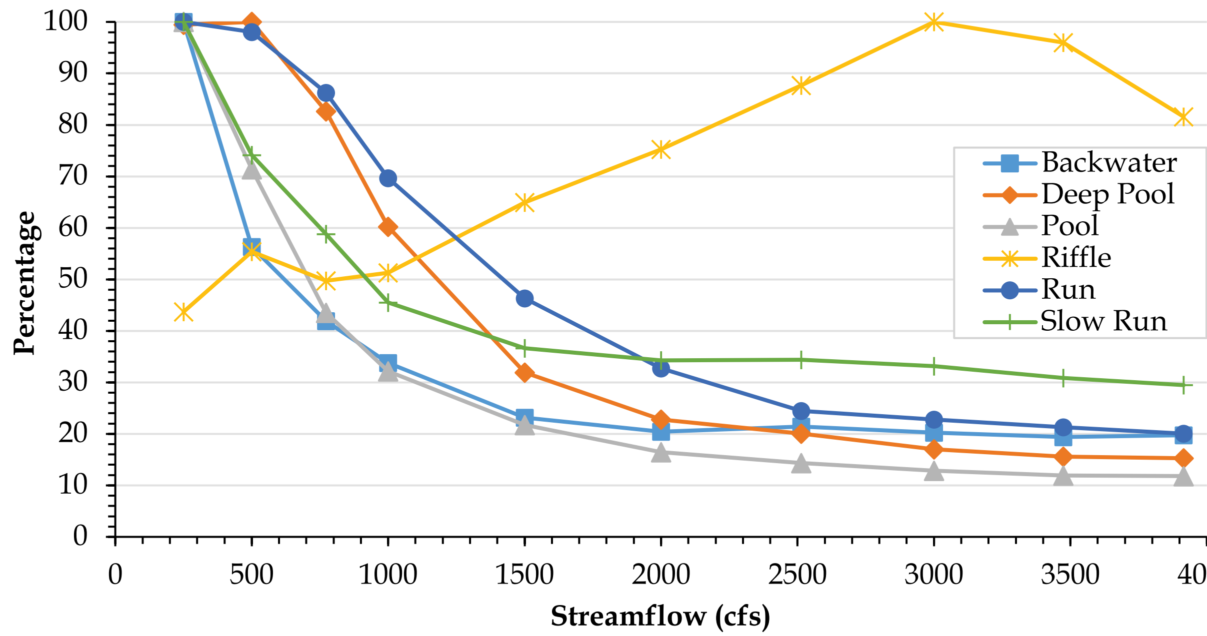


Figure 26. Percent maximum of weighted usable area of high quality habitat (composite suitability index ≥ 0.8) at the Brazos River Allens Creek study site.

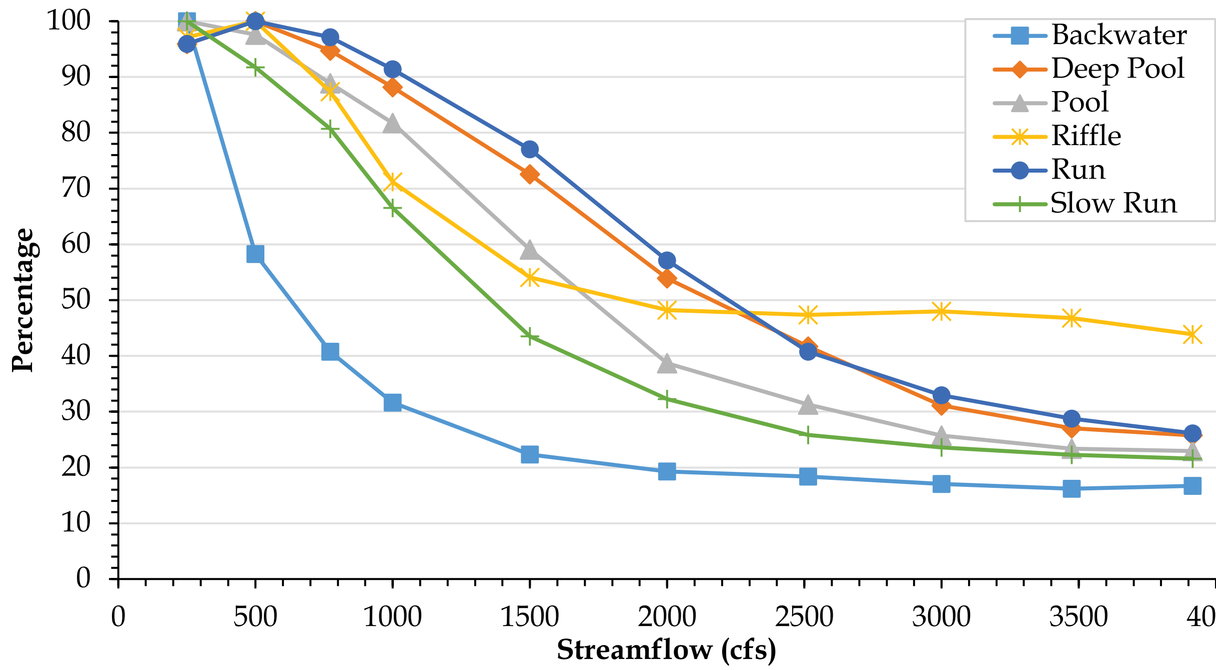


Figure 27. Percent maximum of weighted usable area of moderate-high quality habitat (composite suitability index ≥ 0.5) at the Brazos River Allens Creek study site.

As an example of how interpretation of WUA results can be used to identify ranges of base flows needed to support all guild habitats, total WUA for riffle and run habitats at the Allens Creek study site are maximized between streamflows of 500 to 750 cfs (Figure 24); moderate-high quality for run, riffle, and deep pool habitats reach maximums at 500 cfs and maximums for backwater, pool, and slow run occur at the lowest base flows modeled (Figure 24). All habitat guilds are maintained at 90% maximum in a flow range from 350 to 1,000 cfs (Figure 25). The high quality WUA-streamflow relationship (Figure 26) shows similar trends although high quality riffle habitat peaks at 3,000 cfs. To evaluate if this unique response was related to a modeling error or the presence of a significant habitat feature, we mapped riffle habitat (as defined by the riffle guild data) across all simulated flows at the Allens Creek study site. At 3,000 cfs, a relatively large area of contiguous high quality riffle habitat emerged indicating a potentially important habitat occurring at a fairly high base flow (Figure 28). Interpretations of habitat-streamflow relationships to inform base flow recommendations at all study sites are discussed in Section 2.3.13.1 – 2.3.13.6.

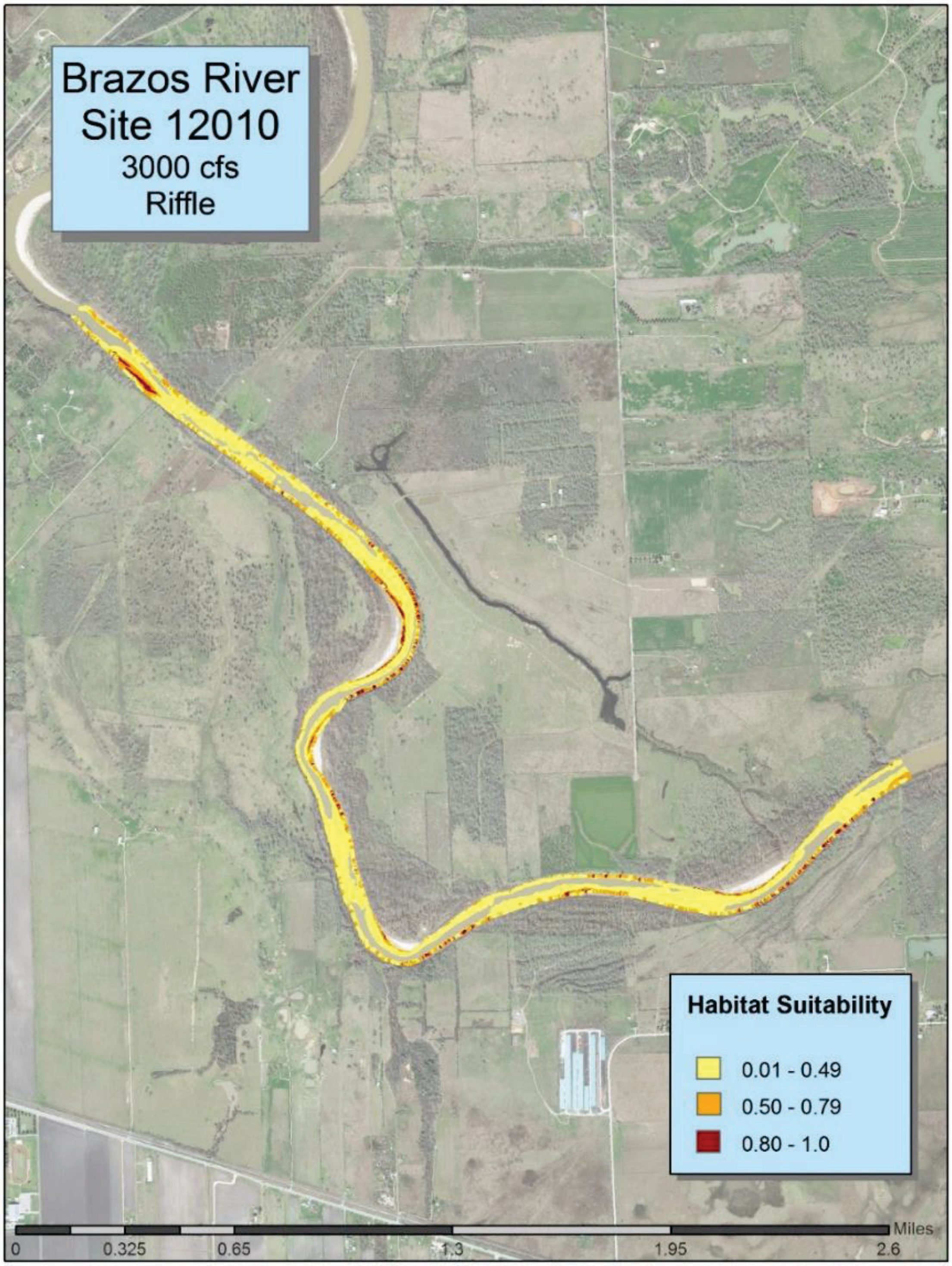


Figure 28. High quality riffle habitat illustrated near the upstream boundary of the Allens Creek study site at 3000 cubic feet per second.

2.3.9 *Shoal Chub Recruitment*

In a TPWD-funded study of flow-dependent fishes in the Brazos River, Rodger *et al.* (2016) provided findings of a relationship between high flow pulses and recruitment of one of the key species, Shoal Chub. Using drift nets, larval fish were collected at night from March 2013 to March 2014. Otoliths from Shoal Chub were examined to estimate age to evaluate the relationship between streamflow and hatch date. Greater levels of recruitment were found during flow pulses (Figure 29). This relationship identifies a 2 per season flow pulse recommendation of 5000 cfs during the Shoal Chub reproductive season (April-September) for all study sites in the middle and lower Brazos Study Area. We assigned a duration of seven days to each seasonal pulse to support actual spawning in addition to the length of time eggs and larvae broadcast spawning cyprinids (including *Macrohybopsis* spp.) need to remain suspended in the current following spawning. Eggs hatch within one to two days depending on temperature and larvae require an additional two to three days to reach swim-up and have capabilities to move into low velocity feeding habitats (Moore 1944, Platania and Altenbach 1998, Perkin and Gido 2011).

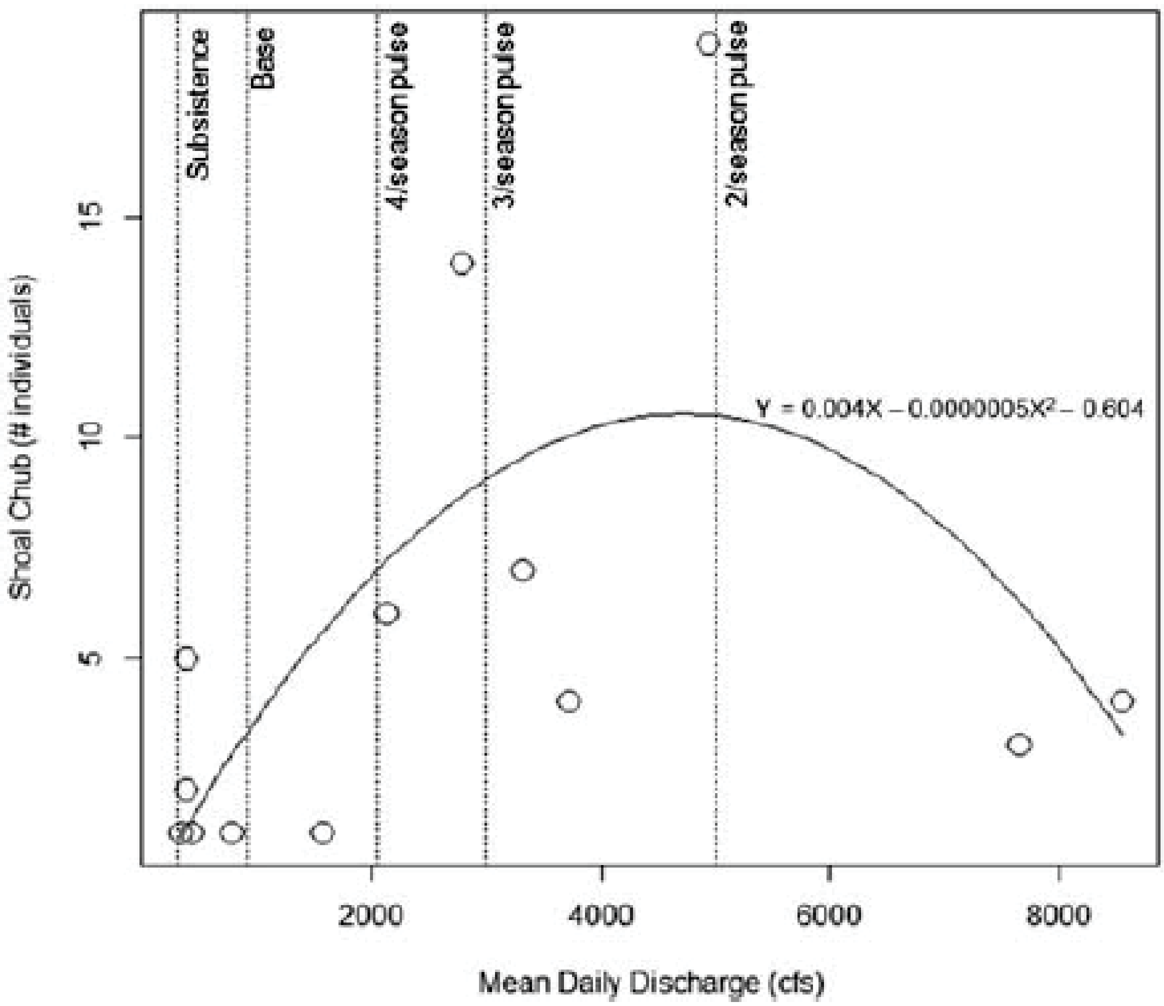


Figure 29. Relationship between Shoal Chub recruitment and streamflow in the Brazos River. Figure from Rodger *et al.* (2016).

2.3.10 *Alligator Gar Spawning Recruitment*

Alligator Gar (*Atractosteus spatula*) are the largest of the fish species occurring in Texas, reaching maximum lengths of around three meters (nearly 10 feet) (Lee and Wiley 1980) and maximum weights of approximately 127 kilograms (280 pounds) (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 July (May and Echelle 1968, Lee and Wiley 1980, Buckmeier *et al.* 2017). 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 have been shown to be important spawning and rearing grounds (Zeug *et al.* 2005, Robertson *et al.* 2008) for Alligator Gar.

In order for successful recruitment of Alligator Gar to occur, floodplain inundation and oxbow connectivity duration have to be of sufficient magnitude to connect floodplain spawning habitats and duration for the eggs to hatch and the larvae to develop to swim up stage so that they are not left stranded on vegetation as flood waters recede. Flood pulse magnitudes necessary to connect important oxbow spawning and rearing habitats are location specific and summarized in Table 16 and range from 17,000 – 72,000 cfs. To determine flood pulse duration, Buckmeier *et al.* (2017) summarized available Alligator Gar egg and larval development information and showed that eggs hatched in two to three days and free swimming larvae occurred around five days after hatching. Young of the year Alligator Gar grow exceptionally fast (Aguilera *et al.* 2002, Snow 2014) and although providing seven days of floodplain inundation to ensure sufficient development may lead to successful recruitment, 14 days of floodplain inundation would facilitate rapid growth and allow for better young of the year survival (Buckmeier *et al.* 2017). An additional study on the middle Trinity River in Texas looked at historical Alligator Gar recruitment success and found that strong year classes were associated with floodplain inundation events with durations greater than 30 days (Robertson *et al.* 2018).

2.3.11 *Mussels*

Baseline mussel surveys were conducted between 2006 and 2007 to determine current species richness and distribution in the middle and lower Brazos River basin (Karatayev and Burlakova 2008). In addition to this qualitative study, a quantitative study to assess mussel habitat associations was also initiated (Randklev *et al.* 2010). Study sites sampled included the Brazos River at FM 485 (near Hearne, TX) and the Brazos River near Hwy 105 (near Navasota, TX) as well as Brazos River tributary sites on Yegua Creek and the Navasota River. Results from this study indicated that mussel presence was associated with complex hydraulic variables (see Figure 30).

With the information obtained from the baseline studies, in order to develop complex hydraulic habitat suitability criteria for mussels, an additional quantitative study was developed at three TIFP study sites (Wildcat Bend, Navasota, and Mussel Shoals; Randklev *et al.* 2014). A stratified-random sampling design was employed to collect mussel habitat occurrence and habitat data. Sample sites were stratified by habitat type (bank habitat, front of point bars, behind point bars, backwater, and mid-channel). Sampling sites within habitats were delineated by an area 50 meters (m) in length by 15 m in width. Habitat data and mussels were collect from 15 to 17 0.25 square meter quadrats randomly placed within the sampling area. Mussel sampling and initial habitat data collections, such as field observations of shear stress derived from

FliessWasserStammtisch (FST) hemispheres, were conducted during low base flow conditions. Additional habitat data was collected at each previously sampled quadrat during higher base flow conditions to assess the range of habitat conditions at mussel sampling locations to develop habitat suitability criteria. Randklev *et al.* (2014) found that complex hydraulic habitat criteria such as shear stress, relative substrate stability (RSS), and the associated relative changes in these two criteria between low and high flows correlated with mussel abundance. Suitability criteria were developed for these parameters (Figure 30). For each of the study sites, mussel habitat suitability criteria were utilized with hydraulic habitat models output to assess mussel habitat distribution and persistence at base flow conditions. This ensured that subsistence and base flow recommendations were not limiting to mussel habitat availability. Because of increased bed mobility, higher flows such as pulse and overbanking flows are expected to limit mussel habitat availability.

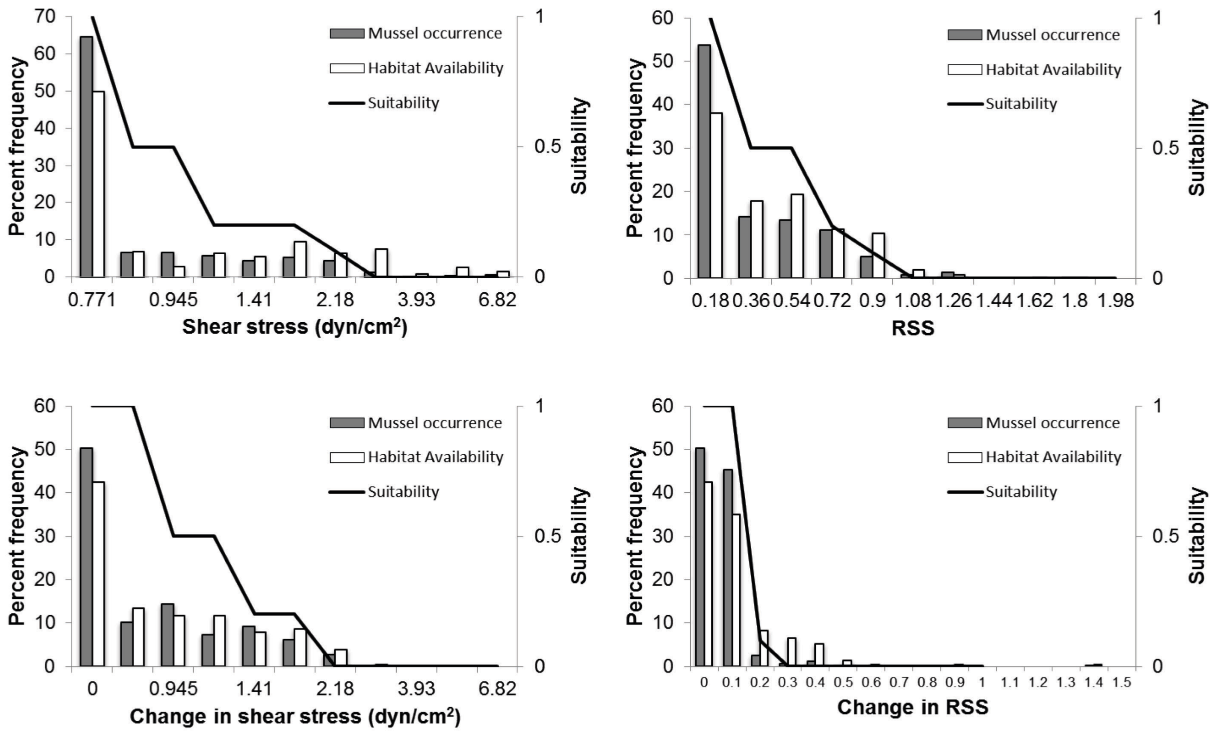


Figure 30. Habitat suitability criteria from Randklev *et al.* (2014) for all mussel species and four hydraulic habitat parameters: shear stress, relative substrate stability, change in shear stress, and change in RSS.

Because mussels are generally immobile, identifying habitat patches that are suitable for mussels at all modeled flow levels is a tool that can be utilized to identify currently occupied habitat or habitat available for future occupation (Maloney *et al.* 2012). Each node in the hydraulic habitat model was evaluated across all modeled flows for mussel habitat suitability. Only nodes that had mussel habitat suitability values greater than zero across all flows were considered persistent. In addition, all persistent mussel habitat nodes were then binned into three habitat quality groupings (0.01-0.19, 0.20-0.49, 0.50-1.00 modeled suitability values), that represent the level of suitability that each node maintained at all flow levels to identify the differing quality levels of habitat patches at each study site (Appendix C).

Mussel environmental requirements, specifically temperature, were also assessed to inform flow recommendations. Although upper thermal tolerance limit data does not currently exist for most mussel species in Texas, this data is available for congener mussel species. Work in nearby Oklahoma identified *Quadrula* spp. and *Truncilla* spp. as thermally intolerant (Spooner and Vaughn 2008), where physiological performance was impacted by water temperatures of 35°C. Smooth Pimpleback *Quadrula houstonensis* and Texas Fawnsfoot *Truncilla macrodon* are located in the middle and lower Brazos River and are state threatened and would be assumed thermally intolerant with adult upper thermal limits of 35°C as these are sister taxa to those studied in Oklahoma. Patterns in thermal sensitivity based on reproductive condition (brooding) and glochidia and larval stage were also assessed based on several studies (Pandolfo *et al.* 2010, Archambault 2012, Ganser *et al.* 2013). These studies show that glochidia and juvenile mussel stages are more sensitive to temperature than adults and thermal stress reduces glochidia viability, attachment and juvenile recruitment. A water temperature of 30°C is predicted to have a 50% mortality rate on glochidia and juveniles and could also have sublethal effects on adult affecting health and reproduction (Gascho Landis *et al.* 2012, Luo *et al.* 2014). Smooth Pimpleback is a short-term brooder and so sperm and egg production likely occurs from January to early April followed by brooding from March to August (Tsakiris 2016, C. Randklev, pers. comm.). Texas Fawnsfoot is likely a long-term brooder with glochidial releases in spring and brooding from July-November based on research of a sister taxa, *T. donaciformis* (Williams *et al.* 2008, C. Randklev, pers. comm.). To reduce thermal stress on glochidia and juvenile stages of these two state threatened species, the TIFP identified 30°C (roughly the LT50 or 50% mortality rate) as the thermal tolerance limit during the important brooding months of March through November. An analysis of water quality data was conducted to inform subsistence flow and base flow recommendations. SWQM temperature data was combined for each study site and related to appropriate flow data. Only accredited data was selected for analysis. Data were subsequently filtered to remove special studies to ensure a representative dataset (see TCEQ 2015). Data from 1980 to present was utilized for analysis. Data points that met or exceeded 30°C were ranked according to the corresponding flow.

Data analysis determined flows that respectively caused 25%, 50%, and 75% of the ranked data to meet or exceed the 30°C thermal tolerance limit for each study site. To inform flow recommendations, the flow corresponding to the 75th percentile exceedance was used for subsistence and dry base, the flow corresponding to the 50th percentile exceedance was used for average base, and the flow corresponding to the 25th percentile exceedance was used for wet base to adjust for different hydrologic conditions (Table 15). Due to no occurrences of temperature levels above 30°C within SWQM data during non-summer months, mussel thermal tolerance flows were limited to the months of May through September.

Due to insufficient data within Study Reach BR3, empirical flow recommendations based on mussel thermal criteria are not available for the Mussel Shoals and Navasota study sites. As detailed in section 2.5.1.4, overall DO and temperature levels within the study reaches met the TIFP water quality goals and are expected to be protective of aquatic life under low flow conditions. Therefore, to provide adequate temperature levels for mussel glochidia, the Q95 (discussed in section 2.5.1.4) is recommended for subsistence flows at these study sites.

Table 15. Flows (in cubic feet per second) that support a 30°C thermal tolerance criteria for mussel recruitment at all study sites and at subsistence and three base flow conditions during mussel brooding months of March-November.

Study Site	Subsistence	Dry Base	Average Base	Wet Base
Marlin	190	190	570	1185
Hearne	190	190	570	1185
Mussel Shoals	299	-	-	-
Navasota	299	-	-	-
Wildcat Bend	824	824	1140	1500
Allens Creek	626	626	946	1943

2.3.12 *Hydraulic Habitat Criteria Development*

While fish guild-based habitat-streamflow relationships work well to identify important trends in habitat types for sampled fishes, there are limitations in how well they represent big river habitats (such as deep runs and pools) that are difficult to sample effectively with active gear types (see Section 2.3.4). In our review of hydraulic-habitat model output, we found that substantial amounts of lotic habitats were not represented by the six guild-based habitats over the range of modeled streamflows. In a previous study of the lower Brazos River near the Allens Creek study site, Osting *et al.* (2004) developed hydraulic habitat criteria (HHC) for use in habitat modeling to account for, in part, sampling limitations in available fish habitat suitability data (Li and Gelwick 2005). Osting *et al.* (2004) developed four primary classes: shallow lentic, shallow lotic, deep lentic, and deep lotic. Other studies have also developed HHC for use in assessing instream flow needs (*e.g.,* Vadas and Orth 1998, Bowen *et al.* 2003). To address similar limitations in our fish data set and to account for the full complement of instream habitats in the middle and lower Brazos, HHC were derived and used to provide a complementary assessment of habitat-streamflow relationships (TIFP 2008). Because HHC were mutually exclusive, (see Figure 31) habitat diversity indices could be calculated to support biological indicators for native species richness and instream habitat diversity (see Table 2). Habitat diversity is an important indicator because biodiversity increases with environmental heterogeneity (Crowder 1990, Ward and Tockner 2001) and plays a strong role in supporting aquatic biodiversity (Gorman and Karr 1978, Schlosser 1982, Poff and Ward 1990, Reeves *et al.* 1993, Bunn and Arthington 2002, Robinson *et al.* 2002). This analysis also supports examination of our key species and those with insufficient abundances or occurrences in fish-habitat data collections (*e.g.,* Chub Shiner) to include in the development of guilds (Table 12).

Using fish-habitat suitability data (see Section 2.3.7; Figure 21 and 22) as guidance, 10 hydraulic habitat classes were identified to parse out depth and velocity combinations (Figure 31). Fish-habitat sample occurrences and key species occurrences were mapped out on the HHC plot to assess how well our HSC sampling addressed each of the HHCs and to help refine boundaries between HHCs. Figure 32 illustrates all fish-habitat samples and highlights sampling limitations in depths greater than six feet especially at higher velocities (HHC 9) where few fish were caught (see Section 2.3.4) and indicates the lack of sampling at velocities greater than 3.5 feet per second (fps) (HHC 10). Figure 33 indicates the HHCs where Spotted Bass were found (1, 2, 4 and 7) and also the single specimen of Alligator Gar (HHC 4). Figure 34 maps occurrences of small and large Channel Catfish on the HHC plot; small Channel Catfish primarily occur in HHC 1, 4, and 7 (less than three feet in depth) with some occurrences in deeper HHCs. Key species of minnows (Chub Shiner, Shoal Chub, and Silverband Shiner) were typically collected in shallow water HHCs (1, 4, and 7) and current velocities up to 3.5 fps (Figure 35). All of these graphs were used to help refine boundaries between each HHC class. For example, 3.5 fps was set as a lower boundary for HHC 10 velocity and six feet was set as a lower boundary for the depths of HHCs 3, 6, and 9. These three HHCs ranges included all depths greater than 6 feet.

The area of each of these 10 HHCs was calculated for each simulated flow using the hydraulic models calibrated for each study site. The percent maximum of hydraulic habitat area was calculated for each streamflow at each study site. Figure 36 shows results for the Allens Creek study site. A habitat diversity index (Shannon's H diversity index) was then calculated to reflect the relationship between hydraulic habitat diversity and streamflow. Percent maximum of diversity was plotted against streamflow to inform base flow recommendations. For example, the percent maximum of the HHC diversity and streamflow for the Allens Creek study site (Figure 37) indicates that maximum diversity occurs between 750 and 1,000 cfs while 80% of the maximum diversity occurs between 300 and 2,350 cfs. Plots for all study sites are included in Appendix B. Analysis of habitat-streamflow relationships to inform base flows for all study sites is provided in 2.3.13.1-2.3.13.6.

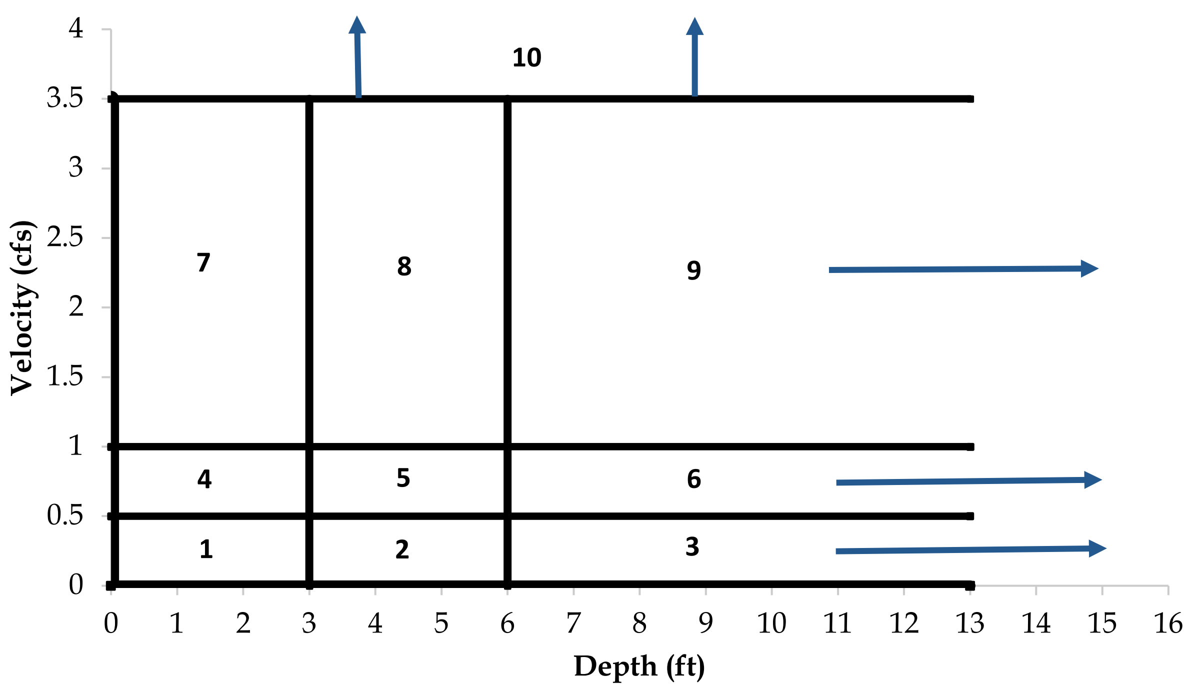


Figure 31. Hydraulic habitat criteria reflecting different combinations of velocity and depth. Velocities are in feet per second and depths are in feet.

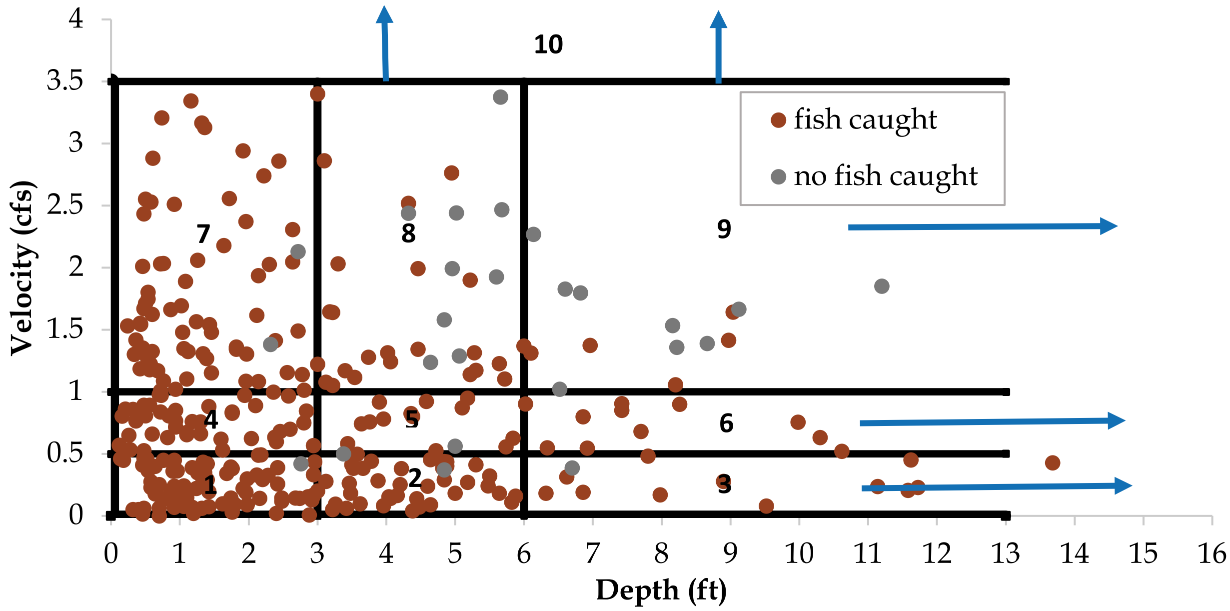


Figure 32. Fish-habitat samples mapped on hydraulic habitat criteria plot. Velocities are in feet per second and depths are in feet.

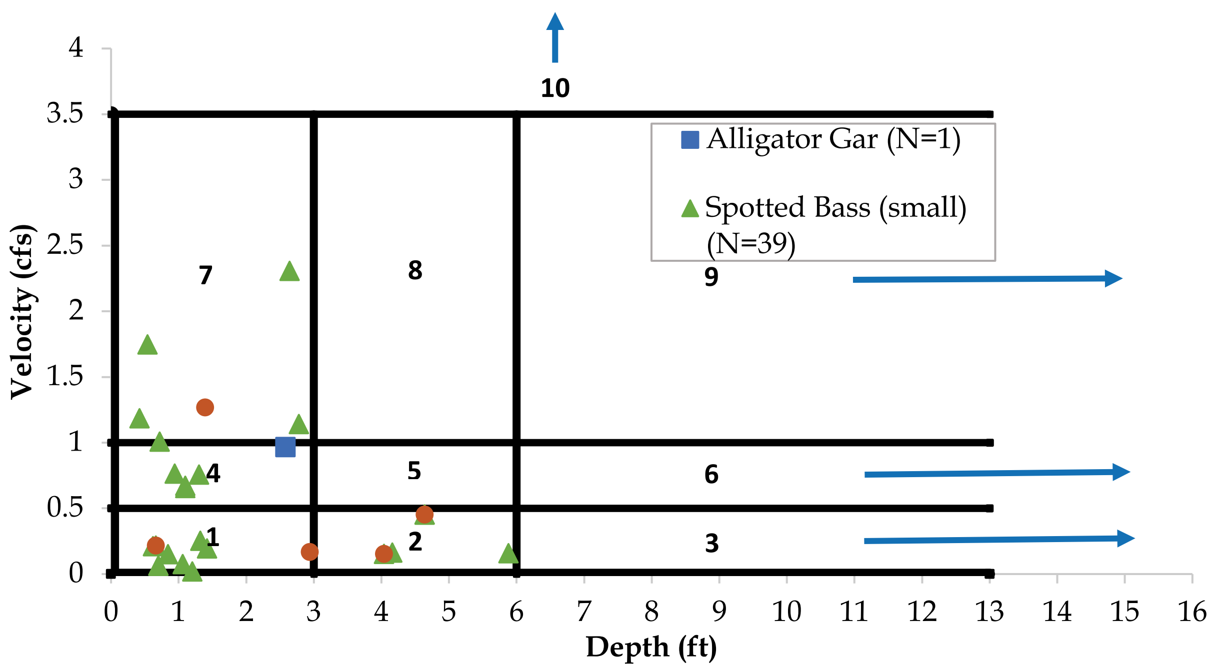


Figure 33. Spotted Bass and Alligator Gar hydraulic habitat criteria occurrences from fish-habitat sampling. Velocities are in feet per second and depths are in feet.

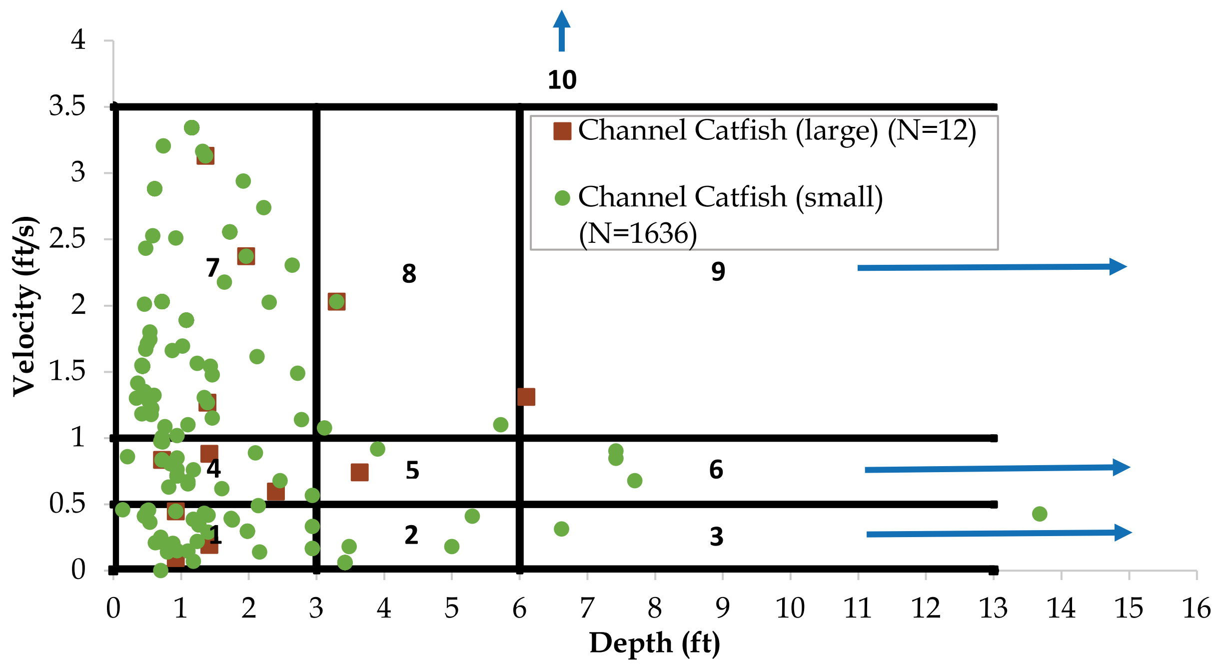


Figure 34. Channel Catfish hydraulic habitat criteria occurrences from fish-habitat sampling. Velocities are in feet per second and depths are in feet.

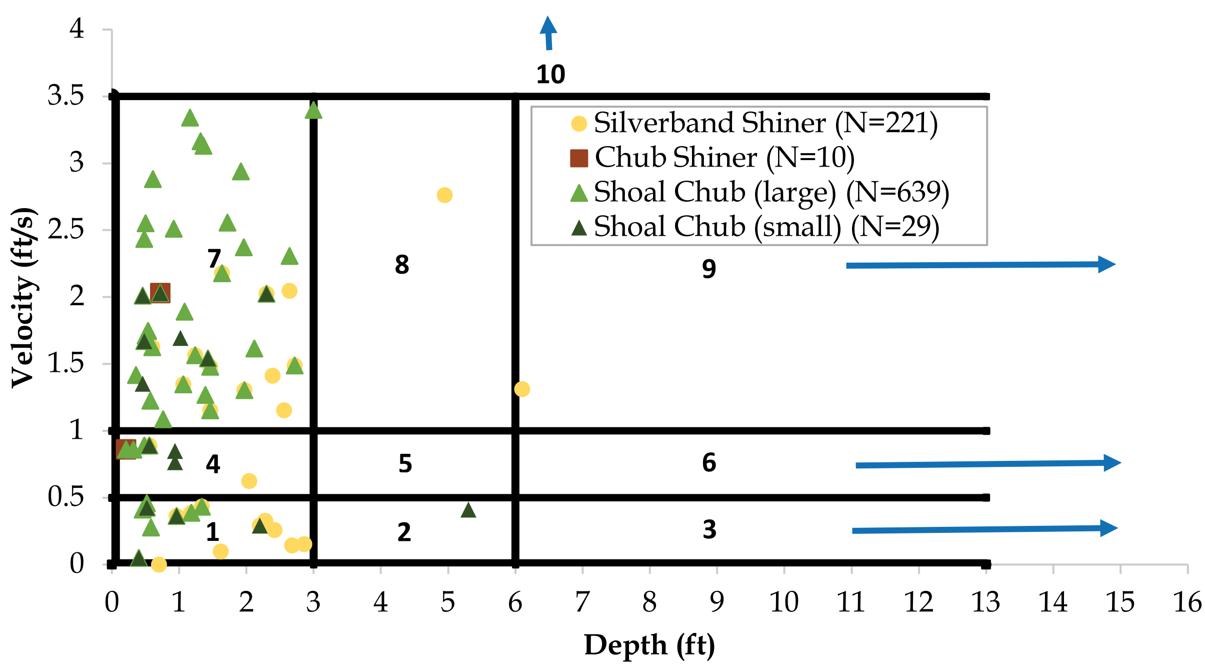


Figure 35. Minnow species hydraulic habitat criteria occurrences from fish-habitat sampling. Velocities are in feet per second and depths are in feet.

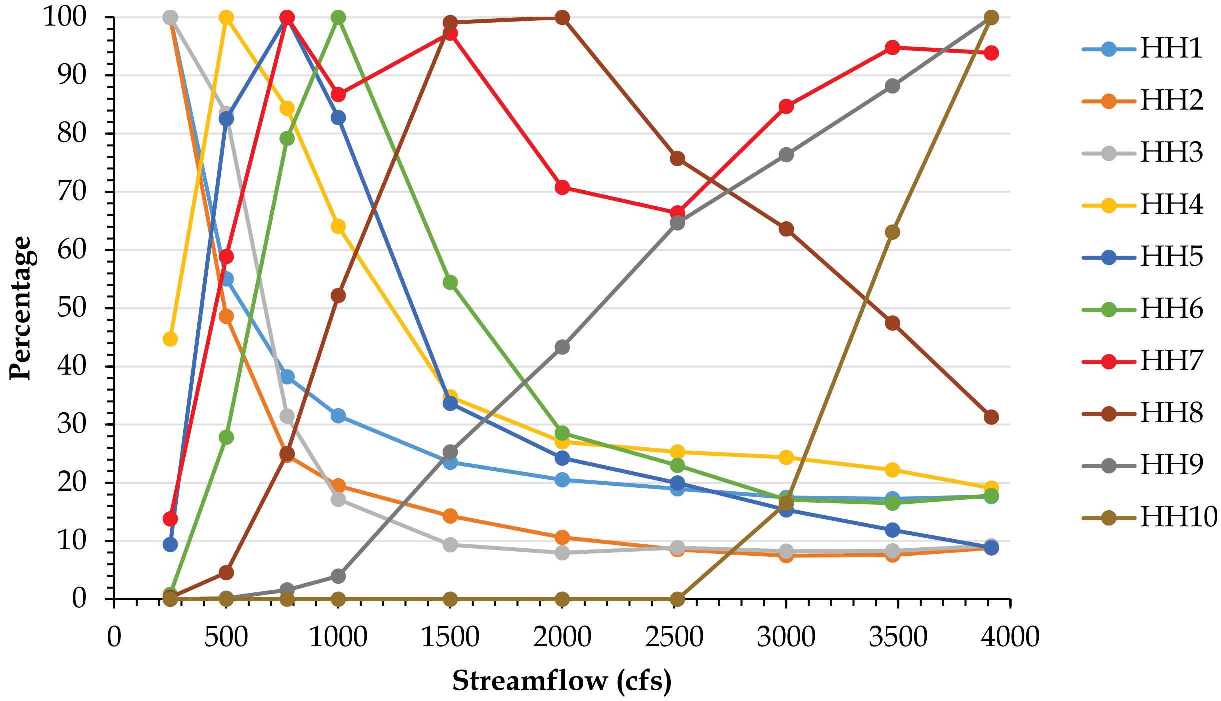


Figure 36. The percent maximum of hydraulic habitat area vs. streamflow for the Allens Creek study site. Hydraulic habitat criteria are defined in Figure 31.

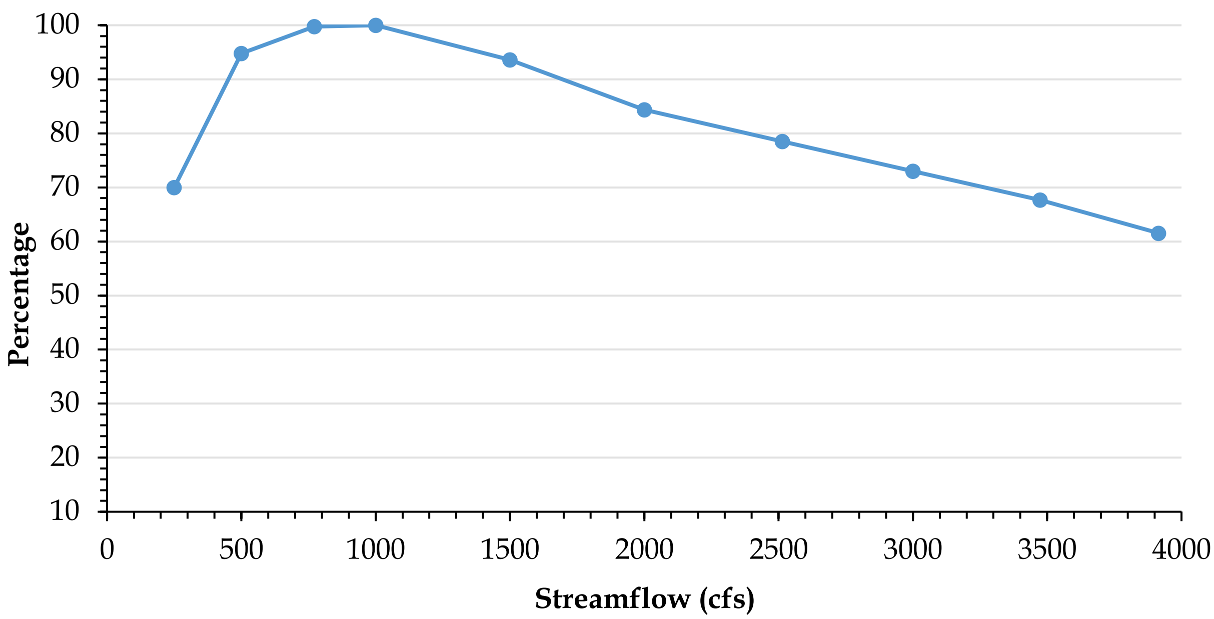


Figure 37. Percent maximum of hydraulic habitat diversity (Shannon's H) at the Allens Creek study site.

2.3.13 *Interpretation of Habitat-Streamflow Relationships*

For each study site, we examined total and percent maximum WUA-streamflow relationships to identify streamflows that supported moderate to high quality habitat based on habitat guilds derived from fish-habitat associations (2.3.8). Using hydraulic habitat criteria and Shannon's H diversity indices, base flows and peaks were identified that maintain all ecologically-important hydraulic habitat conditions and habitat diversity (2.3.12). Spatial maps of habitat quality were also examined to assess contiguity of habitat patches (i.e., were patches clumped into larger areas or was the total area distributed among many smaller patches), as needed. Based on the information examined, base flow ranges were derived for three hydrologic conditions (wet, average, and dry). Average hydrologic conditions are expected to occur roughly 50 percent of the time. Wet and dry conditions are expected to occur roughly 25 percent of the time. Thus, through time (*i.e.*, annual time step), dry, average, and wet base flow conditions support the full complement of fish biodiversity because a proportion of species do well in wet conditions (*e.g.*, more habitat available for growth, recruitment, and survival), others in average conditions, and other species in dry conditions (see Annear *et al.* 2004, Sabine-Neches BBEST 2009) as reflected by different life history strategies, species traits (Craven *et al.* 2010), and environmental requirements.

2.3.13.1 Marlin

Figures for Marlin habitat responses are in Appendix B: 1-6. The percent maximum of the total WUA for the Marlin study site indicates that most habitats peak at 500 cfs or lower although riffle habitat is maintained at the 90% level across a range of streamflows from 300-1,850 cfs and peaks between 1,000-1,250 cfs. High quality riffle habitat peaks at 1500 cfs.

The percent maximum of the HHC diversity and streamflow relationship for the Marlin study site (Figure B-6) indicates that percent maximum diversity occurs at 623-750 cfs (623 cfs chosen for hydraulic modeling purposes) and percent maximum diversity remains above 90% from 300-2,600 cfs.

Spatial maps of riffle WUA at each flow were generated to confirm the contiguity of riffle habitat patches at the Marlin study site. Hydraulic conditions in contiguous riffle patches at Marlin (Section 2.1.1) should be supported during base flow ranges of 600 to 2,000 cfs. Figure 38 shows riffle habitat at 1,500 cfs where high quality habitat was maximized.

Using all of the information for the Marlin study site, the dry range was set to 300-500 cfs; the average to 500-1,750 cfs encompassing the peak range in HHC diversity, total riffle habitat area, as well as peaks in high quality riffle at 1,500 cfs; and wet to 1,750-2,600 cfs to ensure that habitat diversity is maintained.

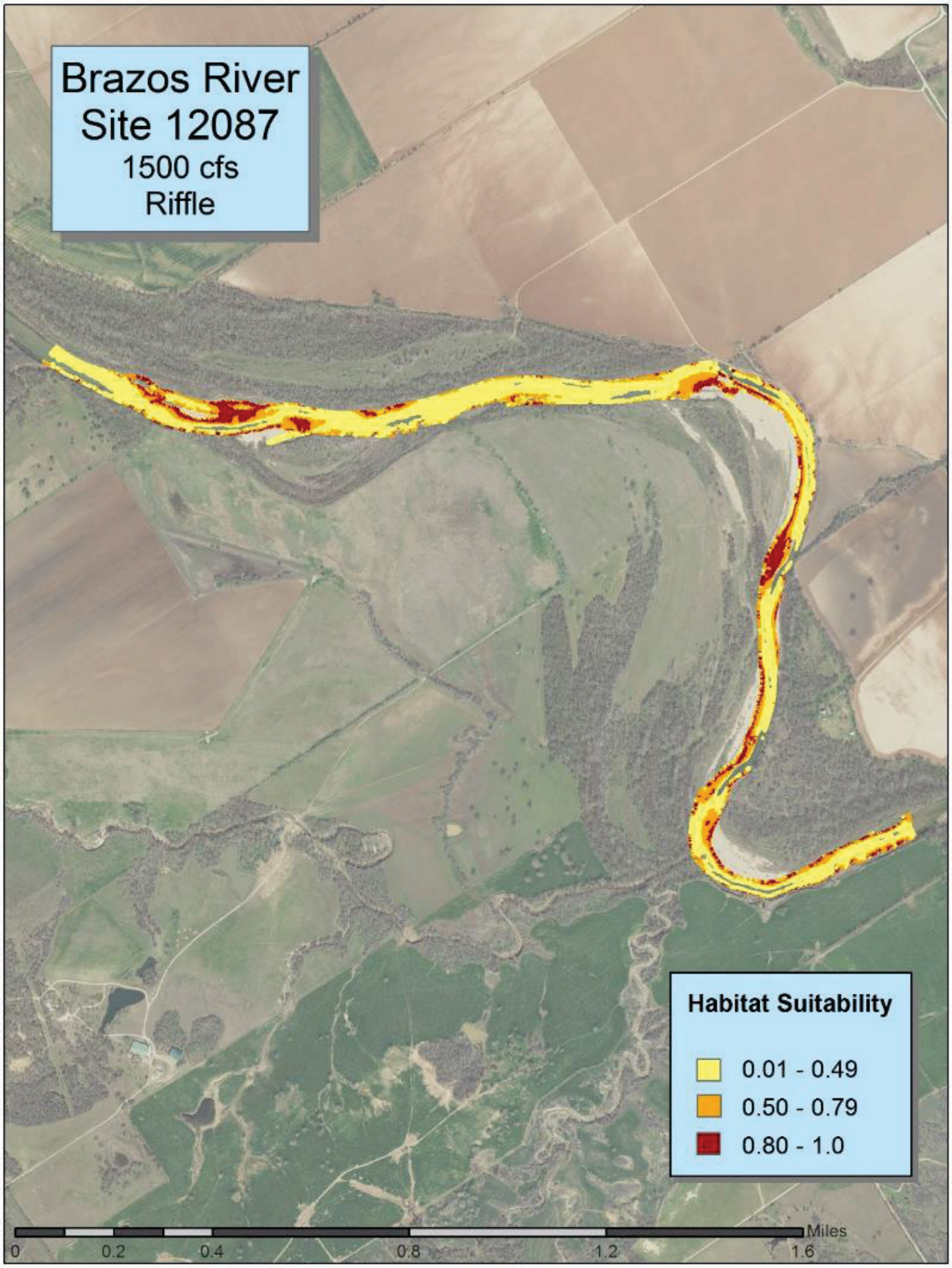


Figure 38. Riffle habitat weighted usable area by suitability class at 1500 cubic feet per second at the Marlin study site on the Brazos River.

2.3.13.2 Hearne

Figures for Hearne habitat responses are in Appendix B: 7-12. At the Hearne study site, total WUA peaked for riffle and run habitats at 500-750 cfs (Figure B-7) and 90% maximum riffle habitat WUA ranged from 250-1,500 cfs. Other habitats peaked at flows less than 500 cfs. For moderate to high quality habitat (CSI≥0.5; Figure B-9), run habitat peaked at 750 cfs and 1,250 cfs maintained 90% of maximum WUA, while riffle WUA peaked at 500 cfs. The same patterns were exhibited for high quality habitat (CSI≥0.8; Figure B-8).

The percent maximum of the HHC diversity and streamflow relationship for the Hearne study site (Figure B-12) indicates that percent maximum diversity occurs at 750 cfs and percent maximum diversity remains above 80% from 250-2,000 cfs. HHC 8 reaches maximum area at 2,500 cfs (Figure B-10) setting the upper end of the wet range.

Using all of the information for the Hearne study site, the dry range was set to 250-500 cfs; the average base flow to 500-1,500 cfs encompassing the peak range in HHC diversity and peak ranges for run and riffle habitat WUA; and wet range was set to 1,500-2,500 cfs.

2.3.13.3 Mussel Shoals

Figures for Mussel Shoals habitat responses are in Appendix B: 13-18. At the Mussel Shoals study site, total WUA peaked for most habitats at 500-750 cfs (Figure B-13) and 90% maximum WUA for several habitats (run, pool, deep pool) ranged from 250-1,400 cfs. For moderate to high quality habitat (CSI≥0.5; Figure B-15), run habitat peaked at 500-750 cfs; 1,000 cfs provided at least 80% maximum WUA for run, deep pool, and pool; and riffle peaked from 300-600 cfs. For high quality habitat (CSI≥0.8; Figure B-14), all habitats peaked at 500 cfs or less.

The percent maximum of the HHC diversity and streamflow relationship for the Mussel Shoals study site (Figure B-18) indicates that percent maximum diversity occurs at 500-750 cfs and percent maximum diversity remains above 80% from 300-2,500 cfs. The wet range was capped at 2,500 cfs and low range for dry base set at 500 cfs as seven out of ten HHCs peak at 500 cfs and greater (Figure B-17).

Using all of the information for the Mussel Shoals study site, the dry range was set to 500-700 cfs; the average to 700-1,325 cfs (containing the peak range in HHC diversity as well as peaks for total WUA); and wet to 1,325-2,500 cfs.

2.3.13.4 Navasota

Figures for Navasota habitat responses are in Appendix B: 19-24. At the Navasota study site, total WUA for most habitats peaked at 500-750 cfs (Figure B-19) while riffle peaks from 500-1,000 cfs; 80% maximum riffle habitat WUA was supported at streamflows up to 2000 cfs and 90% max WUA for most habitat types ranged from 400-1,400 cfs. Approximately the same patterns played out for moderate to high quality habitat (CSI≥0.5; Figure B-21) and for high quality habitat (CSI≥0.8; Figure B-20).

The percent maximum of the HHC diversity and streamflow for the Navasota study site (Figure B-24) indicates that percent maximum diversity occurs at 750 cfs and percent maximum diversity remains above 90% at almost all simulated flows (300-2,600 cfs). The wet range was capped at 2600 cfs.

Using all of the information for the Navasota study site, the dry range was 500-750 cfs; the average was set to 750-1,750 cfs (this range contains peaks in HHC diversity and total WUA for most habitats including riffles); and wet base flow was set to 1,750-2,600 cfs.

2.3.13.5 Wildcat Bend

Figures for Wildcat Bend habitat responses are in Appendix B: 25-30. Total WUA for run habitats at the Wildcat Bend study site are maximized between streamflows of 850-1,000 cfs (Figure B-25) while riffle WUA peaks at 1250-1500 cfs; other habitat types peak at the lowest modeled flow of 500 cfs. Moderate-high quality riffle habitat WUA peaks at 1,000 cfs and is maintained at 90% max WUA from 570-2000 cfs (Figure B-27). The high quality WUA-streamflow relationship (Figure B-26) shows similar trends although high quality riffle habitat peaks between 1,250 and 1,500 cfs and 80% of the maximum WUA for riffle between 570-2,500 cfs.

The percent maximum of the HHC diversity and streamflow for the Wildcat Bend study site (Figure B-30) indicates that maximum diversity occurs at 840 cfs while 80% of the maximum diversity occurs at 500-3,000 cfs which aligns well with where most HHCs begin declining in area (Figure B-29). Although HHC 9 (deep and fast) increases linearly across all flows we limited the top range at 3,000 cfs.

Using all of the information for the Wildcat Bend study site, the dry range was set to 500-600 cfs; the average to 600-1,750 cfs encompassing peaks in HHC diversity and WUA for riffles and run; and wet to 1,750-3,000 cfs to maintain habitat diversity.

2.3.13.6 Allens Creek

Figures for Allens Creek habitat responses are in the body of the report and in Appendix B: 31-36. Total WUA for riffle and run habitats at the Allens Creek study site are maximized between streamflows of 500 to 750 cfs (Figure 24); moderate-high quality for run, riffle, and deep pool habitats reach maximums at 500 cfs and maximums for backwater, pool, and slow run occur at the lowest base flows modeled (Figure 27). All habitat guilds are maintained at 90% maximum in a flow range from 350 to 1,000 cfs (Figure 27). The high quality WUA-streamflow relationship (Figure 26) shows similar trends although high quality riffle habitat peaks at 3,000 cfs. To evaluate if this unique response was related to a modeling error or the presence of a significant habitat feature, we mapped riffle habitat (as defined by the riffle guild data) across all simulated flows at the Allens Creek study site. At 3,000 cfs, a relatively large area of contiguous high quality riffle habitat emerged indicating a potentially important habitat occurring at a fairly high base flow (Figure 28). The percent maximum of the HHC diversity and streamflow for the Allens Creek study site (Figure 36) indicates that maximum diversity occurs in the range of 750 – 1,000 cfs while 80% of the maximum diversity occurs between 350 and 2,350 cfs.

Using all of the information for the Allens Creek study site, the dry range was set to 350-750 cfs; the average range was set to 750-2,350 cfs; and the wet range was set to 2350-3000 cfs to maintain the high-quality riffle that occurs at higher base flow conditions.

2.3.14 Oxbow Assessments

In meandering lowland floodplain rivers like the middle and lower Brazos River, oxbows are an important component of the river-floodplain ecosystem. Oxbows serve as spawning and nursery habitat for many fish species (Penczak *et al.* 2003, King *et al.* 2003), and contribute to the overall species richness in these systems (Miranda 2005). This contribution to species richness in river-floodplain systems is attributed to movement of species into and out of these habitats during river-floodplain connectivity during high flow pulses or overbanking flow events (Kwak 1988, Barko *et al.* 2006, Stoffels *et al.* 2016). Understanding the importance of oxbow connectivity in the middle and lower Brazos River specifically addresses multiple stakeholder identified objectives, but most importantly maintaining a diverse aquatic community and lateral connectivity with these habitats.

Multiple studies have been conducted to assess the importance of oxbow connectivity in relation to the fish community and food web dynamics in the middle and lower Brazos River. Zeug *et al.* (2005) showed that oxbow connectivity played an important role in structuring the fish assemblage in oxbows and the main river channel and connectivity events were essential for maintaining fish species diversity in the system. Several studies have also shown the importance of oxbow habitats in the Brazos River for fish recruitment. Nest building species like fishes in the family Centrarchidae and other species such as fishes in the family Clupeidae are abundant in oxbow habitats in the lower Brazos River and have higher recruitment in oxbow habitats than in the main river channel (Zeug and Winemiller 2007, 2008a). Oxbow connectivity events allow for the movement of these species from the oxbow to the river channel and species abundant in the river channel, such as fishes in the family Cyprinidae, to move into oxbow habitats to utilize the abundant resources available in these habitats. Because of this movement of fish species from the river and oxbows, these connection events play an important role in the food web dynamics of these systems.

River connectivity in oxbows has been shown to play an important role in the diet of both oxbow and river species. For example, Longnose Gar that are abundant in the river utilize river-oxbow connection events to exploit the abundant prey resources available in most oxbow habitats and for Spotted Gar that are mostly found in oxbow habitats to take advantage of prey resources imported from the river channel (Robertson *et al.* 2008). Terrestrial carbon sources, such as from black willow leaves, and algal production play an important role in forming the basis of the food web in the main river channel and oxbow habitats respectively (Zeug and Winemiller 2008b). These dynamics are largely controlled by river-oxbow connectivity and the import and export of productivity between these habitats are essential in maintaining a sound ecological environment. Giardino and Lee (2012) modeled the flows that were necessary to connect 28 oxbow lakes identified within the middle and lower Brazos River basin (Figure 39 and Table 16). These flow values were utilized for determining the magnitude and duration of high flow pulse and/or overbanking flow events necessary to maintain oxbow connectivity.

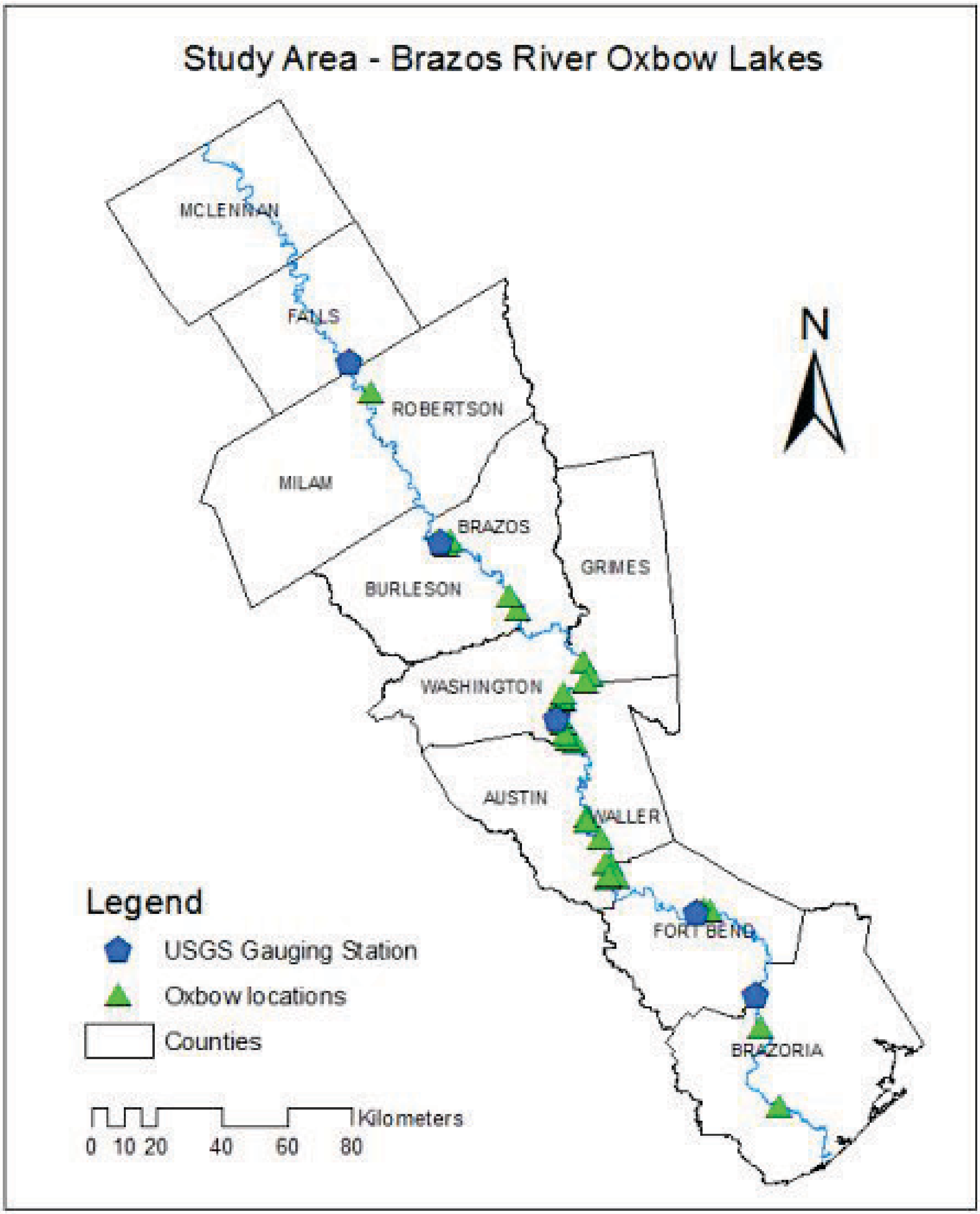


Figure 39. Figure from Giardino and Lee (2012) identifying oxbow lakes in the middle and lower Brazos River.

Table 16. Modeled river discharge (in cubic feet per second-cfs) identified in Giardino and Lee (2012) to connect oxbows in the middle and lower Brazos River.

Oxbow Lake	Modeled Flood Flow (cfs)
1	68,934
2	45,062
3	21,012
4	38,281
5	46,050
6	52,795
7	68,934
8	24,720
9	78,646
10	40,117
11	40,506
12	40,506
13	22,072
14	17,022
15	30,936
16	68,087
17	72,890
18	60,988
19	25,744
20	46,863
21	25,744
22	23,449
23	26,027
24	29,629
25	47,286
26	35,809
27	24,226
28	62,436

Understanding the flows that are necessary to connect the various oxbows found at varying distances from the main channel within the middle and lower Brazos River is critical to ensure the previously described relationships between river and oxbow connectivity are maintained.

2.3.15 *Riparian Communities*

The riparian assessment aims to investigate the diversity, health, and functionality of riparian habitat on the middle and lower Brazos River. Vegetation communities within the riparian zone are typically characterized by hydrophilic plants along the banks of the river, and occur in many forms including grassland, woodland, wetland, or even non-vegetative. These zones are important natural biofilters, protecting aquatic environments from excessive sedimentation, polluted surface runoff, and erosion. They also supply shelter and food for many aquatic and terrestrial animals, and shade that is an important part of stream temperature regulation.

Due to hydrological variation of water levels between base, pulse, and overbank flows, the plant species that grow in the middle and lower Brazos River riparian zones are adapted to a disturbance regime. Riparian plants in the region have adaptations to enable them to either withstand periods of inundation or to seed and recolonize following high flow conditions. The hydrologic regime, coupled with other environmental variables, produces riparian vegetation of herbaceous, shrub, and forest type communities that segregate spatially across the floodplain. A conceptual model of these relationships is presented in Figure 40.

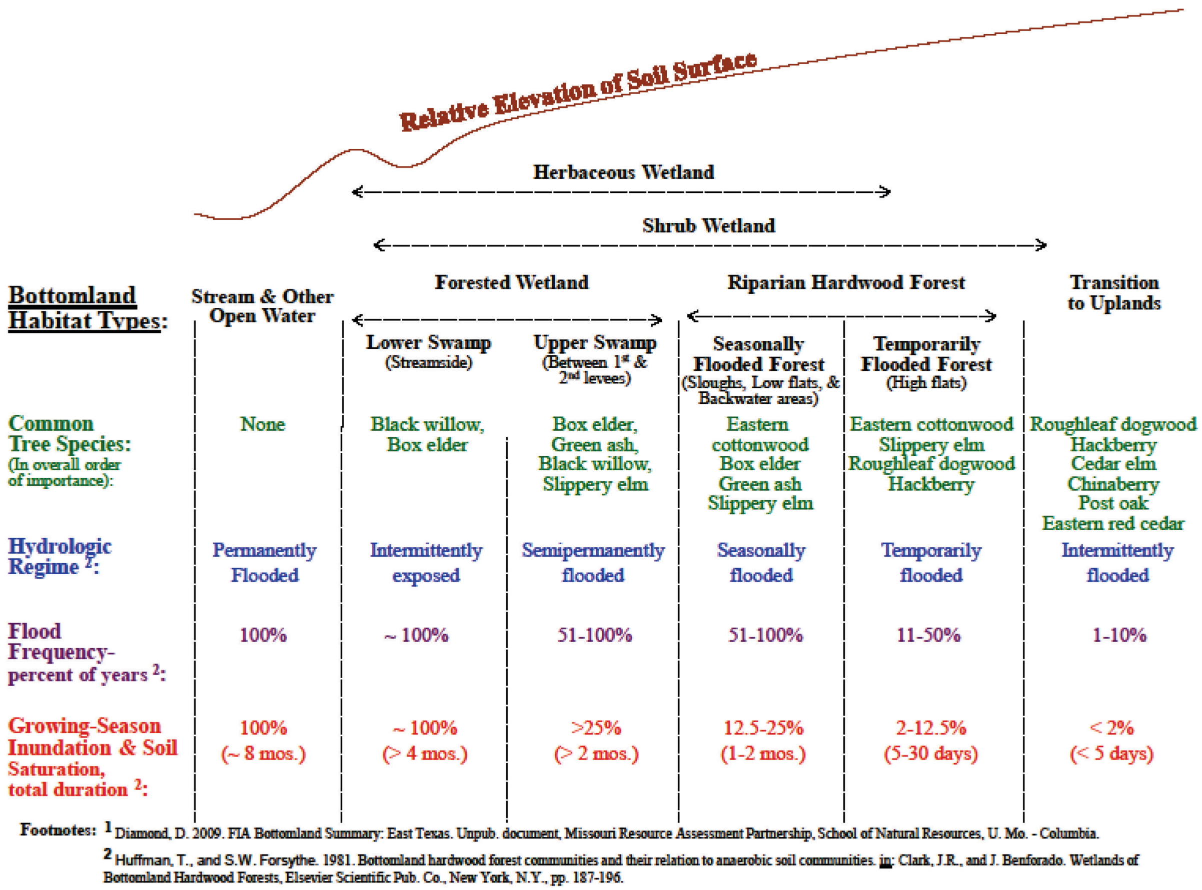


Figure 40. Conceptual model of relationships between riparian habitats and hydrology.

Riparian vegetation inventories and inundation analyses were conducted at six sites along the middle and lower Brazos River: Wallis, San Felipe, Navasota, Bryan, Hearne, and Marlin (see Figure 3). Vegetation inventories at each site provide an overview of tree, herb-seedlings, and shrub-sapling layers occupying riparian forest types. Vegetation inventories were conducted along 50 meter transects at each site. A tape measure was extended into the forest from the mean high water mark (MHWM) in the direction determined to be perpendicular to the river channel. In the field, the MHWM was delineated as the lowest streamside extent of permanent woody vegetation. Areas where the undisturbed riparian forest extended further into the floodplain, transects may be stacked, so that the length of selected transects is extended in 50 meter increments (Hayes 2016a, Hayes 2016b, Hayes 2016c). All trees and shrubs within the transect grid were identified to species. For each individual, diameter at breast height (dbh) (to the nearest centimeter) and distance to water's edge (to the nearest meter) was recorded. Seedlings were classified as having a dbh less than one centimeter. Saplings were classified as having a dbh of one to five centimeters. Herbaceous plants were measured using a line-intercept method along the center of the 50 meter long transect.

Inventories were collected from 4-7 transects at each site within vegetation communities that were observed to be representative of the dominant riparian communities present within the reach. The number of transects sampled at each site is shown in Table 17 and depicted in Figures 41 - 46. Elevation of each transect (except for a few) was surveyed to relate water stage to occurrence of indicator tree species and saplings (see Section 2.2.3 on riparian stage modeling).

Table 17. Number of riparian transects sampled at the Brazos River riparian assessment sites.

Site	Number of Transects
Marlin	7
Hearne	6
Bryan	6
Navasota	4
San Felipe	4
Wallis	6

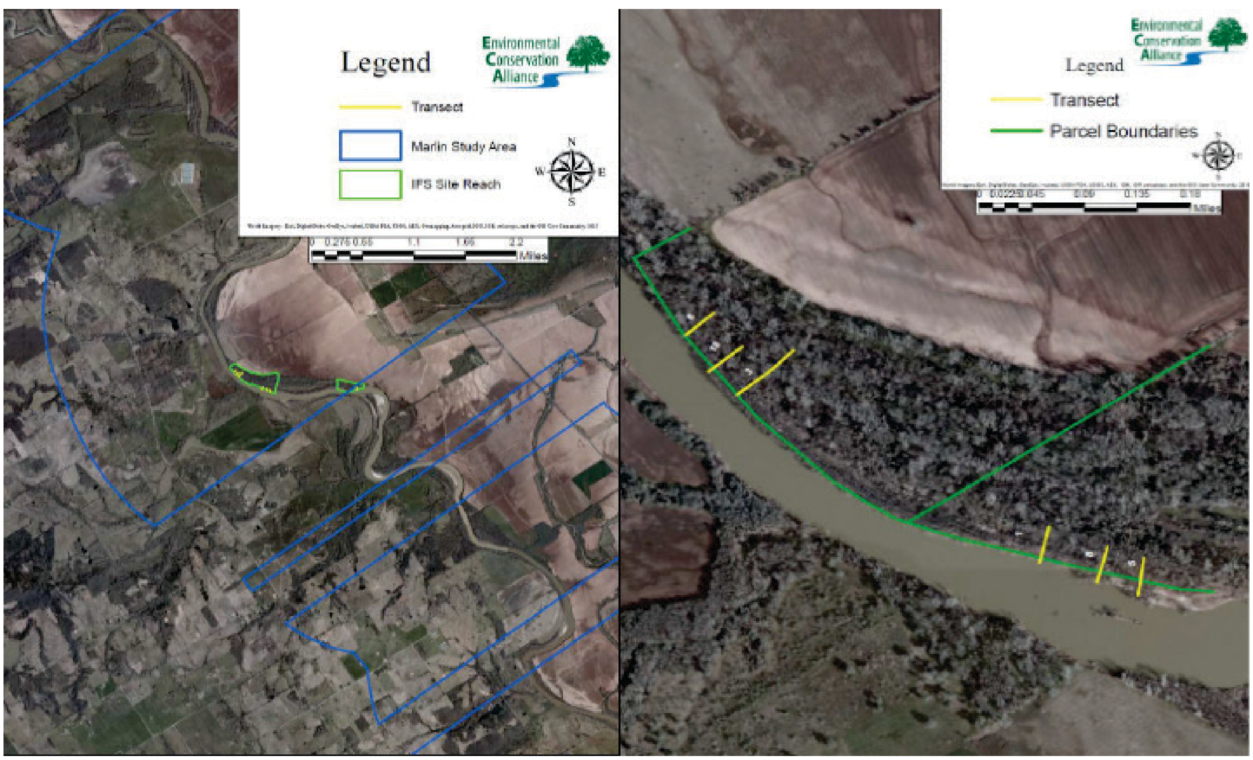


Figure 41. Riparian site at Marlin (left panel). Close-up of riparian transects (right panel). Transect number 4 not depicted.

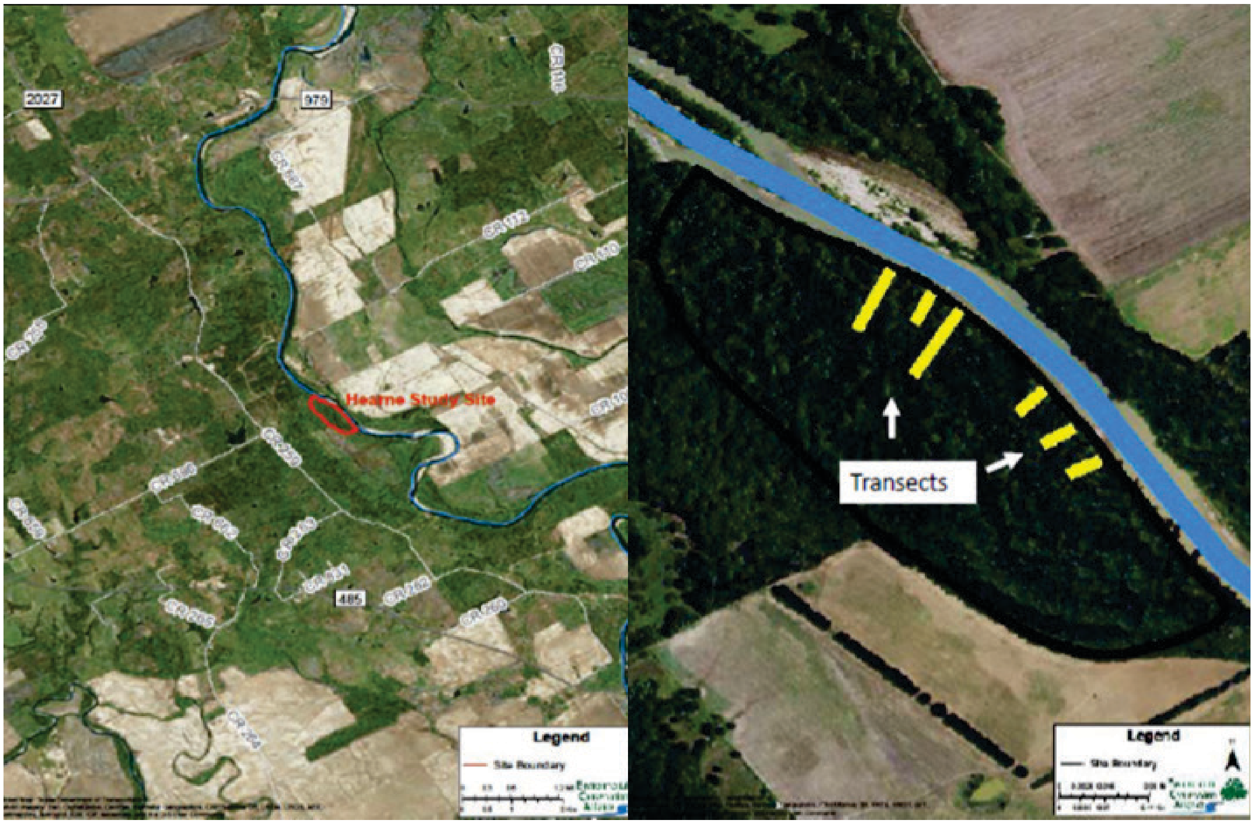


Figure 42. Riparian site at Hearne (left panel). Close-up of riparian transects (right panel).

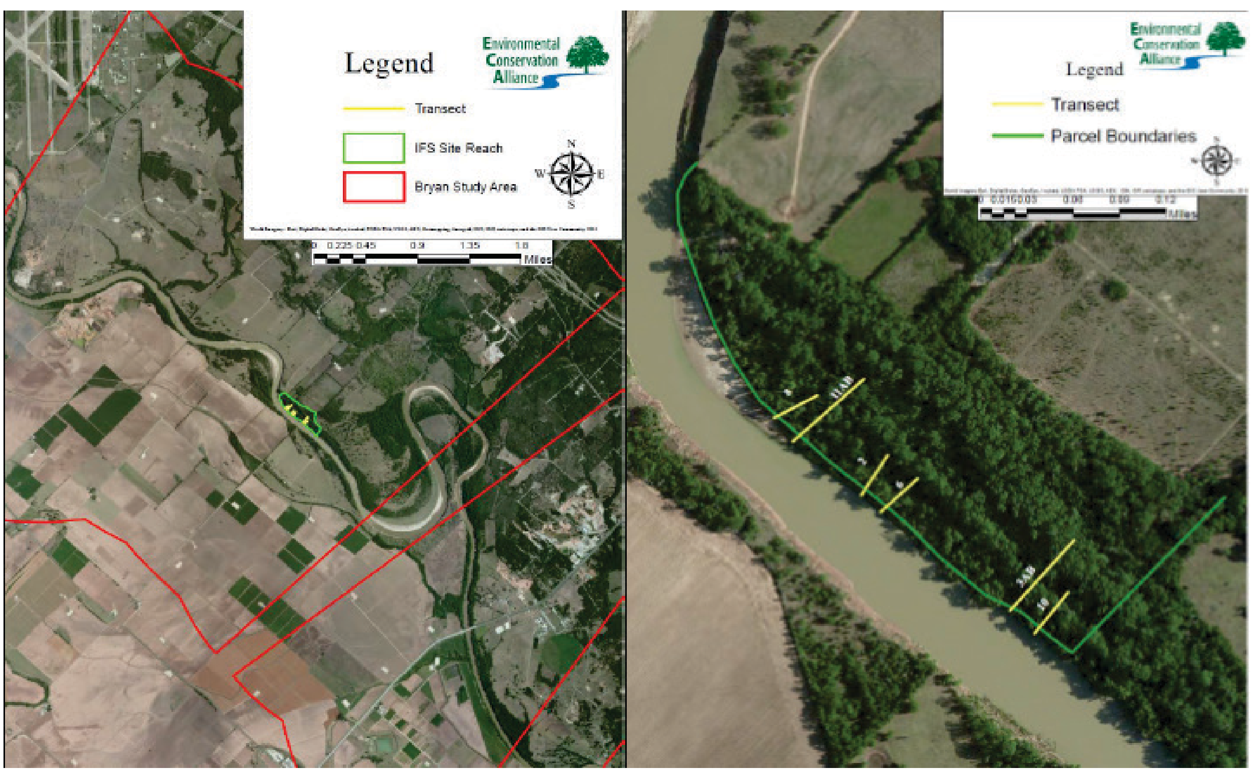


Figure 43. Riparian site at Bryan (left panel). Close-up of riparian transects (right panel).

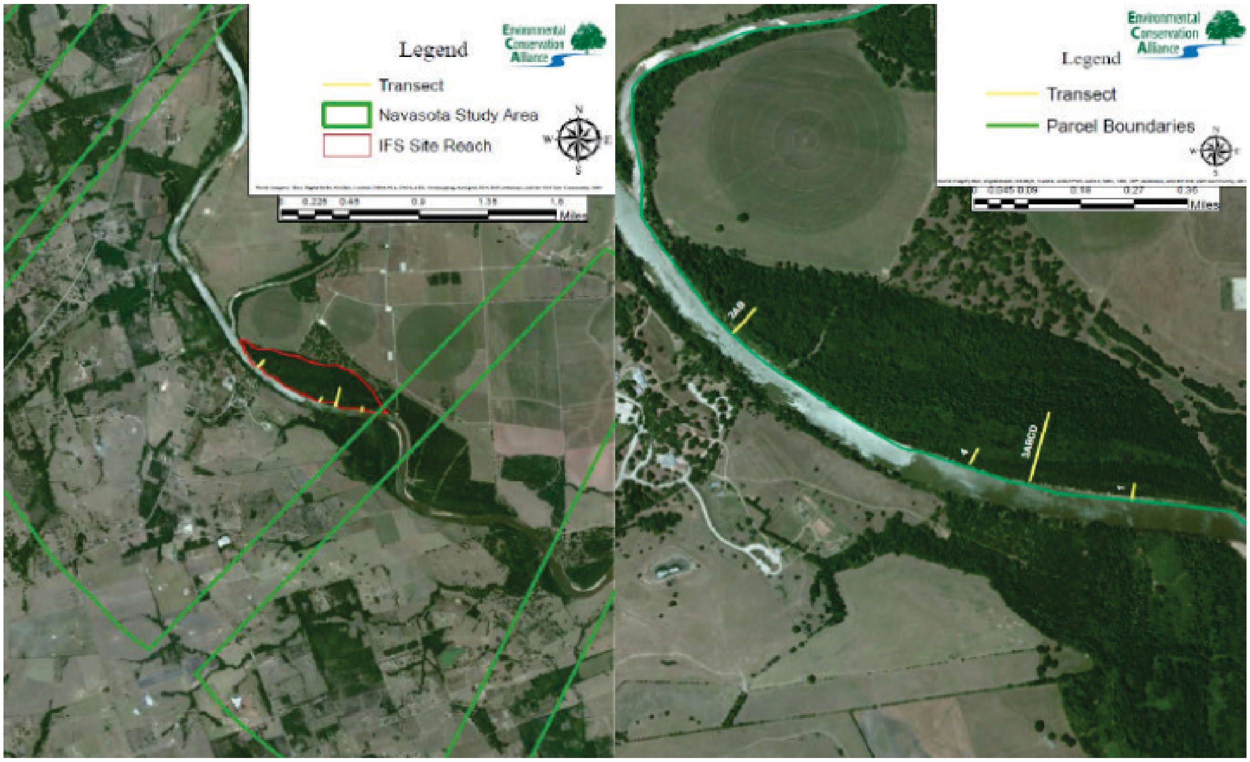


Figure 44. Riparian site at Navasota (left panel). Close-up of riparian transects (right panel).

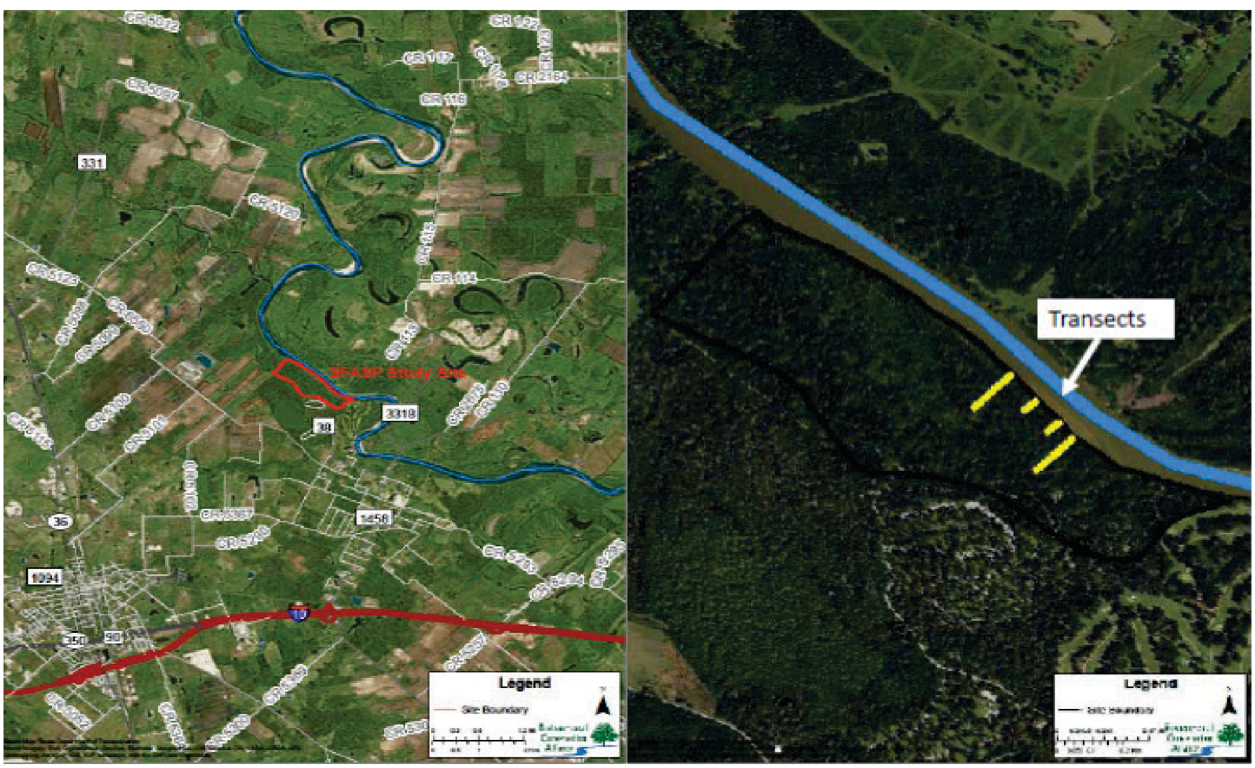


Figure 45. Riparian site at San Felipe (left panel). Close-up of riparian transects (right panel).

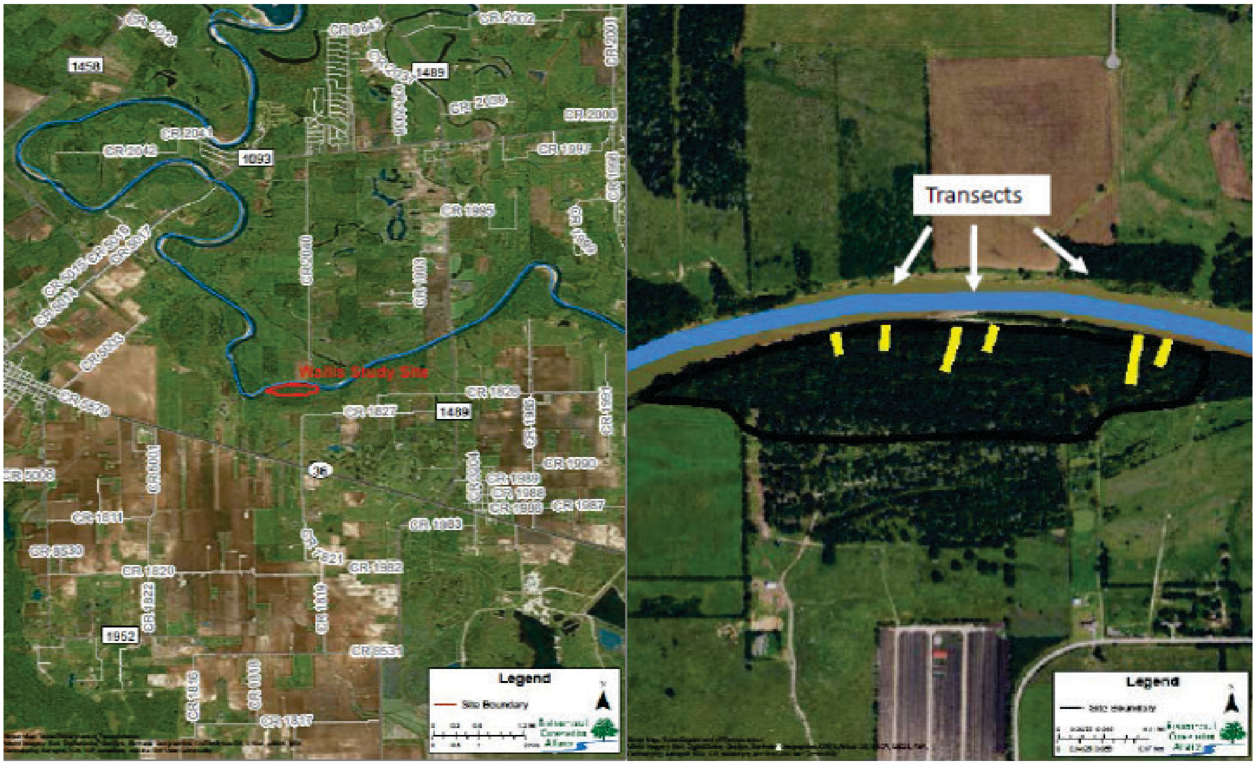


Figure 46. Riparian site at Wallis (left panel). Close-up of riparian transects (right panel).

Elevations from each riparian transect were plotted and overlayed with tree and sapling locations. Plots were reviewed to identify key elevations where water would provide connections to and/or inundate indicator trees or saplings. The riparian species information collected at each site is presented in Appendix D and the transect profile plots in Appendix E. Figure 47 below is an example of the transect profile plots and the analysis undertaken at each riparian site. Gray horizontal bars at the bottom of the figure indicate the extent of indicator tree species and transects where indicator species were observed. Blue vertical lines indicate 80% extent inundation for each indicator species. Blue numbered polygons indicate key elevations of flow pulses and the intended benefit of each flow pulse (provided in the caption). Streamflow magnitudes to reach key elevations, timing of pulses, frequency, duration, and benefits to riparian indicator species were assembled.

Habitat inundation analyses (wetted surface rather than transect profiles) were empirical evaluations designed to directly measure riparian habitat inundation. Transitions among riparian habitats and from wetland to non-wetland floodplain communities can occur with a change in elevation of only a few centimeters (Alldredge and Moore 2012). Therefore, the following empirical approach may more accurately delineate wetted surfaces within the geomorphic complexity of riparian areas. In this manner, the wetted surface created by a given river stage provides a direct estimate of the affected elevations and habitat areas within riparian areas. Detailed descriptions of the methodology utilized and limitations can be found in Hayes (2016a, 2016b, 2016c). Inundation analysis output for the Wallis riparian site is shown in Figure 48 and Figure 49.

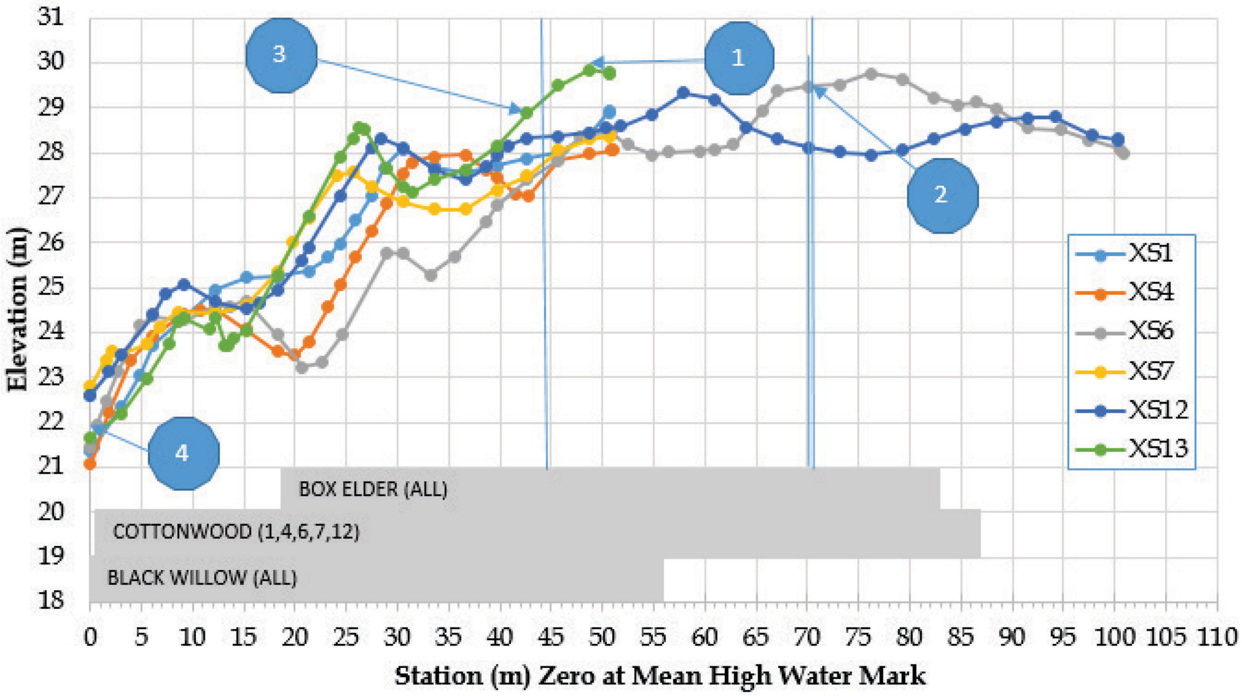


Figure 47. Riparian transect profiles at the Wallis site. (1) Elevation of 29.8 meters to inundate 80% extent of box elder. (2) Elevation 29.47 meters to inundate 80% extent of cottonwood. (3) Elevation of 28.88 meters to inundate 80% extent black willow. (4) Elevation of 22 meters, estimate of average mean high water mark, needed for routine channel maintenance.

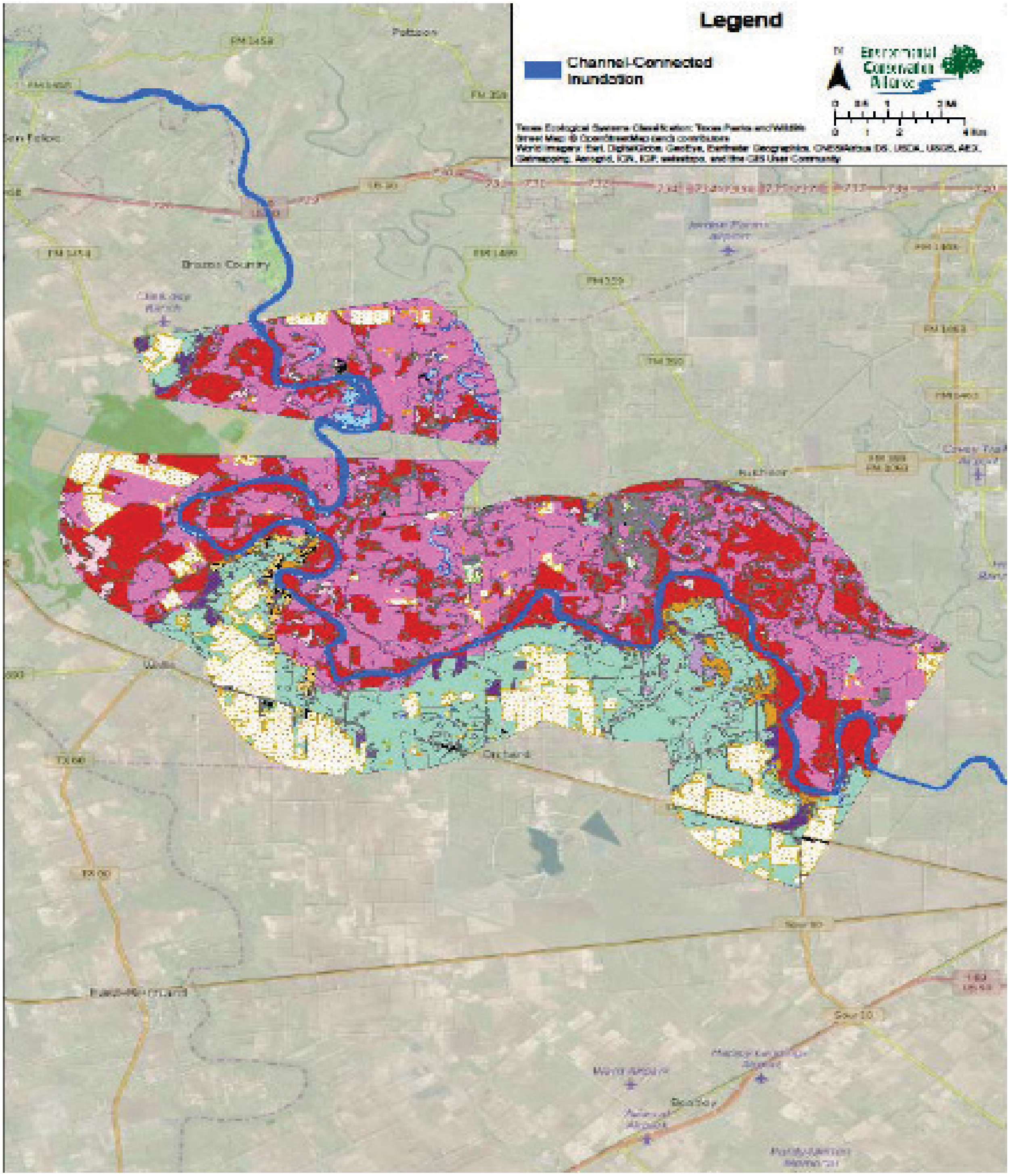


Figure 48. Channel-connected inundation map at Wallis riparian site at a flow of 56,100 cubic feet per second on January 19, 1992.

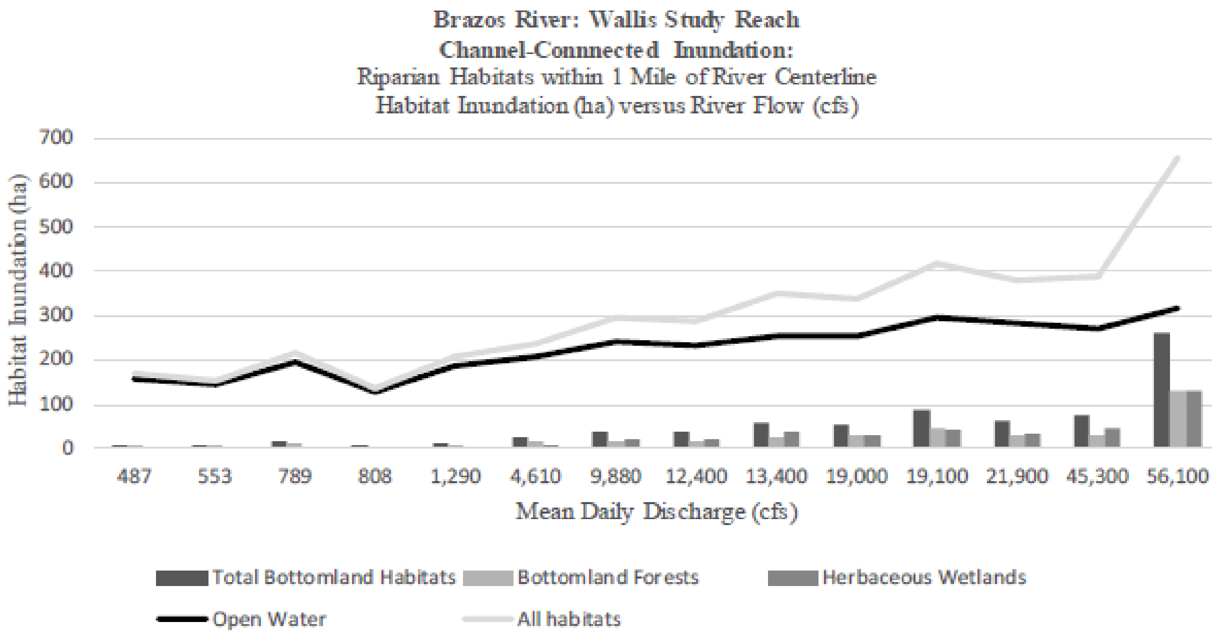


Figure 49. Riparian habitat inundation versus streamflow at the Wallis riparian site.

2.4 *Physical Processes*

The primary objective of investigations of physical processes (or geomorphology) was to identify relationships between flow and maintenance of the channel and banks that form the physical habitats along and within the middle and lower Brazos River (TIFP/BRA 2010). These habitats are of great importance to the biological features of the riverine ecosystem, including fish and riparian vegetation. Other objectives related to physical processes included examining the available literature describing the relationship between the river and alluvial and associated aquifers (discussed in Section 2.6.2) and summarizing the impacts of overbank flows on human activities and infrastructure. To meet these objectives, a geomorphic history of the middle and lower Brazos was summarized from the available literature (Section 2.4.1), historical stream gage measurement data was analyzed (Section 2.4.2), and sediment transport modeling was completed (Section 2.4.3). Flood impact summaries provided by the National Weather Service at USGS locations in the sub-basin were also reviewed (Section 2.4.4).

2.4.1 *Geomorphic History of the Brazos River*

Phillips (2007) describes some of the changes that the Brazos River has undergone prior to human influence on the landscape. Similar to other Texas coastal plain rivers, abandoned channels indicate that in earlier geologic eras, the Brazos River was larger than its current size. The ancient Brazos built up a large floodplain with thick alluvial sediments in which the current channel is sculpted. About 8,500 years before present, the Brazos transitioned to a much smaller stream incised in earlier deposits. By 500 years ago, the Brazos was already deeply entrenched (Waters and Nordt 1994). Descriptions of early European settlers confirm that the middle and lower Brazos had high banks well before intensive human alteration of the landscape. For example, Dr. Felix Robertson described banks nearly 50 feet high when he visited the Brazos River near its confluence with the Little River during the winter of 1825-26 (McLean 1984). Phillips (2007) describes several other natural processes that have impacted the middle and lower Brazos, including changes in sea level and channel avulsions (rapid transitions to a substantially different channel location).

As described in Section 2.2.1, the hydrology of the middle and lower Brazos River sub-basin has been altered by construction and operation of large reservoirs on tributaries and the main-stem of the river upstream of the study area. Changes in hydrology also impact the amount of sediment transported by the river, which, over time, can lead to changes in channel shape and associated habitats. River channel responses downstream of large dams can be complex (Williams and Wolman 1984, Kondolf 1997, Shields *et al.* 2000, and Brierely and Fryirs 2005). Depending on distance downstream, interactions with other variables such as underlying geology, riparian vegetation, and time since dam closure, the channel may experience incision (degradation) or deposition (aggradation), channel widening or narrowing, and a reduction in lateral channel migration.

Investigators have long recognized the potential for reservoirs to affect channel conditions in the middle and lower Brazos River. However, little data have been collected to clearly identify what changes in the channel have occurred or are taking place. Mathewson and Minter (1976) determined that reductions in peak flows below Whitney Dam reduced the Brazos River's ability to transport sand downstream. They anticipated that the impact of upstream dams would be reduced with distance downstream from Waco. Therefore, they expected sand to accumulate in the channel in the upstream end of the middle and lower Brazos, but be evacuated from the lower portions. A suitable set of historic and contemporary channel surveys was not available to directly confirm or deny their hypothesis. To this day, scant data regarding the condition of the channel are available, but what is available (at USGS gage locations, discussed in Section 2.4.2) does not support significant sand accumulation anywhere along the middle and lower Brazos River.

Giardino and Lee (2011) used aerial photography to examine changes in channel width and the rate of channel migration on the Brazos River between Waco and Highway 21 near Bryan before and after construction of large reservoirs in the basin. They limited their study to this area because they believed channel migration rates downstream of Highway 21 were small even before completion of large reservoirs in the basin. This is consistent with an observation by Heitmuller and Greene (2009) that lateral migration rates along the Brazos River are greater between Waco and Hempstead and lower below Hempstead. Giardino and Lee (2011) found that both channel width and migration rate between Waco and Highway 21 decreased in the period after dam construction. This would be consistent with vegetation encroaching on the channel due to reduced peak flows, resulting in additional incision and increased resistance to lateral migration of the river channel, an impact that has been observed in channels below dams in other systems (Kondolf 1997). Survey data for the channel, however, were not collected as part of the Giardino and Lee study and, in any event, there are few historical data available with which to compare to evaluate changes.

Heitmuller and Greene (2009) examined aerial and ground photographs and gage data including field notes to evaluate historical channel adjustments along the middle and lower Brazos River. Channel cross-section and other data are repeatedly collected at USGS gaging stations to maintain flow versus stage relationships (or "rating curves"). Although limited to a few locations along the river, these data sets provide valuable information describing how the channel has changed over time. Based on this data, Heitmuller and Greene (2009) made several observations. First, by means of repeat photos at gage locations, they observed that since the 1960's, point bars have grown vertically and vegetation has encroached on the channel at all sites on the Brazos they observed (Waco, Highbank, Bryan, Hempstead, Richmond, and Rosharon). Such conditions, which promote channel incision, are consistent with what has been observed below dams in other systems (Kondolf 1997). Second, Heitmuller and Greene (2009) observed channel incision at all gaging stations along the main stem, with the general trend being greater incision farther downstream. While channel incision is consistent with the impact of dams, the general trend would be less incision further downstream of the dams (Williams and Wolman 1984). The trend for greater incision downstream opens up the possibility that additional factors beyond upstream dams are responsible for incision in the middle and lower Brazos.

Based on data available from six USGS gaging stations, Phillips (2013) identified the magnitude of flow events required to carry out specific geomorphic functions including mobilization of bed and bank material. He also examined how often these flows have occurred in the recent hydrologic record (1983-2012) and concluded that flows are currently sufficient to preserve the Brazos River's character as an actively laterally-migrating channel. He also described expected geomorphic changes if the frequency of flows increased or decreased in the future.

Other human activities in addition to dam building have the potential to influence the physical channel of a river, including land use change, dredging and removal of large woody debris, channelization and levees, and sand and gravel mining. Over the past nearly two centuries, the middle and lower Brazos River has experienced many of these influences. Because of the many human activities that may have impacted the channel, it is difficult to estimate the contribution of individual activities to channel change along the middle and lower Brazos River. However, an examination of when activities occurred and when channel changes were observed does provide some insight.

Land use changes related to rural and agricultural lands might have influenced the middle and lower Brazos. As an example of one such change, Dunn and Raines (2001) reported that harvested acres of non-hay crops in the lower third of the Brazos River basin decreased from about 32 percent of the area in 1924 to about eight percent in 1992. This change in land use had the potential to decrease the amount of silt and clay sized sediments ("wash load") reaching the Brazos River channel and would have occurred gradually since about 1924.

To reduce damages due to flooding, levees have been constructed at various locations along the length of the middle and lower Brazos. In 1910, a 27-mile length of levee was constructed near Bryan and protected portions of Brazos, Burleson, and Washington counties (Fuller 1913). However, interest in levees in the middle Brazos waned after construction of large flood control reservoirs in the basin (TSHA 2017). At present, actively maintained levees are restricted to Fort Bend County along the lower Brazos River (FBC 2017).

With one notable exception, there have been few attempts to channelize the middle and lower Brazos River. The exception occurred in 1929 when a new, seven-mile channel was dredged to the west of Freeport near the mouth of the Brazos River (Smith 1964). The river was subsequently diverted to the new channel, reducing the threat of flooding in Freeport and sedimentation in the harbor. The river remains in this "new" channel to this day.

Activities to reshape the Brazos River channel to accommodate navigation began midway through the 19th century. Many steamboats operated on the Brazos River from 1830 to 1895 (Smith 1964). To ease navigation, attempts were made to remove shoals from the lower river as early as 1857 (Burke 1976). Removal of snags and cutting of overhanging trees was an ongoing activity by 1913 (TGDN 1914). The dredge boat *C.W. Howell* (see Figure 50), capable of dredging a channel as deep as seven feet (Houston Post 1910), operated on the lower Brazos at least as far upstream as Richmond (Houston Post 1906) in the early 20th century. More intensive efforts to promote navigation as far inland as Waco included plans for construction of a system of eight locks and dams. The US Army Corps of Engineers began work on the lock and dam system in 1905, but abandoned the work in 1922 after only three locks were constructed (CIC 1981). The US Army Corps of Engineers continues to dredge the Gulf Intracoastal Waterway, which intersects the Brazos River about a mile from the coast.

Though dredging of the river channel to promote navigation has now ceased for all but the lowest portions of the river, the river is still dredged as a source of sand and gravel (Figure 51). From 1979 through 1995, 11 million cubic yards of sand and gravel were mined from a 115-mile length of the Brazos River between Hempstead and the Fort Bend-Brazoria county line (Gustavson and Bullen 1996). That is the equivalent to 650,000 cubic yards of material per year removed from the reach. For comparison purposes, Mathewson and Minter (1976) reported that since 1952 the river transported an average of 1.2 million cubic yards of sand per year past the Richmond gage location. Dunn and Raines (2001) surmised that the quantity of sand mined from the Brazos River from 1979 to 1995 could represent as much as 25 percent of the total sand transported by the river, but could not quantify the overall long-term effects. Gustavson and Bullen (1996) studied downstream meander rates and the composition of sediment bars and concluded that these characteristics of the river had not been impacted by sand and gravel mining. However, incision, the most typical geomorphic impact of sand and gravel mining (Kondolf 1997), was not investigated by their study.

Figure 50. Dredge C.W. Howell on the lower Brazos River, circa 1907. (Schauerhammer and Roesch 1907).

Figure 51. Sand and gravel dredge on the lower Brazos River, circa 2013.

In-channel sand and gravel mining causes incision (or degradation) both upstream and downstream of an excavation pit (Figure 52). Part (a) of Figure 52 shows the profile of a stable river channel prior to mining. The flow and sediment load moved by the flow are the same along the length of the stream segment. Excavation of a mining pit, shown in part (b), lowers the channel elevation in a portion of the channel. Flow in the entire stream segment remains the same as during the pre-mining condition. At the top of the stream segment (right side of the figure), the sediment moved by the flow also remains at pre-disturbance levels. However, in the area of the pit, flow depth increases dramatically, reducing the capacity of the flow to transport sediment. A portion of the sediment carried by the water drops out and begins to build up the bottom of the pit. Below the pit (left side of the figure), a much shallower flow depth is reestablished, increasing the capacity of the flow to move sediment. The "hungry water" that has lost some of its sediment in the excavation pit now mobilizes sediment from the bed of the channel downstream of the pit until the sediment load reaches pre-disturbance levels. This process lowers the bed of the channel downstream of the pit (termed degradation or incision). At the same time, the steep head wall of the pit is susceptible to collapse, further building up the material in the bottom of the pit. Head wall collapse sends a nick point moving upstream, much like a head cut in a gully, lowering the bed elevation of the channel upstream of the pit as well.

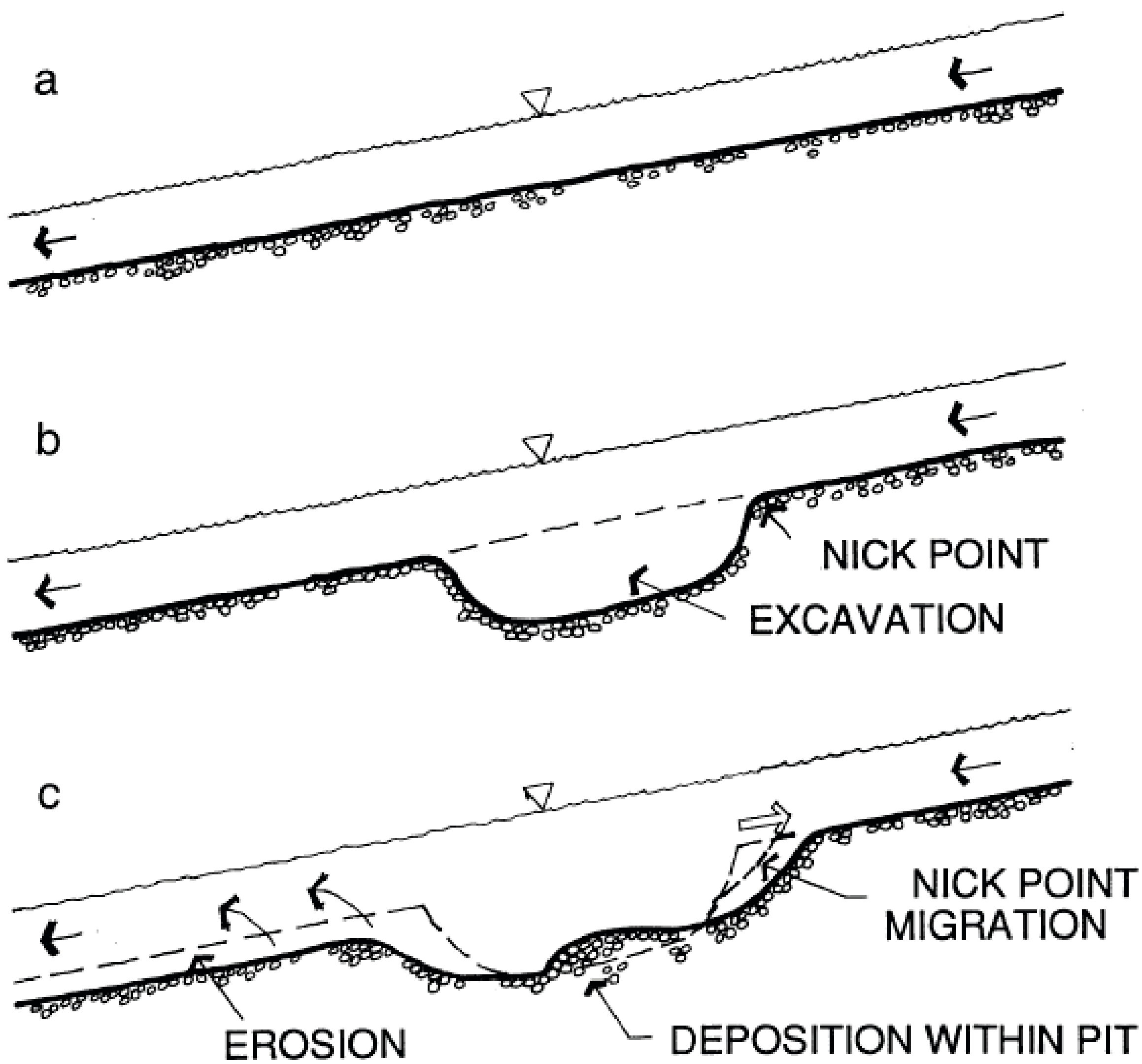


Figure 52. Impact of an in-channel sand and gravel mining pit on channel stability. A stable channel (a) is lowered in a localized area by excavation of sand and gravel (b). Over time, (c) the channel is lowered by means of nick point migration (upstream) and erosion (downstream) (Kondolf 1997).

2.4.2 *Historical Measurement Data from USGS Gages*

As part of this study, USGS gage data similar to that examined by Heitmuller and Greene (2009) were examined. Measurement data for USGS Gage No. 08114000 Brazos River at Richmond are shown in Figure 53 and Figure 54. Similar figures for additional stream gage locations are included in Appendix A. Figure 53 shows measurement data collected at the Richmond gage for three time periods: 1921-1940, 1961-1980, and 1996-2015. Flow (or discharge) is plotted on the x-axis and water surface elevation is plotted on the y-axis. The data for each time period provides the general shape of the stage-discharge rating curve during the time period. Similar to results of Heitmuller and Greene (2009), this figure shows the channel has incised over time at this location. Across the range of flows, water surface elevations for equivalent flows are lower for successive time periods.

Figure 54 shows water surface elevation data for a specific range of flows (2,500 to 3,500 cfs) across the time of available measurement data for the USGS gage at Richmond. Note a period of slightly rising water surface elevations from 1930 to 1940, prior to large reservoir construction in the basin. This is followed by a period of decrease in water surface elevation (indicating channel incision) beginning in 1940 and seeming to stabilize by about 1980. This is consistent with the typical impact of large reservoirs on downstream channels which includes rapid incision immediately after dam closure followed by much slower incision in later decades (Williams and Wolman 1984). Also notice that after 1980 there is another large drop in water surface elevation, indicating another period of incision that has continued to the present time.

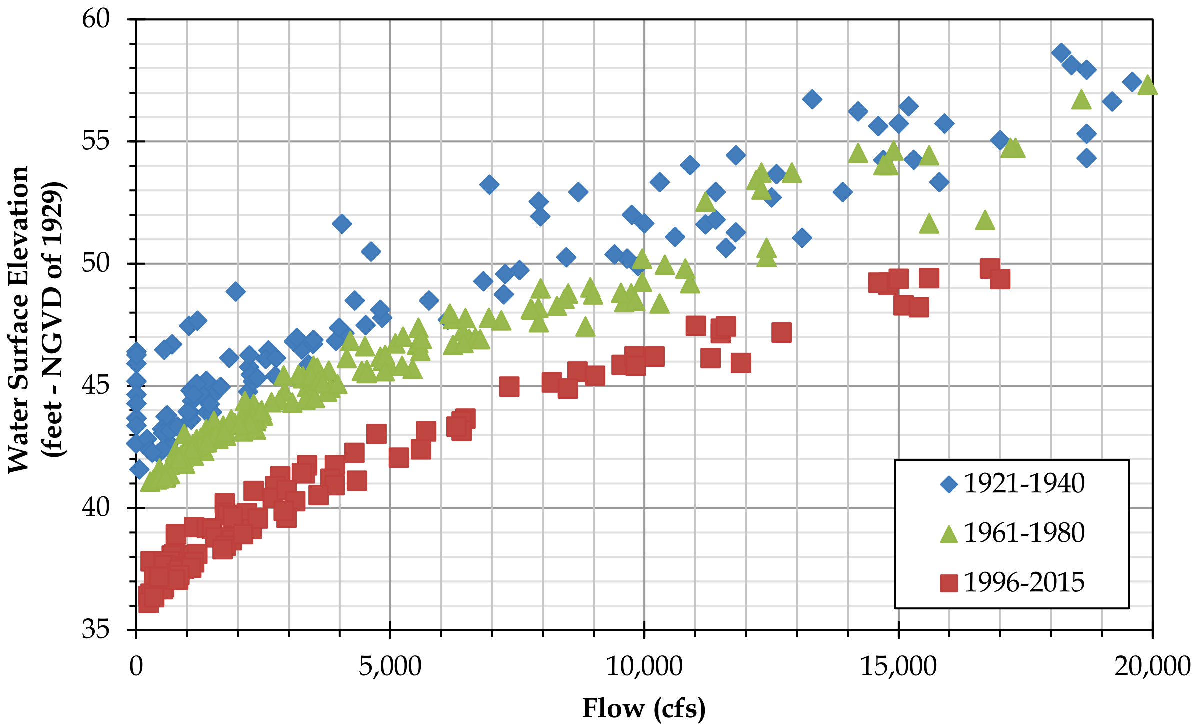


Figure 53. Water surface elevation versus flow (in cubic feet per second-cfs) measurements collected during 1921-1940, 1961-1980, and 1996-2015 at the location of United States Geological Survey Gage No. 08114000 Brazos River at Richmond.

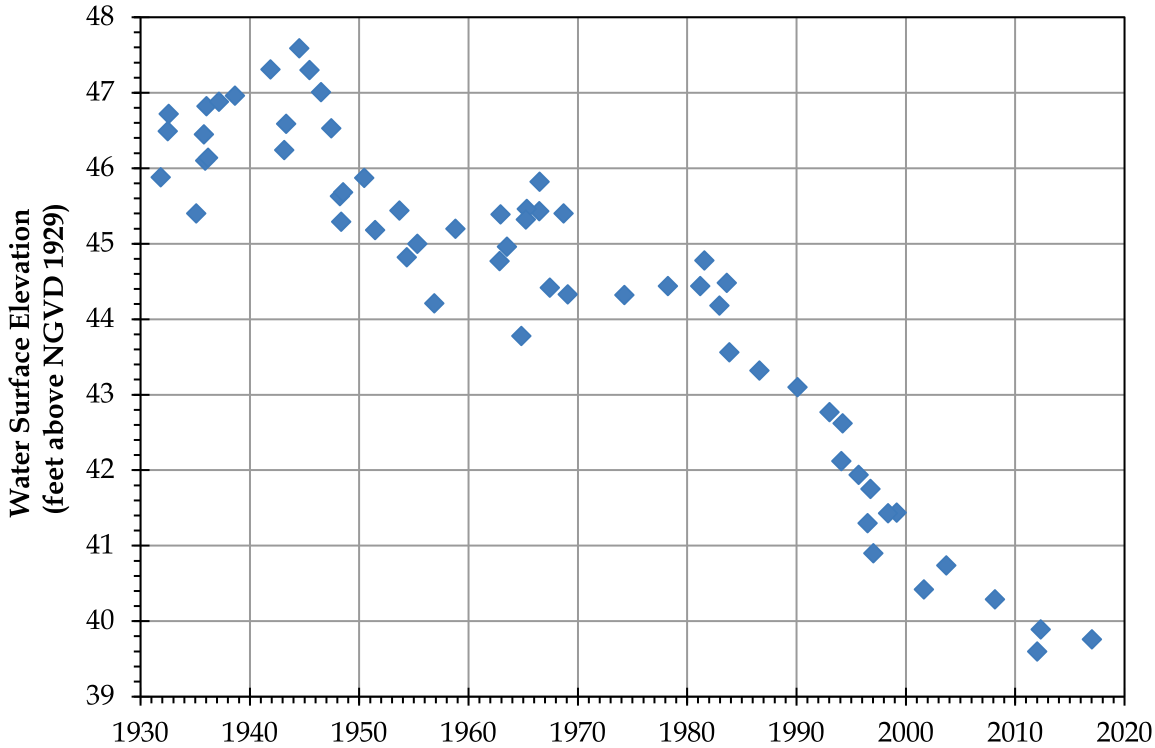


Figure 54. Water surface elevation for flows in the range of 2,500 to 3,500 cubic feet per second at United States Geological Survey Gage No. 08114000 Brazos River at Richmond.

Tables 18 and 19 show estimates of the incision rates at USGS gage station locations on the middle and lower Brazos River. Table 18 provides data for 1950-1980, a period just after the beginning of large dam construction in the basin. Note that some gage stations do not have measurement data beginning as early as 1950. For those stations, calculations were made with the available data. Table 19 shows data for a later time period, 1980-2010. Again, note that one station did not have measurement data for this entire period. Calculations for this station were based on part of the time period. Incision data from these tables were estimated from figures similar to Figure 54 for each gaging station, which are included in Appendix A.

Table 18. Approximate channel incision rates at United States Geological Survey gage stations on the middle and lower Brazos River, 1950-1980.

USGS Gage No.	USGS Gage Name	River Mile	Flow Range (cfs)	Time Period	Approximate Incision (feet)	Incision Rate (feet/ decade)
08096500	Waco	401	500-1,000	1950-1980	4.0	1.3
08098290	Highbank	347	750-1,250	1965-1980	<0.3	<0.2
08109000	Bryan	281	1,500-2,000	1950-1980	1.3	0.4
08111500	Hempstead	194	2,000-3,000	1950-1980	1.5	0.5
08114000	Richmond	92	2,500-3,500	1950-1980	1.5	0.5
08114000	Rosharon	57	3,000-4,000	1967-1980	<0.5	<0.3

Table 19. Approximate channel incision rates at United States Geological Survey gage stations on the middle and lower Brazos River, 1980-2010.

USGS Gage No.	USGS Gage Name	River Mile	Flow Range (cfs)	Time Period	Approximate Incision (feet)	Incision Rate (feet / decade)
08096500	Waco	401	500-1,000	1980-2010	2.0	0.7
08098290	Highbank	347	750-1,250	1980-2010	0.6	0.2
08108700	SH21 near Bryan	286	1,400-2,000	1992-2010	<0.5	<0.3
08111500	Hempstead	194	2,000-3,000	1980-2010	2.0	0.7
08114000	Richmond	92	2,500-3,500	1980-2010	4.4	1.5
08114000	Rosharon	57	3,000-4,000	1980-2010	4.7	1.6

Data for the earlier time period in Table 18 show a pattern of greater incision at Waco, with decreased incision moving downstream. An exception to this pattern is the incision at Highbank. It should be noted that bedrock outcrops in the area of that gage limit the channel's ability to incise. But the general pattern of decreased incision downstream of Waco is what would be expected if the cause of the incision were the effects of large reservoirs on the Brazos upstream of Waco.

The rate of incision at Waco has slowed in the later time period (1980-2010) compared to the earlier time period (1950-1980), as would be expected in later decades if the cause of incision at this location was the construction of large dams upstream during the previous time period. Note, however, that the incision rate at the lower gages (Richmond and Rosharon) has increased from the earlier time period. Total incision for the entire time period (1950-2010) is also greater at these gages than at Waco. Incision caused by dams is typically greatest at or near the dam and decreases with time (Williams and Wolman 1984). The pattern of greater incision farther from the dams decades after dam construction supports the idea that one or more disturbances initiated in the lower part of the river network about or shortly before 1980 are major contributors to, if not the main cause, of the current incision in the lower part of the river.

It is beyond the scope of this study to determine the main causes of incision in the sub-basin and their relative contribution to channel change. However, the ongoing incision has a profound impact on the TIFP study of the middle and lower Brazos River. First, as will be discussed in Section 2.6.1, the ongoing incision impacts the flows that support riparian trees and connect with oxbow lakes. At some locations in the basin, flows that carry out these functions today will no longer do so in a decade or two. Second, channel instability, as represented by incision rates of more than half a foot per decade, presents a challenge to sediment transport analysis of the sub-basin.

2.4.3 *Sediment Transport Modeling*

The goal of sediment transport modeling carried out for this study was to ensure that flow recommendations would not contribute to instability in the middle and lower Brazos River. As noted in Section 2.4.2, the lower Brazos River is currently degrading. As noted by Phillips (2013) a reduction in the flows that carry out geomorphic functions such as mobilizing bed material could lead to channel aggradation. Therefore, it might seem plausible to reduce flows in the system to balance aggradation and degradation, thereby achieving a geomorphically stable channel. Such a scheme would be analogous to dealing with a stuck throttle on a car by installing and applying more powerful brakes. Although theoretically possible, this would require very careful study (beyond the scope of this effort) and manipulation of the flow regime in this area of the river. Given the magnitude of the incision rate near Richmond and Rosharon (more than a foot per decade), it would require a very significant reduction of flow to achieve a "balance" between aggradation and degradation. In addition, the resulting flow alteration would adversely impact lower reaches of the river. Identifying and removing the source of the degradation and mitigating impacts would be a less costly and more plausible remedy.

The channel shape (geometry or bathymetry) of an alluvial river adjusts in response to the range of flows that mobilize the boundary sediments. A stable channel shape is important because it maintains habitat conditions that support biological resources both within the channel and in near-channel riparian areas. Flow recommendations will only be successful if they support the long-term creation and maintenance of desired aquatic and riparian habitats. Changes in the flow regime of a stable channel can cause unstable conditions due to changes in the rate of erosion, sediment transport, and/or sediment deposition. The existing instability in the system makes predicting the outcome from changing the flow regime of an unstable channel more difficult.

While sediments are moving in any river and channel shape is always adjusting, a stable channel exhibits what river engineers call "dynamic equilibrium." Once dynamic equilibrium is disrupted, the channel will be unstable while these processes work to reestablish equilibrium by changing the channel geometry (width, depth), width-depth ratio, sinuosity, and slope (Schumm 1969). Such changes in channel geometry have the potential to alter the amount and nature of aquatic and riparian habitats and therefore biological communities.

There is some scientific literature regarding the flows required to maintain the physical characteristics/habitats of stable river systems. Biedenharn *et al.* (2000) report that channels should remain dynamically stable if the sediment transport capacity of a reach is within 10% of the sediment supplied to the reach. Acreman *et al.* (2010) report that environmental standards adopted in the United Kingdom were developed with consideration of biology (macro-invertebrates, fish, and macrophytes) and geomorphology. Those standards allow diversion of from 7.5 to 30% of the mean annual flow, depending on geomorphology, flow conditions, and desired ecological status. In addition, at least some of the reported impacts on biological communities due to flow alterations are probably due to changes in river geomorphology (and therefore habitat). Poff and Zimmerman (2010) found that a 50% change or greater in flow magnitudes (including peak, total or mean, base or hourly discharge) had a negative impact on fish communities. They could not precisely identify the level of flow alteration when fish were likely to be impacted, however, because of limited data related to systems with flow alterations in the range of 0 to 50%. Carlisle *et al.* (2010) found that a 60% decrease in the mean annual maximum flow was likely to lead to degraded fish communities. In most systems, mean annual maximum flows significantly affect the channel's shape or morphology. The impact on fish communities related to changes in mean annual maximum flow may be directly related to changes in habitat, though disruptions to spawning cues, access to floodplain habitats, or other factors may also play a role.

Very little research has been devoted to identifying suitable flows for unstable river systems. Given that current conditions of an unstable channel will not maintain existing characteristics and habitats, maintaining the current sediment transport rate may or may not lead to a desirable outcome. By its nature, an unstable channel is transitional between a past stable condition and a future stable condition. Left on its own, an unstable channel will continue to aggrade or degrade until it reaches a future configuration of channel width, depth, and slope that promotes stability. This transition may take many decades to be completed, but in most cases, the future configuration will not support the habitats (such as oxbow lakes and riparian areas) associated with the past configuration. Without other intervention activities (such as physical channel restoration), the habitats currently associated with an unstable channel cannot be maintained simply by maintaining a flow regime.

As part of this study, sediment transport calculations were made for one study site on the lower Brazos River. Because the channel in this area is unstable due to ongoing incision, a more sophisticated analysis than was completed for the TIFP study of the lower San Antonio River (TIFP 2017) was required. In addition to calculating sediment transport rates at the Richmond gage location with the SAMWIN software, a Hydrologic Engineering Center River Analysis System (HEC-RAS) computer model was developed for the 4.5-mile study site near Allens Creek. This model allowed channel characteristics such as width, depth, and slope to adjust in response to flow regime and sediment inputs. The model was run with successive iterations of the historical 1996-2015 flows recorded at the Richmond gage until a stable channel was achieved. The transition to a stable channel is currently ongoing along this reach of river and may not be achieved for decades. After stability was achieved in the modeled channel, alternative flow scenarios were applied to the model and results were analyzed to determine if flow scenarios were capable of maintaining a stable channel. Results from the analysis are summarized in Section 3.3.3. Methods are described in more detail in Appendix F.

2.4.4 *Flood Impact Summaries*

During the stakeholder process, concern was expressed regarding the impact of flooding that may be associated with high flow pulse and overbank flows. To address those concerns, flood impact summaries provided by the National Weather Service for USGS gage locations on the middle and lower Brazos River were examined. The results are summarized in Table 20. In this table, stage estimates provided by the National Weather Service were converted to flow values using the latest stage discharge curve at each USGS gage. Rating curves at Waco and Highbank were extended to 80,000 cfs. No attempt was made to determine flows in excess of 80,000 cfs.

Table 20. Flood impact levels at United States Geological Survey gages on the middle and lower Brazos River.

USGS Gage No.	USGS Gage Name	Description	Stage (ft)	WSE (ft)	Flow (cfs)
08096500	Waco	Major flooding along the river. Water will reach plants along the river. Major Flood	37.0	386.3	62,000
		Moderate flooding along the river.	30.0	379.3	47,000
		Minor flooding along the river.	27.0	376.3	41,000
08098290	Highbank	Major flooding along the river.	40.0	319.3	79,000
		Moderate flooding along the river.	38.0	317.3	74,000
		Minor flooding along the river.	35.0	314.3	67,000

Table 20 (cont). Flood impact levels at United States Geological Survey gages on the middle and lower Brazos River.

USGS Gage No.	USGS Gage Name	Description	Stage (ft)	WSE (ft)	Flow (cfs)
08108700	SH21 near Bryan	Backwater flooding up Little Brazos River and creeks. Church threatened. Major Flood	66.0	255.3	+80,000
		Widespread inundation of downstream floodplain.	60.0	249.3	+80,000
		Farm land along the river inundated.	52.0	241.3	+80,000
08111500	Hempstead	Major flooding along the river.	55.0	162.9	+80,000
		Moderate flooding along the river.	53.0	160.9	+80,000
		Minor flooding along the river.	50.0	157.9	+80,000
08111850	San Felipe	Approach to FM 1458 impassable and upstream home flooded.	129.3	129.4	+80,000
		Water over the gravel driveway of upstream homeowner.	127.8	127.9	+80,000
		Water escapes the channel.	122.5	122.6	+80,000
08114000	Richmond	Homes in Richmond, Simonton and Thompsons flooded.	50.0	77.9	80,000
		Homes in Simonton and Thompsons threatened. Many roads inundated.	48.0	75.9	73,000
		Baudet Rd, Redbird Ln, and south-bound turnaround US 59 threatened. Flood	45.0	72.9	63,000
08116650	Rosharon	Half a foot of water on FM 1462. Many roads impassable. Homes threatened. Major Flood	51.3	51.3	74,000
		River Oaks Road and County Road 25 still passable.	47.0	47.0	58,000
		Minor flooding begins. Cattle should be removed from low areas. Flood	43.0	43.0	49,000

2.5 *Water Quality*

The water quality and subsistence flow evaluations focused on five USGS gages near study sites within three study areas in the middle and lower Brazos River as follows:

- BR 4 - Study Area 4: Brazos River immediately below Lake Brazos near Waco, Texas downstream to Little River confluence near Hearne, Texas. This reach includes the Marlin and Hearne study sites.
- BR 3 - Study Area 3: Brazos River from Little River confluence downstream to Navasota River confluence near Washington, Texas. This reach includes the Mussel Shoals and Navasota study sites.
- BR 2 - Study Area 2: Brazos River from Navasota River confluence downstream

to a point 100 meters upstream of State Highway 332 near Lake Jackson, Texas. This reach includes the Wildcat Bend and Allens Creek study sites.

The TCEQ's Surface Water Quality Monitoring (SWQM) Program monitors and evaluates physical, chemical, and biological characteristics of aquatic systems. The SWQM program coordinates the collection of physical, chemical, and biological samples from more than 1,800 surface water sites statewide, including surface water sites within the middle and lower Brazos TIFP Study area. The locations of the TIFP study sites, USGS gages and SWQM stations are shown in Figure 55.

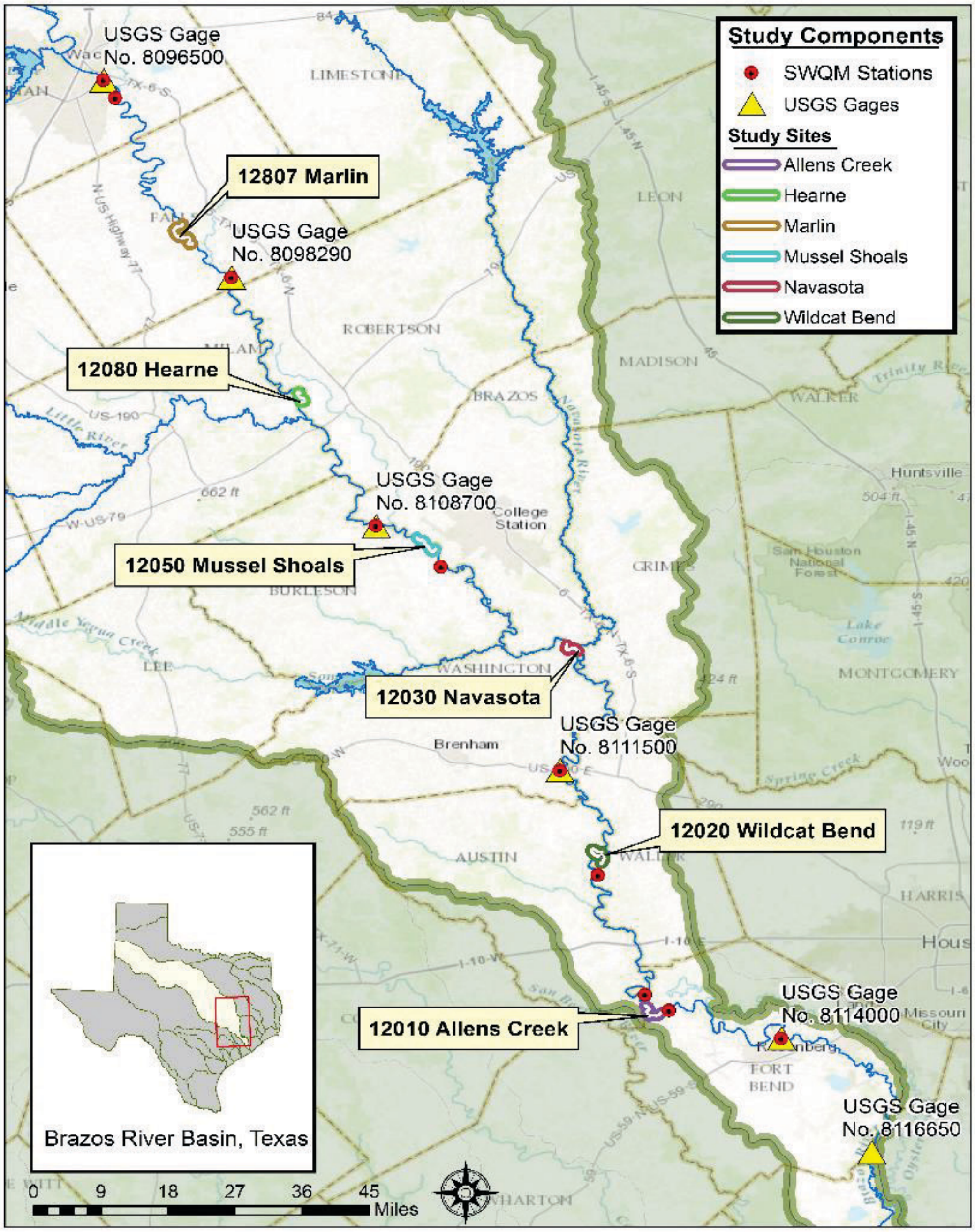


Figure 55. Brazos River study sites, surface water quality monitoring stations and United States Geological Survey gage locations utilized for water quality analysis.

The TIFP developed water quality goals, objectives, and indicators associated with the middle and lower Brazos River Instream Flow Study in collaboration with the stakeholder workgroup (TIFP/BRA 2010). These were utilized to develop water quality goals to assess current water quality conditions relative to historical trends and water quality standards (EC 2010a and 2010b). Water quality goals for the middle and lower Brazos River study are presented in Table 21. Parameters in italics are preliminary water quality indicators identified within the Brazos Study Design. Additional criteria, beyond those identified in the study design, were evaluated to provide a thorough analysis of water quality and determine study goal attainment. These goals are considered by TIFP to be adequate to provide for a sound ecological environment for the middle and lower Brazos River. Temperature and dissolved oxygen are considered by the TIFP as parameters of primary concern and will be the focus of additional analysis, as detailed below.

Table 21. Water quality goals for study areas BR 4, BR 3, and BR2 (adapted from EC 2011).

Parameter	**Instream Flow Goals (Values)**
Tier 1 – Primary Priority	
Dissolved oxygen (DO)	*≤ 12 hours below 3.0 mg/L** *≤ 2 hours below 2.0 mg/L** *> 1.5 mg/L*
Temperature	*≤ 35°C (95°F)*
Tier 2 – Secondary Priority	
DO	*≥ 5.0 mg/L daily average** *= 3.0 mg/L minimum for ≤ 8 hours* *Spring Conditions:* *≥ 5.5 mg/L daily average** *= 4.5 mg/L minimum for ≤ 8 hours*
Temperature	*≤ 27°C (86°F) January - May*
Temperature	*< 35°C (95°F)*
*Total Suspended Solids (90th percentile)***	Study Area BR4 and BR3: ≤ *160.3 mg/L* Study Area BR2: ≤ *518.4 mg/L*
Nitrate	*≤ 1.95 mg/L*
Ammonia	*≤ 0.33 mg/L*
Orthophosphate	≤ 0.37 mg/L
Tier 3 – Additional Parameters	
E. coli	*≤ 126/100 mL (geometric mean)*
Total Nitrogen	no value*
NO_x	*≤ 2.76 mg/L**
Organic Nitrogen	no value*
Total Phosphorous	≤ 0.69 mg/L
Chlorophyll-*a*	≤ 14.4 µg/L*
Salinity	≤ 2 ppt*
Chloride	Study Areas BR4 and BR3: ≤ 350 mg/L Study Area BR2: ≤ 300 mg/L
Sulfate	≤ 200 mg/L
Specific Conductance	≤ 3077 µS/cm
pH	6.5-9.0
Total Dissolved Solids	Study Areas BR4 and BR3: ≤ 1,000 mg/L Study Area BR2: ≤ 750 mg/L

* Water quality data unavailable to evaluate TIFP goal.

**There is no water quality standard for TSS.

2.5.1 *Water Quality Analysis*

Subsistence flows are naturally occurring low flow events that can be seasonal in nature. These episodic low flow events can be represented by extreme conditions that still maintain survival of aquatic organisms although may not always provide for suitable or even optimal water quality conditions at varying spatiotemporal scales. The ecology of river systems is influenced by extreme events on both the high and low flow ends of the spectrum. Having occasional extremes supports populations of native species that have evolved life history strategies in response to the natural flow regime (Poff *et al.* 1997, Bunn and Arthington 2002). The data and analyses used to determine subsistence flow recommendations are discussed in the following sections.

2.5.1.1 Water Quality Models

Water quality goals in Table 21 were used to evaluate water quality conditions and develop water quality models for a wide range of flows to assist in the development of instream flow recommendations (EC 2011, RPS 2016). Espey Consultants, Inc. also assessed available SWQM water quality data within each flow regime component and determined that water quality was generally good. Primary priority goals were achieved at all flow conditions throughout the study area, where data were available (EC 2011, RPS 2016).

TIFP reviewed reports on existing water quality models for the study area to determine their utility for this study. Espey Consultants, Inc. developed water quality models for study reach BR2 (EC 2011). EPD-RIV1 was used to evaluate temperature and dissolved oxygen under various scenarios, including low-flow conditions, pulse flows, diversions, and wastewater treatment plant discharges. QUAL2K was used to further evaluate temperature during low-flow conditions. The EPD-RIV1 predictions for temperature had a much greater range of diurnal variability than observed data. The authors concluded that additional calibration was needed to accurately model daily temperature variation using EPD-RIV1. The QUAL2K temperature model indicated potential for temperature exceedances at lower flows. However, the authors noted that calibration data was very limited for the QUAL2K temperature model and the EPD-RIV1 dissolved oxygen model and recommended additional calibration and field verification.

In 2016, RPS extended the 2011 modeling effort by developing water quality models for study reaches BR2, BR3, and BR4 (RPS 2016). EPD-RIV1 was used to evaluate temperature and dissolved oxygen for the June 2009 low-flow period under various scenarios, including low-flow conditions, pulse flows, diversions, and wastewater treatment plant discharges. All of the modeling scenarios predicted that TIFP primary priority goals for temperature and dissolved oxygen would be met, except at flows well below the subsistence flow recommendations discussed in more detail below. The authors noted that channel geometries had to be assumed because of limited transect data and that the models did not completely match the limited validation data. Although these models can be used to help inform flow recommendations, the TIFP is not solely relying on these models to generate flow recommendations in this study because of the calibration and validation limitations noted by the authors.

2.5.1.2 TIFP Water Quality Data

TIFP conducted additional water quality sampling as shown in Table 22. This data was collected to obtain more site-specific water quality data that could be used to inform model and water quality analyses to support instream flow recommendations.

Table 22. Summary of Texas Instream Flow Program water quality sampling data by study reach.

Study Reach	Study Site	Date(s) Collected
BR4	Marlin	6/19/12 – 6/20/12
		7/25/12 – 7/26/12
		8/7/12 – 8/8/12
	Hearne	8/17/10 – 8/19/10
		8/17/10 – 9/17/10
BR3	Mussel Shoals	6/20/11 - 7/13/11
		8/9/11 – 8/31/11
	Navasota	5/2/12 – 5/4/12
		8/29/12 – 8/30/12
BR2	Wildcat Bend	5/31/12 – 6/1/12
		8/7/12 – 8/9/12
		7/1/14 – 7/2/14
	Allens Creek	N/A

According to the TCEQ 2014 Guidance for Assessing and Reporting Surface Water Quality in Texas (TCEQ 2015), to determine attainment of applicable water quality criteria, assessments must utilize sample sets that are temporally representative of conditions within the study area. Sampling should be conducted on a routine basis over several years (two years minimum) with approximately the same time intervals between sampling events (TCEQ 2015). The frequency or duration of TIFP water quality sampling events did not meet these requirements and therefore the data was not used in the TIFP water quality analysis (discussed in Section 2.5.1.4). Diurnal sonde data was collected from five study sites during summer (June-August) low flow conditions from 2010-2012 and additional sampling was conducted at the Wildcat Bend study site in 2014. At the Allens Creek study site, temperature data was not available and although long-term diurnal data was available at Stephen F. Austin State Park just upstream of the study site, correlating flow data was not available. The USGS gage at San Felipe was established in August 2013, two years after TIFP diurnal sonde data was collected at Stephen F. Austin State Park; therefore, flow data at this gage was not used. It was also determined that the Hempstead and Richmond gages were not appropriate to use due to distance and potential contributing flow. Temperature was outside the primary priority goal of 35°C at the Hearne study site for approximately 3.5 hours (maximum temperature recorded was 35.15°C) and at the Mussel Shoals study site on two occasions during the July 2011 sampling event for approximately 2.5 hours (maximum temperatures recorded were 35.15°C and 35.19°C). Dissolved oxygen and temperature collected at the five study sites overall did not exceed the TIFP water quality goals. Data collected from the other five study sites could be used in combination with other future studies to provide valuable information on temperature and DO levels during extreme summertime temperatures and low flow conditions during drought. Graphs of water quality data from these study sites are provided in Appendix G.

2.5.1.3 Other Scientific Information

The TIFP Technical Overview document (TIFP 2008) supported utilizing data from existing Texas Commission on Environmental Quality water quality programs for SB2 water quality evaluations. Review of TCEQ's 2014 Integrated Report of Surface Water Quality (TCEQ 2014) indicates that the lower mainstem Brazos River is fully supporting of the water quality standards that were assessed. However, a concern for water quality based on screening levels for chlorophyll-*a* was identified for Segments 1201 (Brazos River Tidal), 1202 (Brazos River Below Navasota River), and 1242 (Brazos River Above Navasota River) (TCEQ 2014). These TCEQ segments are located within the TIFP study reaches.

In addition to TCEQ's Integrated Report, water quality analyses conducted by the Brazos Basin and Bay Expert Science Team (BBEST) were reviewed. The BBEST performed a water quality analysis to inform their recommendations for environmental flow standards during the Senate Bill 3 process. The BBEST reviewed available water quality data in the TCEQ Surface Water Quality Monitoring Information System (SWQMIS) database collected at or near selected USGS gages to analyze for variations in water quality with flow (Brazos BBEST 2012) for a period of record through 2010. The BBEST encouraged the TIFP to use the BBEST hypothesis in developing environmental flow recommendations and validate and refine the BBEST flow regime recommendations instead of developing flow recommendations independent of the BBEST (See Section 8 Adaptive Management, Brazos BBEST 2012). Based on concerns related to the water quality models and TIFP collected data discussed above, the Brazos BBEST methodologies were used in the evaluation of subsistence flow recommendations as part of the middle and lower Brazos River Instream Flow Study.

The gages evaluated by the BBEST and the corresponding TIFP study sites are shown in Table 23.

Table 23. Texas Instream Flow Program study sites, corresponding United States Geological Survey gages, and correlating Basin and Bay Expert Science Team gage locations for the Brazos River basin.

TIFP Study Site	USGS Gage No.	Location	Brazos BBEST E-Flow Gage
Marlin & Hearne	08098290	Brazos River near Highbank	No*
Mussel Shoals	08108700	Brazos River at SH 21 near Bryan	Yes
Navasota	No gage available	No gage available	No**
Wildcat Bend	08111500	Brazos River near Hempstead	Yes
Allens Creek	08114000	Brazos River at Richmond	Yes

*BBEST did not use Highbank gage because gages with longer period of records were preferred. Highbank period of record is from 10/1/1965 to current.

** There is no active USGS gage at or near Navasota. USGS Gage No. 08110200, Brazos River at Washington, period of record is from 11/1/1965 to 3/15/1987.

The BBEST recommended subsistence flows based on the 5th percentile flow (Q95) (Brazos BBEST 2012). The subsistence flow recommendations for the middle and lower mainstem Brazos River are shown in Table 24.

Table 24. Brazos Basin and Bay Expert Science Team subsistence flow recommendations (Brazos BBEST 2012) in cubic feet per second.

USGS Gage No.	Location	BBEST Subsistence Flow Recommendations (cfs)
08096500	Brazos River near Waco	56
08108700	Brazos River at SH21 near Bryan	300
08111500	Brazos River at Hempstead	510
08114000	Brazos River at Richmond	550
08116650	Brazos River near Rosharon	430

2.5.1.4 *Evaluation of Subsistence Flow Recommendations*

Subsistence flows are infrequent and seasonal in nature; therefore, they should never occur regularly or for long periods of time (TIFP 2011). As stated in the Lower San Antonio Interim Recommendations Report (TIFP 2011) "increasing the frequency and or duration of these low flow events could affect the structure and function of the river (Rolls *et al.* 2012), and more importantly have been shown to adversely impact fish and macroinvertebrate communities (Lake 2003, Jowett *et al.* 2005, Walters and Post 2011)." Studies on the Klamath River in California, (United States) utilized monthly Q95 flows to develop "base" flow recommendations similar to subsistence flow recommendations (Hardy *et al*. 2006). Other studies in Texas have utilized the Q95 method to develop flow recommendations for water bodies in Texas (BIO-WEST 2008, Sabine and Neches BBEST 2009, TIFP 2011).

Additionally, the Brazos BBEST recommended subsistence flow values were based on the 5th percentile (Q95) (through 2010) (Brazos BBEST 2012). The Q95 was recalculated based on gage data through 2016, to evaluate whether or not the Q95 values have significantly changed as a result of drought conditions that occurred during 2011-2016. The Q95 (updated through 2016) is not significantly different from the BBEST calculated Q95 values and the values are shown in Table 25.

Table 25. Evaluation and comparison of updated Q95 to the Basin and Bay Expert Science Team Q95 values.

USGS Gage No.	Location	BBEST Q95 (Through 2010)	Q95 (Updated through 2016)
08109000 (includes 08108700)	Brazos River near Bryan	299 cfs	299 cfs
08111500	Brazos River at Hempstead	508 cfs	485 cfs
08114000	Brazos River at Richmond	550 cfs	517 cfs

After inconclusive modeling results (as discussed in Section 2.5.1.1), the water quality evaluation focus shifted to identifying subsistence level flows that might cause an exceedance of the primary priority (Table 21) parameters (specifically DO and water temperature). A water quality analysis was conducted and evaluation of the TIFP water quality goals (Table 21) by extending the previous work of the BBEST through 2016. In addition, the entire period of record for dissolved oxygen and temperature are discussed below. The updated 2014 Surface Water Quality Monitoring Guidance for Assessing and Reporting Surface Water Quality (TCEQ 2015) and TIFP water quality goals (Table 21) were used to review available water quality data in the TCEQ SWQMIS database. This document also provides additional guidance regarding sample size, methods for determining sampling uncertainty, and determining criteria attainment (TCEQ 2015).

To evaluate subsistence flow recommendations, the water quality analysis was performed for SWQM water quality data collected at or near USGS Gage Nos. 08096500 (Brazos River at Waco), 08098290 (Brazos River at Highbank), 08108700 (Brazos River at SH21 near Bryan), 08111500 (Brazos River at Hempstead), and 08114000 (Brazos River at Richmond). The entire period of record of water quality data for dissolved oxygen and temperature was used for this analysis and the TIFP primary and secondary priority values were used to assess the data. TIFP water quality goals that were not evaluated due to lack of available data are noted in Table 21.

To evaluate TIFP Tier 2 (secondary priority) and Tier 3 (additional parameters) water quality goals as shown in Table 21, the analysis was performed for SWQM water quality data collected at or near USGS Gage Nos. 08098290 (Brazos River at Highbank), 08108700 (Brazos River at SH21 near Bryan), and 08111500 (Brazos River at Hempstead). These SWQM stations were at or near a TIFP study site and were selected for this analysis based on the following criteria, 1) proximity to USGS gaging stations, 2) proximity to TIFP study sites, 3) data availability, and 4) hydrologic influences. One exception occurred for SWQM Station Nos. 15767 and 13666 where a low sample size was noted.

TIFP performed scatterplot analyses to determine variations in water quality at different flows (Figures G-6 through G-25 in Appendix G). Overall water quality data indicated DO and temperature levels within the study reaches met the TIFP water quality goals and are expected to be protective of aquatic life under low flow conditions. In addition, DO and temperature concentrations met primary priority water quality goals within all three study reaches (BR4, BR3, and BR2) under flow conditions sampled. The results for DO and temperature are discussed here.

The scatterplot analyses showed that temperature did not exceed the TIFP primary priority water quality goal (Table 21). The scatterplot analysis showed that during January-May timeframe, temperature for some individual sampling events were above the TIFP secondary priority water quality goal value of 27°C (January-May); however, the temperature results for the majority of sample events was below 27°C and overall did not exceed the TIFP secondary priority water quality goal (Figure 56). In addition, some of the temperatures above 27°C (January-May) were during flow conditions that would be considered base flow or higher. The scatterplot analyses showed that overall DO did not exceed the TIFP primary or secondary priority water quality goals (Table 21) (Figure 57). See Appendix G for results for other parameters and the additional scatterplot analyses for DO and temperature.

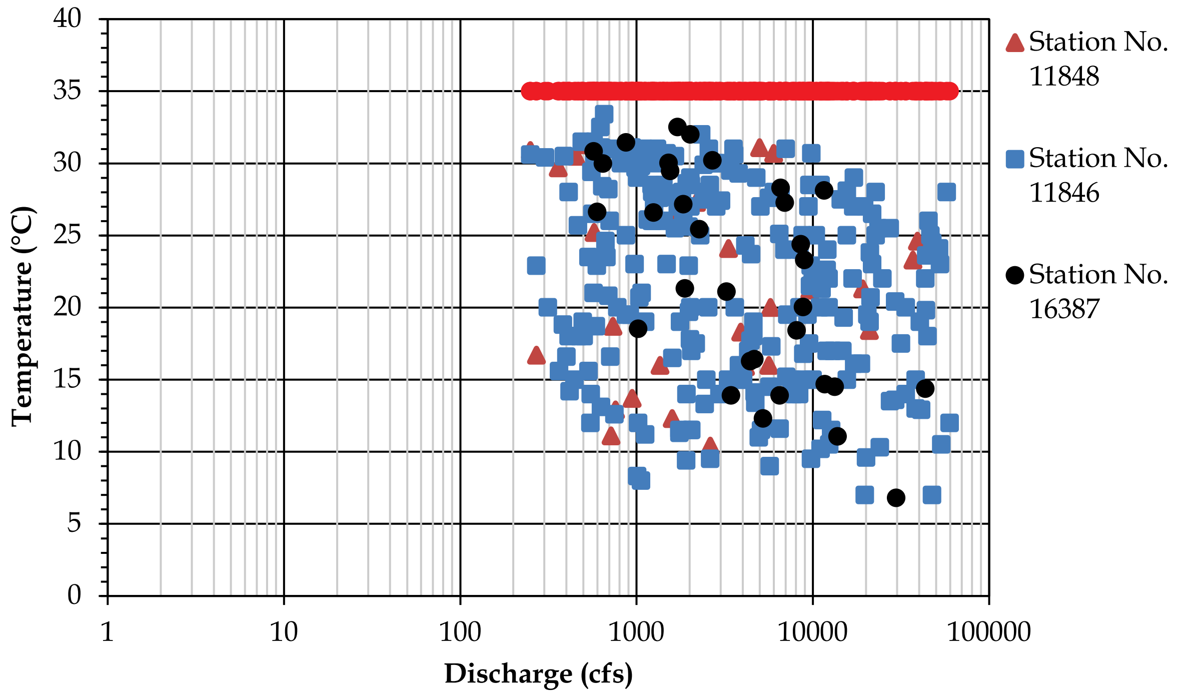


Figure 56. Temperature data for surface water quality monitoring stations near United States Geological Survey Gage No. 08114000 (Richmond) Texas Instream Flow Program primary priority (all dates).

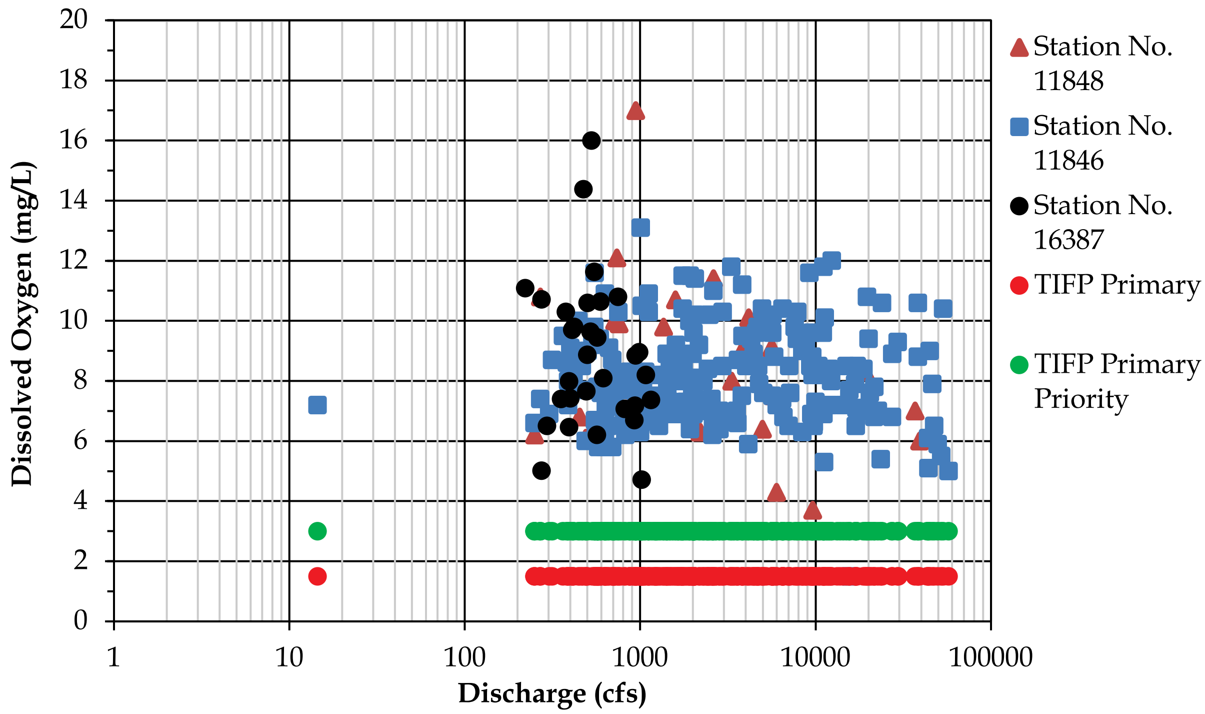


Figure 57. Dissolved oxygen data for surface water quality monitoring stations near United States Geological Survey Gage No. 08114000 (Richmond) Texas Instream Flow Program primary priority (all dates).

As previously stated, additional water quality parameters were evaluated to provide a thorough analysis of water quality and determine study goals attainment. As shown in Appendix G, water quality parameters identified in Table 21 achieved goal attainment for all parameters except Total Suspended Solids (TSS). While these were identified as priority parameters for consideration, the TIFP did not conduct additional modeling or analyses to develop flow recommendations to maintain these parameters given current goals were achieved for these parameters. Water quality impairments related to bacteria and nutrients are currently addressed by other water management strategies outside the scope of the TIFP and were not considered further by the TIFP in developing subsistence flow recommendations.

The 5th percentile flow and water quality considerations were used to develop subsistence flow recommendations based solely on water quality. Other factors were considered in developing the final subsistence flow recommendations (see Section 3.1).

2.6 *Connectivity*

Study activities related to connectivity focused on lateral connectivity of the river to riparian areas and oxbow lakes and groundwater-surface water interaction along the middle and lower Brazos River. During the stakeholder process, these aspects of connectivity were identified as being of greatest concern (TIFP/BRA 2010).

2.6.1 *Lateral Connectivity to Riparian Areas and Oxbow Lakes*

Continued channel incision along the middle and lower Brazos River represents a significant challenge to flow recommendations intended to support connectivity. Development of flow recommendations to support connectivity with riparian areas and oxbow lakes followed a process described in Sections 2.3.13 and 2.3.14. Results of this process are specific flow recommendations for high flow pulse and overbank flows for each of the study sites (Section 3.3). The ability of these flows to meet their objectives is dependent on the current channel configuration being maintained in the future. However, as described in Section 2.4.2, many portions of the middle and lower Brazos River are experiencing incision rates of more than 0.5 feet per decade. If this rate of incision is not arrested, in only a few years, recommended high pulse and overbank flows will not accomplish their desired ecological objectives.

For example, consider a flow of rate of 20,000 cfs at USGS Gage No. 08114000 Brazos River at Richmond. Based on the current rating curve, a flow of 20,000 cfs would result in a water surface elevation at the gage of about 52 feet above National Geodetic Vertical Datum of 1929 (NGVD 1929). In the last 20 years (1996-2015), flows of this magnitude or larger have occurred about 10% of the time (about 37 days per year, on average) (see Table 8 in Section 2.2.1). This frequency of occurrence of a flow rate of 20,000 cfs is little changed from the time period prior to large dams being built in the basin (1922-1940). However, in 1940, a flow rate of 20,000 cfs was capable of providing a water surface elevation of 57 feet above NGVD 1929 (see Figure 54 in Section 2.4.2), about five feet higher and extending much farther laterally from the river's banks. With the current channel incision rate of about 1.5 feet per decade at the Richmond gage (see Table 19 in Section 2.4.2), in less than a decade a flow rate of 20,000 cfs will achieve a water surface elevation below 51 feet (NGVD 1929). A flow of 20,000 cfs provided inundation for a much larger riparian area in 1940 than currently benefits from such a flow. If the current incision rate continues unabated, a 20,000 cfs flow will provide benefits to a much smaller riparian area in the next decade. Although the percentage of time that the river provides a flow of 20,000 cfs has not changed significantly since 1940, the riparian area supported by such a flow has decreased. In a similar manner, channel incision rates along the length of the middle and lower Brazos River erode the capacity of specific flow recommendations to meet desired ecological benefits.

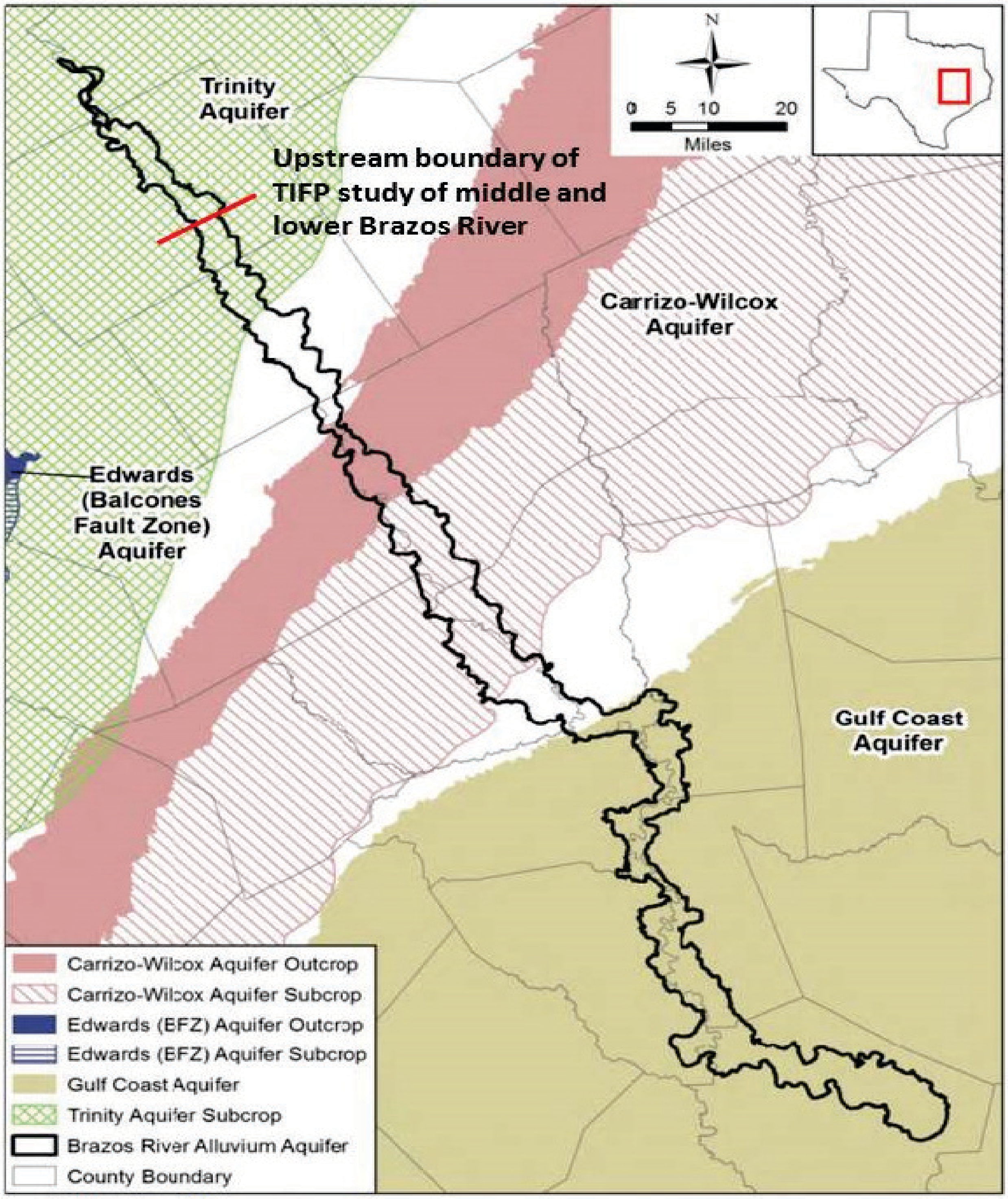
2.6.2 *Groundwater-Surface Water Interaction*

As shown in Figure 58, the middle and lower Brazos River is underlain by the Brazos River Alluvium Aquifer (BRAA) and other, deeper aquifers. Recent studies related to the BRAA include a gain-loss study of the middle and lower Brazos (Turco *et al.* 2007), hydrogeologic characterization (Shah and Houston 2007, Shah *et al.* 2007a, Shah *et al.* 2007b, Shah *et al.* 2009), conceptual model (Ewing *et al.* 2016), and a groundwater availability model (Ewing and Jigmund 2016). The picture that emerges from these studies is an unconfined, alluvial aquifer that extends along the river from Bosque County (upstream of the study boundary for the TIFP study of the middle and lower Brazos River) to Fort Bend County. The BRAA is underlain by geologic units that crop out in bands roughly parallel to the coast and perpendicular to the BRAA. Several of these units are also aquifers, including the Trinity, Carrizo-Wilcox, and Gulf Coast aquifers. The BRAA has a width of up to seven miles and a thickness as great as 168 feet. Median specific capacity is 23.5 gallons per minute per foot, with values ranging from less than 2 to more than 130 gallons per minute per foot. The median transmissivity and hydraulic conductivity are, respectively, about 4,500 square feet per day and 220 feet per day.

During 2006, the USGS completed a gain loss study of the middle and lower Brazos River (Turco *et al.* 2007). This effort included analysis of gaged records and completion of synoptic surveys of the river from McLennan County to Fort Bend County. The first survey was conducted in March to be representative of wetter hydrologic conditions and a period when diversion from the river and alluvial aquifer are relatively low. The second survey was conducted in August during a drier period when diversions from the river and alluvial aquifer are relatively high. During the March survey, five out of 35 stream reaches were found to be gaining (surface water body receives water from groundwater) and no reaches were found to be losing (surface water body contributes to groundwater). During the August survey, four segments were found to be gaining and two loosing. For both studies, somewhere between 37 to 40 percent of the flow at the Richmond gage could be attributed to groundwater contributions.

Ewing *et al.* (2016) estimated the total gain in base flow for the Brazos River pre-development from the BRAA to be approximately 760,000 acre-feet per year, equivalent to about 15% of the total annual flow volume at the USGS Gage No. 08114000 Brazos River at Richmond. During low flow periods, the percent contribution of groundwater to flow of the Brazos River would have been greater. The net result of development in the basin was estimated by Ewing *et al.* (2016) to have caused a net reduction in aquifer discharge to the Brazos River of about 50,000 acre-feet per year (equivalent to an average flow of about 70 cfs per day).

Total pumping from the BRAA, as estimated by Ewing *et al.* (2016), is shown in Figure 59. Pumping began in the 1950's in response to drought conditions across much of the state during that decade. Historically, 90 percent or more of pumping has been for irrigation purposes. During irrigation, some amount of water percolates past the root zone of the crop and results in additional recharge to the BRAA. However, as irrigation practices have become more efficient over time, this additional recharge has decreased to about 10,000 acre-feet per year (Ewing *et al.* 2016).



BFZ = Balcones Fault Zone

Figure 58. Brazos River Alluvium Aquifer and underlying aquifers in middle and lower Brazos River study area (modified from Ewing *et al.* 2016).

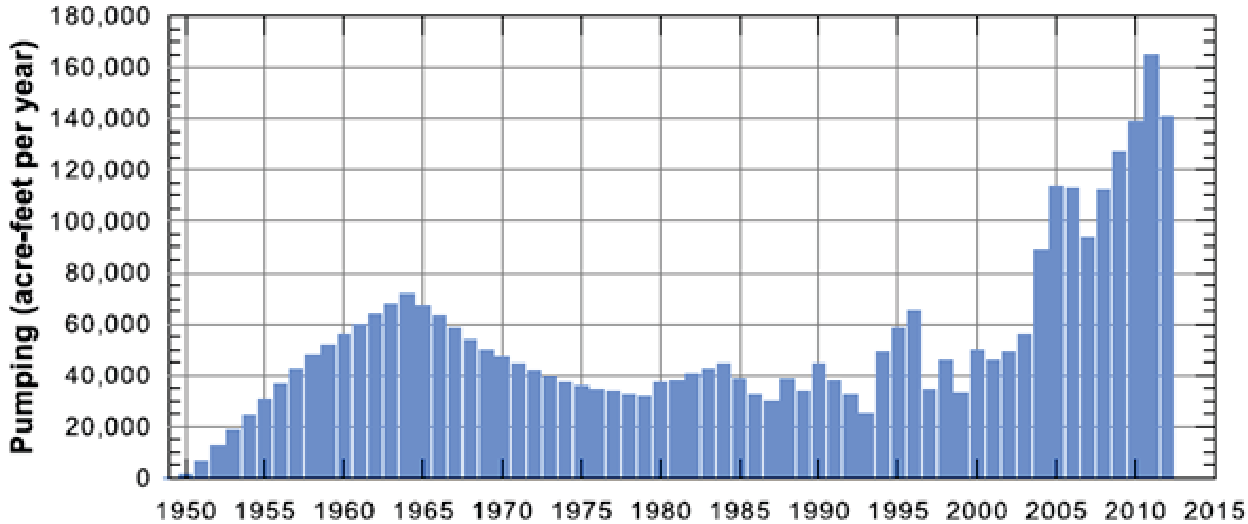


Figure 59. Total annual pumping from the Brazos River Alluvium Aquifer from 1950 to 2012 (from Ewing *et al.* 2016).

Portions of the BRAA fall into three groundwater management areas (8, 12, and 14), six groundwater conservation districts (Prairielands, Middle Trinity, Southern Trinity, Brazos Valley, Post Oak Savannah, and Bluebonnet Groundwater Conservation Districts), and one subsidence district (Fort Bend Subsidence District). Desired future conditions have been adopted for the BRAA in Falls, McLennan, Hill, Bosque, Milan, and Burleson counties and call for 80 to 100 percent of the thickness of the aquifer to remain saturated through 2060. A recently developed Groundwater Availability Model makes it possible to estimate how future pumping scenarios will impact flows from the BRAA to the middle and lower Brazos River (Ewing and Jigmond 2016, Shi and Wade 2017).

3 INTEGRATION OF STUDY RESULTS

The development of instream flow recommendations requires the integration of multiple disciplines at several key stages in the process. During the analysis phase, integration of the analytical results is necessary to develop specific flow recommendations (subsistence flow, base flow, etc.). Once specific flow recommendations are developed, an integration of those flow recommendations into a proposed flow regime is required. Once a proposed flow regime is generated, a myriad of testing and overlays are employed to assess if the recommendations are meeting the goals established.

The goal established by the stakeholders is for the middle and lower Brazos River sub-basin to "*provide for sustainable environmental, economic, and social uses.*" Additionally, the TIFP has internal objectives to conserve biodiversity and maintain biological integrity. To accomplish these goals and objectives, the integration process involves the development of a flow regime centered on four components of the hydrologic regime: subsistence flows, base flows, high flow pulses, and overbank flows. A brief overview of the definitions and objectives of the instream flow components as presented in TIFP (2008) is presented in Table 26.

Table 26. Definitions and objectives of instream flow components (adapted from TIFP 2008).

Subsistence Flows	
Definition:	Infrequent, seasonal periods of low flow.
Objectives:	Primary objective is to maintain water quality criteria. Secondary objectives to provide important low flow life cycle cues or refugia habitat.
Base Flows	
Definition:	Normal flow conditions between storm events.
Objectives:	Ensure adequate habitat conditions, including variability, to support the natural biological community.
High Pulse Flows	
Definition:	Short duration, within channel, high flow events following storm events.
Objectives:	Maintain important physical habitat features. Provide longitudinal connectivity along the river channel.
Overbank Flows	
Definition:	Infrequent, high flow events that exceed the normal channel.
Objectives:	Maintain riparian areas. Provide lateral connectivity between the river channel and active floodplain.

3.1 *Subsistence Flow*

The primary objective of subsistence flows according to TIFP (2008) is to "maintain water quality criteria". Therefore, the subsistence flow evaluation initially focused on water quality conditions, water quality modeling, and other scientific information as described in Section 2.5. The 5^{th} percentile flow and water quality considerations were used to develop subsistence flow recommendations based solely on water quality. The 5^{th} percentile flows were updated through 2016 for the BBEST recommended USGS gages for the middle and lower Brazos River and a water quality evaluation (updated through 2016) was conducted to assess if streamflows and water quality conditions had changed since the BBEST recommendations were made. An updated water quality evaluation of the TIFP water quality goals (Table 21) was also conducted. Water quality conditions were generally good and there were no significant differences between the BBEST recommended subsistence flows and the Q95 updated through 2016. The water quality-based subsistence flows are shown in Table 27.

Table 27. Water quality-based subsistence flow values (in cubic feet per second-cfs) and United States Geological Survey measurement points for middle and lower Brazos River study sites.

Study Site	Subsistence Flow (cfs)	Measurement Point	Gage Location
Marlin and Hearne	119	USGS Gage No. 08098290	Brazos River at Highbank
Mussel Shoals & Navasota*	299	USGS Gage No. 08108700	Brazos River at SH 21 near Bryan
Wildcat Bend	485	USGS Gage No. 08111500	Brazos River near Hempstead
Allens Creek	517	USGS Gage No. 08114000	Brazos River at Richmond

* No active USGS gage at or near close proximity to this TIFP study site.

Once water quality based considerations were identified, the TIFP study team integrated biological considerations into the final subsistence flow recommendations. A thermal tolerance limit of 30°C was also used to identify streamflows, under subsistence flow conditions, that support mussel recruitment during mussel brooding season as discussed in Section 2.3.11. During the months of May through September where Q95 based subsistence flows were lower than mussel thermal tolerance flows, Q95 subsistence flow values were replaced with thermal tolerance flows for mussels. Mussel thermal tolerance flows associated with subsistence flows were developed for the months of May through September, and are presented in Figure 65 - Figure 70 (Section 4).

3.2 *Base Flow*

Base flows are the normal flow conditions between storm events and naturally vary in discharge depending upon ambient climatological conditions. Base flows that vary inter-annually by hydrologic condition provide a mosaic of key habitat features as quantified through guild-based fish habitat-flow relationships, hydraulic habitat-flow relationships, and resultant habitat diversity. Thus, through time (*i.e.*, annual time step), dry, average, and wet base flow conditions support the full complement of fish biodiversity because a proportion of species do well in wet conditions (*e.g.*, more habitat available for growth, recruitment, and survival), others in average conditions, and other species in dry conditions (see Annear *et al.* 2004, Sabine-Neches BBEST 2009) as reflected by different life history strategies, species traits (Craven *et al.* 2010), and environmental requirements. In addition to providing diverse habitat conditions for aquatic flora and fauna, base flows also provide longitudinal connectivity along the river corridor and maintain water table levels in floodplain lakes and soil moisture for riparian plants (SAC 2009, Duke 2011). Base flows can also provide frequent, direct connections to recently formed oxbow lakes in the Brazos River (see Appendix in Winemiller *et al.* 2004). Base flows also serve an important role in structuring riparian communities. Both low and high base flows can limit encroachment of invasive species and maintain high species diversity (Stromberg *et al.* 2007). Maintaining healthy and diverse riparian zones provides many benefits to the river, such as buffering thermal effects of high temperatures, increasing habitat structure, and influencing food web structure (Pusey and Arthington 2003). High base flow conditions also correlate with higher groundwater tables within the riparian zone and support increased riparian productivity (Duke 2011), especially in species such as black willow which could play an important role in food web dynamics (Zeug and Winemiller 2008b). For these reasons, providing a single flow value or base flow regime cannot simultaneously meet the requirements for all species or maintain diverse fish and wildlife resources.

Habitat-streamflow relationships (Section 2.3.12) and water quality considerations were used to set base flow recommendations. WUA-streamflow relationships were used to identify streamflows that supported moderate to high quality habitat based on habitat guilds derived from fish-habitat associations. Further, using hydraulic habitat criteria and Shannon's H diversity indices, base flows and peaks were identified that maintain hydraulic habitat conditions and diversity (Sections 2.3.12.1-2.3.12.6). Spatial maps of habitat quality were examined to assess contiguity of habitat patches (*e.g.*, riffle habitat at Marlin), as needed. Based on all of the relationships examined, base flow ranges (Table 28) were derived for three conditions (wet, average, and dry base flows) to ensure inter-annual variability as proposed in the TIFP Technical Overview (TIFP 2008) and the middle and lower Brazos River Study Design (TIFP/BRA 2010). Figure 60 is a flowchart that illustrates the approach used to identify base flow conditions for each study site in the middle and lower Brazos River study area. Each step is discussed below and, when appropriate, refers back to relevant sections for rationale and analyses performed to support each component.

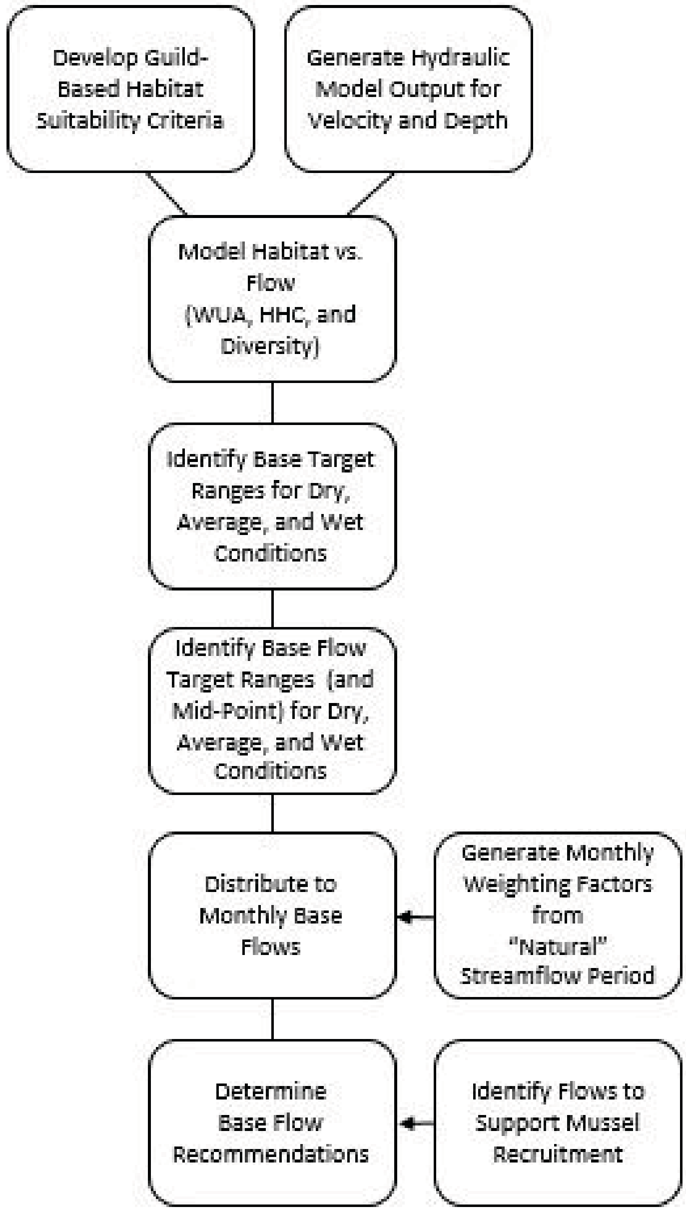


Figure 60. Process to determine base flow recommendations at each study site.

To address intra-annual variability (Section 3.2.1), base flow ranges were used to calculate a mid-point (Table 28) to distribute flows into monthly base flow recommendations using weighting factors (TIFP 2008, TIFP/BRA 2010).

Table 28. Base flow ranges (in cubic feet per second-cfs) and mid-points used in deriving monthly recommendations for middle and lower Brazos River study sites using habitat-streamflow relationships.

Base Flow Ranges (cfs)				
		Flow (cfs)		
Study Site	**Hydrologic Condition**	**Low**	**High**	**Mid-Point**
Marlin	Wet	1,750	2,600	2,175
	Average	500	1,750	1,125
	Dry	300	500	400
Hearne	Wet	1,500	2,500	2,000
	Average	500	1,500	1,000
	Dry	250	500	375
Mussel Shoals	Wet	1,325	2,500	1,913
	Average	700	1,325	1,013
	Dry	500	700	600
Navasota	Wet	1,750	2,600	2,175
	Average	750	1,750	1,250
	Dry	500	750	625
Wildcat Bend	Wet	1,750	3,000	2,375
	Average	600	1,750	1,175
	Dry	500	600	550
Allens Creek	Wet	2,350	3,000	2,675
	Average	750	2,350	1,550
	Dry	350	750	550

3.2.1 *Establishing Intra-Annual Variability*

The ecology of river systems and taxa have evolved life histories that are keenly adapted over long periods of time to the natural hydrologic characteristics including the timing and seasonality of flows (Mims and Olden 2012). To address these life history needs, the more natural pattern of hydrology exhibited during the early time period (see Figure 11) was considered to be paramount, and to the extent warranted maintained in the monthly base flow recommendations. Utilization of natural variability for managing ecological systems is not a new concept (Landres *et al.* 1999), and incorporation of these small-scale flow variability (*i.e.,* intra-annual base flow) has been shown to be beneficial in riverine ecosystems (Biggs *et al.* 2005). To develop base flow recommendations which follow a natural hydrologic pattern and thus establish intra-annual variability (*i.e.,* monthly patterns), the mid-point of the base flow ranges derived from the habitat-streamflow relationships from each study site and hydrologic condition (Table 28) was distributed to a monthly base flow recommendation via monthly weighting factors (Table 29). Monthly weighting factors (Figure 611) were derived from median monthly flow values (Figure 11) for three USGS gage locations (Waco, Bryan, and Richmond) using an early period of record (1923-1942). For each location, monthly weighting factors were developed by dividing each month's median flow value by the sum of monthly medians for the year. Waco monthly weighting factors were utilized at the Marlin and Hearne study sites, Bryan factors for Mussel Shoals and Navasota study sites, and Richmond factors for the Allens Creek study site. A set of monthly weighting factors utilized at the Wildcat Bend study site was developed by averaging the weighting factors from the two locations upstream and downstream (Bryan and Richmond; Figure 611). The early period of record was chosen to reflect a more natural monthly pattern which has high median flows in May and June, the lowest median flows July-December, and greater differences in magnitudes reflecting high inter-annual variability. The modern period of record (1996-2015) reflects a shift in higher flows to earlier in the year (January-April) and the inter-annual variability is compressed (Figure 11).

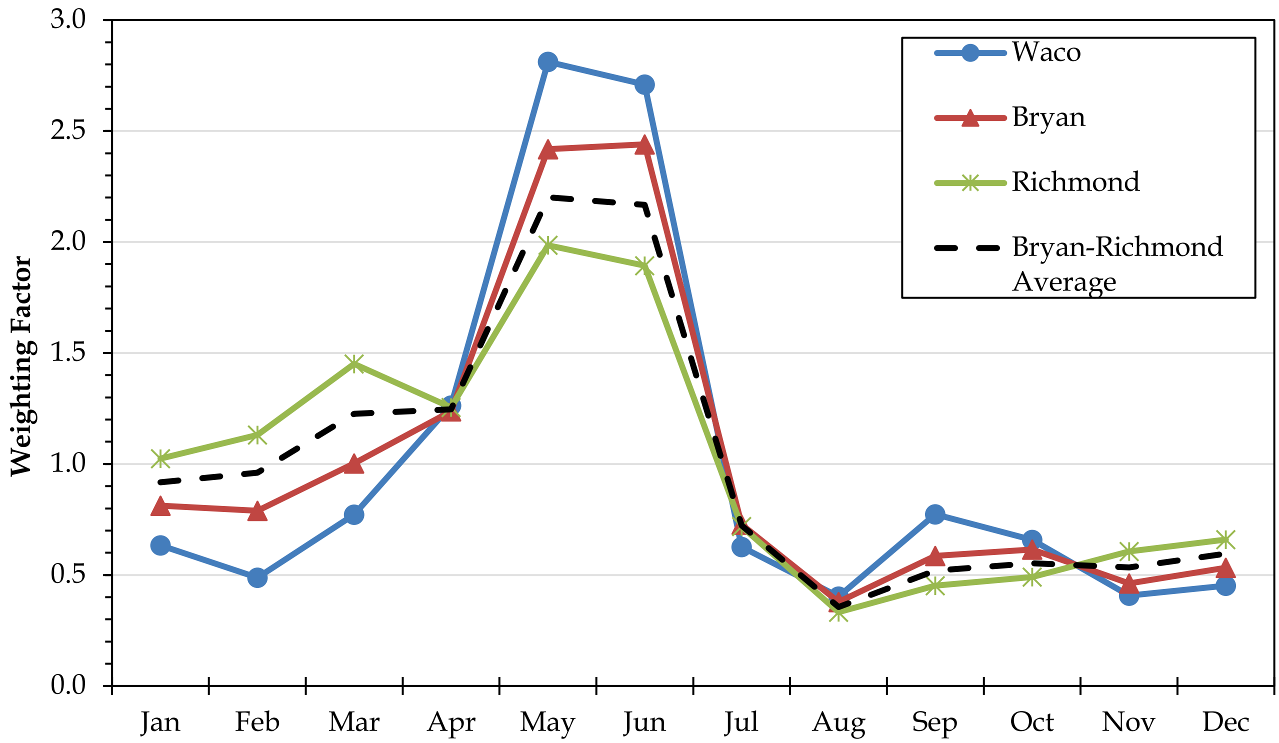


Figure 61. Monthly weighting factors based on median monthly flows for the time period 1923-1942 for the Brazos River at Waco, Bryan, and Richmond and an average for Bryan and Richmond.

Monthly wet base flow recommendations that exceeded the habitat-based flow ranges were compared to the Q25 while monthly dry base flow recommendations were compared to the Q75 and subsistence flow recommendations to evaluate if any adjustments were warranted at each study site.

When applying these monthly weighting factors at each study site, it is possible that the monthly flow recommendations may be lower or higher than our identified habitat-based flow ranges. To assess the magnitudes and significance of these deviations from the previously identified habitat-based flow ranges for each study site, the resulting monthly base flows (Table 29) were examined relative to the habitat-based base flow ranges (Table 28), flow-habitat curves, flow duration statistics, and subsistence flows. Monthly flow duration statistics from the early period of record (1923-1942 to match the time period used for weighting factors) at each gage were utilized for this comparison (Figure 61). Monthly wet base flow recommendations that exceeded the habitat-based flow ranges were compared to the Q25 while monthly dry base flow recommendations were compared to the Q75 and subsistence flow recommendations to evaluate if any adjustments were warranted at each study site.

As expected, when applying the monthly weighting factors to mimic a natural hydrologic pattern of the Brazos River, some flows were lower than the low flows of the habitat-based flow ranges and some flows exceeded the high flows of these ranges as well. The overall general pattern in these exceedances is that during the months of May and June, all flows at every hydrologic condition at every study site were exceeded. Most flows during April, and some flows during February and March were also exceeded. In addition to exceedances on the high end of the ranges, it appears that the majority of flows from July to December had flows that were lower than the lower end of the flow ranges. Overall, when evaluating the flow exceedances at the low end of the habitat-based flow ranges (lower than the low end of the flow range), several of the dry base flows were below the subsistence flow recommendation so those flows were adjusted up to the subsistence flow level. Low flow exceedances also occurred at flows in the average and wet base conditions, but these flows occurred within our fish guild and hydraulic habitat modeled flow range. Evaluation of modeled habitat outputs suggested that habitat availability and diversity is still present so no adjustments were necessary to preserve the pattern of monthly flows.

For flows that exceeded the high flow of the flow range, most flows in average and dry base were within the fish guild and hydraulic habitat modeled flow range. Evaluation of modeled habitat outputs suggested that habitat availability and some diversity is still present so no adjustments were necessary to preserve the pattern of monthly flows. For the flows that exceeded modeled flow range of our habitat models, such as for most wet base and some average base flows, additional assessment was necessary. Although fish habitat guilds developed for this study cannot inform this assessment as discussed in Section 2.3.4, reviewing the hydraulic habitat model outputs at each study site shows that for every study site, hydraulic habitats HH9 and HH10 availability increase with increasing flows and are analogous to deep lotic and swift water habitats. These exceedances were beyond our modeled flows, but the assumption is that these habitat types will be the most abundant at these higher flow levels.

To assess habitat suitability of HH9 and HH10 for fishes occurring in the Brazos River, we reviewed published reports of collection data and habitat suitability criteria. For example, Mayes *et al.* (2013) reported results from a survey of expert opinion of habitat suitability for Texas fishes (Table 5 in Mayes *et al.* 2013) and developed habitat suitability criteria using fish and habitat data collected from the Brazos River (BRA 2007). Fourteen fishes were found to have habitat suitability that reflects depth and current velocities as defined by HH9 (≥6.0 feet depth and ≥ 1.0 fps velocity) including: Flathead Catfish, Silverband Shiner, Shoal Chub, Longear Sunfish, Bluegill, Orangespotted Sunfish, Longnose Gar, Mississippi Silvery Minnow, Threadfin Shad, Gizzard Shad (juvenile), Blacktail Shiner, Red Shiner, and River Carpsucker. Five fishes were found to have habitat suitability the reflects depth and current velocities as defined by HH10 (any depth with velocities ≥3.5 fps) including: Flathead Catfish (juvenile), Silverband Shiner, Channel Catfish (juvenile), Gizzard Shad (juvenile), and Red Shiner.

Adult fishes (15 spp.) found in the habitat suitability criteria literature that utilize depths and velocities as defined by HH9 (≥6.0 feet depth and ≥ 1.0 fps velocity) include: Bowfin (Scheidegger and Bain 1990); Freshwater Drum (Scheidegger and Bain 1990); Blacktail Shiner (Killgore and Hathorn 1987, Scheidegger and Bain 1990); Gizzard Shad (Williamson and Nelson 1985, Scheidegger and Bain 1990); Threadfin Shad (Scheidegger and Bain 1990); Blue Catfish (Scheidegger and Bain 1990); Channel Catfish (Scheidegger and Bain 1990, McMahon and Terrell 1982); Smallmouth Buffalo (Scheidegger and Bain 1990); Spotted Gar (Scheidegger and Bain 1990); Longnose Gar (Scheidegger and Bain 1990); Bluegill (Stuber *et al.* 1982, Scheidegger and Bain 1990); Longear Sunfish (Scheidegger and Bain 1990); Spotted Bass (a key species; McMahon *et al.* 1984, Killgore and Hathorn 1987, Layher *et al.* 1987, Scheidegger and Bain 1990); Largemouth Bass (Scheidegger and Bain 1990); and Emerald Shiner (Scheidegger and Bain 1990). Adult fishes (three spp.) found in the habitat suitability criteria literature that utilize depths and velocities as defined by HH10 (any depth with velocities ≥3.5 fps) include: Smallmouth Buffalo (Edwards and Twomey 1982); Flathead Catfish (Lee and Terrell 1987); and Freckled Madtom (Orth and Maughn 1982).

More importantly, multiple key species are utilizing these hydraulic habitat types as well. Overall, Blue Catfish, Channel Catfish, Flathead Catfish, Spotted Bass, Shoal Chub and Silverband Shiner were shown to utilize habitats associated with HH9. Overall, Flathead Catfish and Channel Catfish were key species shown to utilize habitats associated with HH10. Given that these big river habitat types are being utilized by several fishes including eight key species, no adjustments were deemed necessary to preserve the pattern of monthly flows. Detailed analysis of base flow ranges by study site are presented below.

At the Marlin study site, dry base flows for several months (Jan-Feb, Jul-Aug, Oct-Dec) were less than 300 cfs (the low point of the dry base flow range in Table 29). These dry base flows were greater than the monthly Q75 (early period) and all subsistence flows except for August thus, August dry base was increased to 190 cfs. Wet base flows for the months of April-June were greater than 2,600 cfs (the high point of the wet base flow range in Table 29). The wet base flows in April-June were less than the monthly Q25 in the early time period (1923-1942) and an evaluation of habitat response curves provided additional evidence that base flows outside of the wet base range continue to support important habitat types. Specifically, hydraulic habitats HH3, HH9, HH10, and HH6 show an upward trend in habitat area (Figure B-5) which are all deep habitat classes with varying current velocities; often difficult to sample with boat electrofishers and other active gear types used for habitat suitability assessment (see Section 2.3); and occupied by key species such as Channel Catfish (Figure 34) and likely other fishes less susceptible to sampling with our gear types (Li and Gelwick 2005). For example, adult Alligator Gar and other gar species, Flathead Catfish, Gizzard Shad, River Carpsucker, and other species utilize deep pools in rivers including the lower Brazos (TPWD unpublished data, Kane-Sutton and Gelwick 2013, Suttkus 1963, Gelwick and Morgan 2000,, Thomas *et al.* 2007). In addition to providing diverse habitat conditions for aquatic flora and fauna, base flows also provide longitudinal connectivity along the river corridor and maintain water table levels in floodplain lakes and soil moisture for riparian plants (SAC 2009, Duke 2011). High base flow conditions also correlate with higher groundwater tables within the riparian zone and support increased riparian productivity (Duke 2011), especially in species such as black willow which could play an important role in food web dynamics (Zeug and Winemiller 2008b). No downward adjustment in wet base flows were made.

At the Hearne study site, dry base flows for the months of August-December were less than 250 cfs (the low point of the dry base flow range in Table 29). These dry base flows were greater than the monthly Q75 (early period) and all subsistence flows except for August thus August was increased to 190 cfs. Wet base flows for the months of April-June were greater than 2,500 cfs (the high point of the wet base flow range in Table 29). The wet base flows in April-June were less than the monthly Q25 in the early time period (1923-1942) and an evaluation of habitat response curves provided additional evidence that base flows outside of the wet base range continue to support important habitat types. Specifically, as flows increase, hydraulic habitats HH9 and HH10 show an upward trend in habitat area (Figure B-11) which are both deep habitat classes with faster current velocities; often difficult to sample with boat electrofishers and other active gear types used for habitat suitability assessment (see Section 2.3); fish were rarely collected in these classes (Figure 31); and likely occupied by fishes less susceptible to sampling with our gear types. For example, adult

Alligator Gar and other gar species, Flathead Catfish, Gizzard Shad, River Carpsucker, and other species utilize deep pools in rivers including the lower Brazos (TPWD, unpublished data, Kane-Sutton and Gelwick 2013, Suttkus 1963, Gelwick and Morgan 2000, Thomas *et al.* 2007). HH2 and HH5 (occupied by bass and catfish species) also show a slight upward trend as does the habitat diversity index. In addition to providing diverse habitat conditions for aquatic flora and fauna, base flows also provide longitudinal connectivity along the river corridor and maintain water table levels in floodplain lakes and soil moisture for riparian plants (SAC 2009, Duke 2011). High base flow conditions also correlate with higher groundwater tables within the riparian zone and support increased riparian productivity (Duke 2011), especially in species such as black willow which could play an important role in food web dynamics (Zeug and Winemiller 2008b). No downward adjustment in wet base flows are warranted.

At the Mussel Shoals study site, dry base flows for the months of July-December and January-February were less than 500 cfs (the low point of the dry base flow range in Table 29). These dry base flows were more than the monthly Q75 (early period) in January but less than the monthly Q75 in all other months. January, February, and July were not substantially less than 500 cfs so no adjustments warranted. Dry base flows in August-December were less than the monthly subsistence flows and were increased to appropriate subsistence flow levels (Figure 67). Wet base flows for the months of May-June were greater than 2,500 cfs (the high point of the wet base flow range in Table 29). The wet base flows in May-June were far less than the monthly Q25 in the early time period (1923-1942) at the Bryan gage and an evaluation of habitat response curves provided additional evidence that base flows outside of the wet base range continue to support important habitat types. Specifically, hydraulic habitats HH9 and HH10 show an upward trend in habitat area (Figure B-17) which are both deep habitat classes with faster current velocities; often difficult to sample with boat electrofishers and other active gear types used for habitat suitability assessment (see Section 2.3); fish were rarely collected in these classes (Figure 31); and likely occupied by fishes less susceptible to sampling with our gear types. For example, adult Alligator Gar and other gar species, Flathead Catfish, Gizzard Shad, River Carpsucker, and other species utilize deep pools in rivers including the lower Brazos (TPWD, unpublished data, Kane-Sutton and Gelwick 2013, Suttkus 1963, Gelwick and Morgan 2000, Thomas *et al.* 2007). In addition, HH3 and HH2 (occupied by Spotted Bass and Channel Catfish; both key species and important recreational sportfishes) also show a slight upward trend. In addition to providing diverse habitat conditions for aquatic flora and fauna, base flows also provide longitudinal connectivity along the river corridor and maintain water table levels in floodplain lakes and soil moisture for riparian plants (SAC 2009, Duke 2011). High base flow conditions also correlate with higher groundwater tables within the riparian zone and support increased riparian productivity (Duke 2011), especially in species such as black willow which could play an important role in the food web dynamics (Zeug and Winemiller 2008b). No downward adjustment in wet base flows are warranted.

At the Navasota study site, dry base flows for the months of February and July-December were less than 500 cfs (the low point of the dry base flow range in Table 29). February and July were not substantially less. For the remaining months, dry base flows were all less than the monthly Q75 (early period at the Bryan gage) and may warrant adjustment to at least subsistence flow levels. Dry base flows in August and September were increased to 390 cfs while November and December dry base were increased to 300 cfs. Wet base flows for the months of Apr-June were greater than 2,600 cfs (the high point of the wet base flow range in Table 29). The wet base flows in April were just slightly more than 2600 cfs and not considered further. May and June wet base flows were substantially less than the monthly Q25 in the early time period (1923-1942) and an evaluation of habitat response curves provided additional evidence that base flows outside of the wet base range continue to support important habitat types. Specifically, hydraulic habitats HH9 and HH10 show an upward trend in habitat area (Figure B-23) which are both deep habitat classes with faster current velocities; often difficult to sample with boat electrofishers and other active gear types used for habitat suitability assessment (see Section 2.3); fish were rarely collected in these classes (Figure 31); and likely occupied by fishes less susceptible to sampling with our gear types. For example, adult Alligator Gar and other gar species, Flathead Catfish, Gizzard Shad, River Carpsucker, and other species utilize deep pools in rivers including the lower Brazos (TPWD, unpublished data, Kane-Sutton and Gelwick 2013, Suttkus 1963, Gelwick and Morgan 2000, Thomas *et al.* 2007). In addition, substantial area of HH8 remains at the highest flows modeled supporting Channel Catfish and Silverband Shiner, both key species. In addition to providing diverse habitat conditions for aquatic flora and fauna, base flows also provide longitudinal connectivity along the river corridor and maintain water table levels in floodplain lakes and soil moisture for riparian plants (SAC 2009, Duke 2011). No downward adjustment in wet base flows are warranted.

At the Wildcat Bend study site, dry base flows for the months of July-December were less than 500 cfs (the low point of the dry base flow range in Table 29) and were less than subsistence flows. All of these months plus January were increased to subsistence flow levels (824 cfs May-September and 510 cfs all other months). Wet base flows for the months of May-June were greater than 3,000 cfs (the high point of the wet base flow range in Table 29). The wet base flows in May-June were less than the monthly Q25 in the early or full time period at the Hempstead gage. May was also less than the monthly Q25 in the recent time period. An evaluation of habitat response curves provided additional evidence that base flows outside of the wet base range continue to support important habitat types. Specifically, hydraulic habitats HH 6, 9 and 10 show an upward trend in habitat area (Figure B-29) which are all deep habitat classes with varying current velocities; often difficult to sample with boat electrofishers and other active gear types used for habitat suitability assessment (see Section 2.3); and likely occupied by fishes less susceptible to sampling with our gear types. For example, adult Alligator Gar and other gar species, Flathead Catfish, Gizzard Shad, River Carpsucker, and other species utilize deep pools in rivers including the lower Brazos (TPWD, unpublished data, Kane-Sutton and Gelwick 2013, Suttkus 1963, Gelwick and Morgan 2000, Thomas *et al.* 2007). In addition, HH3 and HH2 (occupied by Spotted Bass and Channel Catfish; both key species and important recreational sportfishes) also show upward trends. In addition to providing diverse habitat conditions for aquatic flora and fauna, base flows also provide longitudinal connectivity along the river corridor and maintain water table levels in floodplain lakes and soil moisture for riparian plants (SAC 2009, Duke 2011). High base flow conditions also correlate with higher groundwater tables within the riparian zone and support increased riparian productivity (Duke 2011), especially in species such as black willow which could play an important role in food web dynamics (Zeug and Winemiller 2008b). No downward adjustment in wet base flows are warranted.

At the Allens Creek study site, dry base flows for the months of July-December were less than the subsistence flows for those months. In addition, August-Nov were less than 350 cfs (the low point of the dry base flow range in Table 29). The dry base flows were substantially less than the monthly Q75 (early period) for all these months (Jul-Dec). Dry base flows for those months were replaced with the higher subsistence flows (575 cfs for May-September and 550 cfs all other months). Wet base flows for the months of Feb-June were greater than 3,000 cfs (the high point of the wet base flow range in Table 29). The wet base flows in Feb-Apr were slightly greater and not further considered for adjustment. May-June were substantially less than the monthly Q25 in the early time period (or any of the time periods available). An evaluation of habitat response curves provided additional evidence that base flows outside of the wet base range continue to support important habitat types at the Allens Creek study site. Specifically, hydraulic habitats HH 6, 9 and 10 show an upward trend in habitat area (Figure B-35) which are all deep habitat classes with varying current velocities; often difficult to sample with boat electrofishers and other active gear types used for habitat suitability assessment (see Section 2.3); and likely occupied by fishes less susceptible to sampling with our gear types. For example, adult Alligator Gar and other gar species, Flathead Catfish, Gizzard Shad, River Carpsucker, and other species utilize deep pools in rivers including the lower Brazos (TPWD, unpublished data, Kane-Sutton and Gelwick 2013, Suttkus 1963, Gelwick and Morgan 2000, Thomas *et al.* 2007). HH3 and HH2 (occupied by Spotted Bass and Channel Catfish; both key species and important recreational sportfishes) also show upward trends. In addition, HH1 shows a slight upward trend and supports habitat for key species such as Shoal Chub, Silverband Shiner, Chub Shiner, Channel Catfish, and Spotted Bass. In addition to providing diverse habitat conditions for aquatic flora and fauna, base flows also provide longitudinal connectivity along the river corridor and maintain water table levels in floodplain lakes and soil moisture for riparian plants (SAC 2009, Duke 2011). High base flow conditions also correlate with higher groundwater tables within the riparian zone and support increased riparian productivity (Duke 2011), especially in species such as black willow which could play an important role in the food web dynamics (Zeug and Winemiller 2008b). No downward adjustment in wet base flows are warranted.

Table 29. Monthly base flows derived from habitat-streamflow relationships for each study site and dry, average and wet hydrologic conditions.

Study Site	Hydrologic Condition	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Marlin	Wet	1377	1062	1680	2749	6116	5894	1363	876	1683	1432	885	983
	Average	712	549	869	1422	3163	3049	705	453	871	740	458	509
	Dry	253	195	309	506	1125	1084	251	161	310	263	163	181
Hearne	Wet	1266	977	1545	2528	5623	5420	1253	805	1548	1316	814	904
	Average	633	488	772	1264	2812	2710	627	403	774	658	407	452
	Dry	237	183	290	474	1054	1016	235	151	290	247	153	170
Mussel Shoals	Wet	1553	1510	1918	2367	4624	4667	1392	724	1120	1175	882	864
	Average	822	800	1015	1253	2448	2471	737	383	593	622	467	458
	Dry	487	474	602	743	1451	1464	437	227	351	369	277	271
Navasota	Wet	1766	1718	2181	2692	5259	5307	1582	824	1274	1336	1004	983
	Average	1015	987	1253	1547	3022	3050	909	473	732	768	577	565
	Dry	507	494	627	774	1511	1525	455	237	366	384	288	283
Wildcat Bend	Wet	2180	2281	2914	2961	5223	5150	1718	845	1233	1312	1268	1416
	Average	1078	1129	1441	1465	2584	2548	850	418	610	649	627	701
	Dry	505	528	675	686	1209	1193	398	196	286	304	294	328
Allens Creek	Wet	2739	3027	3881	3358	5297	5074	1924	890	1211	1312	1622	1766
	Average	1587	1754	2249	1946	3069	2940	1115	516	702	760	940	1023
	Dry	563	622	798	691	1089	1043	396	183	249	270	333	363

3.2.2 *Mussel Thermal Tolerance Criteria to Inform Base Flows*

In addition to mussel thermal tolerance criteria to inform subsistence flows, a thermal tolerance limit of 30°C was also used to ensure base flow recommendations support mussel recruitment during mussel brooding season (May through September) as discussed in Section 2.3.11. During the months of May through September where base flows were lower than mussel thermal tolerance flows, base flow values were replaced with thermal tolerance flows for mussels. In some instances, initial base flow recommendations for May through September had values less than those presented in Table 15, indicating an increased chance of water temperatures exceeding 30°C. In those instances, flow recommendations were adjusted to match criteria in Table 15. Final results are presented in Figure 65- Figure 70 (Section 4).

3.3 *High Flow Pulses and Overbank Flows*

3.3.1 *Flows to Support Healthy Riparian Areas*

To identify flow events that are important to maintain the current riparian vegetation on the middle and lower Brazos River and to develop recommendations for high flow pulses and overbank flows at the six study sites, the study team used riparian-transect and elevation data coupled with hydraulic modeling (see Sections 2.3 and 2.3.14) and inundation analyses conducted by Hayes (2016a, 2016b, and 2016c). Literature reviews of life history information (TIFP 2017) were used to identify important time periods, frequencies, and durations of flow events to support indicator tree species.

Based on findings in Duke (2011) and Hayes (2016a, 2016b, 2016c), box elder *Acer negundo*, green ash *Fraxinus pennslyvanica*, black willow *Salix nigra*, and eastern cottonwood *Populus deltoides* were selected as tree indicators for the analysis. These species are characteristic of the dynamic riparian area of the Brazos River, dominant tree types within the riparian/floodplain areas, and have obligate to facultative life histories. The riparian transect data found that black willow was located near the water's edge and on the stream banks while box elder, green ash and cottonwood trees were typically found higher up on the stream banks and on up into the riparian zone. Based on a literature review, seeding and germination periods were identified for several dominant tree species in the riparian community. An estimate of the beneficial frequency (number of times per year) and duration (days) of these pulses is also provided, based on the need for providing soil moisture for seedling and sapling growth and for seed dispersal (Table 30). Based on the life history information, and the modeled extent of pulse flows in the riparian zone, the flows and characteristics specified in Table 30 were considered appropriate to maintain the health of existing riparian communities on the middle and lower Brazos River. Furthermore, Hayes (2016a, 2016b, 2016c) performed inundation analyses using the TPWD Ecological Mapping data and thematic mapper imagery collected at observed high flow events on the middle and lower Brazos. From those analyses, the flow events identified in Table 31 were also determined to be important to maintain the riparian forest community and are provided here as recommendations.

It is important to note that the frequencies shown in Tables 30 and 31 do not correspond to the average number of pulses of these magnitudes that have occurred in the gaged record. Nor do the durations in these tables refer to the average duration of such pulses in the gaged record. Rather, these are estimates of the number of times these pulses can occur each year, and their durations, while still providing benefit to riparian tree species. In other words, additional pulses in one year beyond the recommended frequencies or durations longer than those listed in Tables 30 and 31 are expected to provide little additional benefit to riparian tree species. It is recognized that in many years, pulses of these magnitudes, frequencies, and durations have not occurred in the gaged record. However, when they do occur, they provide important environmental value to the middle and lower Brazos River.

Table 30. High flow pulses (in cubic feet per second-cfs) and characteristics identified to support specific riparian tree species at each study site.

Study Site	Pulse (cfs)	Timing	Freq./ year	Duration	Benefit
Marlin	23,000	Mar-Nov	3	4 days	Inundates channel up to estimated mean high water mark
	30,000	May-Jun	2	3 days	Green ash recruitment (transect 1)
	37,000	Mar-May	3	4 days	Inundates 80% of black willow habitat on lower transects
	37,000	Jun-Aug	2	4 days	Inundates 80% of black willow habitat on lower transects
	37,000	Sep-Nov	2	4 days	Inundates 80% of black willow habitat on lower transects
	47,000	May-Jun	2	3 days	Green ash recruitment (transect 18)
	52,000	Feb-Apr	2	3 days	Inundates most of the box elder, cottonwood, and green ash habitat (80% extent)
	52,000	May-Nov	2	3 days	Inundates most of the box elder, cottonwood, and green ash habitat (80% extent)
	4,500	Mar-Nov	3	4 days	Inundates channel up to estimated mean high water mark
	7,000	Mar-May	3	4 days	Supports black willow (transect 5) and green ash (transect 12) recruitment
	7,000	Jun-Aug	2	4 days	Supports black willow (transect 5) and green ash (transect 12) recruitment
Hearne	7,000	Sep-Nov	2	4 days	Supports black willow (transect 5) and green ash (transect 12) recruitment
	13,000	May-Jun	2	3 days	Green ash recruitment (transect 9A)
	15,000	Mar-May	3	4 days	Supports black willow recruitment (transect 12A)
	15,000	Jun-Aug	2	4 days	Supports black willow recruitment (transect 12A)
	15,000	Sep-Nov	2	4 days	Supports black willow recruitment (transect 12A)
	21,000	Mar-May	3	4 days	Inundates 80% of black willow habitat
	21,000	Jun-Aug	2	4 days	Inundates 80% of black willow habitat
	21,000	Sep-Nov	2	4 days	Inundates 80% of black willow habitat

Table 30 (cont). High flow pulses (in cubic feet per second-cfs) and characteristics identified to support specific riparian tree species at each study site.

Study Site	Pulse (cfs)	Timing	Freq./ year	Duration	Benefit
Hearne	34,000	Feb-Oct	1	2 days	Inundates 80% box elder and cottonwood habitat (transect 9)
Mussel Shoals (Bryan)	6,000	Mar-Sep	3	4 days	Inundates channel up to estimated mean high water mark; black willow recruitment
	9,000	Mar-May	3	4 days	Supports black willow (transect 11) recruitment
	9,000	Jun-Aug	2	4 days	Supports black willow (transect 11) recruitment
	9,000	Sep-Nov	2	4 days	Supports black willow (transect 11) recruitment
	10,000	Mar-May	3	4 days	Supports black willow recruitment (transect 3)
	10,000	Jun-Aug	2	4 days	Supports black willow recruitment (transect 3)
	10,000	Sep-Nov	2	4 days	Supports black willow recruitment (transect 3)
	31,000	Mar-Sep	3	3 days	Inundates lower transacts for green ash, black willow, box elder, cottonwood
	36,000	Jun-Aug	2	4 days	Supports black willow recruitment (transect 8)
	40,000	Jun-Aug	2	4 days	Supports maximum black willow extent; recruitment (transect 2)
	44,000	Mar-May	3	4 days	Inundates 80% of black willow habitat on lower transects
	44,000	Jun-Aug	2	4 days	Inundates 80% of black willow habitat on lower transects
	44,000	Sep-Nov	2	4 days	Inundates 80% of black willow habitat on lower transects
	49,000	Feb-May	1	3 days	Supports 80% extent cottonwood habitat
	49,000	Jun-Oct	1	3 days	Supports 80% extent cottonwood habitat
	53,000	Feb-May	1	3 days	Supports 80% extent box elder habitat
	53,000	Jun-Oct	1	3 days	Supports 80% extent box elder habitat
Navasota	<4,000	Mar-May	3	4 days	Inundates channel up to estimated mean high water mark; black willow recruitment (transect 2)

Table 30 (cont). High flow pulses (in cubic feet per second-cfs) and characteristics identified to support specific riparian tree species at each study site.

Study Site	Pulse (cfs)	Timing	Freq./ year	Duration	Benefit
Navasota	<4,000	Jun-Aug	2	4 days	Inundates channel up to estimated mean high water mark; black willow recruitment (transect 2)
	<4,000	Sep-Nov	2	4 days	Inundates channel up to estimated mean high water mark; black willow recruitment (transect 2)
	6,000	Mar-May	3	4 days	Maximum extent black willow recruitment (transect 4)
	6,000	Jun-Aug	2	4 days	Maximum extent black willow recruitment (transect 4)
	6,000	Sep-Nov	2	4 days	Maximum extent black willow recruitment (transect 4)
	31,000	Feb-May	1	3 days	Supports box elder recruitment (transect 3)
	31,000	Jun-Oct	1	3 days	Supports box elder recruitment (transect 3)
	46,000	Feb-May	1	3 days	Inundates 80% cottonwood habitat
	46,000	Jun-Oct	1	3 days	Inundates 80% cottonwood habitat
	49,000	Feb-Nov	2	4 days	Supports 80% box elder extent (transect 3) and black willow (transects 1 & 2)
Wildcat Bend (Hempstead)	5,000	Mar-May	3	4 days	Inundates channel up to estimated mean high water mark; black willow recruitment (transect 4)
	5,000	Jun-Aug	2	4 days	Inundates channel up to estimated mean high water mark; black willow recruitment (transect 4)
	5,000	Sep-Nov	2	4 days	Inundates channel up to estimated mean high water mark; black willow recruitment (transect 4)
	18,000	Mar-May	3	4 days	Supports black willow recruitment
	18,000	Jun-Aug	2	4 days	Supports black willow recruitment
	18,000	Sep-Nov	2	4 days	Supports black willow recruitment

Table 30 (cont). High flow pulses (in cubic feet per second-cfs) and characteristics identified to support specific riparian tree species at each study site.

Study Site	Pulse (cfs)	Timing	Freq./ year	Duration	Benefit
Wildcat Bend (Hempstead)	24,000	Mar-May	3	4 days	Supports black willow recruitment
	24,000	Jun-Aug	2	4 days	Supports black willow recruitment
	24,000	Sep-Nov	2	4 days	Supports black willow recruitment
	39,000	Mar-May	3	4 days	Supports 80% extent black willow habitat (transect 9)
	39,000	Jun-Aug	2	4 days	Supports 80% extent black willow habitat (transect 9)
	39,000	Sep-Nov	2	4 days	Supports 80% extent black willow habitat (transect 9)
	45,000	Feb-May	1	3 days	Supports 80% box elder and cottonwood extent
	45,000	Jun-Oct	1	3 days	Supports 80% box elder and cottonwood extent
Allens Creek (Wallis)	11,000	Mar-Nov	3	4 days	Inundates channel up to estimated mean high water mark
	27,000	Mar-May	3	4 days	Supports recruitment of black willow (transects 6,7,13)
	27,000	Jun-Aug	2	4 days	Supports recruitment of black willow (transects 6,7,13)
	27,000	Sep-Nov	2	4 days	Supports recruitment of black willow (transects 6,7,13)
	39,500	Feb-May	1	3 days	Supports recruitment of cottonwood (transect 6,7)
	39,500	Jun-Oct	1	3 days	Supports recruitment of cottonwood (transect 6,7)
	54,500	Feb-May	1	3 days	Supports box elder recruitment (transects 1,7,13) and cottonwood (transect 1)
	54,500	Jun-Oct	1	3 days	Supports box elder recruitment (transects 1,7,13) and cottonwood (transect 1)
	60,000	Mar-Nov	3	4 days	Supports 80% extent black willow habitat
	60,000	Mar-May	3	4 days	Supports 80% extent black willow habitat
	60,000	Jun-Aug	2	4 days	Supports 80% extent black willow habitat
	67,000	Feb-May	1	3 days	Supports 80% box elder extent and cottonwood habitat (transect 6)

Table 30 (cont). High flow pulses (in cubic feet per second-cfs) and characteristics identified to support specific riparian tree species at each study site.

Study Site	Pulse (cfs)	Timing	Freq./ year	Duration	Benefit
Allens Creek (Wallis)	67,000	Jun-Oct	1	3 days	Supports 80% box elder extent and cottonwood habitat (transect 6)
	70,000	Feb-May	1	3 days	Supports 80% box elder extent and cottonwood habitat (transect 13)
	70,000	Jun-Oct	1	3 days	Supports 80% box elder extent and cottonwood habitat (transect 13)

Table 31. Flow pulses (in cubic feet per second-cfs) and characteristics identified for maintaining riparian areas based on inundation analyses (Hayes 2016a, 2016b, 2016c).

Study Site	Pulse (cfs)	Timing	Freq./ year	Duration	Benefit
Marlin	38,200	Feb-Nov	1	14 days	Inundates floodplain and riparian forest community
Hearne	36,300	Feb-Nov	1	14 days	Inundates floodplain and riparian forest community
Mussel Shoals (Bryan)	49,500	Feb-Nov	1	14 days	Inundates floodplain and riparian forest community
Navasota	58,200	Feb-Nov	1	14 days	Inundates floodplain and riparian forest community
Wildcat Bend (Hempstead)	58,200	Feb-Nov	1	14 days	Inundates floodplain and riparian forest community
Allens Creek (Wallis)	43,300	Feb-Nov	1	14 days	Inundates floodplain and riparian forest community

3.3.2 *High Flow Pulses and Overbank Flow Events to Support Fish Recruitment and Oxbow Connectivity*

For high flow pulses and overbank flow events to support fish recruitment and oxbow connectivity, we used flow-ecology data for Shoal Chub, a pelagic broadcast spawning cyprinid (see Section 2.3.1), life history information for Alligator Gar (Section 2.3.1), and site-specific streamflows that connect the river channel to oxbow lakes in the floodplain (Giardino and Lee 2012). The timing of events, frequency, and duration is derived from life history information related to key species. Hydrologic characteristics and ecologic benefits to the Brazos River environment are provided in Table 32.

Please note, the frequencies shown in Table 32 do not correspond to the average number of pulses of these magnitudes that have occurred in the gaged record. Nor do the durations in Table 32 refer to the average duration of such pulses in the gaged record. Rather, these are estimates of the number of times these pulses can occur each year, and their durations, while still providing benefit to fish spawning and recruitment, oxbow connectivity, food web dynamics, and fish biodiversity. In other words, additional pulses in one year beyond the recommended frequencies or durations longer than those listed in Table 32 are expected to provide little additional benefit to these ecosystem processes. It is recognized that in many years, pulses of these magnitudes, frequencies, and durations have not occurred in the gaged record. However, when they do occur, they provide important environmental value to the middle and lower Brazos River.

Table 32. High flow pulses (in cubic feet per second-cfs) and overbanking flows that support fish spawning and recruitment, oxbow connectivity, food web dynamics, and fish biodiversity.

Study Site	Pulse (cfs)	Timing	Freq./year	Duration	Benefit
Marlin	5,000	Apr-Sept	2	7 days	PBSC recruitment (pelagic broadcast spawning cyprinids)
Hearne	5,000	Apr-Sept	2	7 days	PBSC recruitment (pelagic broadcast spawning cyprinids)
Mussel Shoals (Bryan)	5,000	Apr-Sept	2	7 days	PBSC recruitment (pelagic broadcast spawning cyprinids)
	25,000	May-July	1	14 days	ALG recruitment, oxbow connectivity
	25,000	All months	1	3 days	Oxbow connectivity, foodweb dynamics, fish biodiversity
	47,000	May-July	1	14 days	ALG recruitment, oxbow connectivity
	47,000	All months	1	3 days	Oxbow connectivity, foodweb dynamics, fish biodiversity
	53,000	May-July	1	14 days	ALG recruitment, oxbow connectivity
	53,000	All months	1	3 days	Oxbow connectivity, foodweb dynamics, fish biodiversity
	80,000	May-July	1	14 days	ALG recruitment, oxbow connectivity
	80,000	All months	1	3 days	Oxbow connectivity, foodweb dynamics, fish biodiversity
Navasota	5,000	Apr-Sept	2	7 days	PBSC recruitment (pelagic broadcast spawning cyprinids)
	25,000	May-July	1	14 days	ALG recruitment, oxbow connectivity
	25,000	All months	1	3 days	Oxbow connectivity, foodweb dynamics, fish biodiversity
	47,000	May-July	1	14 days	ALG recruitment, oxbow connectivity
	47,000	All months	1	3 days	Oxbow connectivity, foodweb dynamics, fish biodiversity
	53,000	May-July	1	14 days	ALG recruitment, oxbow connectivity
	53,000	All months	1	3 days	Oxbow connectivity, foodweb dynamics, fish biodiversity

Table 32 (cont). High flow pulses (in cubic feet per second-cfs) and overbanking flows that support fish spawning and recruitment, oxbow connectivity, food web dynamics, and fish biodiversity.

Study Site	Pulse (cfs)	Timing	Freq./year	Duration	Benefit
Navasota	80,000	May-July	1	14 days	ALG recruitment, oxbow connectivity
	80,000	All months	1	3 days	Oxbow connectivity, foodweb dynamics, fish biodiversity
Wildcat Bend (Hempstead)	5,000	Apr-Sept	2	7 days	PBSC recruitment (pelagic broadcast spawning cyprinids)
	32,000	May-July	1	14 days	ALG recruitment, oxbow connectivity
	32,000	All months	1	3 days	Oxbow connectivity, foodweb dynamics, fish biodiversity
	42,000	May-July	1	14 days	ALG recruitment, oxbow connectivity
	42,000	All months	1	3 days	Oxbow connectivity, foodweb dynamics, fish biodiversity
	73,000	May-July	1	14 days	ALG recruitment, oxbow connectivity
	73,000	All months	1	3 days	Oxbow connectivity, foodweb dynamics, fish biodiversity
Allens Creek (Richmond)	5,000	Apr-Sept	2	7 days	PBSC recruitment (pelagic broadcast spawning cyprinids)
	40,000	May-July	1	14 days	ALG recruitment, oxbow connectivity
	40,000	All months	1	3 days	Oxbow connectivity, foodweb dynamics, fish biodiversity
	50,000	May-July	1	14 days	ALG recruitment, oxbow connectivity
	50,000	All months	1	3 days	Oxbow connectivity, foodweb dynamics, fish biodiversity

To summarize productivity information on mature trees, using both *S. nigra* and *A. negundo* as indicators: to maintain adequate/healthy productivity flows along the Brazos River at Hempstead should be maintained for an annual flow of between 2.5 and 12.2 km^3/year. Flows along the Brazos River at Highbank should be maintained for an annual flow of between 1.8 and 3.6 km^3/year the majority of the time. Flows along the Brazos River at Waco should be maintained for an annual flow of between 3.1 and 3.5 km^3/year the majority of the time. Maintenance for this regime the majority of the time will allow for episodic flood and drought events outside those ranges that have historically been seen along the river to be within the tolerances of the community to withstand such events.

3.3.3 *Sediment Transport*

Assessments of sediment transport associated with environmental flow recommendations were made for one site (location of USGS Gage No. 08114000 Brazos River at Richmond) and one study segment (4.5-mile segment of Brazos River near Allens Creek, about 20 miles upstream of the gage at Richmond). These assessments were carried out to determine if flow recommendations would be adequate to maintain the current channel configuration or if some channel changes could be expected. Analysis at the Richmond gage site made use of the software package SAMWIN and geomorphic data from the gage site. Analysis of the Allens Creek study site made use of a HEC-RAS model, bathymetric survey and other data collected at the site, and geomorphic data from the Richmond gage site. Further description of methods employed in both analyses is provided in Appendix F. Flow scenarios considered in both analyses, along with results from SAMWin, are shown in Table 33.

Table 33. Flow scenarios considered during sediment transport analysis along with results.

Flow Scenario	Average Water Volume (*ac-ft/yr)	Average Sediment Transported (**tons/yr)	Effective Discharge (***cfs)	Percent of 1996-2015 Water Volume	Percent of 1996-2015 Sediment Yield
1. 1996-2015 gaged	5,207,000	1,635,000	35,800	100%	100%
2. Specific Flow Recommendations Only	1,783,000	430,000	58,300	34%	26%
3. Sp. Flows + 75% of flow > 5,000 cfs	3,928,000	1,121,000	27,600	75%	69%
4. Sp. Flows + 95% of flow > 5,000 cfs	4,665,000	1,458,000	34,000	90%	89%

*ac-ft/yr – acre-feet per year
**tons/yr – tons per year
***cfs – cubic feet per second

Baseline flow conditions investigated were daily gaged flow values from 1996 to 2015 (Scenario 1 in Table 33. This scenario was selected to be representative of the flows most responsible for the current channel shape and associated flow ecology relationships. Average sediment transport for this scenario was found to be approximately 1.6 million tons per year. Assuming an average weight of sediment of 100 pounds per square foot, this translates to 1.2 million cubic yards of sediment per year. Mathewson and Minter (1976) reported an equivalent value for average sediment transport per year for 20+ years prior to their report. Therefore, it appears that the amount of sediment transported by the river at this location has been relatively stable over the last 60+ years.

Other flow regimes considered included a "specific flow recommendations only" scenario (Scenario 2 in Table 33). This flow regime was derived from the daily gaged data from 1996 to 2015 by reducing the gaged flow to the values protected by preliminary values of subsistence, base, high flow pulse, and overbank flows (Figure F-10 in Appendix F). After sediment transport analysis was completed, subsistence and base flow recommendations were further refined (see Figure 70 in Section 4). For example, the subsistence flow recommendation for January of 517 cfs (Figure F-10) was reduced to 415 cfs in the final recommendations (see Figure 70). Such a change would reduce sediment transport rate by only a few tons per day (Figure F-8). Base flows also changed from the preliminary values used for sediment transport modeling to final recommendations. For example, the wet base flow in May was reduced from 6,429 cfs (Figure F-10) to 5,297 cfs in the final recommendations (see Figure 70). On days in May when gaged flow was less than 5,297 cfs (about 60% of May days in the time period), there would be no change in the amount of sediment transported. For May days when flow was greater than 5,297 cfs, the transport rate would change by at most a few hundred tons per day (Figure F-8). High flow pulse and overbank flows were identical in the scenarios examined for sediment transport analysis and the final flow recommendations. Because differences in subsistence and base flows between the preliminary and final values are relatively small and these flow ranges move relatively small amounts of sediment, the average annual sediment loads shown in Table 33 provide an adequate estimate of the sediment that would be transported by the final subsistence, base, high pulse and overbank flow recommendations (see Figure 70).

An example hydrograph for January 1, 2015 to March 31, 2015 is shown in Figure 62. In this figure, the green area represents daily gaged flow data. The purple area shows the flows associated with "specific flow recommendations only" (Scenario 2 in Table 33). This scenario includes subsistence and base habitat flows as well as specific high flow pulse and overbank flows. The blue line in Figure 62 shows Scenario 3 from Table 33. This scenario protects all the flow protected by the "specific flow recommendations only" scenario. It also protects 75% of flows above 5,000 cfs that are not already protected by one of the specific pulse or overbank flow recommendations. The red line shows Scenario 4 from Table 33, which protects 95% of flows above 5,000 cfs that are not already protected by one of the specific pulse or overbank flow recommendations. Note that Scenarios 3 and 4 protect more of the rising and receding limbs of pulse flows than the "specific flow recommendations only" scenario.

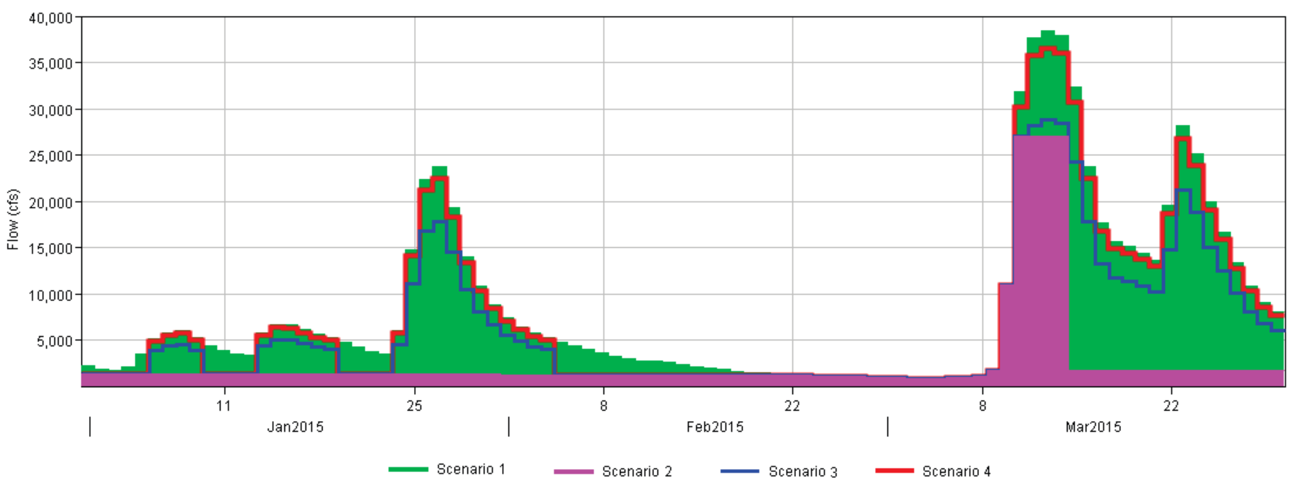


Figure 62. Daily flows for January 1, 2015 to March 31, 2015 for Scenarios 1 through 4 (from Table 33) for the Brazos River at Richmond, Texas.

Possible flow recommendations (Scenarios 2 through 4) are always less than the historical gaged flow (Scenario 1). The flow recommendations are intended to provide for a sound ecological environment; however, recommendations do not require that flow be "topped up" to meet flow recommendations if suitable flow conditions are not already present in the gaged record.

In some cases, existing water rights and infrastructure in the basin may dictate higher flows than those calculated for Scenarios 2 through 4. This is a result of several factors. First, at certain times, downstream senior water rights may require flows in excess of flow recommendations be left in the river. This may result in flows in excess of subsistence or base habitat flow recommendations remaining in the channel. Part or all of some unprotected pulse events may also be required to meet downstream water rights. Another factor that may contribute to flows in excess of flow recommendations remaining in the river is limited infrastructure to impound or divert water upstream of Richmond. This limited capacity to impound or divert water that is not protected by flow recommendations may result in flows greater than the flow recommendations being provided at Richmond. However, if flows in excess of the flow recommendations occur, their existence would be attributable to other factors, not the flow recommendations themselves. For this analysis, only the effects of the flow recommendations themselves were considered; not the combination of flow recommendations, downstream water rights, and upstream infrastructure limitations.

Flow duration curves for each of the flow scenarios are shown in Figure 63. Note that the flow duration curves for Scenarios 2, 3, and 4 are always at or below the curve for gaged flow from 1996-2015 (Scenario 1). The curves for all four scenarios are identical for flows less than 517 cfs, the preliminary value that was used to estimate the subsistence flow recommendation for all months of the year at this gage. Also note that for flows less than 3,750 cfs (75 percent of 5,000 cfs), the curves for Scenarios 3 and 4 are identical. Above 3,750 cfs, the curve for Scenario 4 is closer to the curve for the 1996-2015 gaged data (Scenario 1), while the curve for Scenario 3 is farther below. The curve for Scenario 2 is always at or below the curves for the other scenarios.

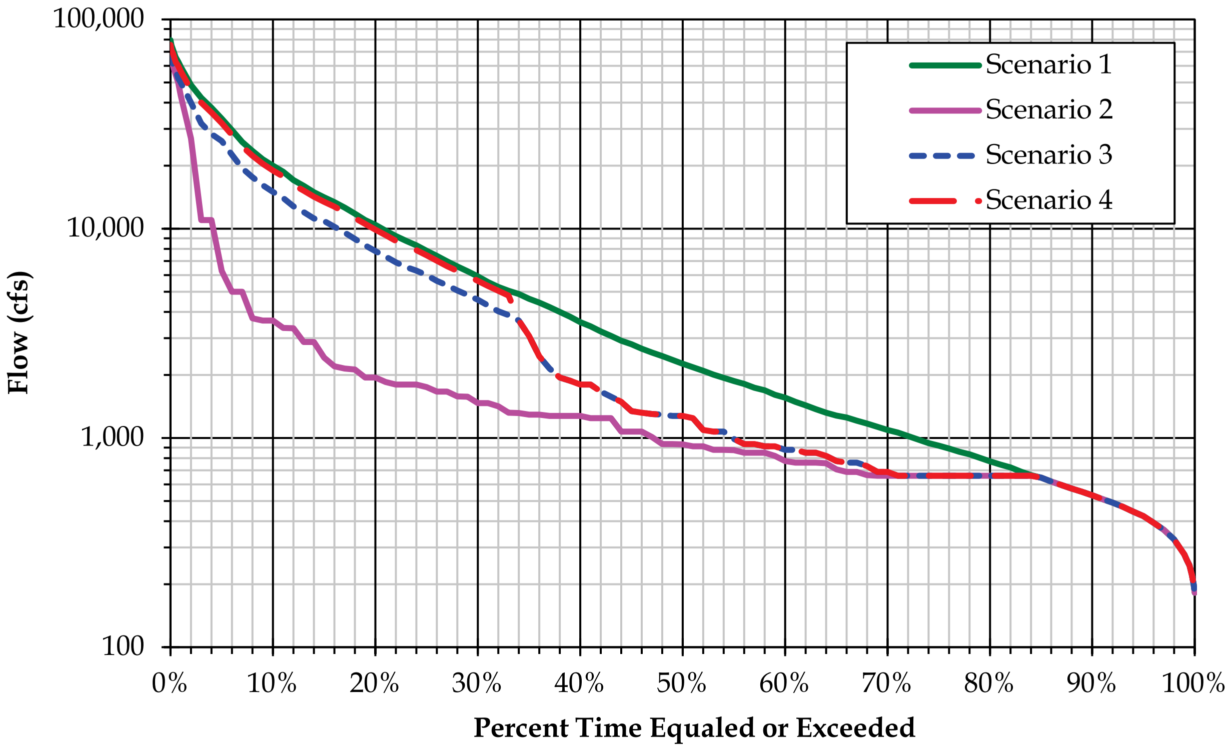


Figure 63. Flow duration curves for Scenarios 1 to 4 (from Table 33) for the Brazos River at Richmond, Texas.

According to Biedenharn *et al.* (2000), maintaining 90 to 110% of the current sediment transport rate will maintain a stable channel that has adjusted to its flow and sediment regime. Results of the sediment transport analysis indicate that Scenario 4 in Table 33 comes very close to achieving a sediment transport rate capable of maintaining a stable channel. Over the 1996 to 2015 time period, Scenario 4 would require approximately 90% of the water to remain in the river. In other words, at this location and over this time period, removing as much as 10% of the flow from the river would still maintain a relatively stable channel. Sediment transport rates associated with Scenarios 2 and 3 are reduced to less than 90% of the rate associated with gaged flows for 1996 through 2015. If the channel were stable, moving to a flow regime similar to Scenarios 2 and 3 would cause instability.

As noted in Section 2.4.2, the channel of the Brazos River at Richmond is not stable and is currently in a degrading (incising) condition. For reasons discussed in Section 2.6.1, this is an undesirable condition for maintenance of the current flow ecology relationships. Restoring the channel to a stable condition would require identification of the disturbance or disturbances causing the degradation (incision), cessation and/or mitigation of those disturbances, plus possible reshaping of the physical channel as needed to maintain important features of the ecosystem. Such activities are beyond the scope of this study. However, as part of this study it is desirable to develop flow recommendations that would be compatible with a stable channel if or when such a channel could be achieved.

Sediment transport analysis with a HEC-RAS model was completed to evaluate the ability of flow scenarios to maintain a stable channel condition, if such a condition could be achieved. Results are shown in Figure 64. This figure shows results at one representative cross-section of the Brazos River within the 4.5-mile study segment near Allens Creek. Results for additional cross-sections are provided in Appendix F. The dark blue line labeled "Start of Simulations," shows the channel cross-section at the beginning of the model runs for each of the scenarios. It represents a stable channel configuration that could be achieved with the current sediment load to the channel and the 1996-2015 gaged flows. This channel configuration was achieved by taking the measured bathymetry of the reach, setting the incision rate at the downstream boundary to zero (as discussed in Section 2.4.2, the current incision rate measured at the Richmond gage is 1.5 feet per decade), and making successive model runs with the 1996-2015 gage flows until channel cross-section shape stabilized. In effect, the "Start of Simulations" condition represents what a stable channel would look like if a grade control structure were successfully installed in the channel at the lower end of the river segment to fix the bottom elevation of the channel to its conditions as surveyed in 2015. This is not a recommendation that such a structure be constructed, merely a technique to provide a stable channel for purposes of analysis.

Given a stable channel configuration, the remaining lines on Figure 64 show what could be expected with each flow scenario. The red line shows the location of the channel after twenty years of daily flows identical to those gaged at Richmond in 1996 to 2015. As expected, the channel shape is little changed from the beginning of the model run, confirming that the dark blue line represents a stable condition.

The green line shows results after 20 years of operation with the "specific environmental flows only" (Scenario 2). This flow regime does not move enough of the sediment supplied to the reach and as a result the channel begins to aggrade (build up). Channel aggradation will be less at the lower end of the study site, where channel elevation has been fixed, and more at the upper end of the model. This will act to increase the slope along the reach, increasing the amount of sediment that the reduced flow of Scenario 2 can move. Adjustments in slope will continue until the flow regime of Scenario 2 can move sediment at the same rate that it is supplied to the reach. At the channel location shown in Figure 64, more than 20 feet of sediment accumulates in the bottom of the channel by the end of the 20-year model run. Also, note the relative uniformity of the cross-section with little to no difference in depth across the channel. This loss of habitat diversity can be detrimental to many organisms.

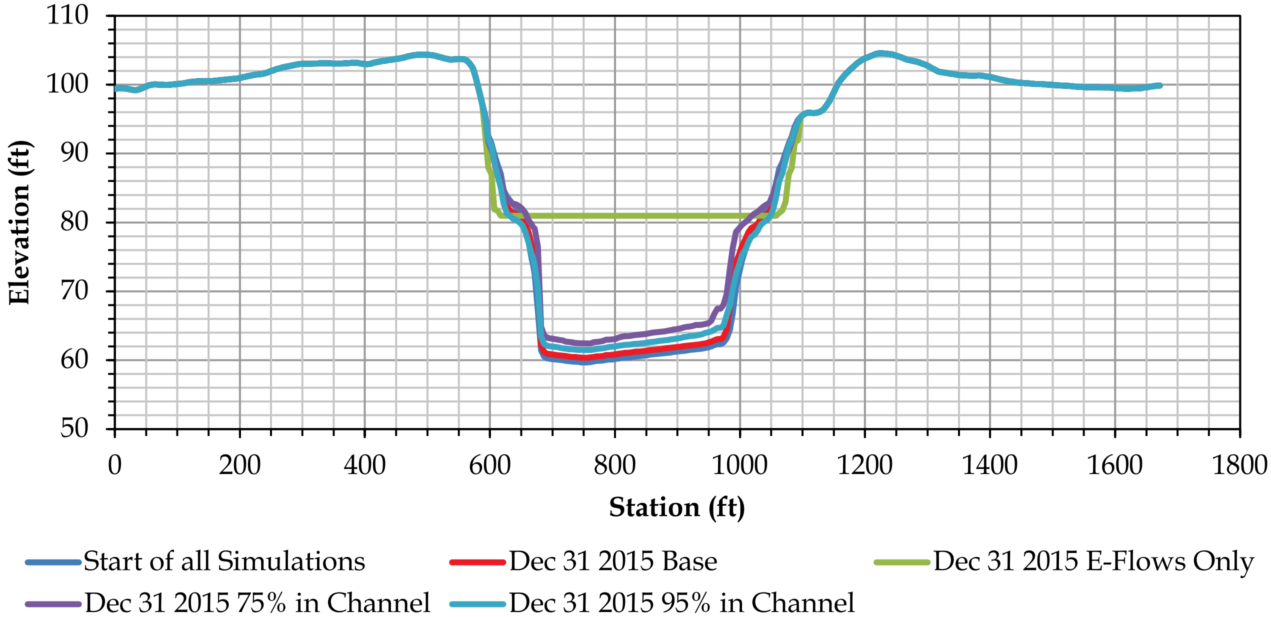


Figure 64. Cross-section profiles at river station 17,169.34 (measured in feet downstream of the upstream study boundary) for Allens Creek study site on the Brazos River for different flow scenarios.

The purple line in Figure 64 shows results after 20 years of operation with the specific environmental flows plus 75% of flows greater than 5,000 cfs (Scenario 3). Note that there is still an accumulation of sediment in the channel bottom, but it is on the order of three feet in 20 years. This is a significant improvement over Scenario 2. Again, aggradation would be greater at cross-sections in the upper portion and less at cross-section in the lower portion of the reach.

Similarly, the light blue line in Figure 64 shows results after 20 years of operation with the specific environmental flows plus 90% of flows greater than 5,000 cfs (Scenario 4). Sediment accumulation in the channel at this location is now reduced to about one foot in 20 years. Again, aggradation would vary from greater to lesser traveling from upstream to downstream. Overall, Scenario 4 comes very close to achieving a stable channel. According to Biedenharn *et al.* (2000), for a channel with some natural capacity to adjust, achieving a sediment transport rate within 10% of that supplied to the reach should ensure dynamic stability.

As mentioned in Section 2.4.2, the middle and lower Brazos River is not stable and is degrading (incising) at a significant rate in the area of the Richmond gage. Stopping incision will be crucial to ensuring any environmental flow recommendations are effective. The longer it takes to arrest incision, the greater the potential impact on riparian areas, oxbow lakes, and other aspects of the riverine ecosystem. A detailed geomorphic study of the causes of instability of the middle and lower Brazos River is recommended, as well as an exploration of means to arrest, mitigate, and/or reverse those impacts. The recent flow regime does not appear to be the cause for ongoing incision as the amount of sediment currently transported by the river compares favorably with amounts calculated decades earlier. Therefore, while the ongoing incision directly impacts the ability of flow recommendations to meet flow-ecology objectives, further investigation of the incision is beyond the scope of this study. If a stable channel is achieved, flow recommendations such as Scenario 4 should be sufficient to maintain a stable channel.

4 INSTREAM FLOW RECOMMENDATIONS

As described in Section 3, specific instream flow recommendations for four categories (subsistence flows, base flows, high flow pulses, and overbank flows) have been developed for the middle and lower Brazos River. Sediment flow recommendations (beyond high flow pulse and overbanking flow recommendations to meet riparian, connectivity, and other needs) were also developed. Figure 65 to Figure 70 summarize the integration of those recommendations into one flow regime for each study site and provide an overview of ecological functions and key indicators supported by each flow category. The relative relationships between flow recommendations and observed hydrologic data for nearby USGS gage locations are shown in Figures A-16 through A-21 in Appendix A. Future long-term monitoring and results may provide additional information that could result in modifications or revisions to these recommendations.

Preventing flows from declining below the subsistence flow recommendations (Table 25) is important in support of the sound ecological environment of the middle and lower Brazos River. Depending upon atmospheric conditions, flows less than those recommended for subsistence can result in the deterioration of water quality to a point that species are negatively affected. Water quality can affect fish survival directly when conditions such as high water temperature become lethal or indirectly through influences on reproduction and growth rates. Much research has been performed examining the effects of water quality on aquatic species. Critical Thermal Maximum (CTM) is a number used to estimate a fish's ability to survive extreme temperatures (Matthews and Zimmerman 1990). CTM is the temperature where a fish loses locomotory movement, and therefore, the ability to escape from conditions or predators that will ultimately lead to its death. In general, most warm water fish have a CTM around 35°C (Beitinger *et al.* 2000). CTM is usually determined through laboratory experiments which may not directly translate to in situ conditions. Factors that influence lethality of water temperatures in situ include the duration at or above CTM, acclimation conditions, and the ability of most river fishes to seek cooler waters. Water temperatures in portions of the Brazos River basin have exceeded 32ºC in the late summer during the hottest parts of the day. This temperature (32ºC) already exceeds or encroaches on the temperature maximums reported for several species such as, Spotted Bass *Micropterus punctulatus*, River Carpsucker *Carpiodes carpio*, and Smallmouth Buffalo *Ictiobus bubalus* (Eaton and Scheller 1996). No routine fish kills due to high water temperature have been noted.

Other fauna, such as freshwater mussels, are also sensitive to high water temperatures. Adult freshwater mussels can experience species-specific, sub-lethal stress when exposed to high water temperatures, generally greater than 35°C, but lower for some species (Spooner *et al.* 2005, Ganser *et al.* 2015). In addition, research has shown that juvenile and glochidial stages of freshwater mussels are more sensitive to high water temperatures than adults as the LT50 (temperature at which mortality occurs in 50% of the exposed population) was lower than the 35°C thermal maxima for adult mussels (Pandolfo *et al.* 2010, Archambault 2012). These high water temperatures can eventually lead to death, which is of particular concern given the presence of more than a dozen mussel species (Randklev *et al.* 2010, Table 7 in TIFP/BRA 2010), including two state-listed species and federal candidates (Smooth Pimpleback and Texas Fawnsfoot), of which multiple species are presumed to be thermally intolerant.

The 5th percentile flow and other water quality considerations were used to set water quality-based subsistence flow recommendations. The water quality evaluation showed that temperature and dissolved oxygen are protective of TIFP primary priority goals. Further, subsistence flows were identified at each study site for the months of May through September to limit exceedances of the 30°C thermal tolerance criteria for mussel recruitment (Table 15) except for the Hearne and Navasota study sites.

<table>
<tr><td rowspan="7">High Flow Pulse</td><td></td><td colspan="3">52,000 cfs, 3 days, 2 events</td><td colspan="7">52,000 cfs, 3 days, 2 events</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="2">47,000 cfs, 3 d, 2 events</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td colspan="10">38,200 cfs, 14 days, 1 event</td><td></td></tr>
<tr><td></td><td></td><td colspan="3">37,000 cfs, 4 days, 3 events</td><td colspan="3">37,000 cfs, 4 days, 2 events</td><td colspan="3">37,000 cfs, 4 days, 2 events</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="2">30,000 cfs, 3 d, 2 events</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td colspan="9">23,000 cfs, 4 days, 3 events</td><td></td></tr>
<tr><td></td><td></td><td></td><td colspan="6">5,000 cfs, 7 days, 2 events</td><td></td><td></td><td></td></tr>
<tr><td>Sediment Flow</td><td colspan="12">95% of any flow > 5,000 cfs left in river
Sediment transport: Channel maintenance</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="9">BASE FLOWS (cfs) - Aquatic Habitat protection (intra- and interannual variability)</td><td colspan="4">Key Indicators: Aquatic Habitat, Water Quality</td></tr>
<tr><td>Base Wet</td><td>1,377</td><td>1,062</td><td>1,680</td><td>2,749</td><td>6,116</td><td>5,894</td><td>1,363</td><td>1185*</td><td>1,683</td><td>1,432</td><td>885</td><td>983</td></tr>
<tr><td>Base Average</td><td>712</td><td>549</td><td>869</td><td>1,422</td><td>3,163</td><td>3,049</td><td>705</td><td>570*</td><td>871</td><td>740</td><td>458</td><td>509</td></tr>
<tr><td>Base Dry</td><td>253</td><td>195</td><td>309</td><td>506</td><td>1,125</td><td>1,084</td><td>251</td><td>190*</td><td>310</td><td>263</td><td>163</td><td>181</td></tr>
<tr><td colspan="9">SUBSISTENCE FLOWS (cfs) - Water quality protection and maintainence of limited aquatic habitat</td><td colspan="4">Key Indicators: Aquatic Habitat, Water Quality</td></tr>
<tr><td>Subsistence</td><td>119</td><td>119</td><td>119</td><td>119</td><td>190*</td><td>190*</td><td>190*</td><td>190*</td><td>190*</td><td>119</td><td>119</td><td>119</td></tr>
<tr><td>MONTH</td><td>January</td><td>February</td><td>March</td><td>April</td><td>May</td><td>June</td><td>July</td><td>August</td><td>September</td><td>October</td><td>November</td><td>December</td></tr>
</table>

* - mussel thermal tolerance flows

** - subsistence override MARLIN

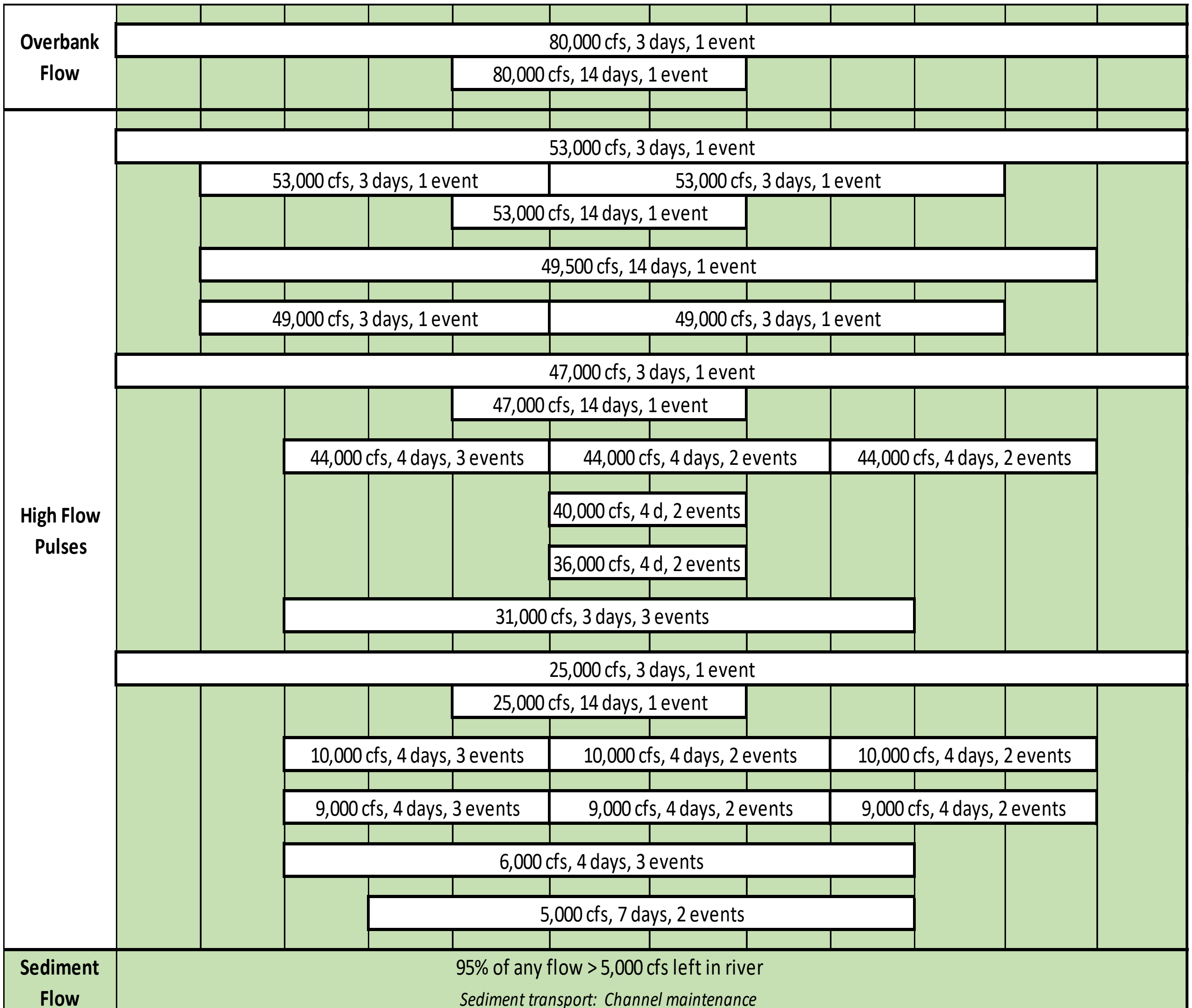
Figure 65. Instream flow recommendations for the Brazos River Marlin study site. See Tables 30-32 for site specific documentation of high flow pulses and overbanking flows; Table 29 for base flows; and Tables 15 and 27 for subsistence flows.

<table>
<tr><td rowspan="8">High Flow Pulses</td><td></td><td colspan="10">36,300 cfs, 14 days, 1 event</td><td></td></tr>
<tr><td></td><td colspan="10">34,000 cfs, 2 days, 1 event</td><td></td></tr>
<tr><td></td><td></td><td colspan="3">21,000 cfs, 4 days, 3 events</td><td colspan="3">21,000 cfs, 4 days, 2 events</td><td colspan="3">21,000 cfs, 4 days, 2 events</td><td></td></tr>
<tr><td></td><td></td><td colspan="3">15,000 cfs, 4 days, 3 events</td><td colspan="3">15,000 cfs, 4 days, 2 events</td><td colspan="3">15,000 cfs, 4 days, 2 events</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="2">13,000 cfs, 3 d, 2 events</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td colspan="3">7,000 cfs, 4 days, 3 events</td><td colspan="3">7,000 cfs, 4 days, 2 events</td><td colspan="3">7,000 cfs, 4 days, 2 events</td><td></td></tr>
<tr><td></td><td></td><td></td><td colspan="6">5,000 cfs, 7 days, 2 events</td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td colspan="9">4,500 cfs, 4 days, 3 events</td><td></td></tr>
<tr><td>Sediment Flow</td><td colspan="12">95% of any flow > 5,000 cfs left in river
Sediment transport: Channel maintenance</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="9">BASE FLOWS (cfs) - Aquatic Habitat protection (intra- and interannual variability)</td><td colspan="4">Key Indicators: Aquatic Habitat, Water Quality</td></tr>
<tr><td>Base Wet</td><td>1,266</td><td>977</td><td>1,545</td><td>2,528</td><td>5,623</td><td>5,420</td><td>1,253</td><td>1185*</td><td>1,548</td><td>1,316</td><td>814</td><td>904</td></tr>
<tr><td>Base Average</td><td>633</td><td>488</td><td>772</td><td>1,264</td><td>2,812</td><td>2,710</td><td>627</td><td>570*</td><td>774</td><td>658</td><td>407</td><td>452</td></tr>
<tr><td>Base Dry</td><td>237</td><td>183</td><td>290</td><td>474</td><td>1,054</td><td>1,016</td><td>235</td><td>190*</td><td>290</td><td>247</td><td>153</td><td>170</td></tr>
<tr><td colspan="9">SUBSISTENCE FLOWS (cfs) - Water quality protection and maintainence of limited aquatic habitat</td><td colspan="4">Key Indicators: Aquatic Habitat, Water Quality</td></tr>
<tr><td>Subsistence</td><td>119</td><td>119</td><td>119</td><td>119</td><td>190*</td><td>190*</td><td>190*</td><td>190*</td><td>190*</td><td>119</td><td>119</td><td>119</td></tr>
<tr><td>MONTH</td><td>January</td><td>February</td><td>March</td><td>April</td><td>May</td><td>June</td><td>July</td><td>August</td><td>September</td><td>October</td><td>November</td><td>December</td></tr>
</table>

* - mussel thermal tolerance flows

** - subsistence override HEARNE

Figure 66. Instream flow recommendations for the Brazos River Hearne study site. See Tables 30-32 for site specific documentation of high flow pulses and overbanking flows; Table 29 for base flows; and Tables 15 and 27 for subsistence flows.



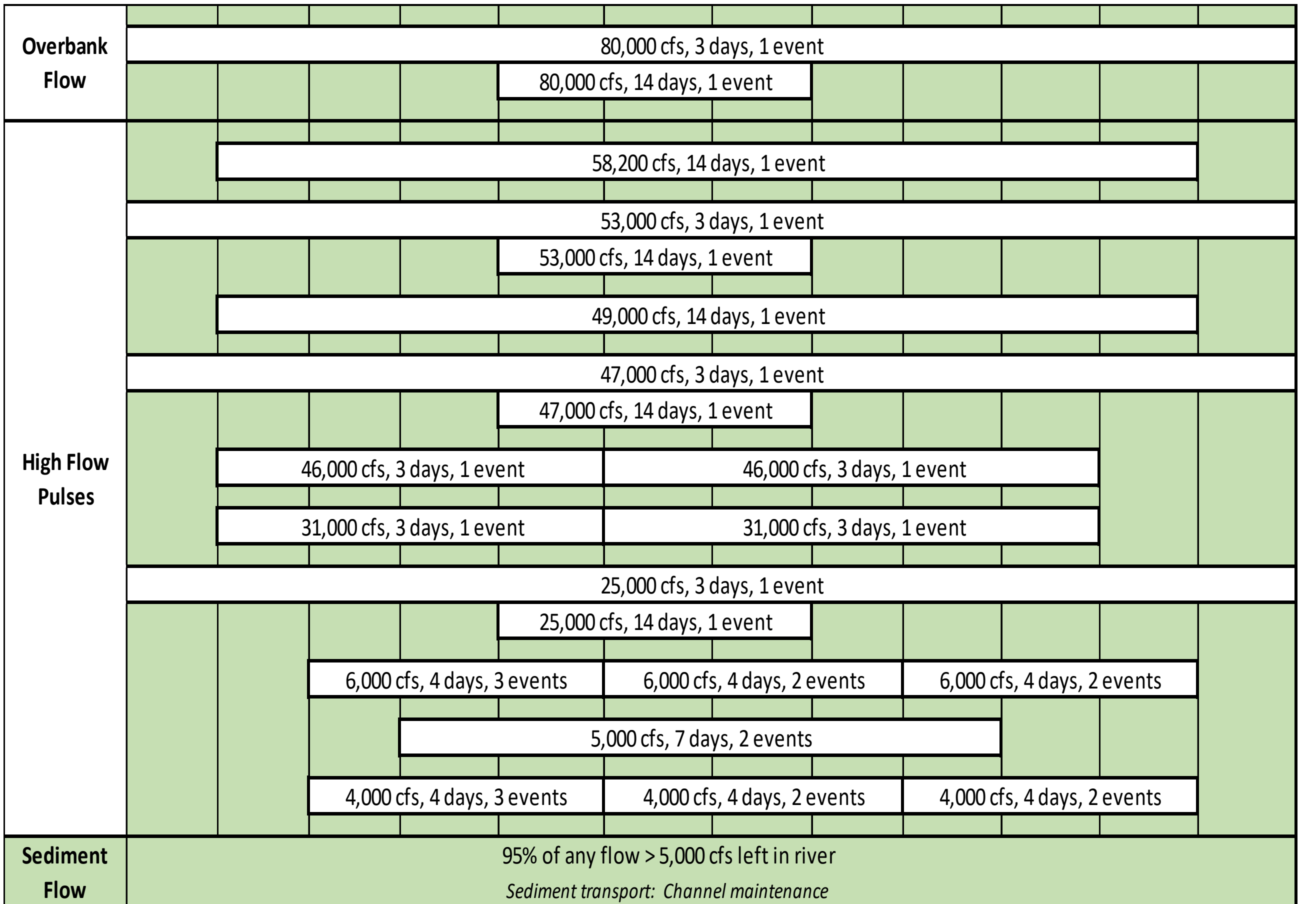
BASE FLOWS (cfs) - Aquatic Habitat protection (intra- and interannual variability)									Key Indicators: Aquatic Habitat, Water Quality			
Base Wet	1,553	1,510	1,918	2,367	4,624	4,667	1,392	724	1,120	1,175	882	864
Base Average	822	800	1,015	1,253	2,448	2,471	737	383	593	622	467	458
Base Dry	487	474	602	743	1,451	1,464	437	299**	351	369	299**	299**
SUBSISTENCE FLOWS (cfs) - Water quality protection and maintainence of limited aquatic habitat									**Key Indicators: Aquatic Habitat, Water Quality**			
Subsistence	299	299	299	299	299	299	299	299	299	299	299	299
MONTH	January	February	March	April	May	June	July	August	September	October	November	December

* - mussel thermal tolerance flows

** - subsistence override

MUSSEL SHOALS

Figure 67. Instream flow recommendations for the Brazos River Mussel Shoals study site. See Tables 30-32 for site specific documentation of high flow pulses and overbanking flows; Table 29 for base flows; and Tables 15 and 27 for subsistence flows.

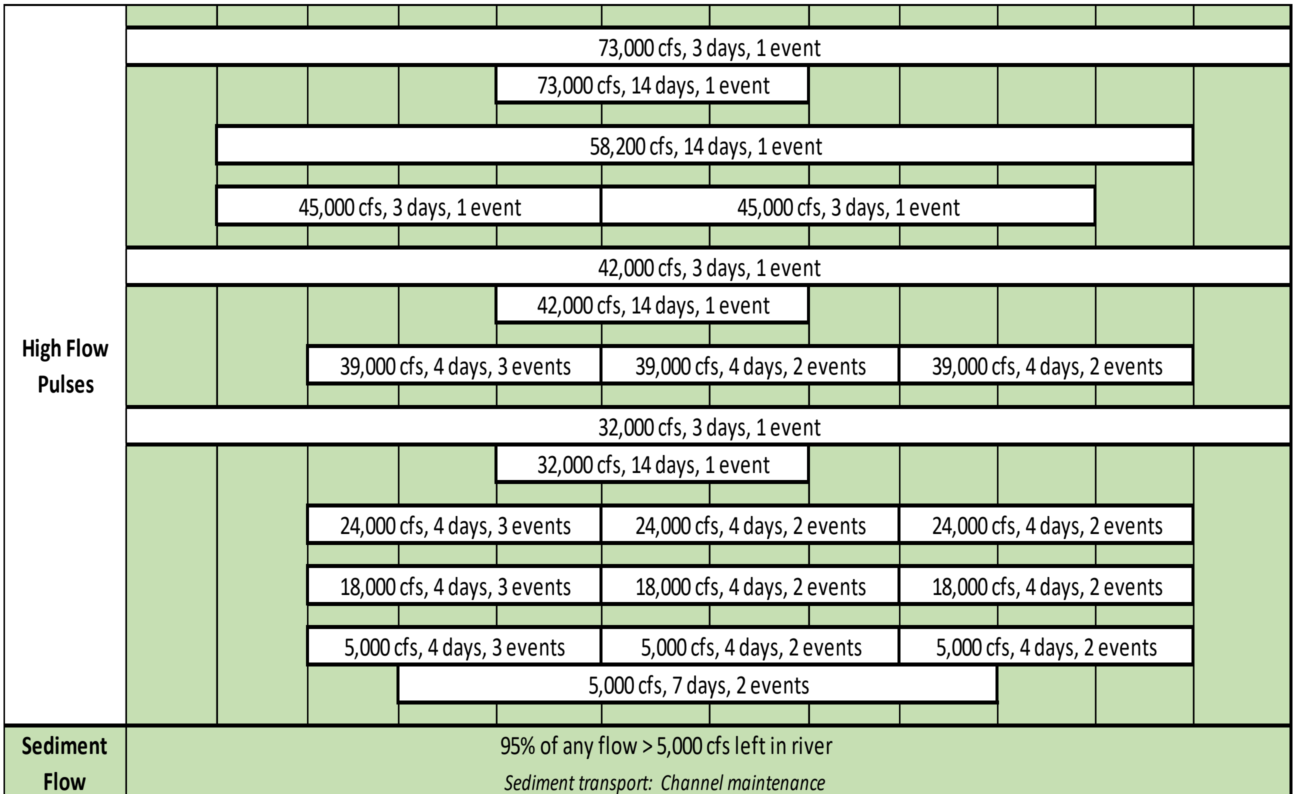


BASE FLOWS (cfs) - Aquatic Habitat protection (intra- and interannual variability)								**Key Indicators: Aquatic Habitat, Water Quality**				
Base Wet	1,766	1,718	2,181	2,692	5,259	5,307	1,582	824	1,274	1,336	1,004	983
Base Average	1,015	987	1,253	1,547	3,022	3,050	909	473	732	768	577	565
Base Dry	507	494	627	774	1,511	1,525	455	299**	366	384	299**	299**
SUBSISTENCE FLOWS (cfs) - Water quality protection and maintainence of limited aquatic habitat								**Key Indicators: Aquatic Habitat, Water Quality**				
Subsistence	299	299	299	299	299	299	299	299	299	299	299	299
MONTH	January	February	March	April	May	June	July	August	September	October	November	December

** - subsistence override

NAVASOTA

Figure 68. Instream flow recommendations for the Brazos River Navasota study site. See Tables 30-32 for site specific documentation of high flow pulses and overbanking flows; Table 29 for base flows; and Tables 15 and 27 for subsistence flows.



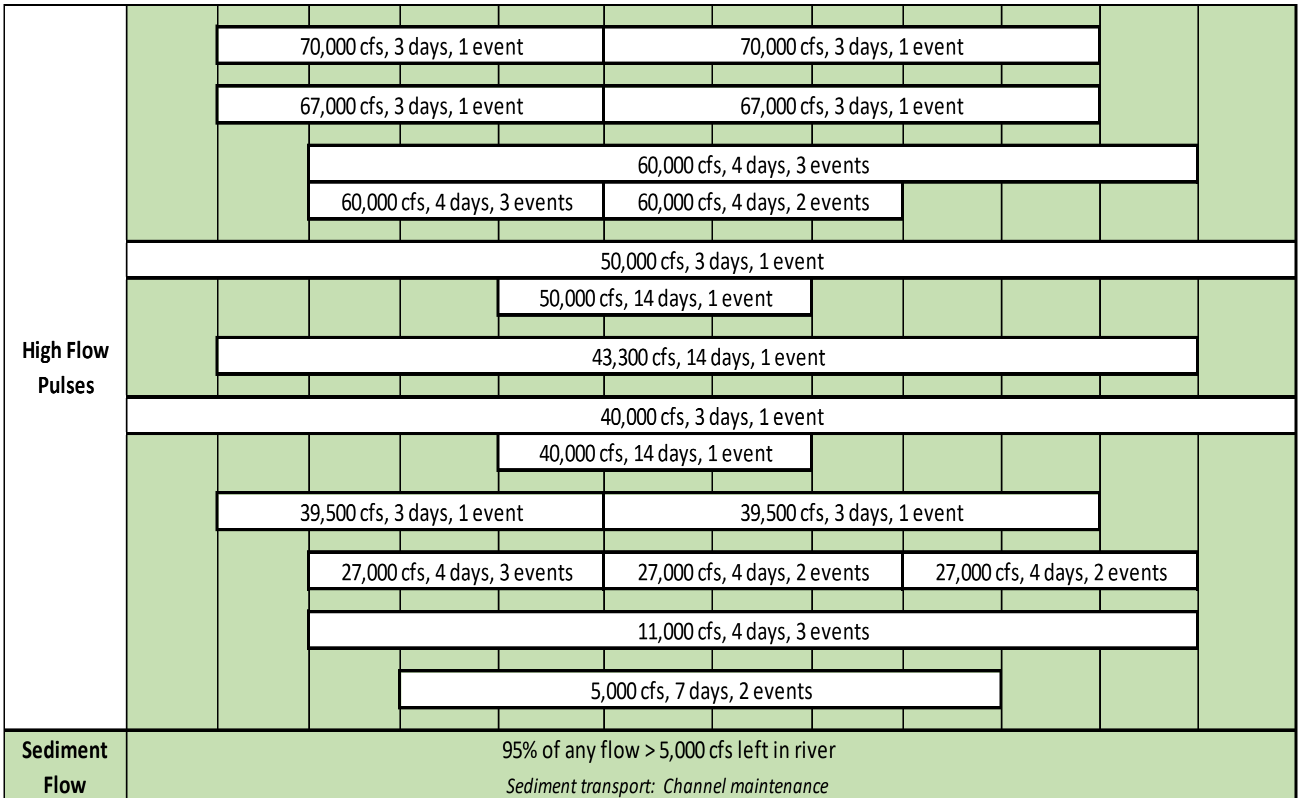
BASE FLOWS (cfs) - Aquatic Habitat protection (intra- and interannual variability)									Key Indicators: Aquatic Habitat, Water Quality			
Base Wet	2,180	2,281	2,914	2,961	5,223	5,150	1,718	1500*	1500*	1,312	1,268	1,416
Base Average	1,078	1,129	1,441	1,465	2,584	2,548	1140*	1140*	1140*	649	627	701
Base Dry	485**	528	675	686	1,209	1,193	824*	824*	824*	485**	485**	485**
SUBSISTENCE FLOWS (cfs) - Water quality protection and maintainence of limited aquatic habitat									Key Indicators: Aquatic Habitat, Water Quality			
Subsistence	485	485	485	485	824*	824*	824*	824*	824*	485	485	485
MONTH	January	February	March	April	May	June	July	August	September	October	November	December

* - mussel thermal tolerance flows

** - subsistence override

WILDCAT BEND

Figure 69. Instream flow recommendations for the Brazos River Wildcat Bend study site. See Tables 30-32 for site specific documentation of high flow pulses and overbanking flows; Table 29 for base flows; and Tables 15 and 27 for subsistence flows.



BASE FLOWS (cfs) - Aquatic Habitat protection (intra- and interannual variability)									**Key Indicators: Aquatic Habitat, Water Quality**			
Base Wet	2,739	3,027	3,881	3,358	5,297	5,074	1943*	1943*	1943*	1,312	1,622	1,766
Base Average	1,587	1,754	2,249	1,946	3,069	2,940	1,115	946*	946*	760	940	1,023
Base Dry	563	622	798	691	1,089	1,043	626*	626*	626*	517**	517**	517**
SUBSISTENCE FLOWS (cfs) - Water quality protection and maintainence of limited aquatic habitat									**Key Indicators: Aquatic Habitat, Water Quality**			
Subsistence	517	517	517	517	626*	626*	626*	626*	626*	517	517	517
MONTH	January	February	March	April	May	June	July	August	September	October	November	December

* - mussel thermal tolerance flows

** - subsistence overlay on base

ALLENS CREEK

Figure 70. Instream flow recommendations for the Brazos River Allens Creek study site. See Tables 30-32 for site specific documentation of high flow pulses and overbanking flows; Table 29 for base flows; and Tables 15 and 27 for subsistence flows.

As defined earlier in the report, subsistence flows are infrequent and seasonal in nature, therefore they should never occur regularly or for long periods of time.

Base flows are the normal flow conditions between storm events and naturally vary in discharge depending upon ambient climatological conditions. Base flow recommendations in this report are intended to provide high relative percentages of moderate to high quality habitat for each fish guild (as well as mussels). Inter- and intra-annual variability in flow are also built into the recommendations. Further, base flows were identified at each study site for certain months to limit exceedances of the 30°C thermal tolerance criteria for mussel recruitment (Table 15). Base flow recommendations are parsed out into three hydrologic categories: dry, average, and wet. These hydrologic conditions are intended to occur at frequencies of 25% for base dry and wet and 50% for base average. Hydrologic variability is critical to ecosystem function, habitat diversity, and native biodiversity (Poff *et al.* 1997). Variation in flow drives processes that periodically reset physical, chemical, and biological functions essential to the ecosystem (Annear *et al.* 2004).

Thus, intra-annual (monthly to seasonal) and inter-annual variability in base flow conditions (dry, average, and wet years) are necessary to ensure that each study site supports a full complement of hydraulic habitat conditions and fish guilds through time. A trend of increasing base flow recommendations occurs from upstream to downstream in the Brazos.

Base flows also serve an important role in structuring riparian communities. Both low and high base flows can limit encroachment of invasive species and maintain high species diversity (Stromberg *et al.* 2007). Maintaining healthy and diverse riparian zones provides many benefits to the river, such as buffering thermal effects of high temperatures, increasing habitat structure, and influencing food web structure (Pusey and Arthington 2003). High base flow conditions also correlate with higher groundwater tables within the riparian zone and support increased riparian productivity (Duke 2011), especially in species such as black willow which could play an important role in the food web dynamics (Zeug and Winemiller 2008b). For these reasons, providing a single flow value or base flow regime cannot simultaneously meet the requirements for all species or maintain diverse fish and wildlife resources.

Pulse and overbanking flow recommendations are also important components of an instream flow regime designed to maintain a sound ecological environment. Specific recommendations for flow magnitude, frequency, duration, and time of year are given for each study site. Each of these prescription components are important for maintaining the health of existing riparian communities and for sediment transport and subsequent channel and habitat maintenance. High flow pulses are also necessary for the successful reproduction and recruitment of broadcast spawning fishes which rely upon flow conditions that are capable of keeping their eggs suspended within the water column for several days while they develop and subsequently hatch (Durham and Wilde 2009). Broadcast spawning is the predominant reproductive mode among North American cyprinids (Johnston and Page 1992). Because most small cyprinid species are short-lived with only a two- to three year maximum life span (Winemiller and Rose 1992, Bonner 2000), a single year without successful reproduction could result in a significant decrease in population abundance or even result in extirpation if recruitment does not occur for two or three consecutive years. Pulse and overbanking flows also provide connectivity to backwaters and floodplain lakes which serve as important reproductive habitat and nursery grounds for many fish species (Shaeffer 1984) including Alligator Gar, one of the key species in the middle and lower Brazos Study Area.

When the balance of sediment load, hydrologic load, and/or channel geometry and slope is changed, there is often a response or adjustment of the fluvial system as it attempts to re-establish the equilibrium condition. Sediment analysis indicated the high flow pulses and overbanking flow recommendations alone would not be sufficient for maintaining sediment transport and the shape of the middle and lower Brazos River channel in a condition similar to that which currently exists or was experienced during the 1996 to 2015 time period. Without specifically including flows for sediment transport, the channel will most likely begin to aggrade. Sediment deposition could negatively affect the river in a number of ways including the degradation of habitat quality and the reduction of the quantity of specific habitat types. Sullivan and Watzin (2010) reported all fish in their study of aggraded environments lost physiological condition over time, indicating that streams and rivers with extensive sediment aggradation are unlikely to support healthy fish assemblages.

4.1 *Monitoring and Adaptive Management*

Future monitoring and adaptive management will provide additional information that may result in modifications or revisions to current recommendations. The project team concurs with the TIFP Technical Overview document (TIFP 2008) and National Research Council guidance (NRC 2005) and recognizes that a critical component for this study is a monitoring program (TIFP 2008). A monitoring program should evaluate the effectiveness of the instream flow recommendations and to what extent the different objectives were met for those recommendations (Higgins *et al.* 2011). Monitoring is recommended for water quality, fish, mussels, riparian vegetation, and channel morphology.

<u>*Water Quality*</u>

As previously discussed in Section 2.5 Water Quality, TIFP reviewed reports on existing water quality models for the study area to determine their utility for this study. Espey Consultants, Inc. developed water quality models for study reach BR2 (EC 2011); however, the authors concluded that additional calibration was needed to accurately model daily temperature variation using EPD-RIV1. The authors also noted that calibration data was very limited for QUAL2K temperature model and the EPD-RIV1 dissolved oxygen model and recommended additional calibration and field verification.

In 2016, RPS extended the 2011 modeling effort by developing water quality models for study reaches BR2, BR3, and BR4 (RPS 2016). EPD-RIV1 was used to evaluate temperature and dissolved oxygen for the June 2009 low-flow period under various scenarios, including low-flow conditions, pulse flows, diversions, and wastewater treatment plant discharges. All of the modeling scenarios predicted that TIFP primary priority thresholds for temperature and dissolved oxygen would be met, except at flows well below the subsistence flow recommendations. The authors noted that channel geometries had to be assumed because of limited transect data and that the models did not completely match the limited validation data. Additional information that may assist with future water quality models include in channel bathymetry data and additional sub-daily data for calibration.

Diurnal sonde data was collected from four study sites during summer (June-August) low flow conditions from 2010-2012 and additional sampling was conducted at the Wildcat Bend study site in 2014. At the Allens Creek study site, temperature data was not available and although long-term diurnal data was available at Stephen F. Austin State Park just upstream of the study site, correlating flow data was not available for reasons discussed in Section 2.5. Data collected from these four TIFP study sites could be used in combination with other future studies to provide valuable information on temperature and DO levels during extreme summertime temperatures and low flow conditions during drought.

One potential avenue for future research is to extend the evaluation of surface water quality monitoring data from this report using recent data (January 2017 to current). Extending the present dataset would allow researchers to determine whether revised instream flow recommendations may be warranted to ensure that designated uses of the water body are attained over time.

Future research could also include updated modeling or additional sub-daily physical monitoring, paired with biological monitoring, to better understand the effects of short-duration temperature spikes. These approaches could help researchers understand which conditions are likely to cause temperature or dissolved oxygen to cross a critical threshold and the extent to which organisms in the system are affected by short-duration exceedances. If additional modeling is performed, updated channel bathymetry and additional sub-daily physical monitoring may also be needed to set up, calibrate, and validate the model. Updated information on sediment oxygen demand, biochemical oxygen demand, and reaeration may be needed for dissolved oxygen modeling.

All water quality monitoring should be conducted in accordance with the most recent approved protocols set forth in the Texas Commission on Environmental Quality Surface Water Quality Monitoring Procedures (RG-415) (TCEQ 2012). In determining attainment of applicable water quality criteria, analysis should follow approved protocols identified in the TCEQ 2014 Guidance for Assessing and Reporting Surface Water Quality in Texas (TCEQ 2015). Sample sets should be temporally representative of conditions within the study area and collected on a routine basis (monthly or quarterly) over several years with approximately the same time intervals between sampling events.

Combined data from past and future studies could be utilized to re-evaluate subsistence flow recommendations to determine if modifications to these recommendations are warranted.

Biology

Studies should be designed and implemented to strengthen quantitative relationships among streamflow, mussel habitat persistence, habitat (WUA) and hydraulic habitat diversity, and biodiversity (fish, mussels, benthic macroinvertebrates, and others). These studies include:

- habitat surveys within our modeled study sites to assess hydraulic habitat model accuracy and persistence through time given the dynamic degrading river channel in the Brazos River;
- assemblage monitoring to assess spatial and temporal patterns in abundance and distributions; and
- population monitoring to assess flow-ecology relationships for species survival, growth, and recruitment. For example, continued monitoring of juvenile broadcast spawning minnows to relate recruitment strength to flow pulse hydrologic characteristics.

Habitat suitability criteria are a critical element of instream habitat modeling. While a traditional approach to calculating criteria for guilds of fishes was used in this study, alternative methods should be explored, including the use of probability density functions (see Som *et al.* 2015) and using presence data rather than abundance.

DEM-based floodplain inundation hydraulic modeling for the middle and lower Brazos River should be developed to quantify flow-ecology relationships for Alligator Gar spawning and recruitment, oxbow connectivity, and riparian productivity. Tree coring studies are underway and should provide quantitative data on the relationship between riparian health/productivity and high flow pulses and overbanking flows.

Water quality data will be important for linking to biological monitoring components and updating parameters in water quality models. Additional field data collection programs and studies to understand the linkage between water temperature and ecological processes (*e.g.*, mussel and fish survival, growth, and recruitment) are needed. USGS streamflow gages throughout the basin should be outfitted with temperature loggers for real-time, long-term data collection. Lab and field experiments should be designed and implemented to refine the understanding of thermal tolerance limits for key species of fish and mussels.

Physical Processes and Geomorphology

Monitoring channel cross-sections within the middle and lower Brazos River study sites should be performed biannually to assess potential changes in channel configuration. The cross-sections should be surveyed when the middle and lower Brazos River typically experiences low flow conditions and a second time each year when the Brazos River typically experiences high flow conditions. The biannual cross-sections at the study sites should be supplemented with a comprehensive hydrographic survey performed every 10 years from the upstream study boundary near Waco to the downstream study boundary near Richmond. The comprehensive hydrographic survey should have cross-sections taken at approximate 500 feet spacing and include the channel from the right top bank to left top bank. When performing the comprehensive hydrographic survey, bed material samples should be taken at the thalweg at an interval not to exceed one mile. The thalweg samples should be analyzed to determine grain size distribution. At the existing USGS gages and at each study site, real-time and synoptic cross-sectional water velocities and discharge should be collected monthly at USGS gaging station and quarterly at TIFP study sites. One significant data gap in the Brazos River is the lack of system-wide suspended load and bed material load data. To fill this data gap, suspended load concentration and grain size distribution should be collected monthly at USGS gaging stations and quarterly at TIFP study sites. Bed material load and flux of sediment occurring through bed form migration should be collected annually during high flow events at the TIFP study sites. These data should be collected simultaneously with suspended load measurements. High turbidity can significantly harm fish and other aquatic life by reducing food supplies, degrading spawning beds, and affecting gill function. Therefore, water column turbidity samples should be taken simultaneously with suspended load measurements.

4.2 *Continued Stakeholder Involvement*

This project has been subject to stakeholder and peer review during the project design, periodic updates during study activities, and the development of flow recommendations. Stakeholder involvement has been and will continue to be an integral part of the TIFP process. As future TIFP studies and monitoring activities are developed, stakeholder input will be solicited and participation encouraged. Periodic stakeholder review will also be requested as on-going TIFP studies, future studies, and monitoring results become available.

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APPENDIX A
HYDROLOGIC AND HYDRAULIC DATA

Table A-1. Flow exceedance statistics for Unites States Geological Survey stations on the Brazos River at Waco and Highbank for three time periods (1921-1940, 1961-1980, and 1996-2015).

Exceedance Probability (%)	Waco USGS Gage No. 08096500 1921-1940 Flow (cfs)	Waco 1961-1980 Flow (cfs)	Waco 1996-2015 Flow (cfs)	Highbank USGS Gage No. 0809290 1921-1940 Flow (cfs)	Highbank 1961-1980* Flow (cfs)	Highbank 1996-2015 Flow (cfs)
0.0	158,000	52,800	35,800	Unavailable	55,800	41,700
0.1	73,287	33,387	32,109		40,402	37,839
0.25	54,496	30,296	29,800		37,600	35,100
0. 5	39,828	26,628	28,748		33,830	32,096
0. 75	31,822	24,222	27,222		30,268	30,800
1.0	28,588	21,200	25,196		26,620	29,696
2.5	17,140	13,000	15,940		17,000	21,740
5.0	10,700	7,872	8,988		10,400	12,200
7.5	7,400	5,402	5,750		7,390	8,312
10.0	5,614	4,530	4,270		5,560	5,850
15.0	3,740	2,944	2,750		3,885	3,824
20.0	2,750	2,250	1,950		2,830	2,600
30.0	1,660	1,400	1,150		1,850	1,488
40.0	985	1,040	755		1,320	952
50.0	590	804	465		995	642
60.0	342	615	293		784	452
70.0	207	441	183		606	312
80.0	125	296	111		403	214
85.0	98	235	79		303	172
90.0	74	180	56		230	138
92.5	62	157	47		204	122
95.0	46	133	37		179	106
97.5	28	99	26		138	83
99.0	13	71	14		81	55
99.25	12	67	12		72	45
99.5	9	61	11		71	40
99.75	3	41	8		56	35
99.9	3	34	5		51	31
100.0	3	27	3		41	30
Average Annual Flow Volume (ac-ft/yr)	1,761,286	1,416,708	1,355,510		1,831,655	1,793,022

***Data unavailable from 1/1/1961 to 9/30/1965.**

Table A-2. Flow exceedance statistics for Unites States Geological Survey stations on the Brazos River at Bryan and Hempstead for three time periods (1921-1940, 1961-1980, and 1996-2015).

Exceedance Probability (%)	Bryan USGS Gage No. 08109000 1921-1940* Flow (cfs)	Bryan USGS Gage No. 08109000 1961-1980 Flow (cfs)	Bryan 08108700 1996-2015 Flow (cfs)	Hempstead USGS Gage No. 08111500 1921-1940** Flow (cfs)	Hempstead 08111500 1961-1980 Flow (cfs)	Hempstead 08111500 1996-2015 Flow (cfs)
0.0	172,000	134,000	84,400	116,000	106,000	91,500
0.1	120,631	72,709	71,344	112,065	78,874	77,687
0.25	103,193	58,222	63,850	106,065	70,548	69,796
0. 5	87,616	49,000	54,148	101,130	61,040	62,228
0. 75	63,920	45,800	48,066	79,383	55,044	57,900
1.0	52,570	39,700	44,500	74,000	50,588	54,996
2.5	33,093	27,100	33,440	52,055	35,000	42,940
5.0	19,385	17,900	23,200	40,055	24,700	32,000
7.5	15,300	13,500	17,700	30,498	19,300	23,900
10.0	12,100	11,000	14,200	24,500	15,800	19,600
15.0	8,140	8,324	8,944	18,785	11,900	13,600
20.0	6,100	6,100	6,284	13,320	9,294	9,436
30.0	3,850	3,850	3,220	7,438	5,690	5,088
40.0	2,540	2,570	1,884	3,800	3,860	3,050
50.0	1,640	1,830	1,220	2,320	2,700	1,990
60.0	1,080	1,430	918	1,376	1,930	1,436
70.0	694	1,100	690	800	1,480	1,090
80.0	477	832	512	540	1,130	800
85.0	400	698	438	470	980	687
90.0	314	586	360	410	810	555
92.5	270	532	321	354	719	496
95.0	224	450	285	332	625	424
97.5	167	374	228	299	530	352
99.0	134	312	181	284	450	286
99.25	125	297	167	281	440	268
99.5	114	274	153	272	425	234
99.75	103	244	141	264	399	207
99.9	95	219	132	260	353	152
100.0	89	166	120	260	318	58
Average Annual Flow Volume (ac-ft/yr)	3,694,881	3,340,691	3,529,001	4,588,425	4,640,955	4,918,415

***Data unavailable from 1/1/1926 to 6/30/1926.**
****Data unavailable from 1/1/1921 to 9/30/1938.**

Table A-3. Flow exceedance statistics for Unites States Geological Survey stations on the Brazos River at Richmond and Rosharon for three time periods (1921-1940, 1961-1980, and 1996-2015).

Exceedance Probability (%)	Richmond USGS Gage No. 08114000			Rosharon USGS Gage No. 08116650		
	1921-1940* Flow (cfs)	1961-1980 Flow (cfs)	1996-2015 Flow (cfs)	1921-1940 Flow (cfs)	1961-1980** Flow (cfs)	1996-2015 Flow (cfs)
0.0	123,000	98,800	79,600	Unavailable	79,700	76,100
0.1	112,334	87,422	75,200		76,128	72,717
0.25	89,001	75,644	71,575		71,667	67,523
0. 5	80,900	67,844	65,951		62,838	63,746
0. 75	75,702	62,722	62,800		56,604	62,200
1.0	69,936	56,976	59,502		52,769	59,200
2.5	44,540	38,840	44,900		40,345	46,230
5.0	29,500	26,100	33,400		29,900	36,400
7.5	23,000	20,600	24,258		23,518	27,300
10.0	18,500	17,000	20,000		19,490	21,720
15.0	13,100	12,900	14,100		14,300	15,600
20.0	10,100	10,200	10,400		11,300	11,800
30.0	6,340	6,618	5,913		7,580	6,990
40.0	4,200	4,480	3,570		4,946	4,570
50.0	2,840	3,070	2,260		3,240	2,880
60.0	1,910	2,160	1,560		2,190	1,910
70.0	1,330	1,590	1,090		1,500	1,310
80.0	930	1,210	775		1,100	889
85.0	760	1,040	645		883	701
90.0	640	864	533		664	499
92.5	565	768	480		573	424
95.0	500	679	423		429	359
97.5	425	553	343		240	278
99.0	301	428	277		119	182
99.25	264	403	260		105	155
99.5	159	375	246		85	118
99.75	103	301	220		68	76
99.9	53	265	200		50	50
100.0	35	229	182		40	27
Average Annual Flow Volume (ac-ft/yr)	5,408,980	5,115,750	5,200,329		5,321,612	5,280,507

***Data unavailable from 1/1/1921 to 9/30/1922.**
****Data unavailable from 1/1/1961 to 3/31/1967.**

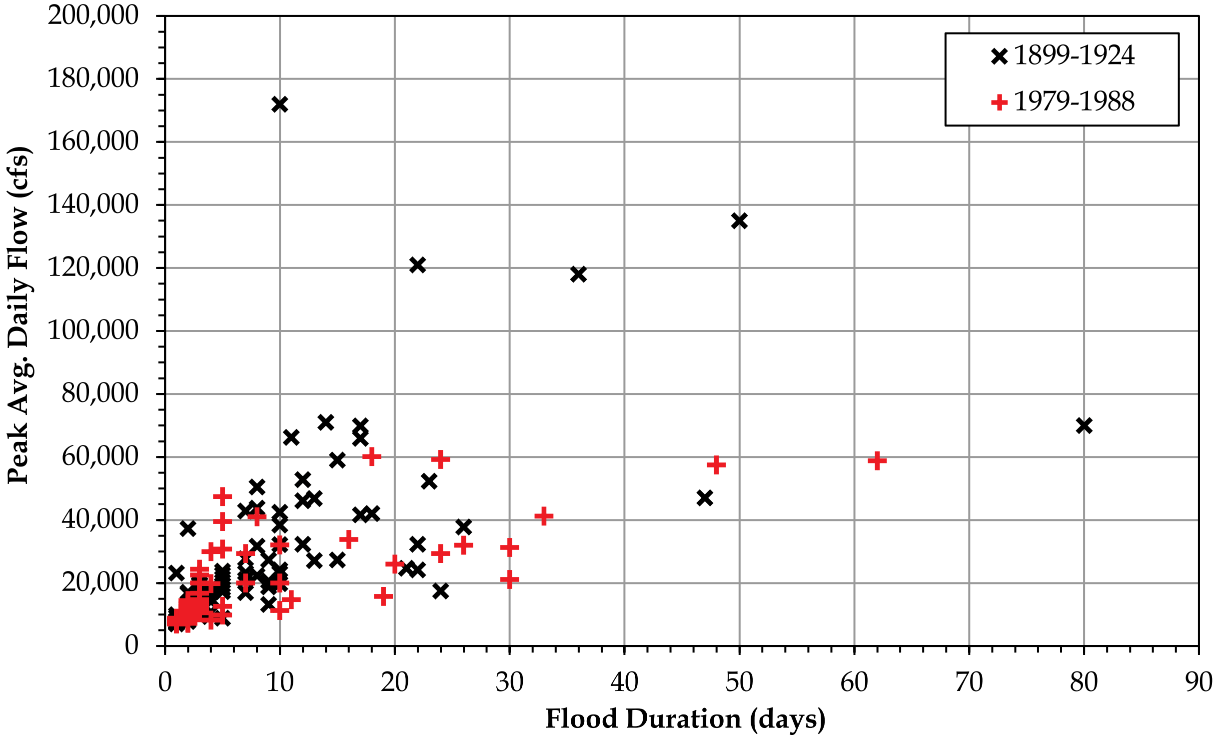


Figure A-1. Peak and duration of flow events greater than 7,000 cubic feet per second at United States Geological Survey Gage No. 08109000 Brazos River near Bryan. (Note: data from 1/1/1899 to 7/31/1899, 1/1/1903 to 2/28/1918, and 10/1/1988 to 12/31/1988 are not available from this gage).

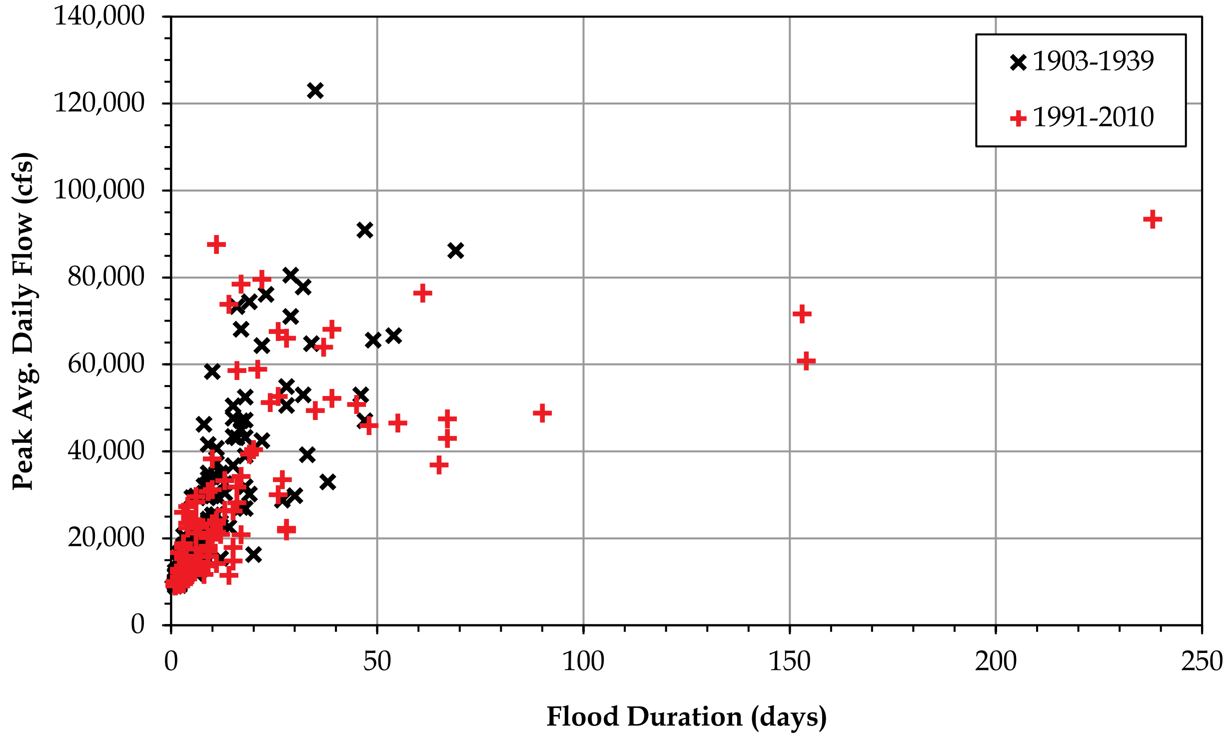


Figure A-2. Peak and duration of flow events greater than 9,000 cubic feet per second at United States Geological Survey Gage No. 08114000 Brazos River at Richmond. (Note: data from 1/1/1903 to 9/30/1903 and 7/1/1925 to 9/30/1922 are not available from this gage).

Table A-4. Water surface elevations along the length of the middle and lower Brazos River (current conditions).

USGS Gage No.	Rosharon 08116650	Richmond 08114000		San Felipe 08111850		Hempstead 08111500			SH 21 nr Bryan 08108700		Highbank 08098290		Waco 08096500
Riparian Site			Wallis		San Felipe		Navasota	Bryan		Hearne		Marlin	
River Mile	56.7	92	119.3*	147	149.1*	193.8	225.5*	276.8*	286	325.5*	346.6	354.6*	400.7
Flow (cfs)	***Water Surface Elevation (feet – NGVD 1929)*****												
80,000	51.71	77.90	99.83	122.03	123.51	155.72	182.73	226.41	234.23	290.17	319.96	330.95	394.30
70,000	50.86	75.23	97.54	120.12	121.59	153.48	180.26	223.55	231.30	286.31	315.61	326.56	389.71
60,000	47.98	71.89	94.55	117.50	118.96	150.73	177.33	220.34	228.04	282.34	311.26	322.18	385.12
50,000	43.21	67.98	90.49	113.28	114.78	147.49	174.01	216.88	224.56	278.28	306.89	317.77	380.53
40,000	37.55	63.40	86.04	108.97	110.51	143.92	170.37	213.14	220.80	274.18	302.61	313.43	375.82
30,000	31.09	58.18	81.41	104.92	106.46	139.94	166.43	209.26	216.93	269.92	298.15	308.98	371.42
20,000	23.80	52.12	76.53	101.24	102.74	135.28	161.94	205.03	212.75	265.33	293.33	304.15	366.58
10,000	15.34	45.85	71.53	97.53	98.90	128.63	155.84	199.82	207.70	260.05	287.93	298.69	360.75
7,000	13.64	43.67	69.83	96.31	97.62	126.03	153.33	197.47	205.38	258.12	286.22	296.92	358.64
4,000	9.72	41.16	67.94	95.04	96.27	122.94	150.33	194.62	202.55	255.95	284.39	294.97	356.03

*River mileage for most downstream Cross section at riparian site. Other cross-sections at site will have larger values for river mileage and water surface elevation.
**Values in unshaded cells from USGS rating curves. Underlined values extrapolated from USGS rating curves. Values in shaded cells interpolated from USGS gage sites.

In Table A-4 and Figure A-3, data for Rosharon, Richmond, San Felipe, Hempstead, and State Highway 21 near Bryan provided by rating curves for USGS Gages No. 08116650, 08114000, 08111850, 08111500, and 08108700, respectively. Data at Highbank for flows of 53,000 cfs or less were obtained from the rating curve for USGS Gage No. 08098290. Data at Highbank for flows greater than 53,000 cfs obtained from the following equation:

$$WSE = 0.0004349 \text{ X } Q + 285.17$$

where WSE is the water surface elevation in feet (NGVD 1929) and Q is the discharge in cfs. Data at Waco for flows of 42,000 cfs or less were obtained from the rating curve for USGS Gage No. 08096500. For flows greater than 42,000 cfs, water surface elevations at Waco were obtained from the following equation:

$$WSE = 0.0004593 \text{ X } Q + 357.56$$

where WSE is the water surface elevation in feet (NGVD 1929) and Q is the discharge in cfs.

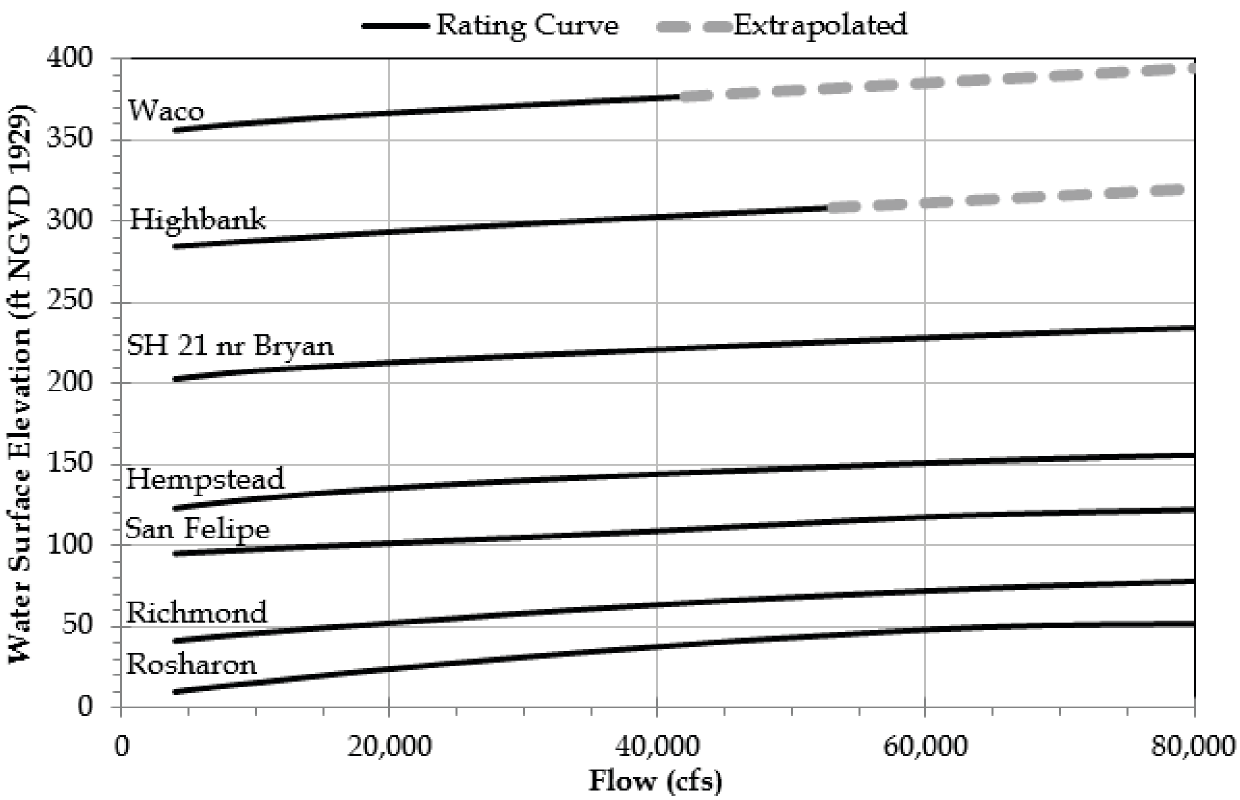


Figure A-3. Water surface elevations along the length of the middle and lower Brazos River (current conditions).

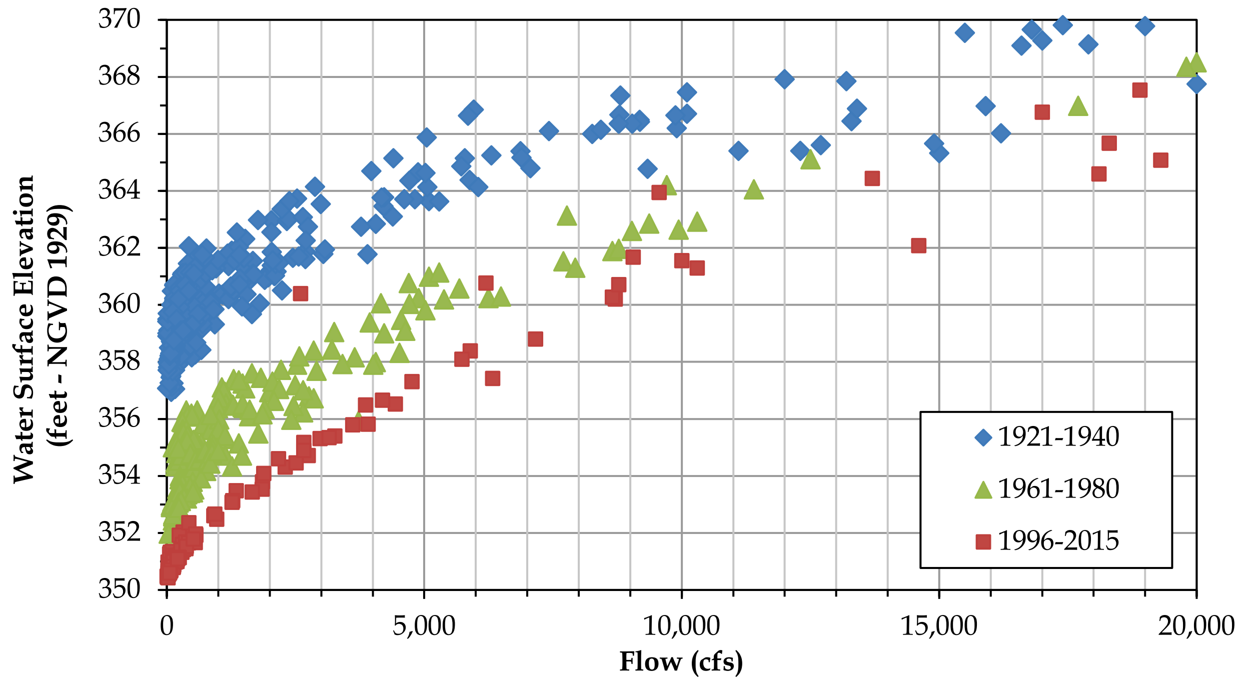


Figure A-4. Water surface elevation versus flow measurements (in cubic feet per second–cfs) collected during 1921-1940, 1961-1980, and 1996-2015 at the location of United States Geological Survey Gage No. 08096500 Brazos River at Waco. Data from 1921-1968 adjusted for old gage location.

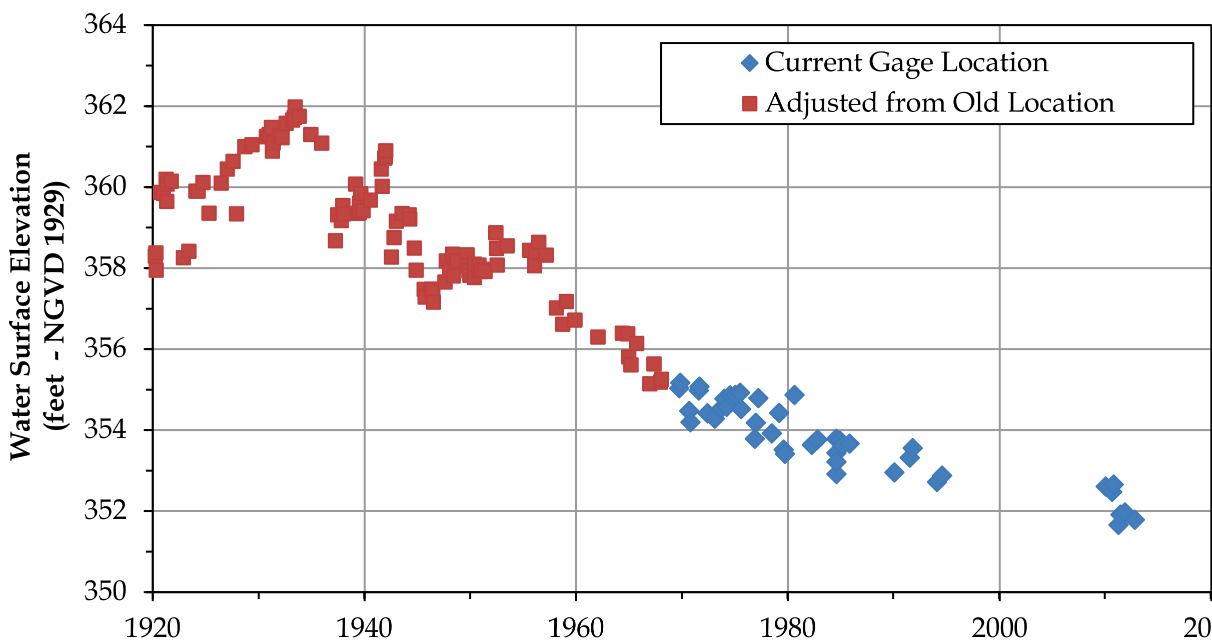


Figure A-5. Water surface elevation for flows in the range of 500 to 1,000 cubic feet per second at United States Geological Survey Gage No. 08096500 Brazos River at Waco.

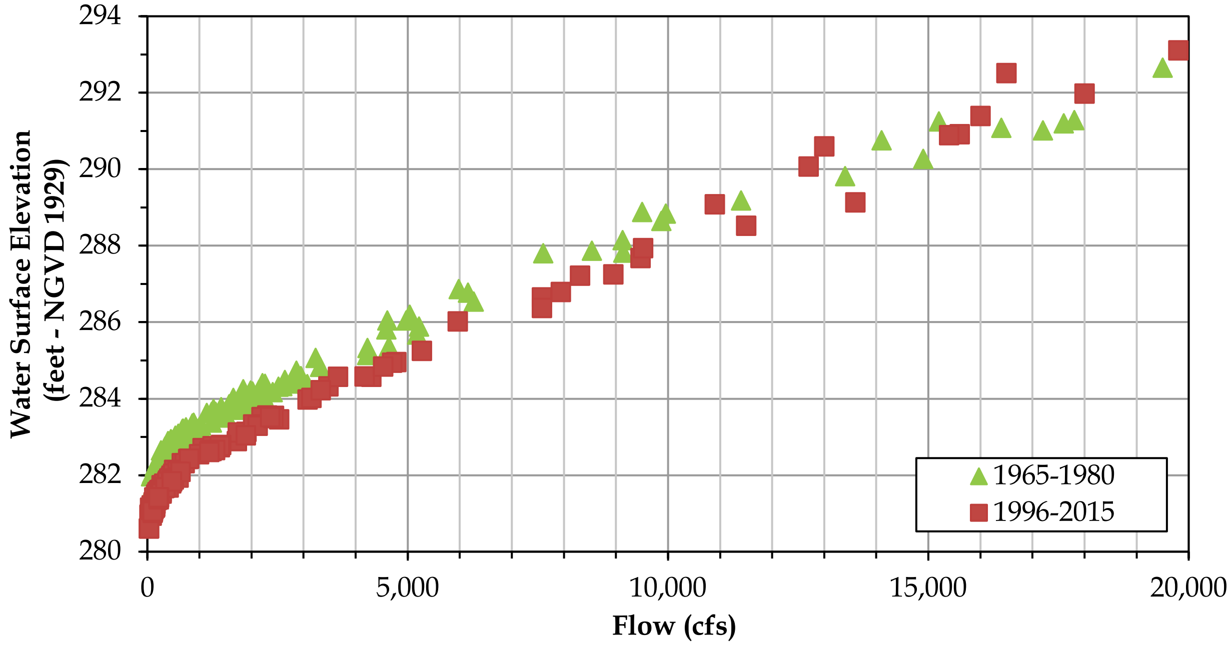


Figure A-6. Water surface elevation versus flow measurements (in cubic feet per second – cfs) collected during 1965-1980 and 1996-2015 at the location of United States Geological Survey Gage No. 08098290 Brazos River near Highbank. Measurement data begins in 1965.

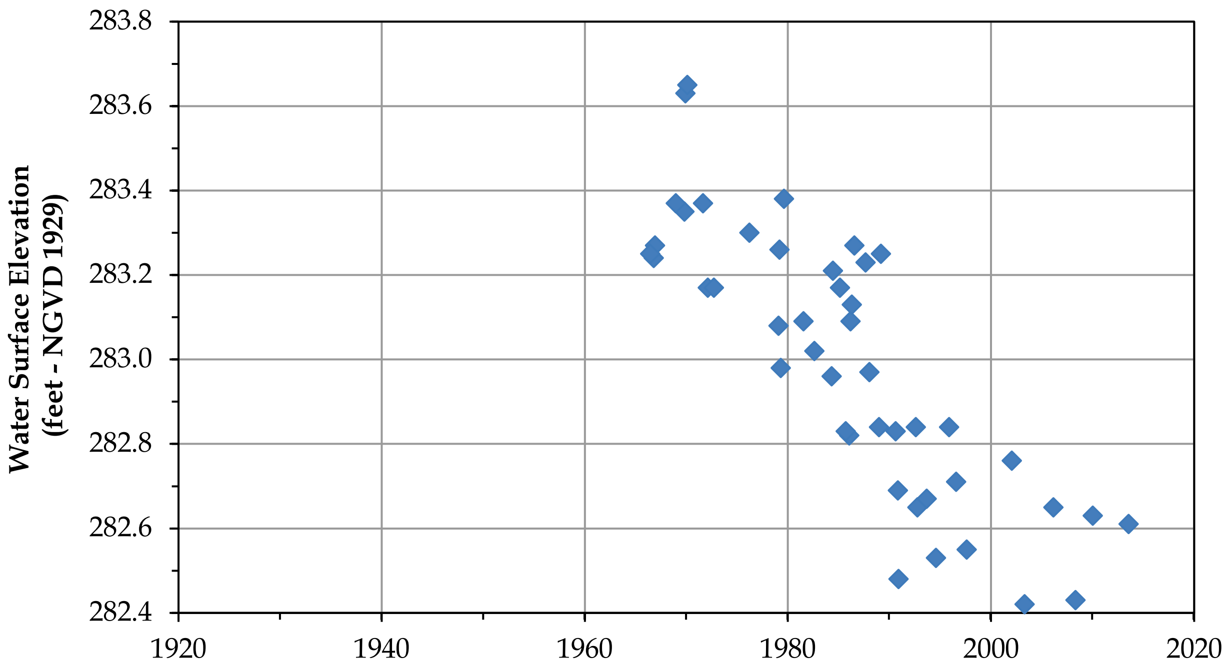


Figure A-7. Water surface elevation for flows in the range of 750 to 1,250 cubic feet per second at United States Geological Survey Gage No. 08096500 Brazos River at Waco.

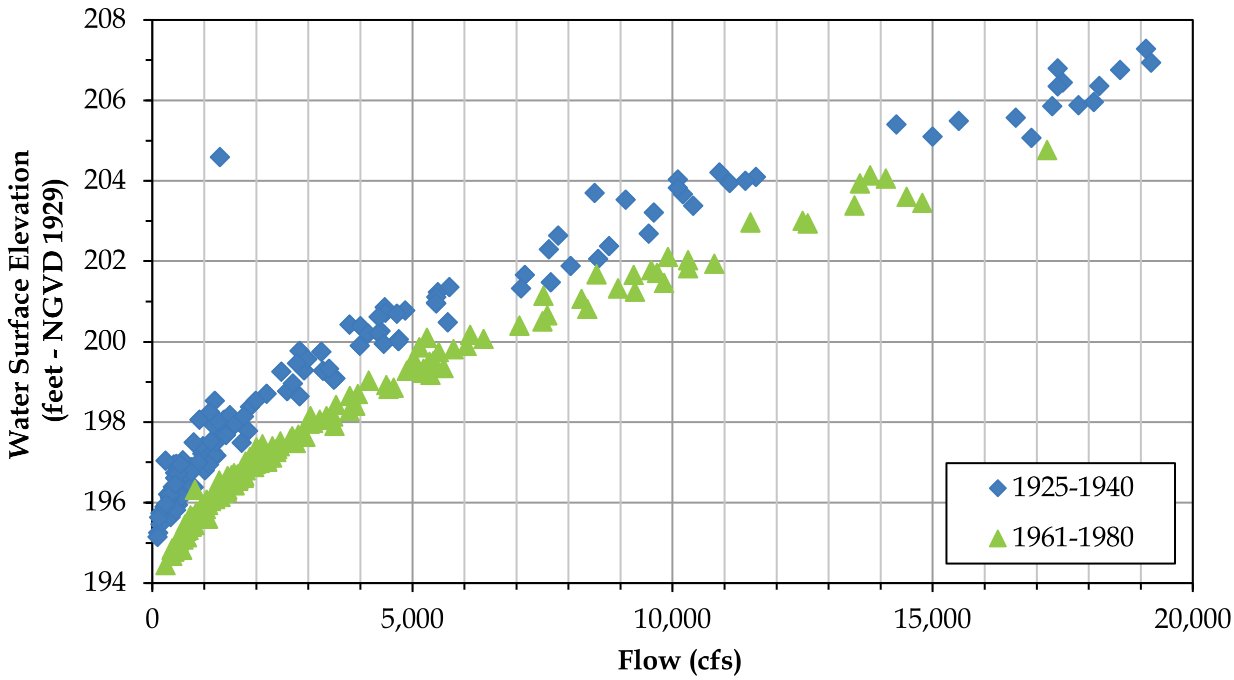


Figure A-8. Water surface elevation versus flow measurements (in cubic feet per second–cfs) collected during 1925-1940 and 1961-1980 at the location of United States Geological Survey Gage No. 08109000 Brazos River near Bryan. Measurement data begins in 1925 and ends in 1993.

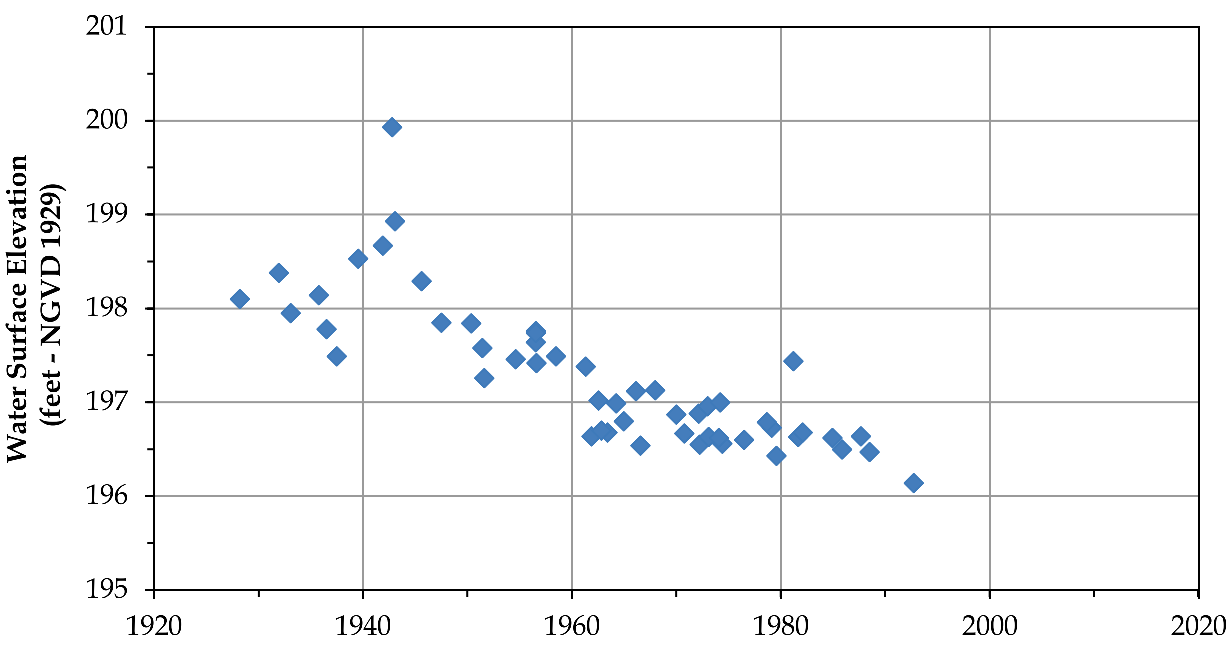


Figure A-9. Water surface elevation for flows in the range of 1,500 to 2,000 cubic feet per second at United States Geological Survey Gage No. 08109000 Brazos River near Bryan.

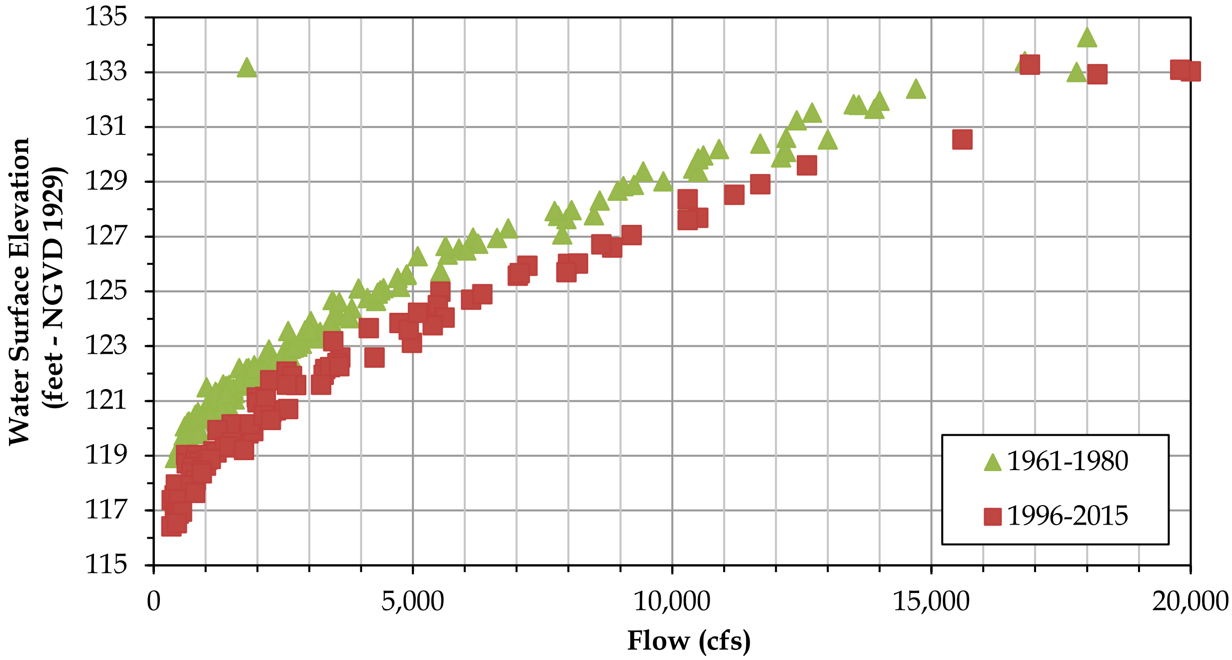


Figure A-10. Water surface elevation versus flow measurements (in cubic feet per second–cfs) collected during 1961-1980 and 1996-2015 at the location of United States Geological Survey Gage No. 08111500 Brazos River near Hempstead. Measurement data begins in 1938.

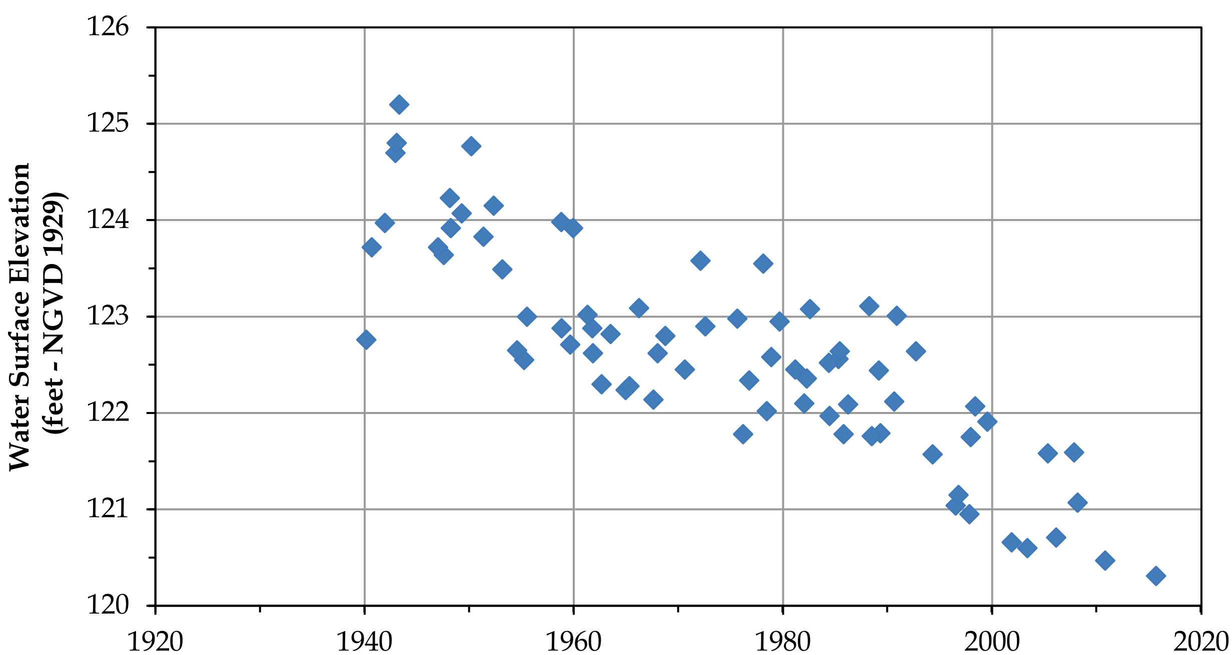


Figure A-11. Water surface elevation for flows in the range of 2,000 to 3,000 cubic feet per second at United States Geological Survey Gage No. 08111500 Brazos River near Hempstead.

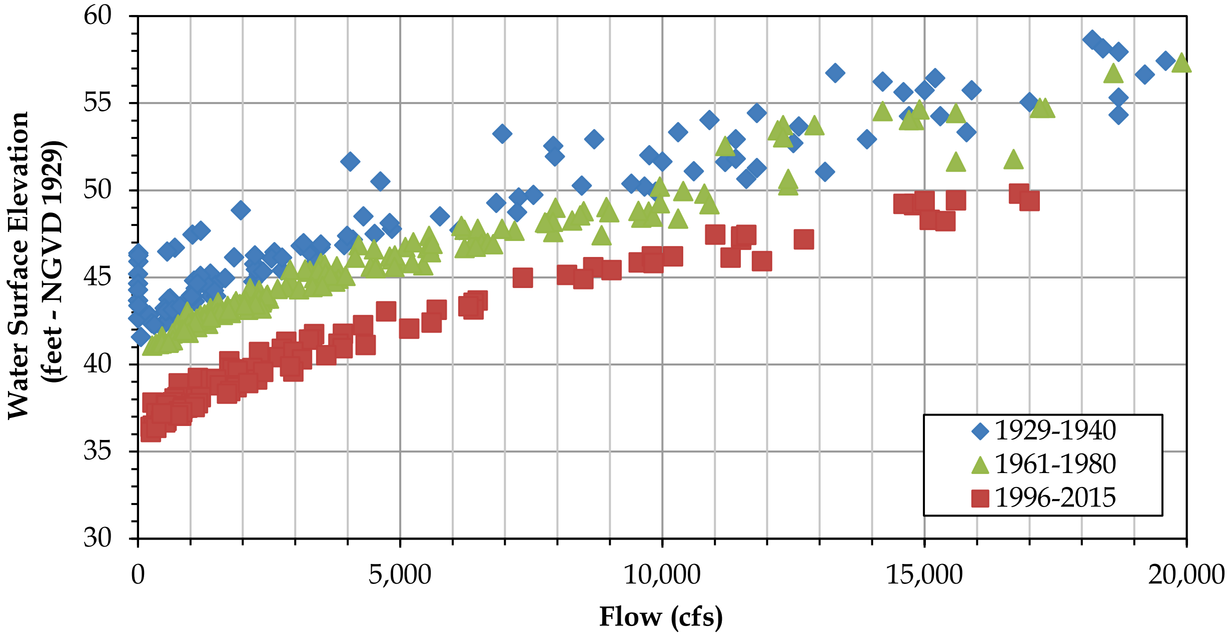


Figure A-12. Water surface elevation versus flow measurements (in cubic feet per second–cfs) collected during 1929-1940, 1961-1980, and 1996-2015 at the location of United States Geological Survey Gage No. 08114000 Brazos River at Richmond. Measurement data begins in 1929.

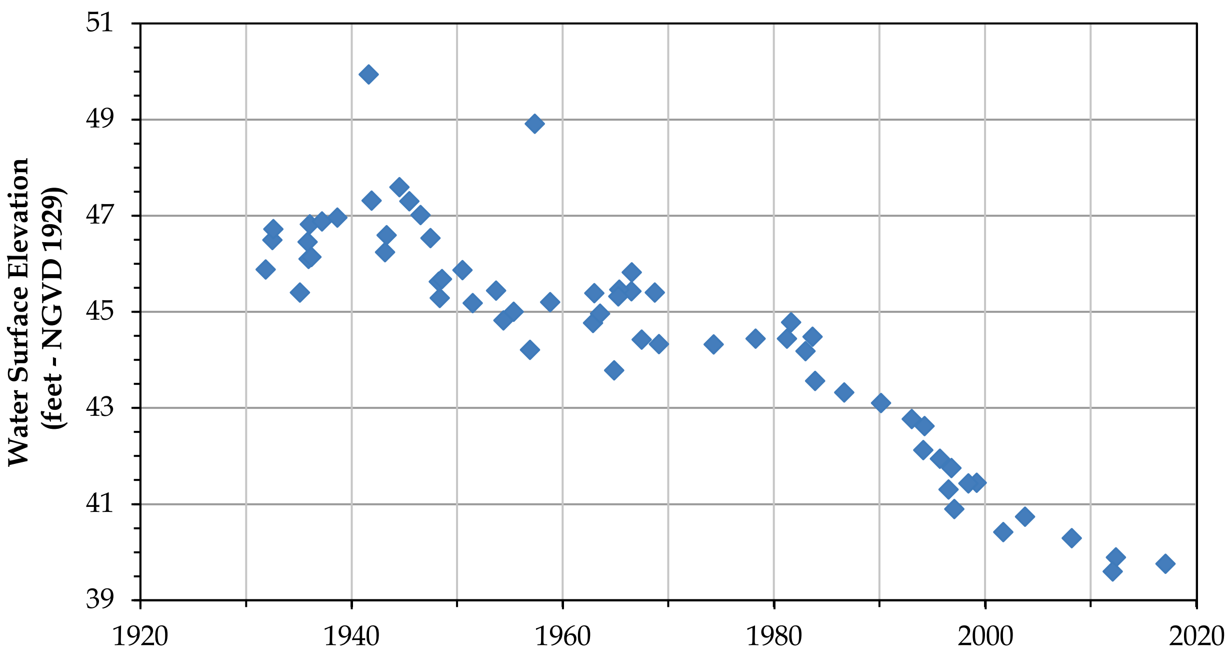


Figure A-13. Water surface elevation for flows in the range of 2,500 to 3,500 cubic feet per second at United States Geological Survey Gage No. 08114000 Brazos River at Richmond.

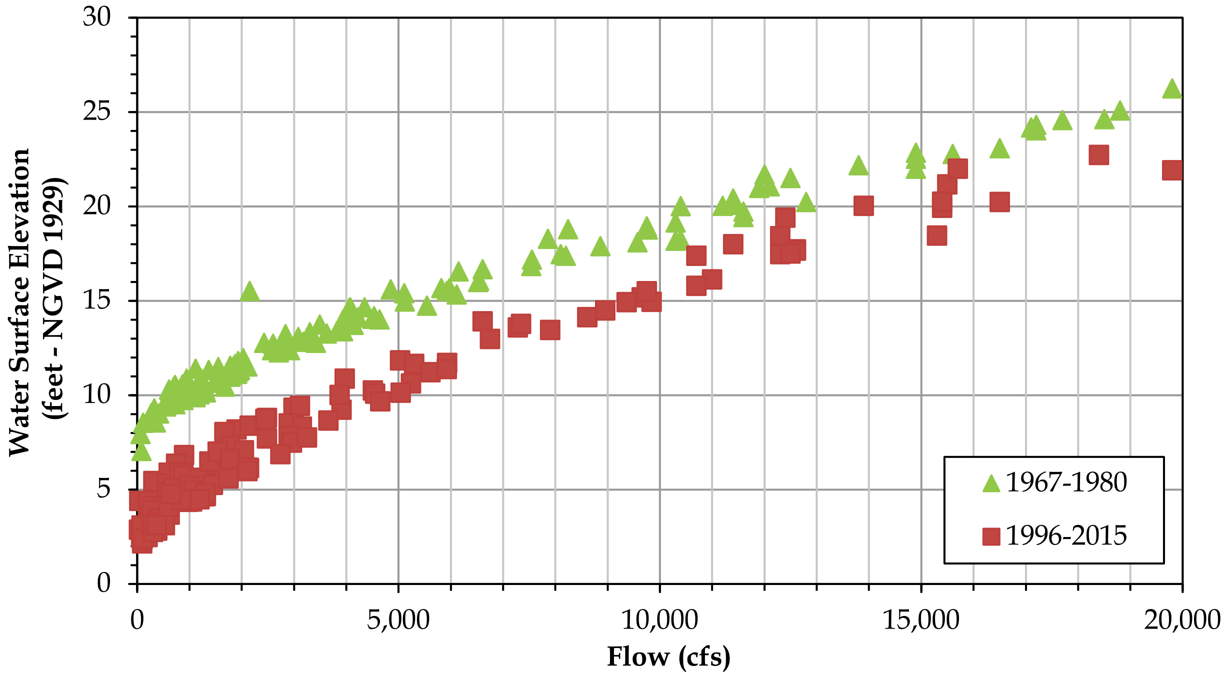


Figure A-14. Water surface elevation versus flow measurements (in cubic feet per second–cfs) collected during 1967-1980 and 1996-2015 at the location of United States Geological Survey Gage No. 08116650 Brazos River near Rosharon. Measurement data begins in 1967.

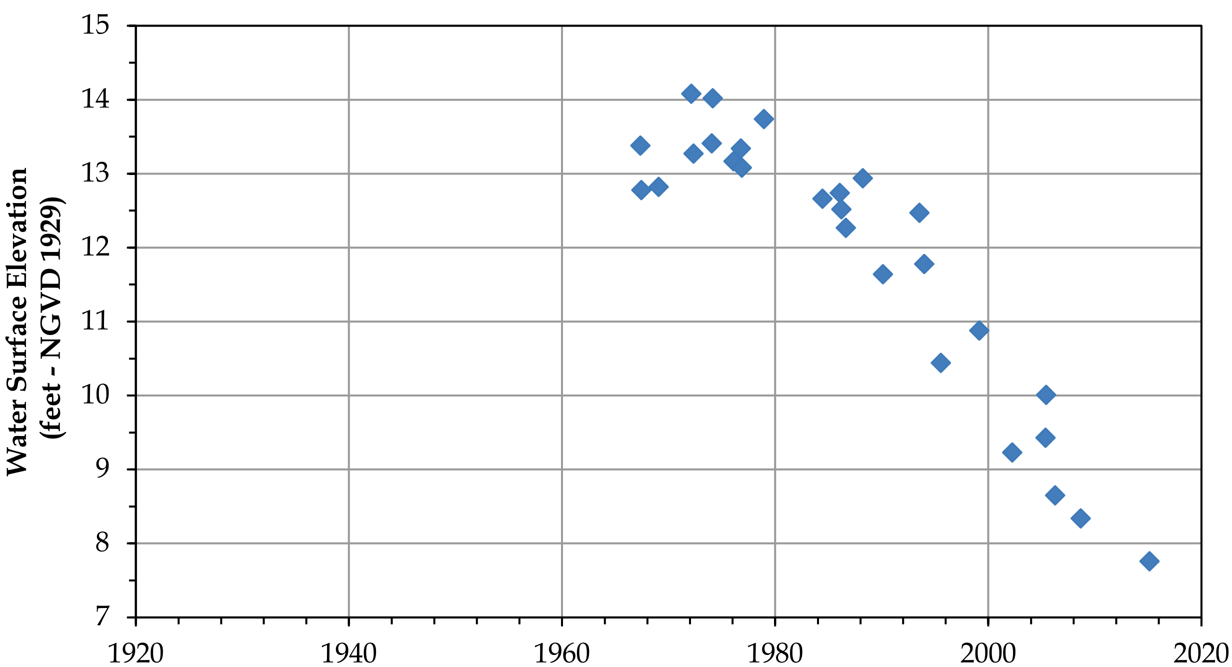


Figure A-15. Water surface elevation for flows in the range of 3,000 to 4,000 cubic feet per second at United States Geological Survey Gage No. 08116650 Brazos River near Rosharon.

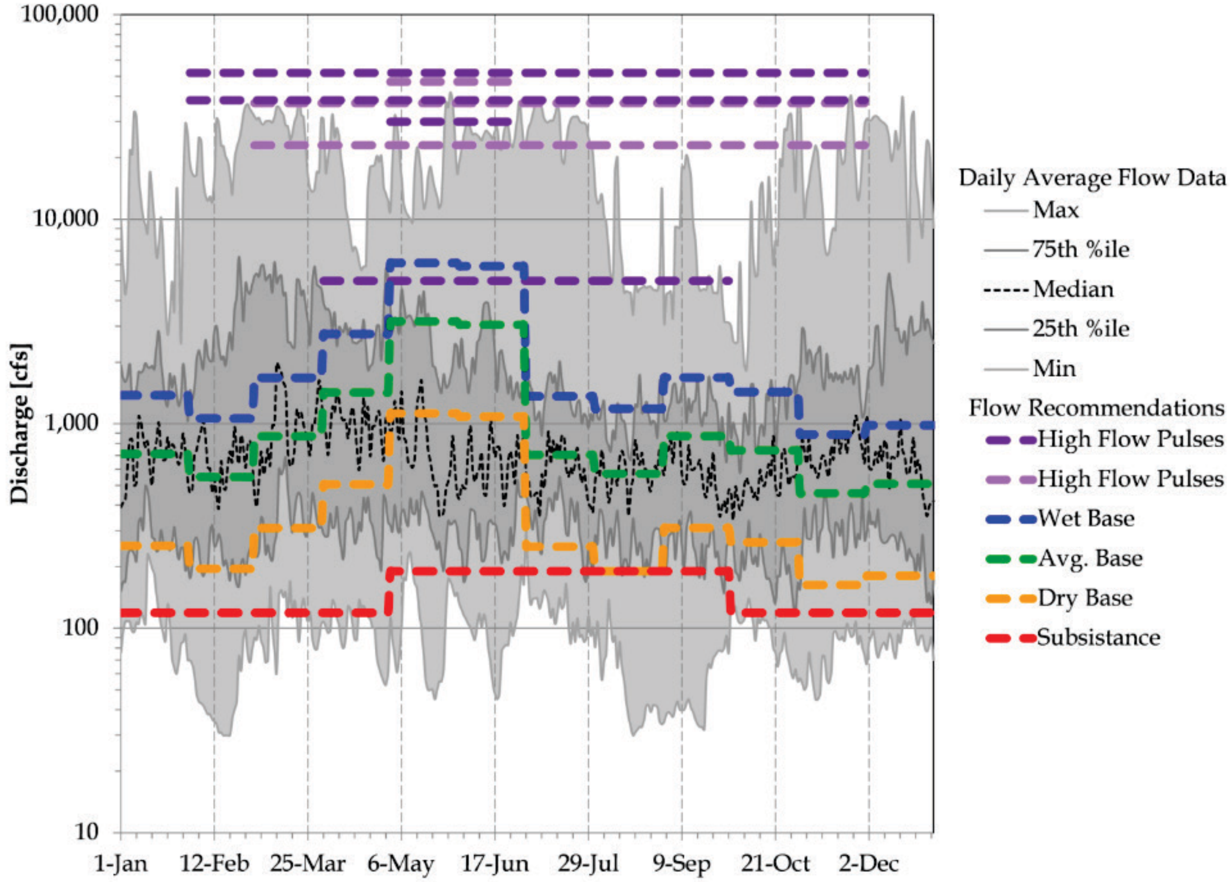


Figure A-16. Instream flow recommendations for the Brazos River Marlin study site (see Figure 65) and daily streamflow data from United States Geological Survey Gage No. 08098290 Brazos River near Highbank for 1996-2015. Flow recommendations for sediment transport are not included in this graph.

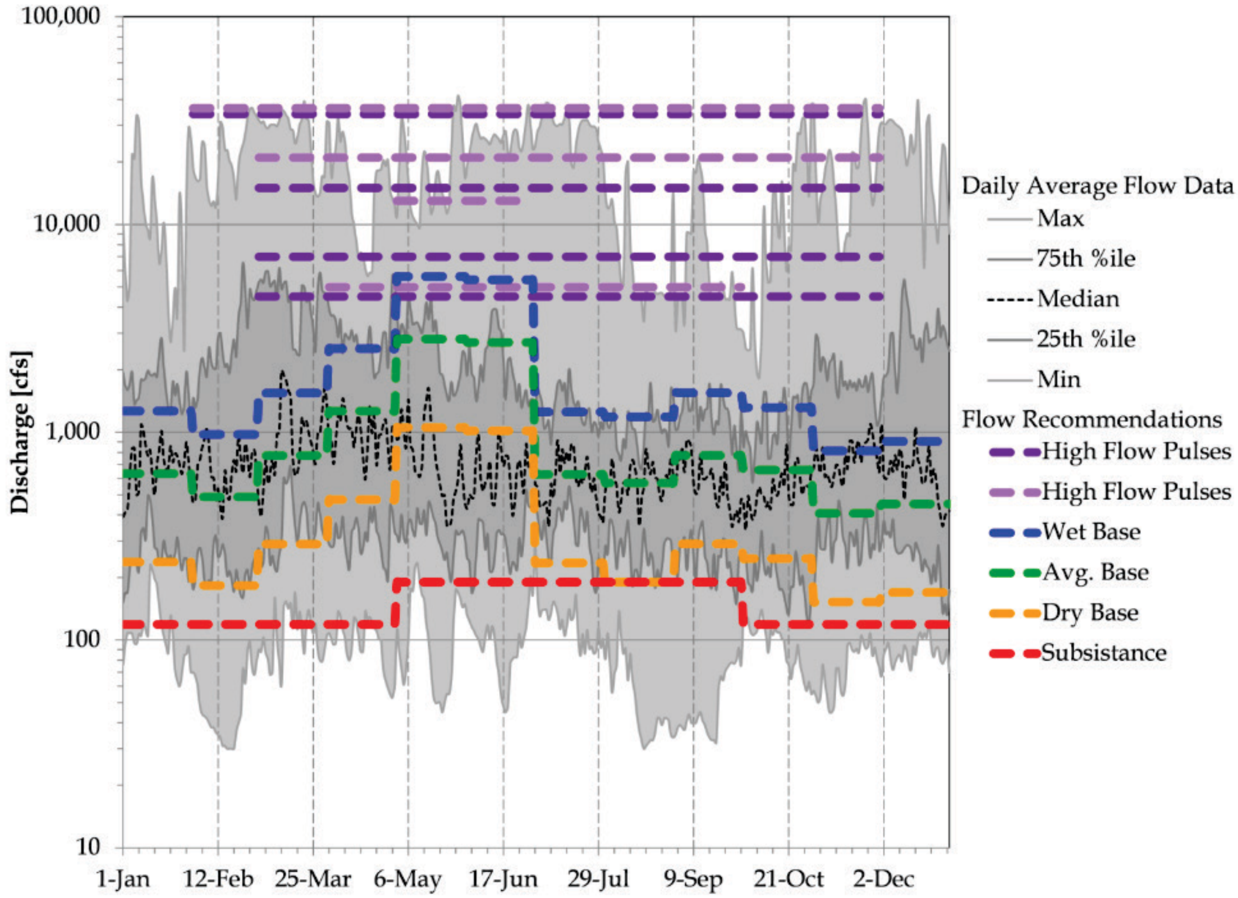


Figure A-17. Instream flow recommendations for the Brazos River Hearne study site (see Figure 66) and daily streamflow data from United States Geological Survey Gage No. 08098290 Brazos River near Highbank for 1996-2015. Flow recommendations for sediment transport are not included in this graph.

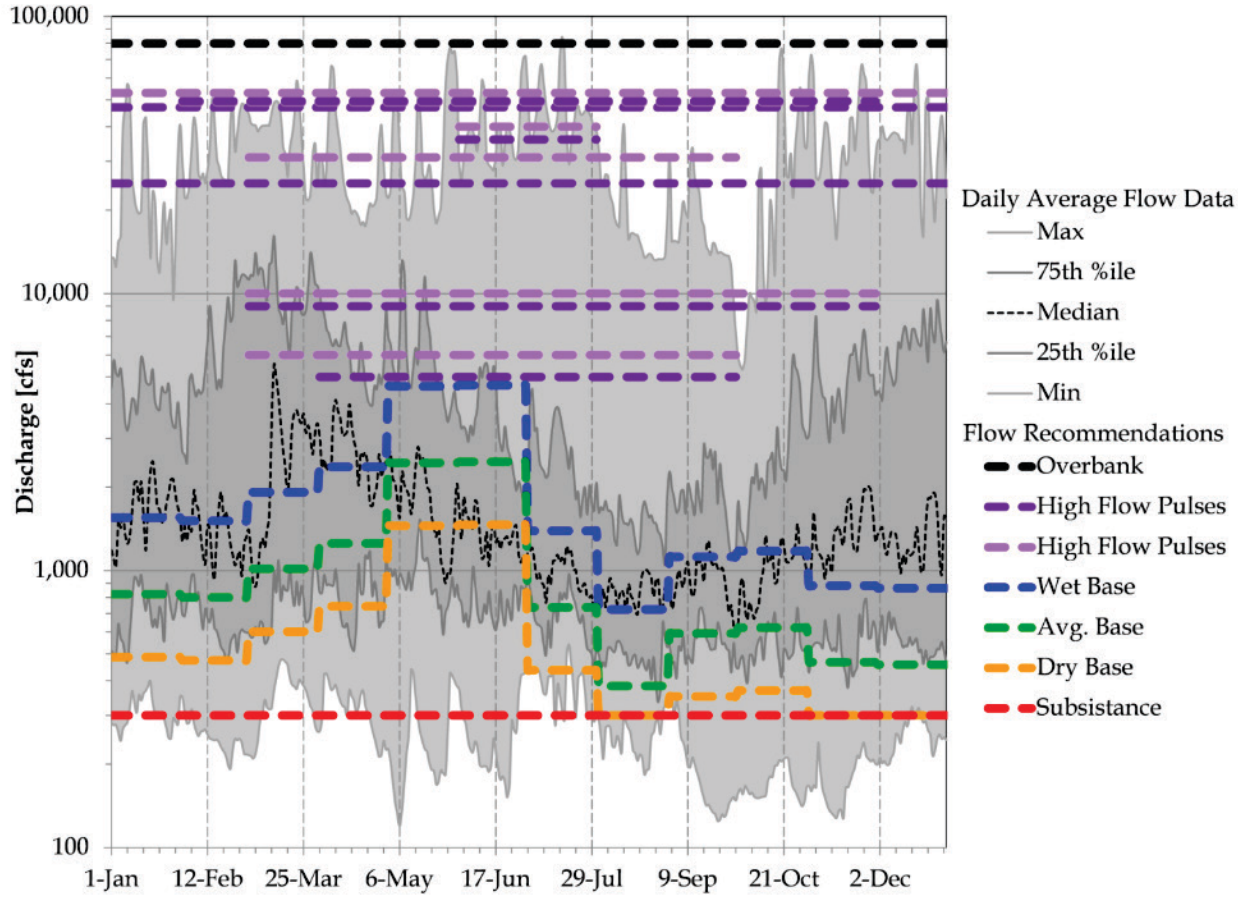


Figure A-18. Instream flow recommendations for the Brazos River Mussel Shoals study site (see Figure 67) and daily streamflow data from United States Geological Survey Gage No. 08108700 Brazos River at SH 21 near Bryan for 1996-2015. Flow recommendations for sediment transport are not included in this graph.

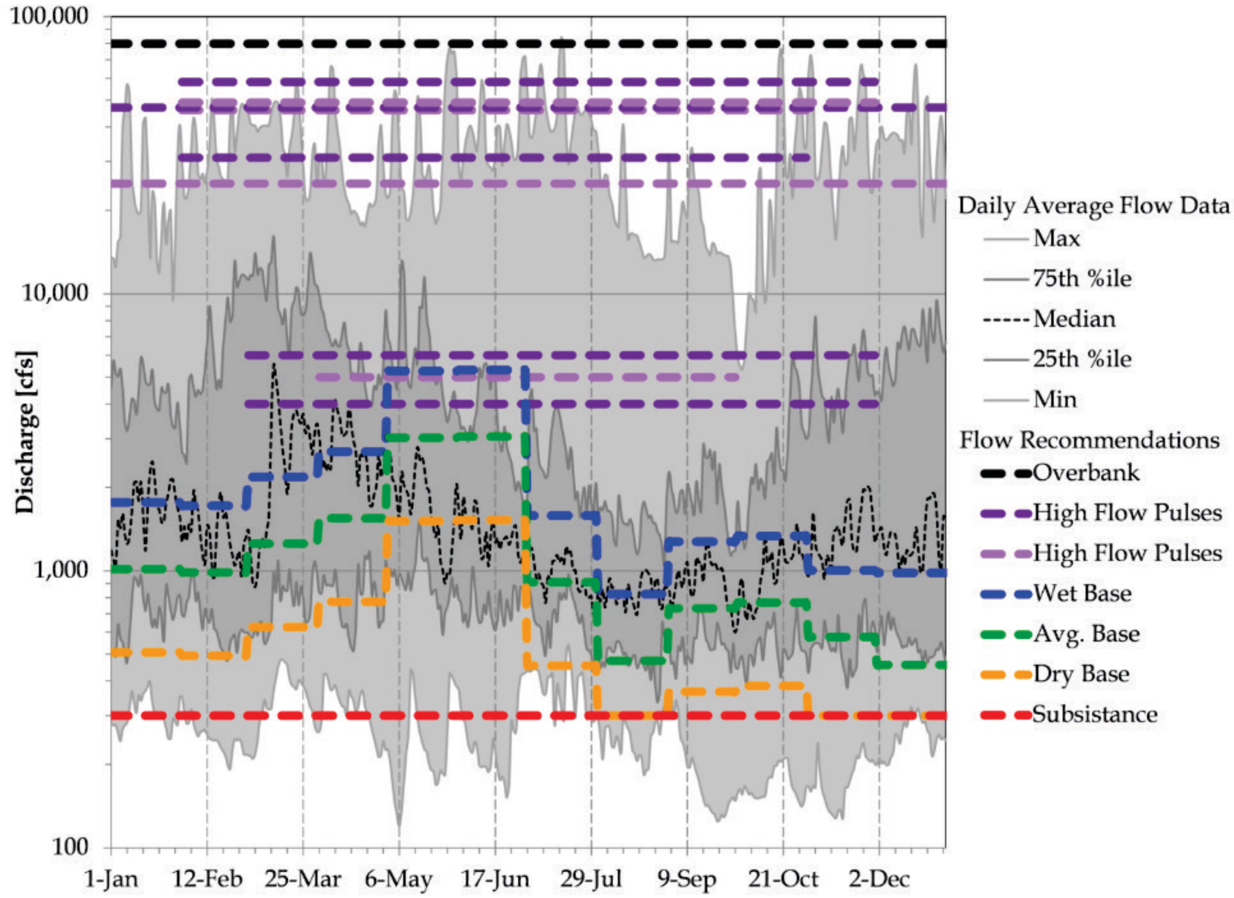


Figure A-19. Instream flow recommendations for the Brazos River Navasota study site (see Figure 68) and daily streamflow data from United States Geological Survey Gage No. 08108700 Brazos River at SH 21 near Bryan for 1996-2015. Flow recommendations for sediment transport are not included in this graph.

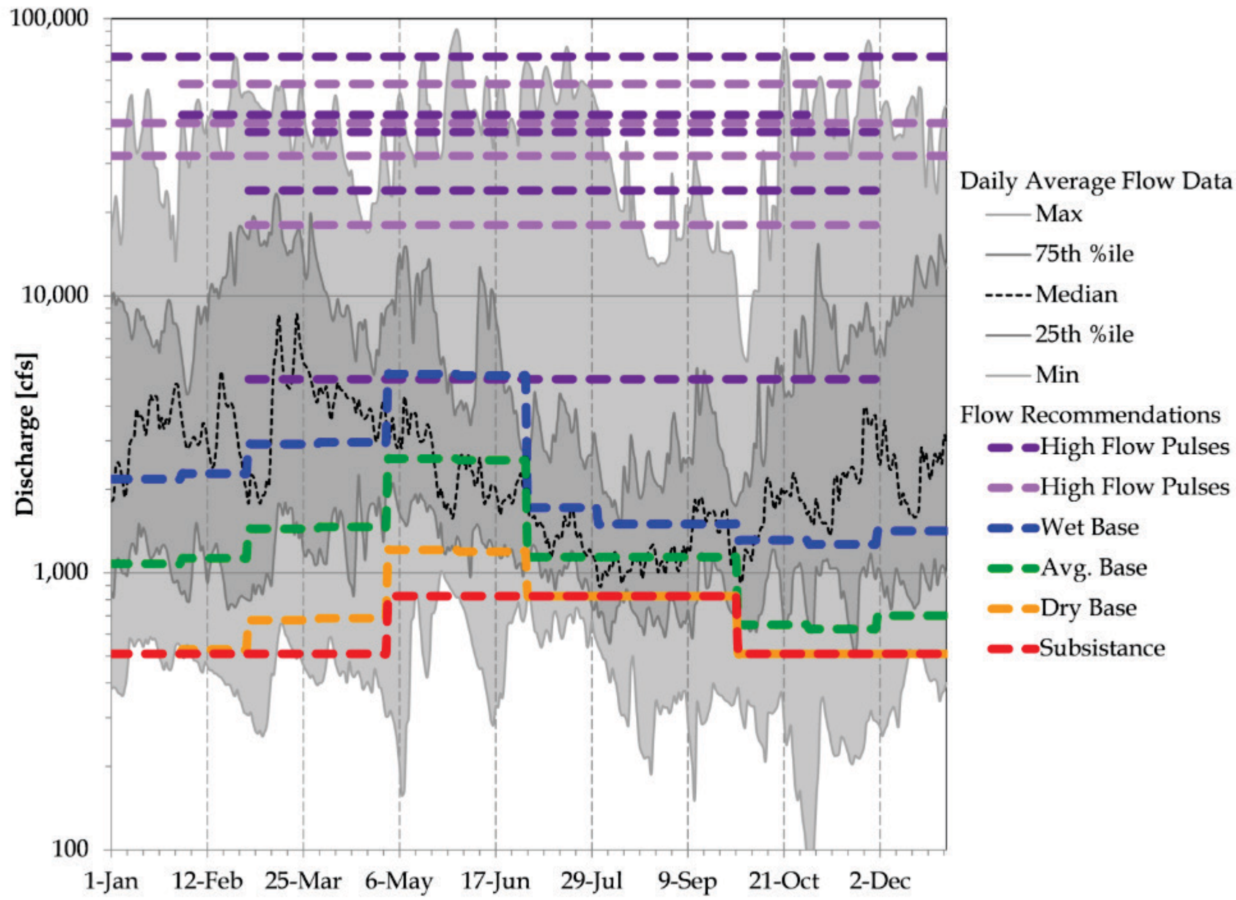


Figure A-20. Instream flow recommendations for the Brazos River Wildcat Bend study site (see Figure 69) and daily streamflow data from United States Geological Survey Gage No. 08111500 Brazos River near Hempstead for 1996-2015. Flow recommendations for sediment transport are not included in this graph.

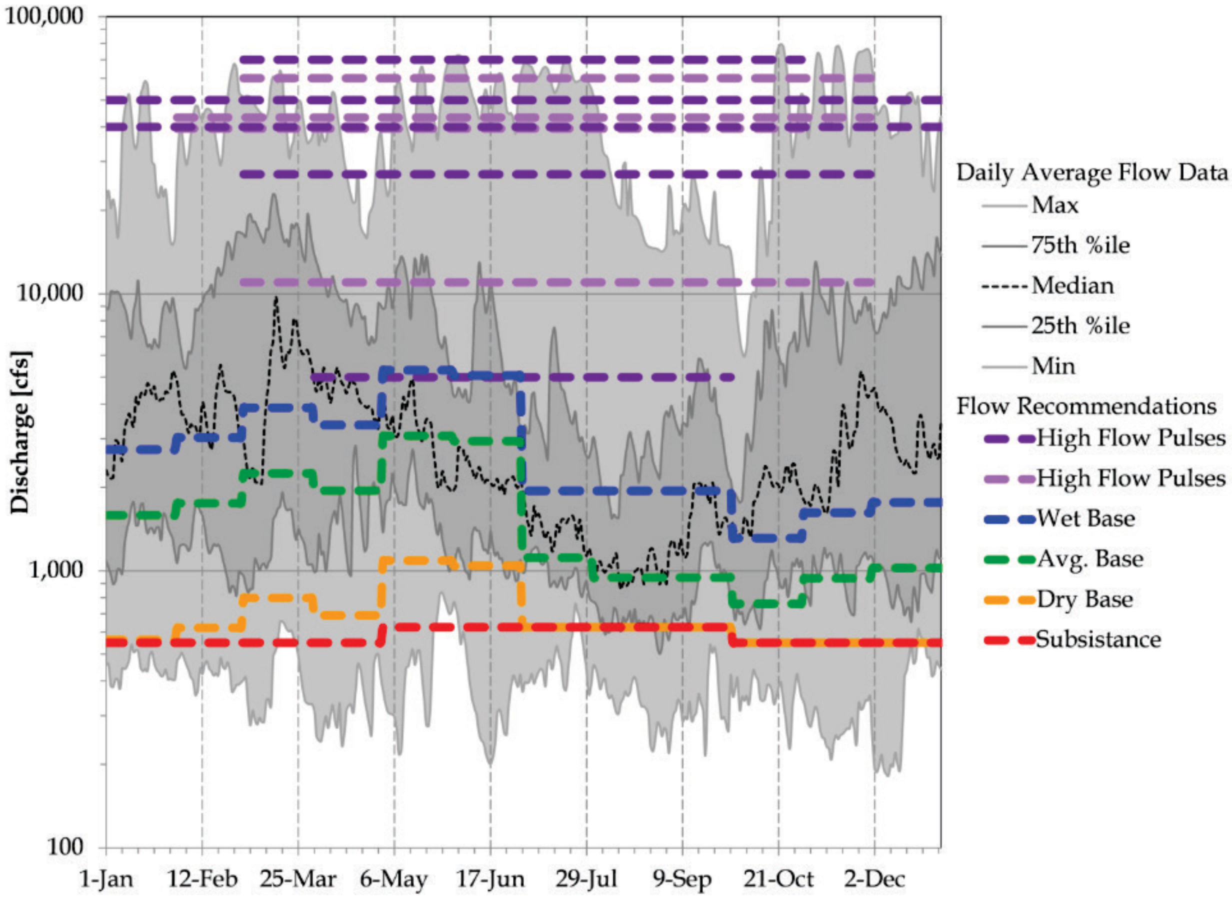


Figure A-21. Instream flow recommendations for the Brazos River Allens Creek study site (see Figure 70) and daily streamflow data from United States Geological Survey Gage No. 08114000 Brazos River near Richmond for 1996-2015. Flow recommendations for sediment transport are not included in this graph.

Table A-5. Calibration and modeled flows for six hydraulic models used to assess in-channel habitat along the middle and lower Brazos River.

Study Site Number	Study Site Name	Calibration Flow (cfs)	Modeled Flow (cfs)	USGS Gage No.	USGS Gage Location	Exceedance Probability* (%)
12087	Marlin		250	08098290	Highbank	76.3
		310	310			70.3
		550	550			54.4
		625	625			51.0
			750			46.1
		1,075	1,075			37.1
			1,250			33.8
			1,500			29.9
			1,750			26.7
			2,000			24.1
			2,500			20.7
			3,000			18.3
12080	Hearne		250	08098290	Highbank	76.3
		360	360			66.5
			500			57.1
			750			46.1
			1,000			39.0
			1,250			33.8
			1,500			29.9
			1,750			26.7
			2,000			24.1
			2,500			20.7
			3,000			18.3
		3,800				15.2
			4,000			14.5
12050	Mussel Shoals	150		08108700	Bryan	99.7
			250			96.6
		300				94.1
			500			80.9
		540				78.3
		630				73.1
		710				69.3
			750			67.6
		860				62.8
		920				59.9
			1,000			57.0
			1,250			49.4
		1,260				49.1
		1,470				45.2
			1,500			44.8

Table A-5. (cont) Calibration and modeled flows for six hydraulic models used to assess in-channel habitat along the middle and lower Brazos River.

Study Site Number	Study Site	Calibration Flow (cfs)	Modeled Flow (cfs)	USGS Gage No.	USGS Gage Location	Exceedance Probability* (%)
12050	Mussel Shoals		2,000	08108700	Bryan	38.6
		2,460				34.8
			2,500			34.5
			3,000			31.2
			3,500			28.8
12030	Navasota		250	08108700	Bryan	96.6
		400	400			87.6
			500			80.9
			750			67.6
			1,000			57.0
			1,250			49.4
		1,419	1,419			45.9
			1,750			41.6
		1,975	1,975			38.9
			2,500			34.5
			3,000			31.2
12020	Wildcat Bend		500	08111500	Hempstead**	92.7
		571	571			89.6
			750			82.6
		840	840			77.9
			1,000			72.5
			1,250			64.6
			1,500			58.4
			1,750			54.3
			2,000			50.7
			2,500			45.3
			3,000			41.1
		5,576	5,576			29.0
12010	Allens Creek		250	08114000	Richmond	99.5
			500			91.6
		772	772			80.2
			1,000			72.7
			1,500			61.0
			2,000			53.2
		2,514	2,514			47.5
			3,000			43.5
		3,437	3,437			40.9
		3,915	3,915			38.5

*Percent of flows greater that specified flow in daily gage record from 1996-2015. For Hempstead, gage record limited to period 9/30/2000 to 12/31/2015.

APPENDIX B
SAMPLING MATRIX TABLES AND FIGURES OF WEIGHTED USABLE AREA, HYDRAULIC HABITAT CRITERIA, AND HYDRAULIC HABITAT DIVERSITY FOR EACH SITE

Table B - 1. Initial sampling matrix allocation of habitat areas.

Overall Sample Allocation with Allens Creek Study Site included

	clay	silt	sand	gravel	large rock
backwater	17	15	16	2	0
pool	6	19	17	3	10
riffle	0	0	7	18	3
run	23	30	155	47	12

400

All Flows

		clay	silt	sand	gravel	large rock
12010	backwater	0	3	3	0	0
12010	pool	3	5	6	0	0
12010	riffle	0	0	0	3	0
12010	run	5	7	28	13	0
12020	backwater	3	5	0	0	0
12020	pool	3	5	0	0	0
12020	riffle	0	0	0	0	0
12020	run	1	8	36	0	5
12030	backwater	0	2	5	0	0
12030	pool	0	3	0	0	0
12030	riffle	0	0	2	0	0
12030	run	5	4	39	0	0
12050	backwater	2	3	1	0	0
12050	pool	0	0	4	0	10
12050	riffle	0	0	2	2	1
12050	run	0	4	18	11	2
12080	backwater	7	0	5	0	0
12080	pool	0	6	0	0	0
12080	riffle	0	0	3	0	0
12080	run	11	3	26	8	5
12087	backwater	5	2	2	2	0
12087	pool	0	0	7	3	0
12087	riffle	0	0	0	13	2
12087	run	1	4	8	15	0

Medium Base Flow

		clay	silt	sand	gravel	large rock
12010	backwater	0	1	1	0	0
12010	pool	1	2	2	0	0
12010	riffle	0	0	0	1	0
12010	run	1	2	9	5	0
12020	backwater	1	2	0	0	0
12020	pool	1	2	0	0	0
12020	riffle	0	0	0	0	0
12020	run	0	3	12	0	2
12030	backwater	0	1	2	0	0
12030	pool	0	1	0	0	0
12030	riffle	0	0	0	0	0
12030	run	2	1	13	0	0
12050	backwater	0	2	0	0	0
12050	pool	0	0	1	0	0
12050	riffle	0	0	0	2	1
12050	run	0	2	7	5	1
12080	backwater	3	0	2	0	0
12080	pool	0	3	0	0	0
12080	riffle	0	0	0	0	0
12080	run	4	1	9	3	2
12087	backwater	2	1	1	1	0
12087	pool	0	0	3	1	0
12087	riffle			0	0	0
12087	run	0	1	3	5	0

Low Base Flow

		clay	silt	sand	gravel	large rock
12010	backwater	0	1	1	0	0
12010	pool	1	2	3	0	0
12010	riffle	0	0	0	2	0
12010	run	2	3	7	4	0
12020	backwater	1	1	0	0	0
12020	pool	1	1	0	0	0
12020	riffle	0	0	0	0	0
12020	run	0	3	12	0	2
12030	backwater	0	1	1	0	0
12030	pool	0	1	0	0	0
12030	riffle	0	0	2	0	0
12030	run	1	1	13	0	0
12050	backwater	1	0	1	0	0
12050	riffle	0	0	0	0	10
12050	pool	0	0	2	0	0
12050	run	0	0	7	5	1
12080	backwater	2	0	1	0	0
12080	pool	0	3	0	0	0
12080	riffle	0	0	3	0	0
12080	run	3	1	8	2	1
12087	backwater	1	0	0	0	0
12087	pool	0	0	2	1	0
12087	riffle	0	0	0	13	2
12087	run	0	1	2	5	0

High Base Flow

		clay	silt	sand	gravel	large rock
12010	backwater	0	1	1	0	0
12010	pool	1	1	1	0	0
12010	riffle			0	0	0
12010	run	2	2	12	4	0
12020	backwater	1	2	0	0	0
12020	pool	1	2	0	0	0
12020	riffle	0	0	0	0	0
12020	run	1	2	12	0	1
12030	backwater	0	0	2	0	0
12030	pool	0	1	0	0	0
12030	riffle	0	0	0	0	0
12030	run	2	2	13	0	0
12050	backwater	1	1	0	0	0
12050	riffle	0	0	3	0	0
12050	pool	0	0	0	0	0
12050	run	0	2	4	1	0
12080	backwater	2	0	2	0	0
12080	pool	0	0	0	0	0
12080	riffle			0	0	0
12080	run	4	1	9	3	2
12087	backwater	2	1	1	1	0
12087	pool	0	0	2	1	0
12087	riffle	0	0	0	0	0
12087	run	1	2	3	5	0

Table B - 2. Final tally and distribution of habitat areas sampled for fish.

Final Sample Tally						
	clay	silt	sand	gravel	large rock	Totals
backwater	10	19	8	5	1	43
pool	8	10	14	2	5	39
riffle	1	0	10	31	7	49
run	17	17	95	55	12	196
Totals	36	46	127	93	25	327

All Flows							
		clay	silt	sand	gravel	large rock	
12010	backwater	0	1	2	0	0	
12010	pool	2	1	1	0	0	
12010	riffle	0	0	0	0	0	
12010	run	1	2	8	3	0	21
12020	backwater	2	7	1	2	0	
12020	pool	2	2	2	0	0	
12020	riffle	1	0	1	7	0	
12020	run	9	9	26	11	0	82
12030	backwater	4	2	2	1	1	
12030	pool	0	1	4	1	2	
12030	riffle	0	0	2	5	1	
12030	run	1	1	23	20	2	73
12050	backwater	0	3	0	0	0	
12050	pool	1	0	3	0	0	
12050	riffle	0	0	4	5	6	
12050	run	0	0	14	11	2	49
12080	backwater	2	4	0	0	0	
12080	pool	1	4	0	0	1	
12080	riffle	0	0	0	4	0	
12080	run	5	4	19	4	6	54
12087	backwater	2	2	3	2	0	
12087	pool	2	2	4	1	2	
12087	riffle	0	0	3	10	0	
12087	run	1	1	5	6	2	48

Medium Base Flow							
		clay	silt	sand	gravel	large rock	
12010	backwater	0	0	0	0	0	
12010	pool	0	0	0	0	0	
12010	riffle	0	0	0	0	0	
12010	run	0	0	0	0	0	0
12020	backwater	0	2	1	1	0	
12020	pool	1	1	1	0	0	
12020	riffle	1	0	0	3	0	
12020	run	2	4	8	3	0	28
12030	backwater	2	0	1	1	1	
12030	pool	0	0	1	0	1	
12030	riffle	0	0	0	2	1	
12030	run	0	1	7	8	1	27
12050	backwater	0	2	0	0	0	
12050	pool	0	0	2	0	0	
12050	riffle	0	0	4	0	3	
12050	run	0	0	7	6	1	25
12080	backwater	0	0	0	0	0	
12080	pool	0	0	0	0	0	
12080	riffle	0	0	0	0	0	
12080	run	0	0	0	0	0	0
12087	backwater	2	1	1	0	0	
12087	pool	0	1	2	1	1	
12087	riffle	0	0	1	4	0	
12087	run	0	0	3	2	1	20
						100	

Low Base Flow							
		clay	silt	sand	gravel	large rock	
12010	backwater	0	0	0	0	0	
12010	pool	0	0	0	0	0	
12010	riffle	0	0	0	0	0	
12010	run	0	0	0	0	0	0
12020	backwater	2	2	0	1	0	
12020	pool	1	1	1	0	0	
12020	riffle	0	0	1	3	0	
12020	run	4	3	5	4	0	28
12030	backwater	0	0	1	0	0	
12030	pool	0	1	2	1	1	
12030	riffle	0	0	1	2	0	
12030	run	0	0	6	8	1	24
12050	backwater	0	1	0	0	0	
12050	pool	1	0	1	0	0	
12050	riffle	0	0	0	5	3	
12050	run	0	0	7	5	1	24
12080	backwater	1	3	0	0	0	
12080	pool	0	1	0	0	0	
12080	riffle	0	0	0	2	0	
12080	run	3	2	9	1	4	26
12087	backwater	0	1	2	2	0	
12087	pool	2	1	2	0	1	
12087	riffle	0	0	2	6	0	
12087	run	1	1	2	4	1	28
						130	

High Base Flow							
		clay	silt	sand	gravel	large rock	
12010	backwater	0	1	2	0	0	
12010	pool	2	1	1	0	0	
12010	riffle	0	0	0	0	0	
12010	run	1	2	8	3	0	21
12020	backwater	0	3	0	0	0	
12020	pool	0	0	0	0	0	
12020	riffle	0	0	0	1	0	
12020	run	3	2	13	4	0	26
12030	backwater	2	2	0	0	0	
12030	pool	0	0	1	0	0	
12030	riffle	0	0	1	1	0	
12030	run	1	0	10	4	0	22
12050	backwater	0	0	0	0	0	
12050	pool	0	0	0	0	0	
12050	riffle	0	0	0	0	0	
12050	run	0	0	0	0	0	0
12080	backwater	1	1	0	0	0	
12080	pool	1	3	0	0	1	
12080	riffle	0	0	0	2	0	
12080	run	2	2	10	3	2	28
12087	backwater	0	0	0	0	0	
12087	pool	0	0	0	0	0	
12087	riffle	0	0	0	0	0	
12087	run	0	0	0	0	0	0
						97	

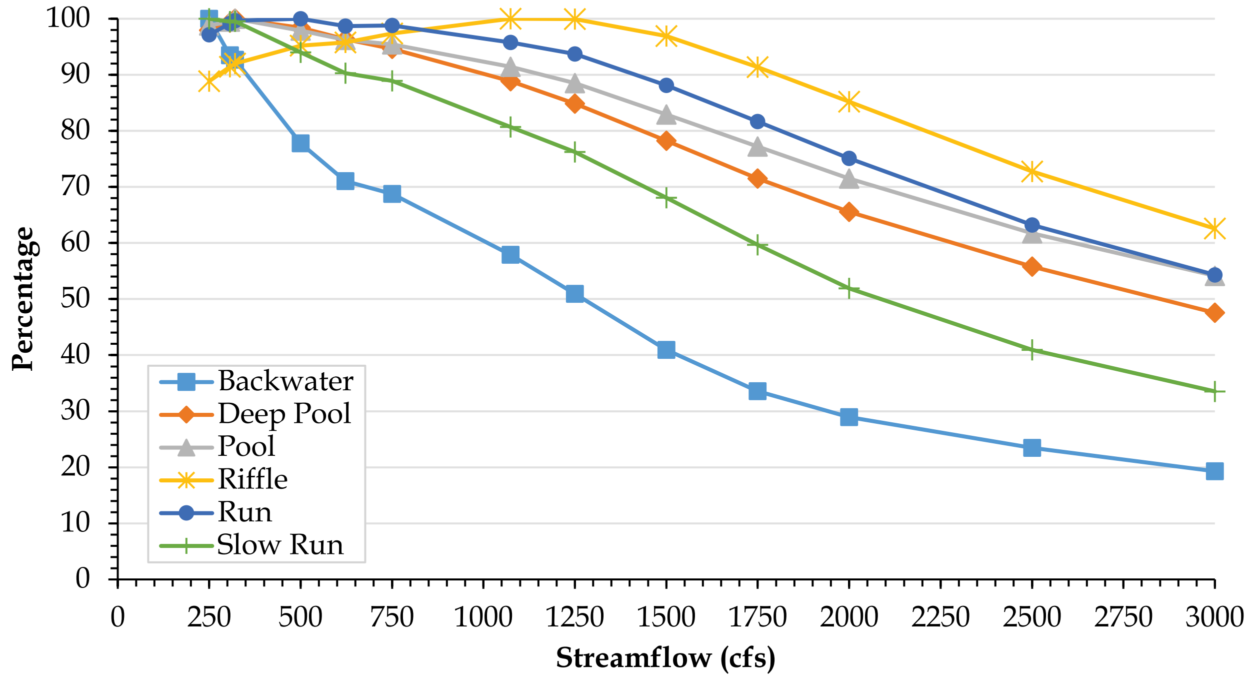


Figure B - 1. Percent maximum of weighted usable area versus simulated discharge for fish habitat guilds at the Marlin study site.

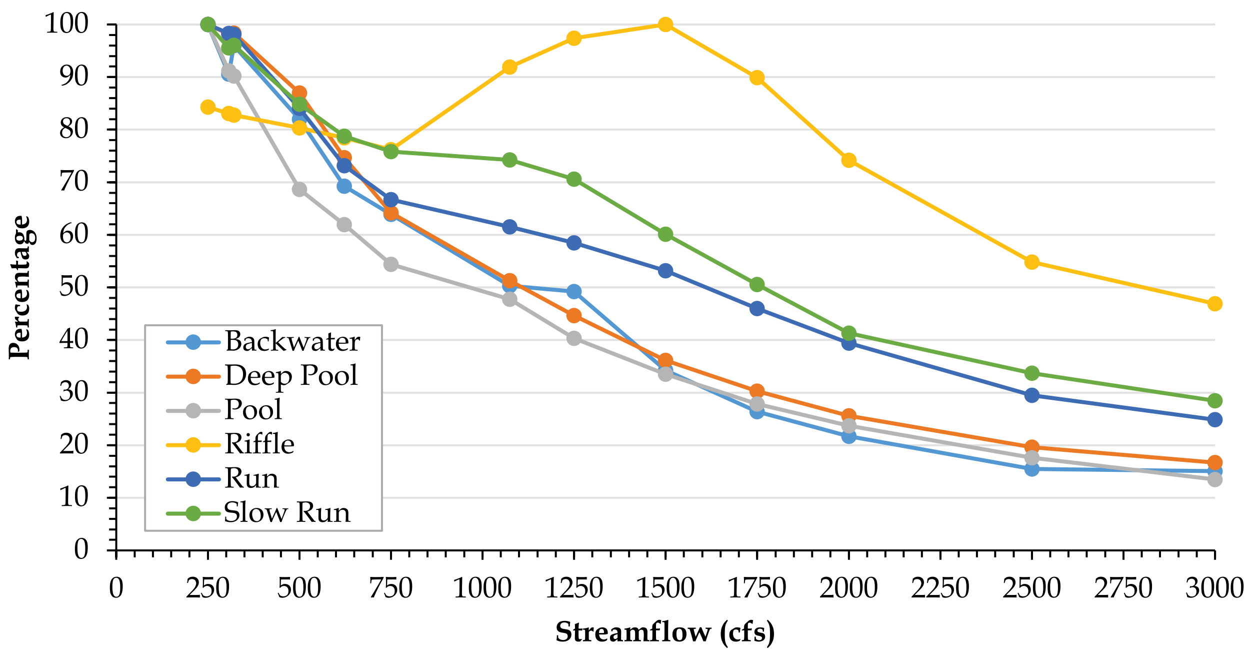


Figure B - 2. Percent maximum of weighted usable area of high quality habitat (composite suitability index ≥ 0.8) at the Marlin study site.

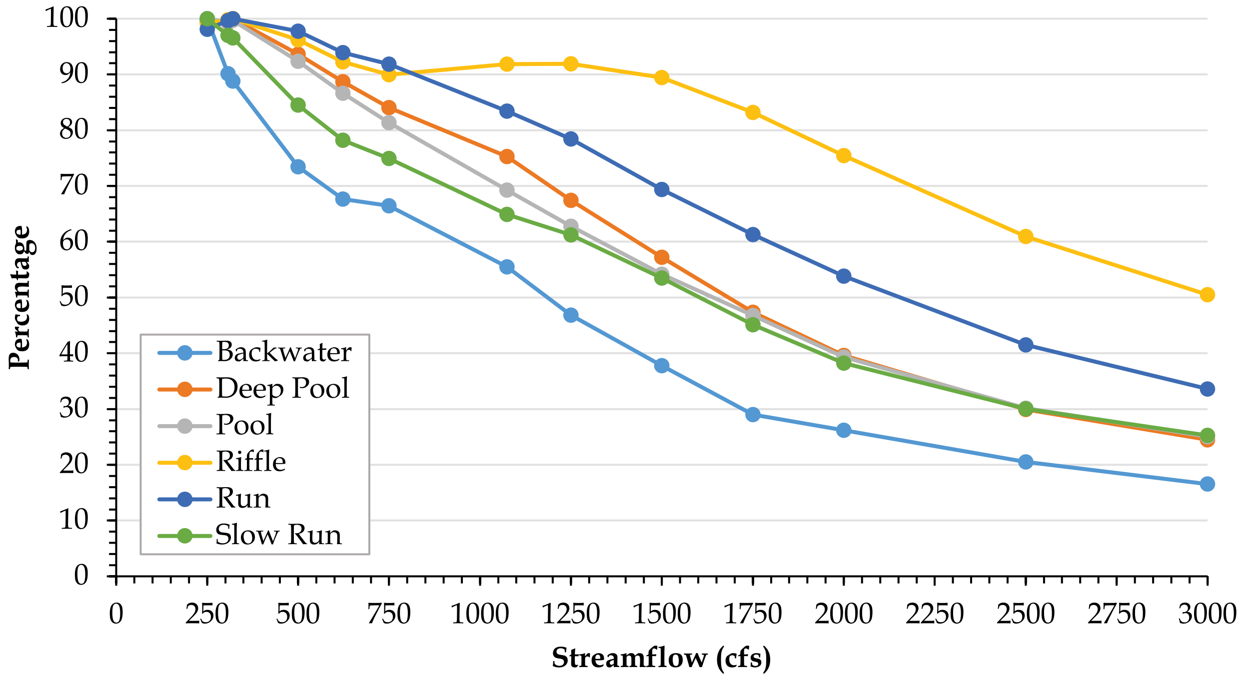


Figure B - 3. Percent maximum of weighted usable area of moderate quality habitat (composite suitability index ≥ 0.5) at the Marlin study site.

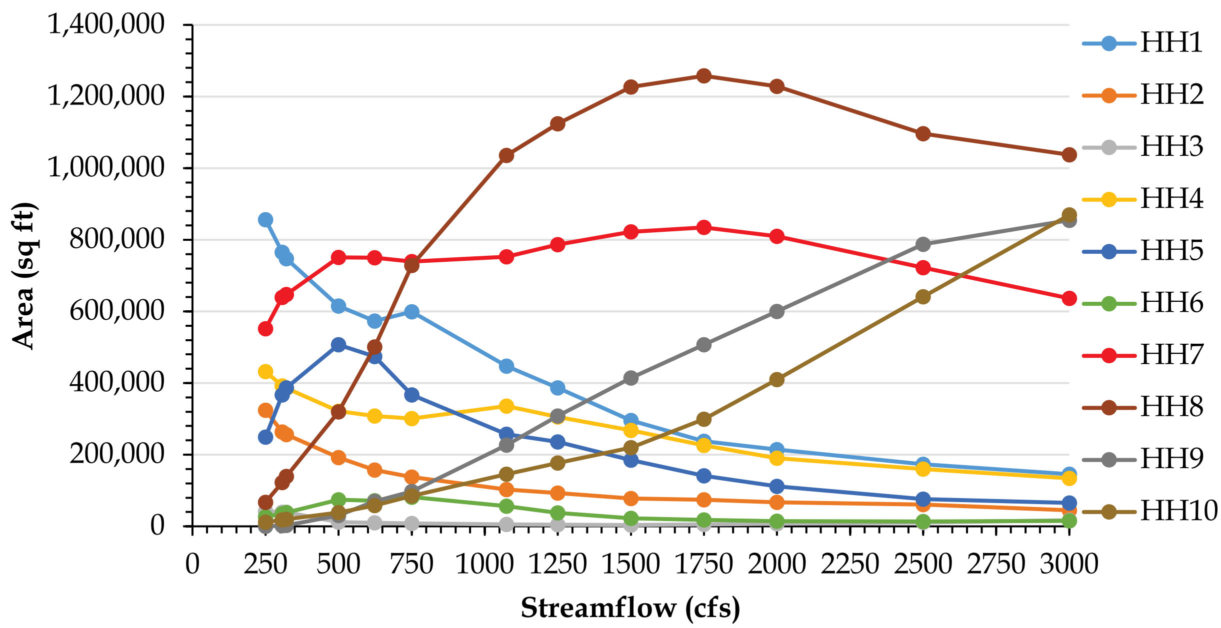


Figure B - 4. Total area of hydraulic habitat criteria versus simulated discharge at the Marlin study site.

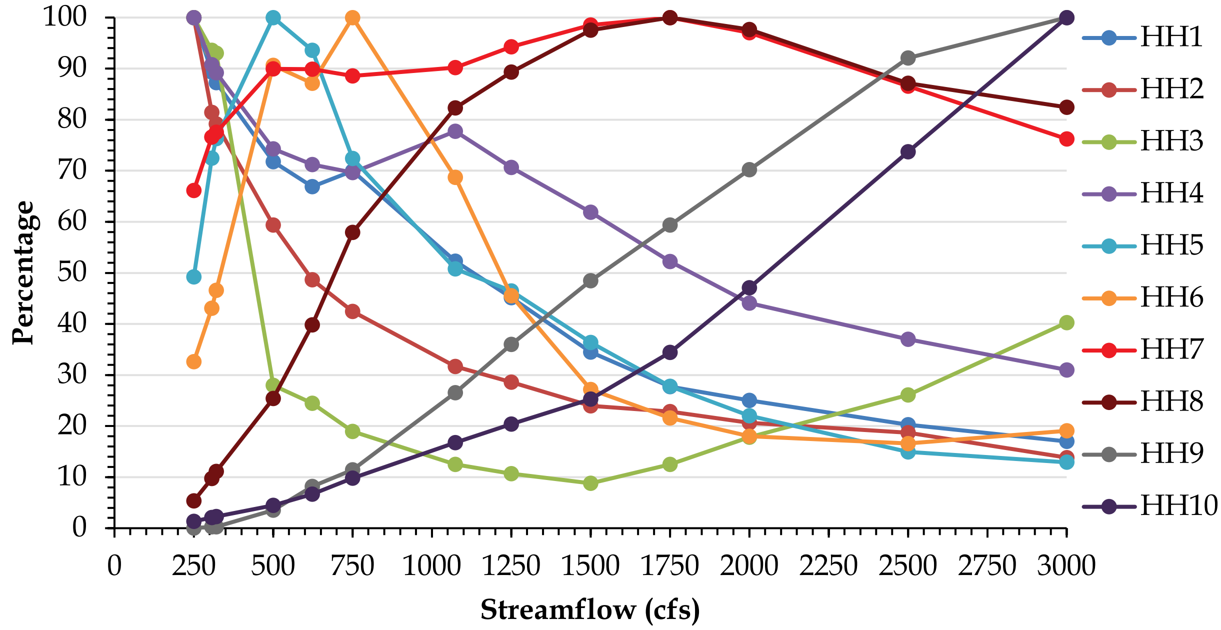


Figure B - 5. Percent maximum of hydraulic habitat criteria at the Marlin study site.

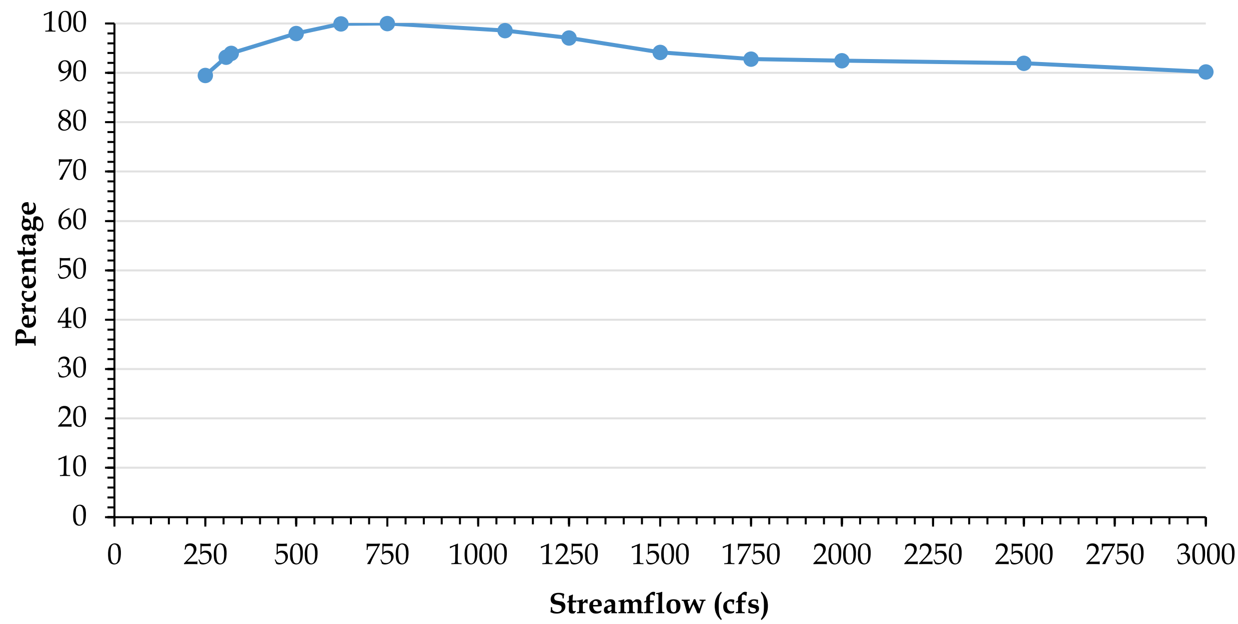


Figure B - 6. Percent maximum of hydraulic habitat diversity (Shannon's H) at the Marlin study site.

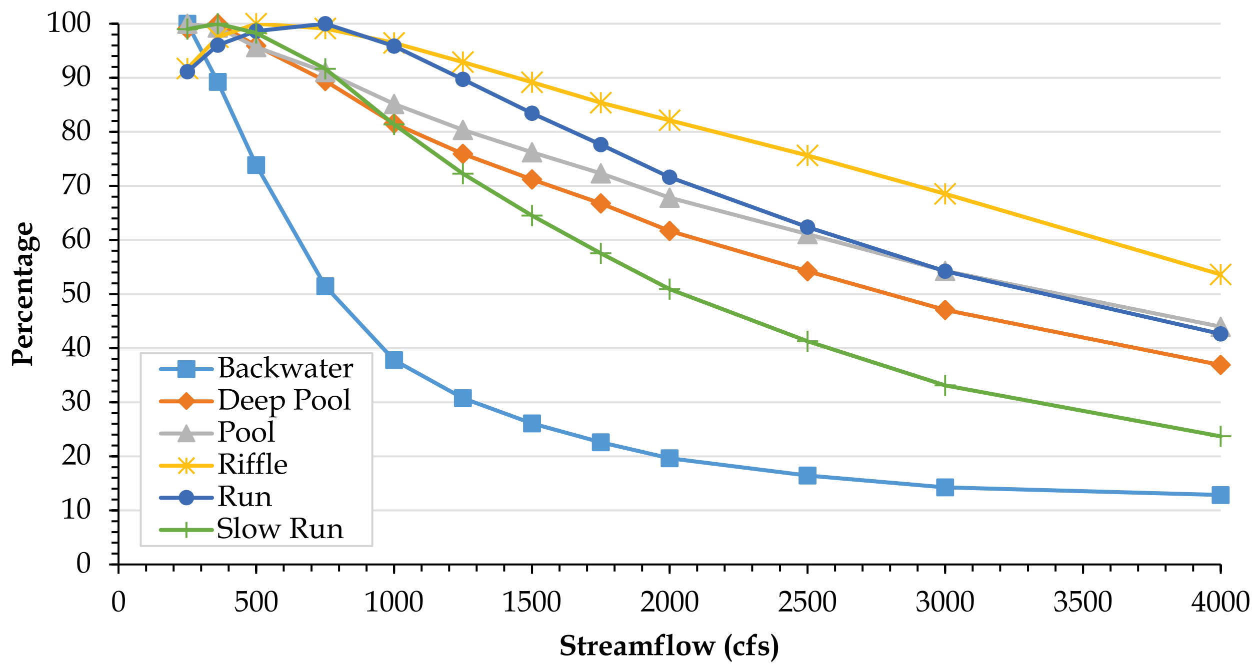


Figure B - 7. Percent maximum of weighted usable area versus simulated discharge for fish habitat guilds at the Hearne study site.

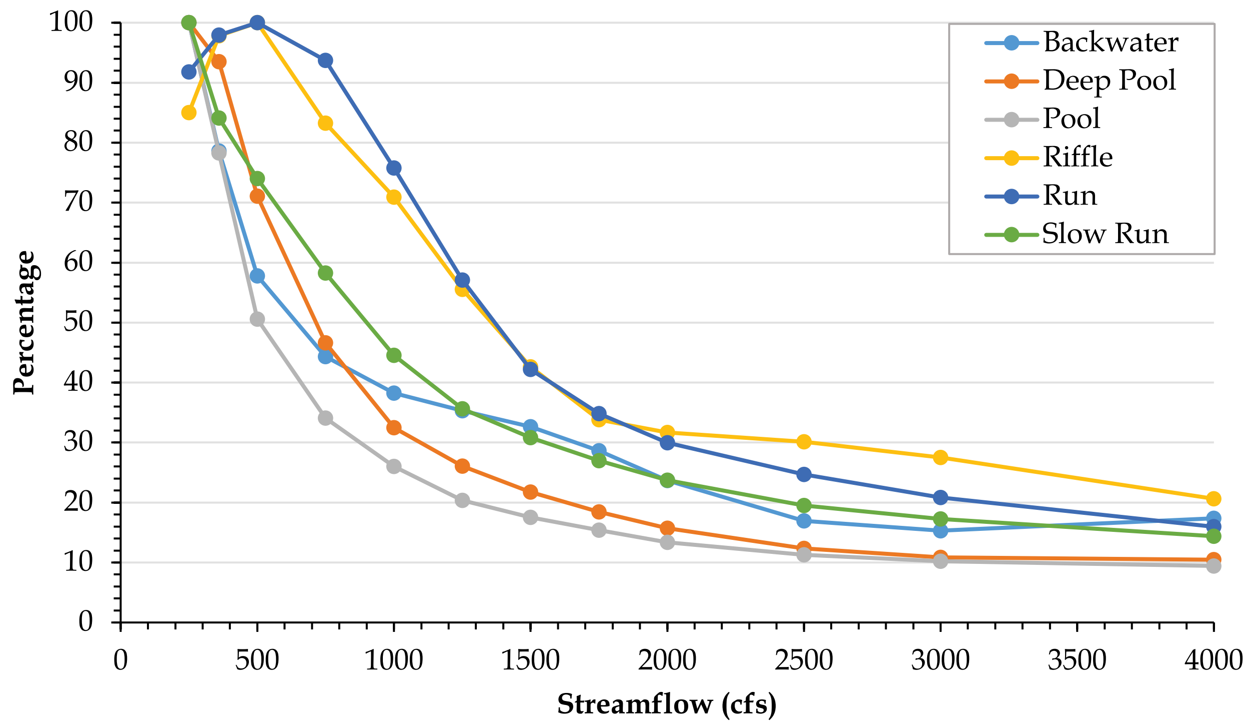


Figure B - 8. Percent maximum of weighted usable area of high quality habitat (composite suitability index ≥ 0.8) at the Hearne study site.

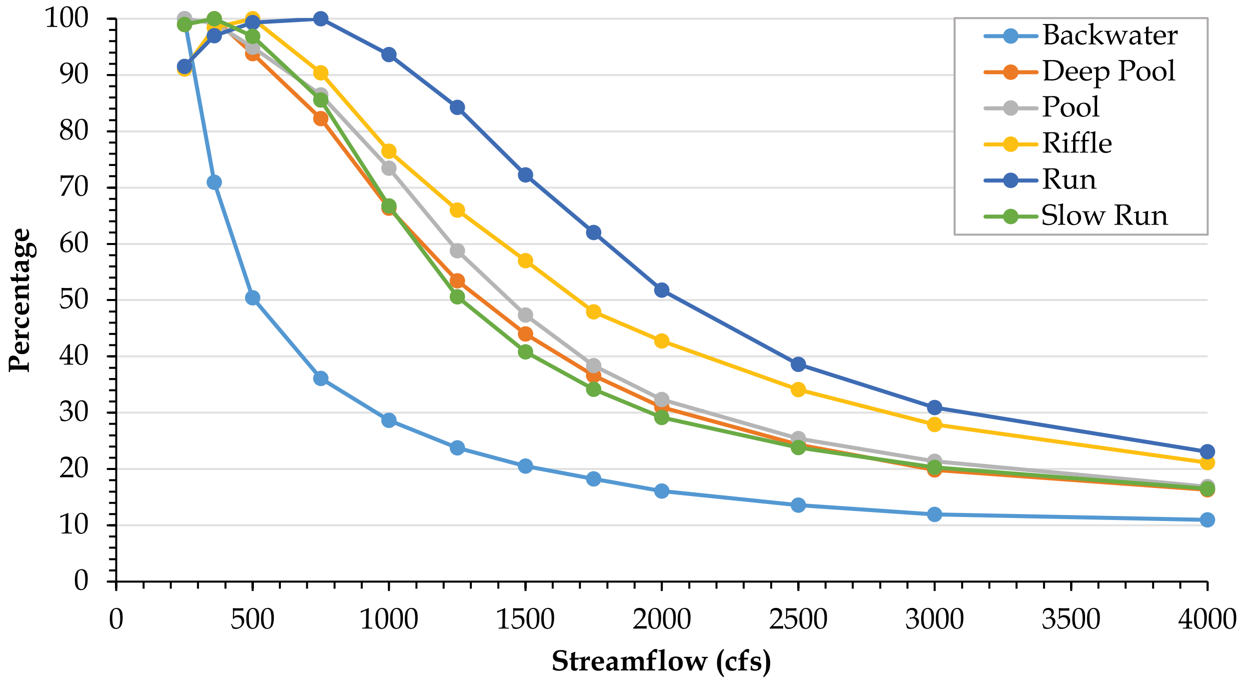


Figure B - 9. Percent maximum of weighted usable area of moderate quality habitat (composite suitability index ≥ 0.5) at the Hearne study site.

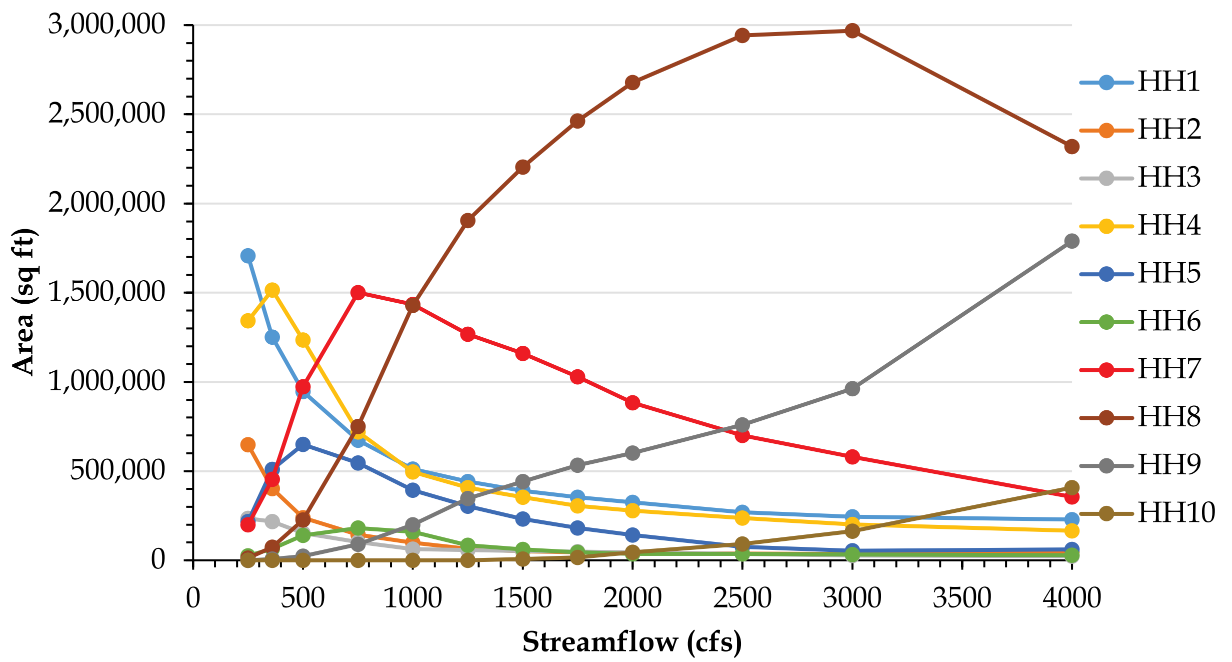


Figure B - 10. Total area of hydraulic habitat criteria versus simulated discharge at the Hearne study site.

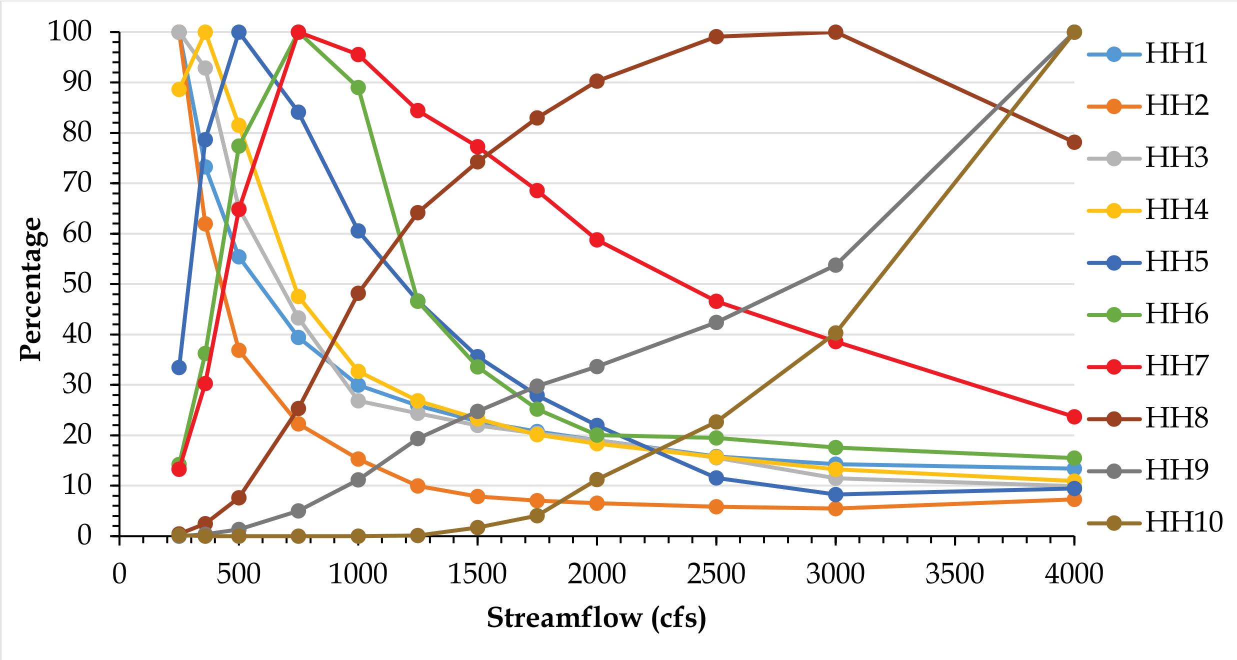


Figure B - 11. Percent maximum of hydraulic habitat criteria at the Hearne study site.

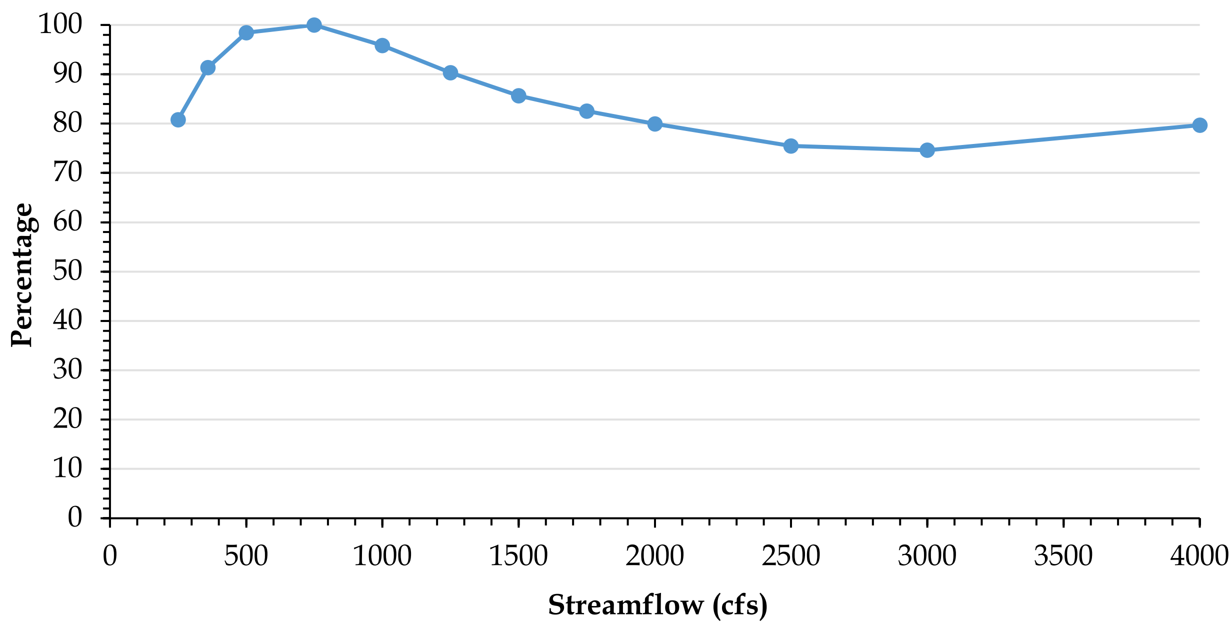


Figure B - 12. Percent maximum of hydraulic habitat diversity (Shannon's H) at the Hearne study site.

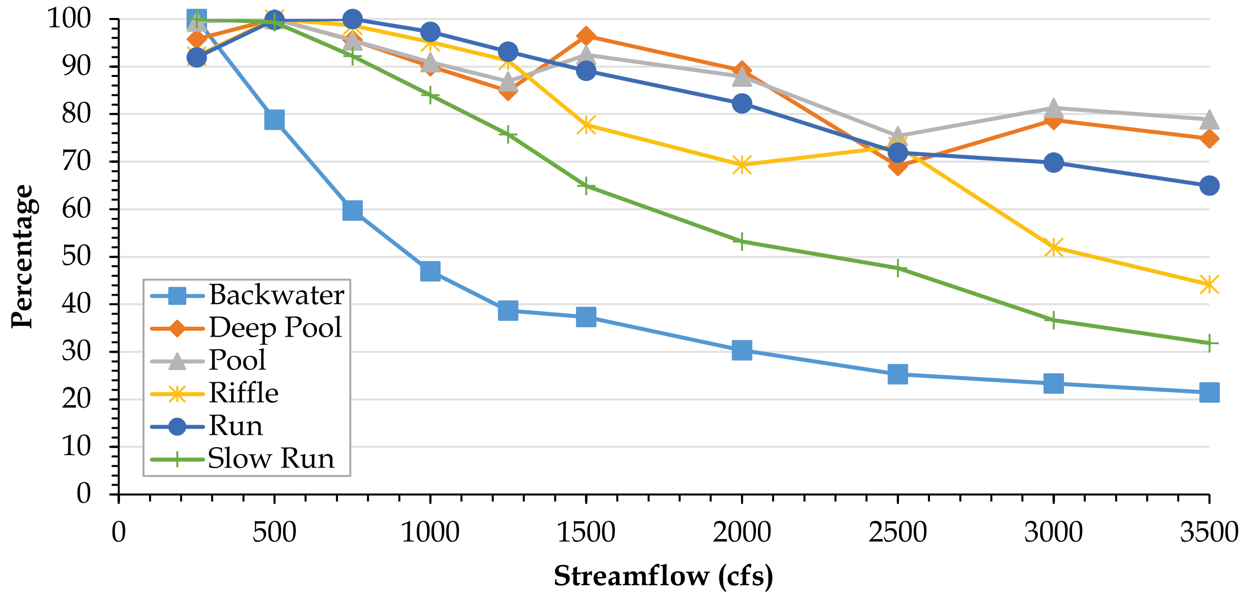


Figure B - 13. Percent maximum of weighted usable area versus simulated discharge for fish habitat guilds at the Mussel Shoals study site.

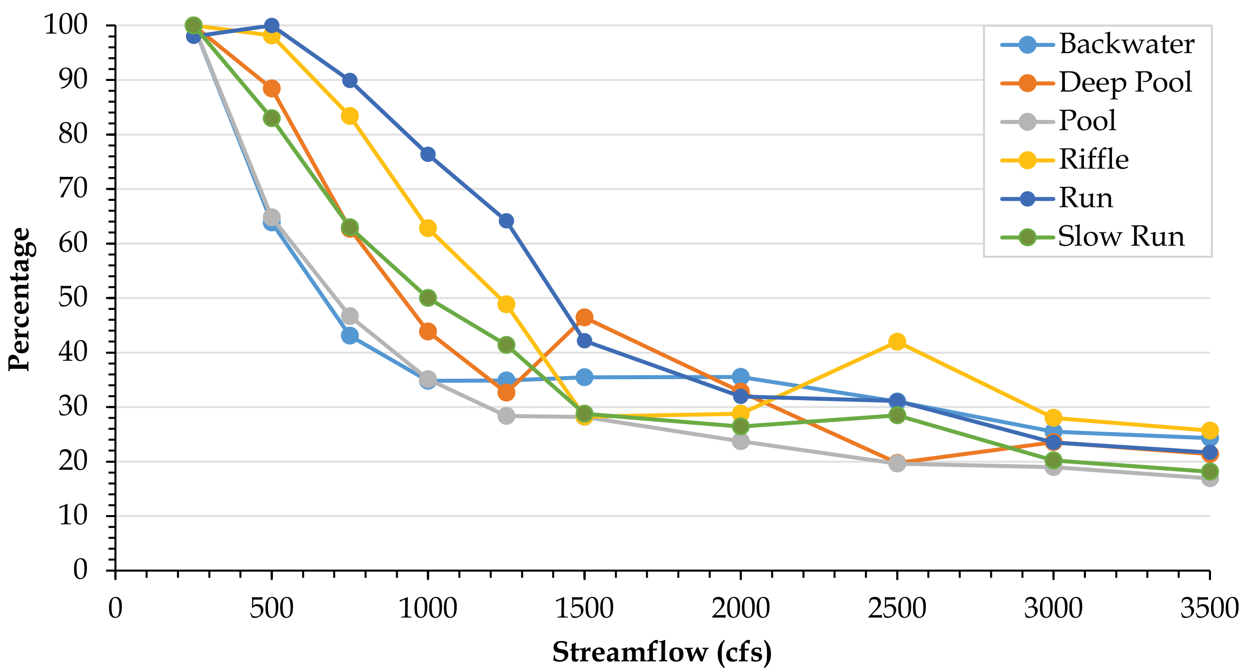


Figure B - 14. Percent maximum of weighted usable area of high quality habitat (composite suitability index ≥ 0.8) at the Mussel Shoals study site.

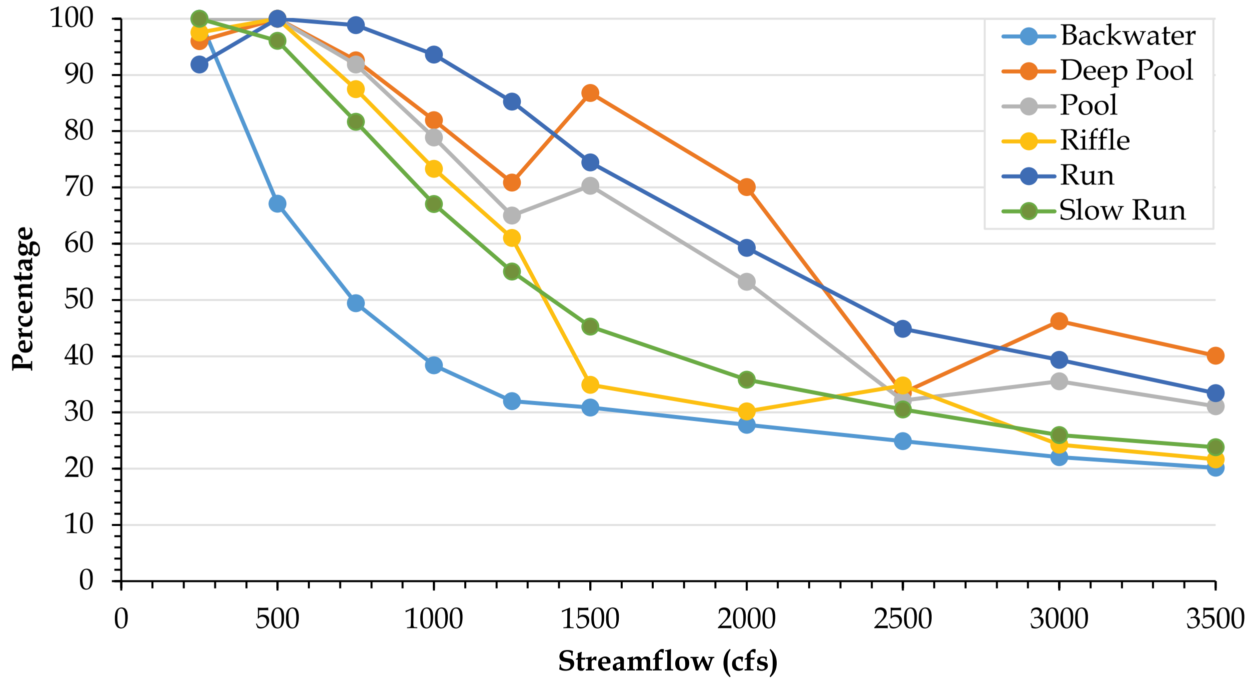


Figure B - 15. Percent maximum of weighted usable area of moderate quality habitat (composite suitability index ≥ 0.5) at the Mussel Shoals study site.

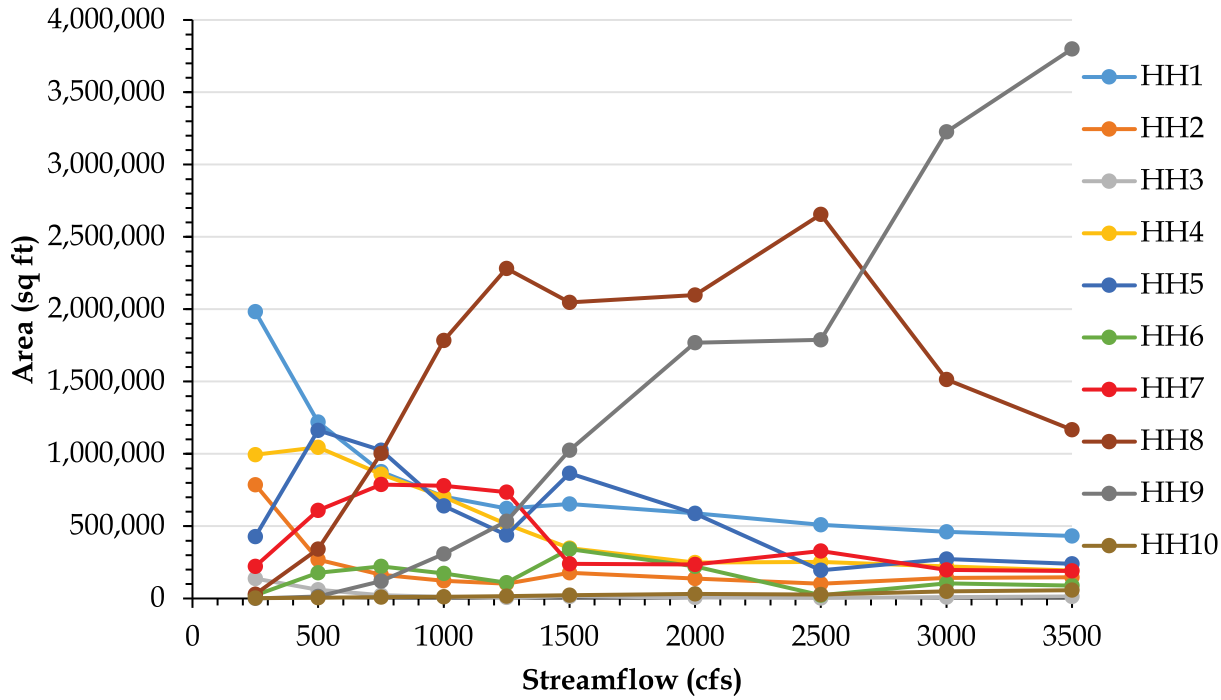


Figure B - 16. Total area of hydraulic habitat criteria versus simulated discharge at the Mussel Shoals study site.

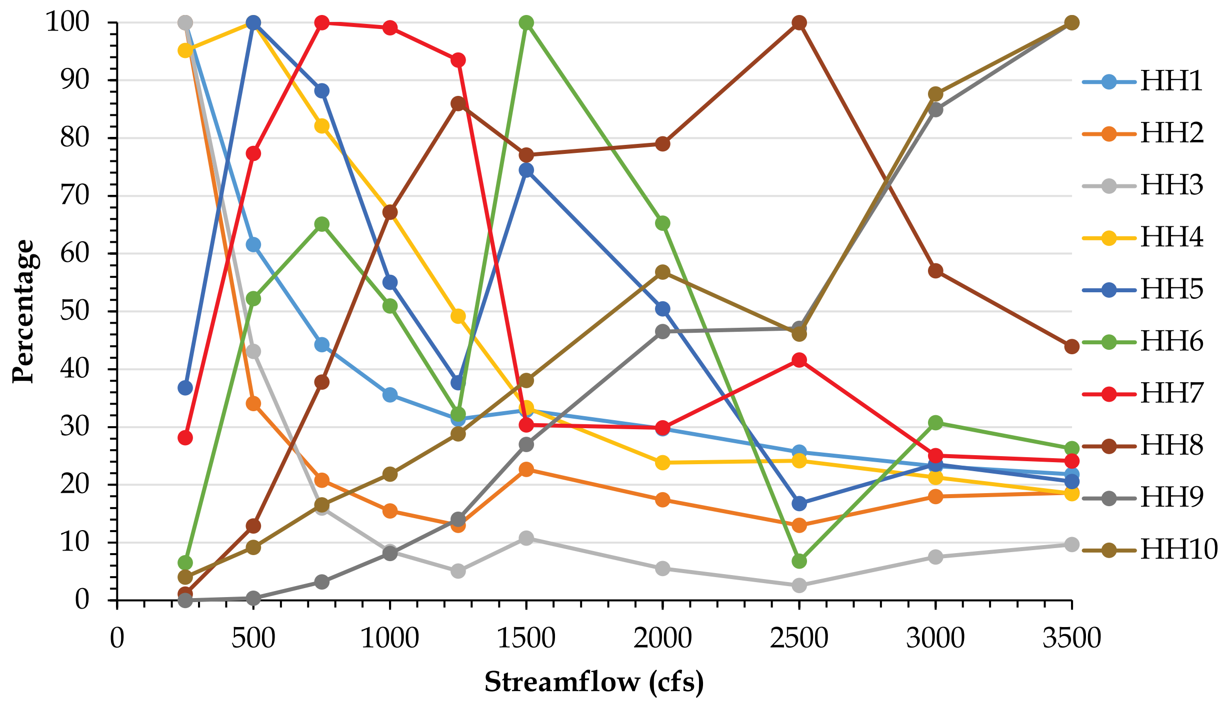


Figure B - 17. Percent maximum of hydraulic habitat criteria at the Mussel Shoals study site.

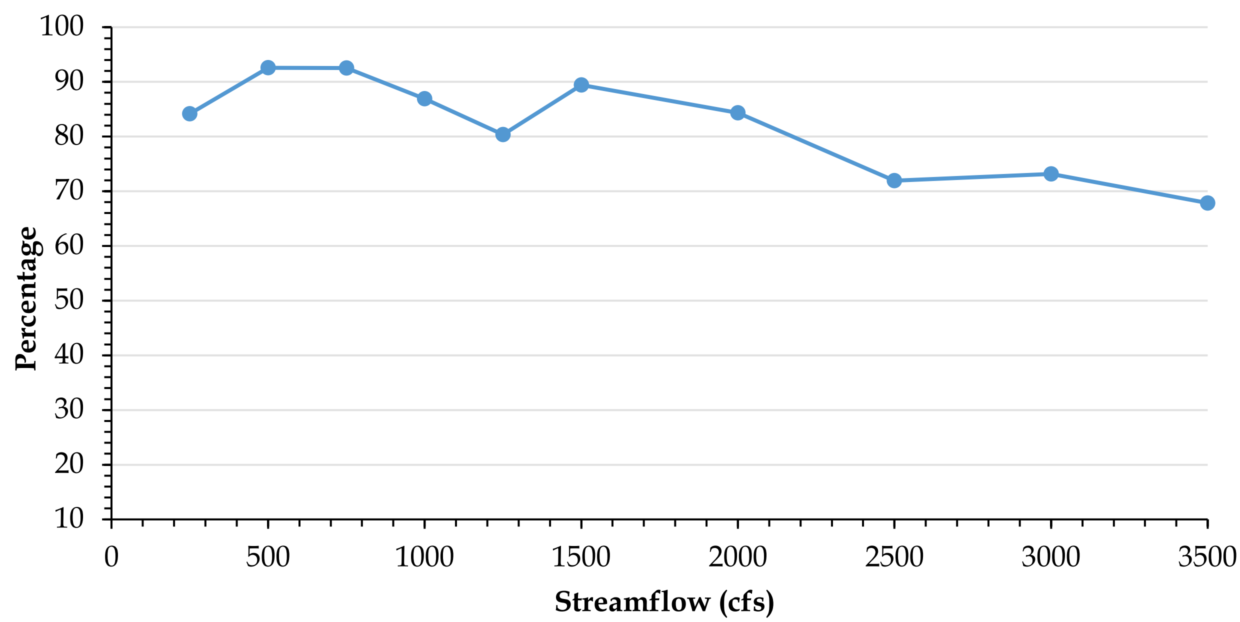


Figure B - 18. Percent maximum of hydraulic habitat diversity (Shannon's H) at the Mussel Shoals study site.

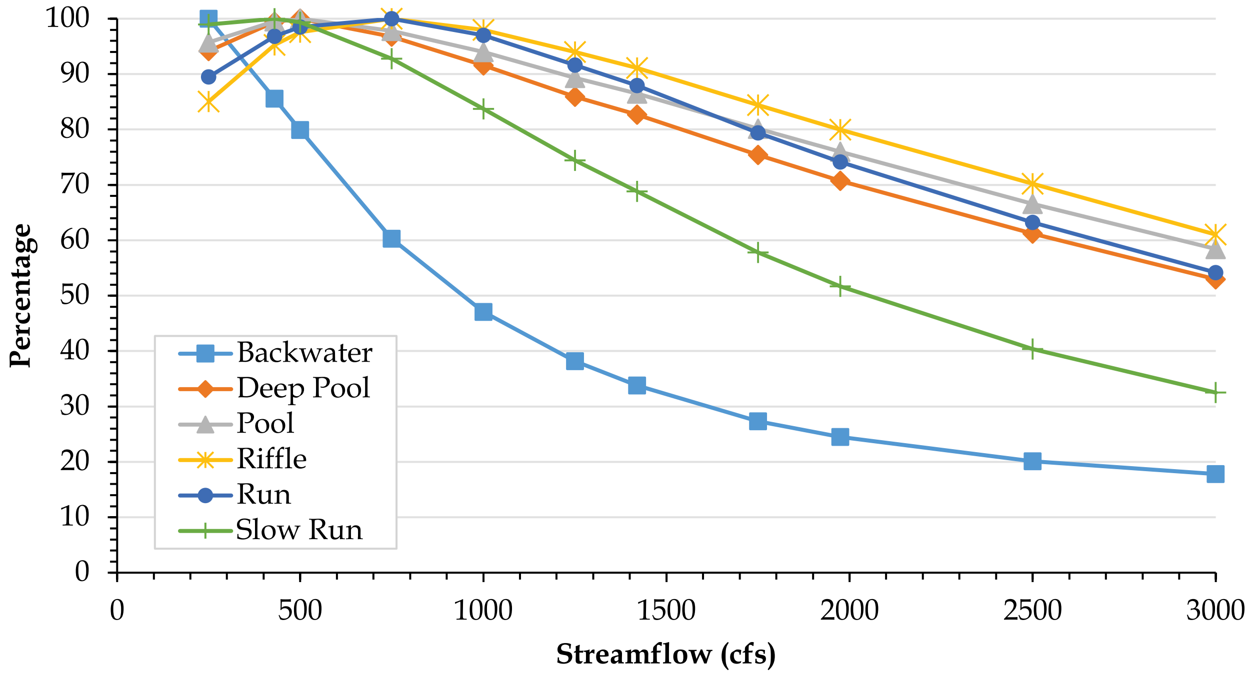


Figure B - 19. Percent maximum of weighted usable area versus simulated discharge for fish habitat guilds at the Navasota study site.

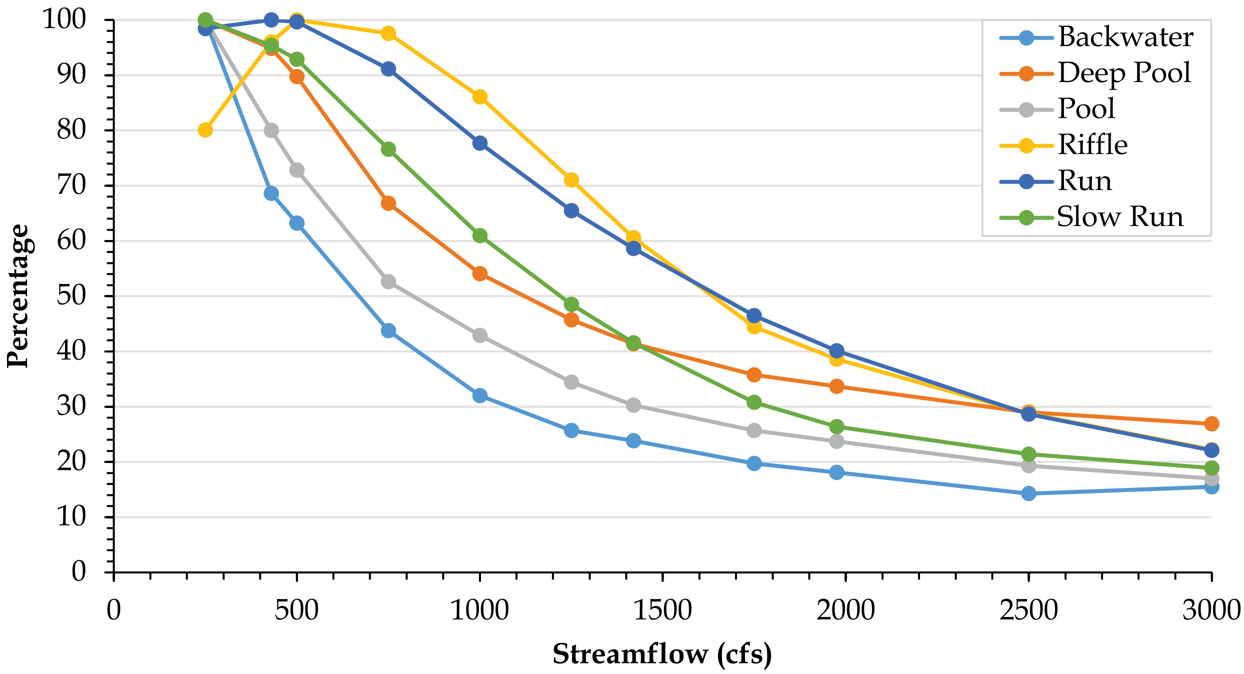


Figure B - 20. Percent maximum of weighted usable area of high quality habitat (composite suitability index ≥ 0.8) at the Navasota study site.

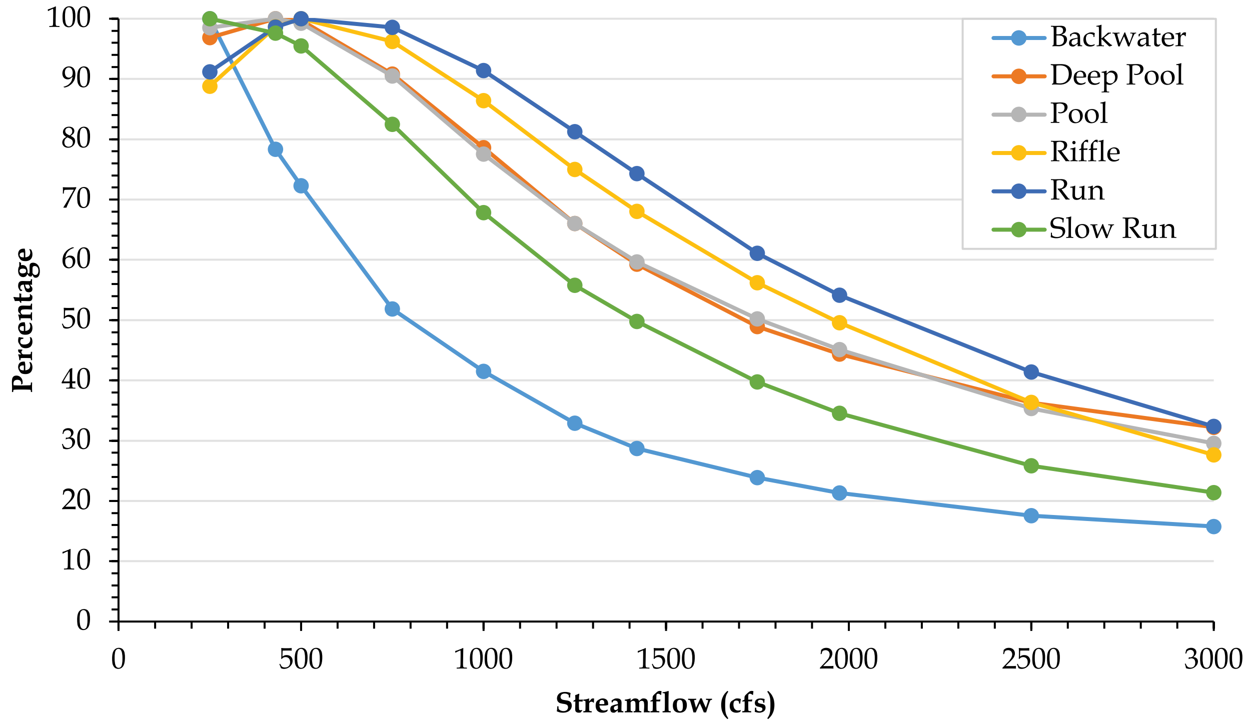


Figure B - 21. Percent maximum of weighted usable area of moderate quality habitat (composite suitability index ≥ 0.5) at the Navasota study site.

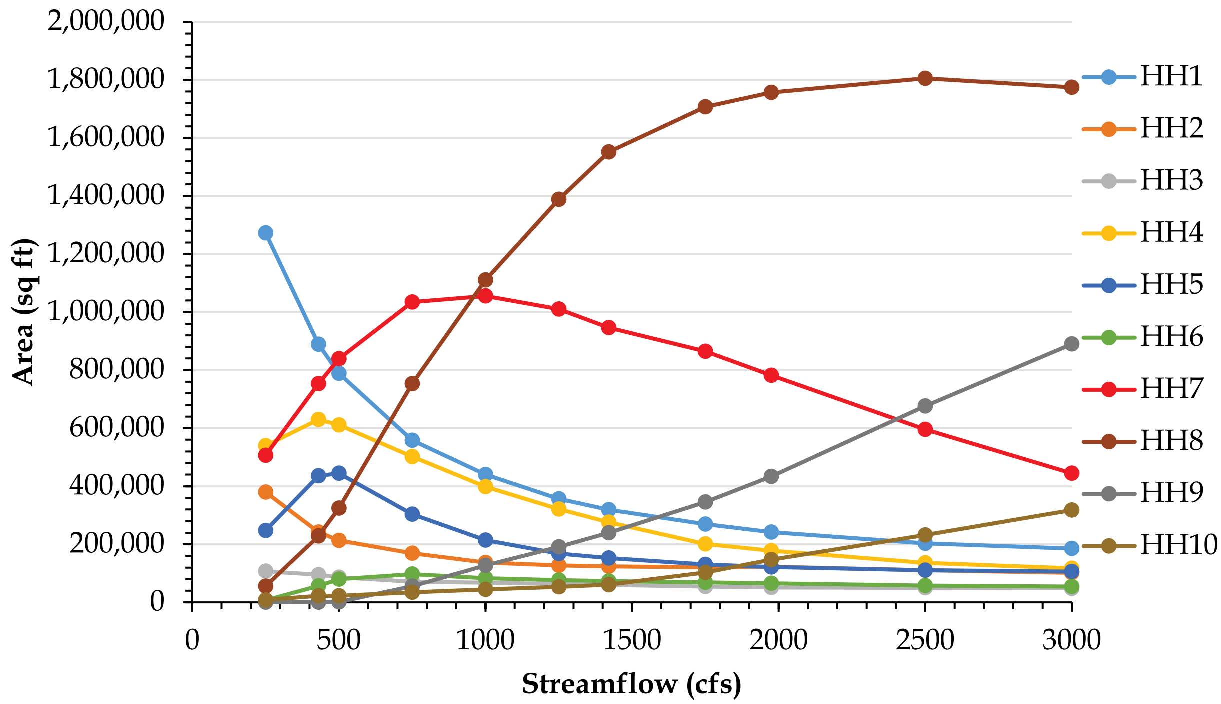


Figure B - 22. Total area of hydraulic habitat criteria versus simulated discharge at the Navasota study site.

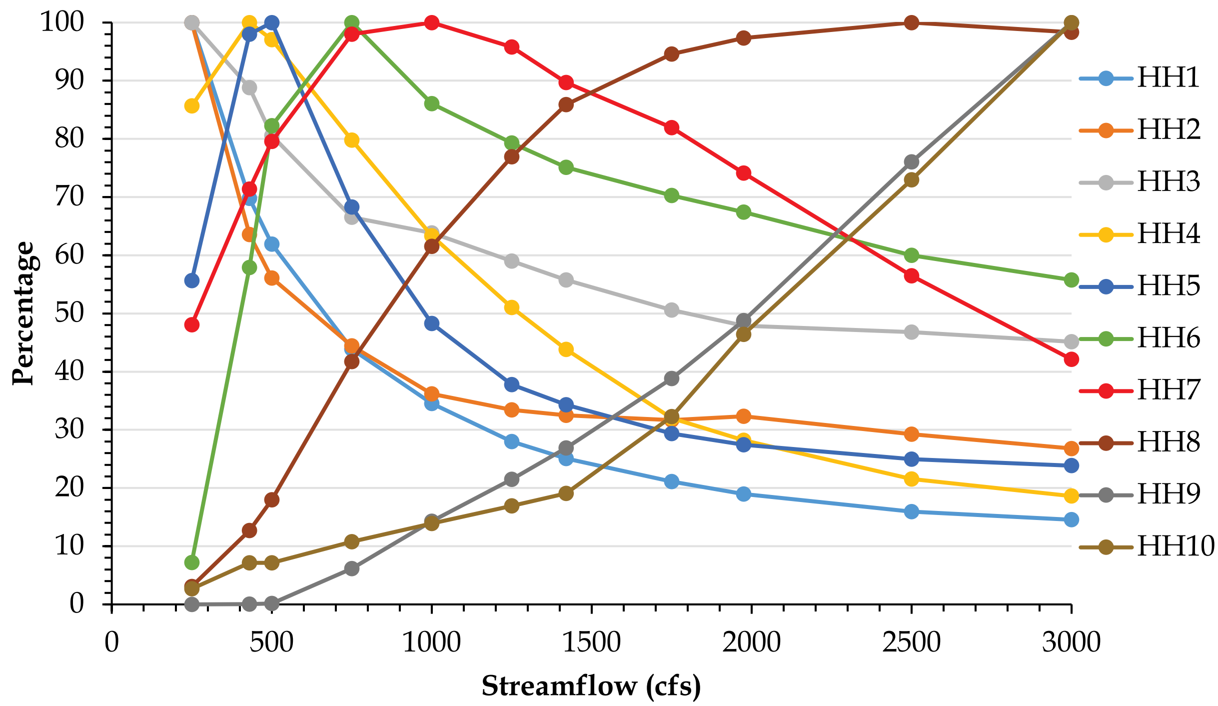


Figure B - 23. Percent maximum of hydraulic habitat criteria at the Navasota study site.

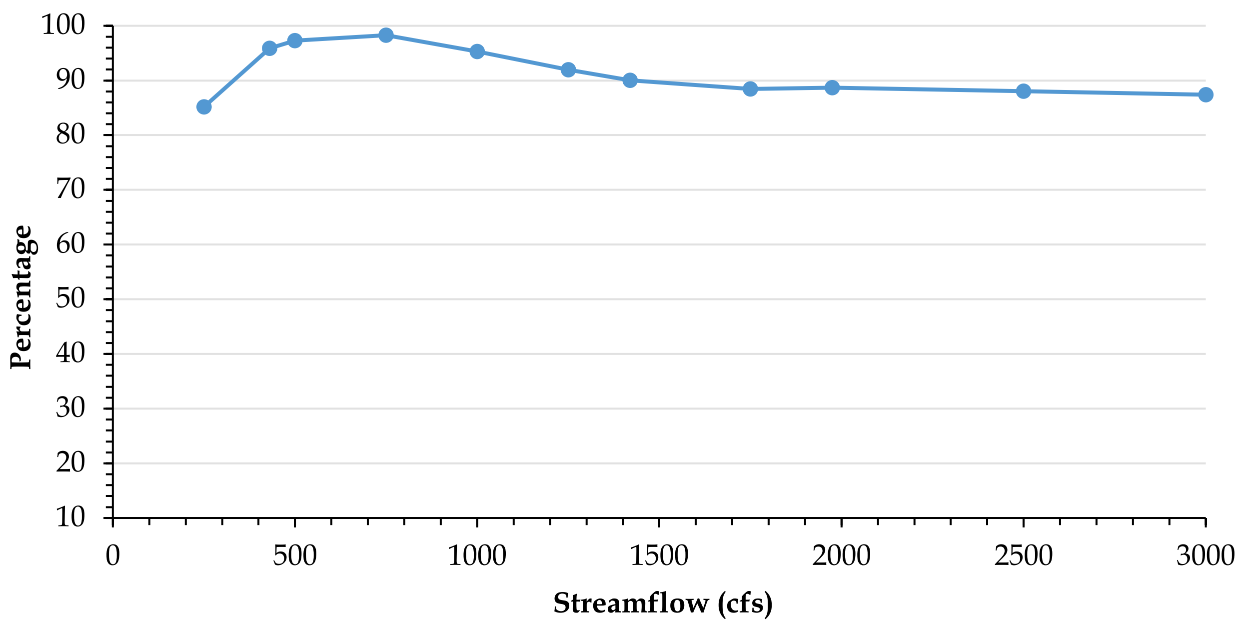


Figure B - 24. Percent maximum of hydraulic habitat diversity (Shannon's H) at the Navasota study site.

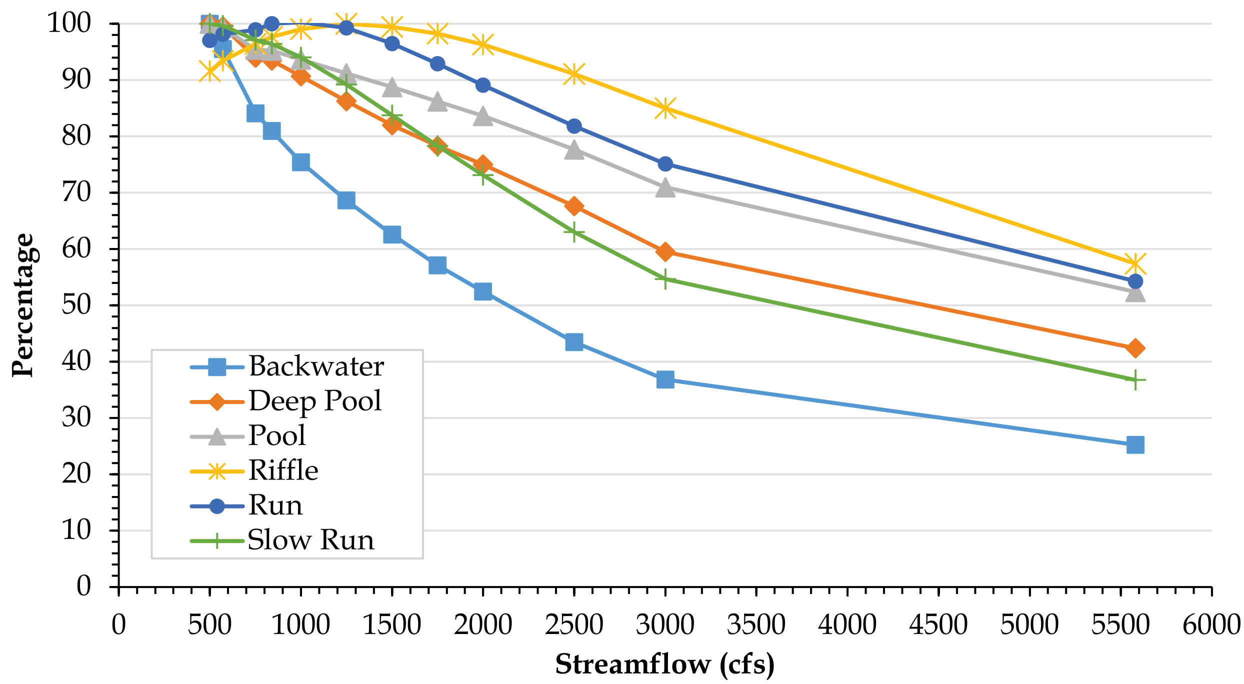


Figure B - 25. Percent maximum of weighted usable area versus simulated discharge for fish habitat guilds at the Wildcat Bend study site.

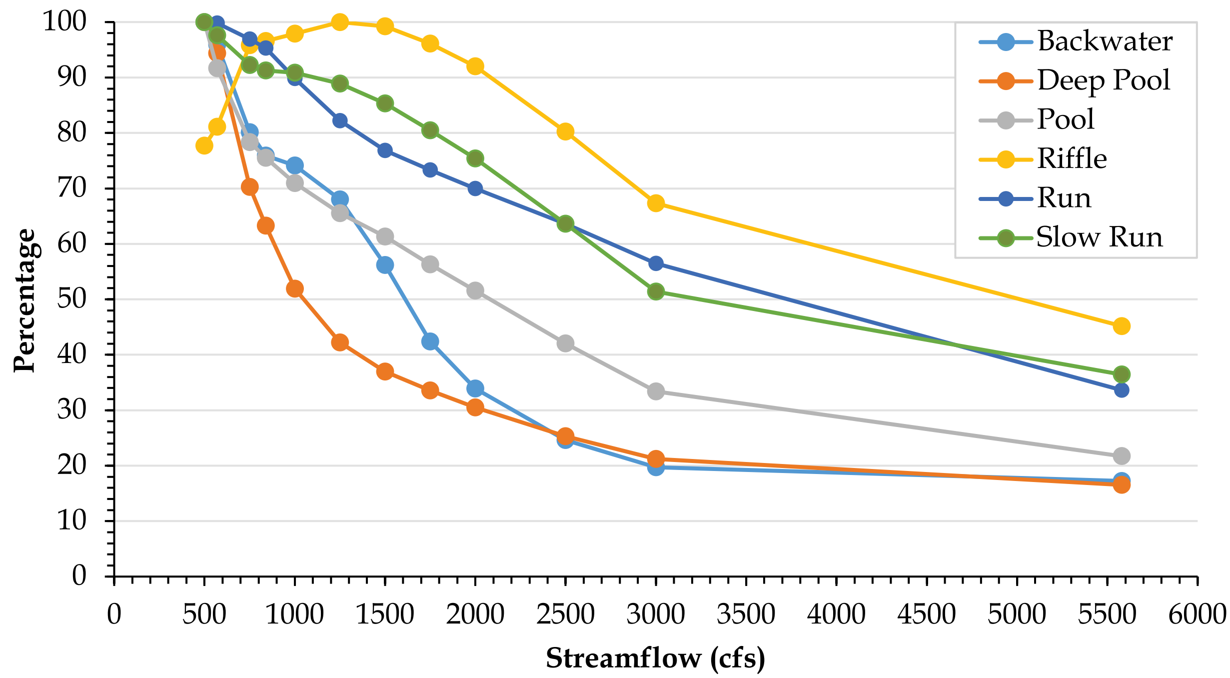


Figure B - 26. Percent maximum of weighted usable area of high quality habitat (composite suitability index ≥ 0.8) at the Wildcat Bend study site.

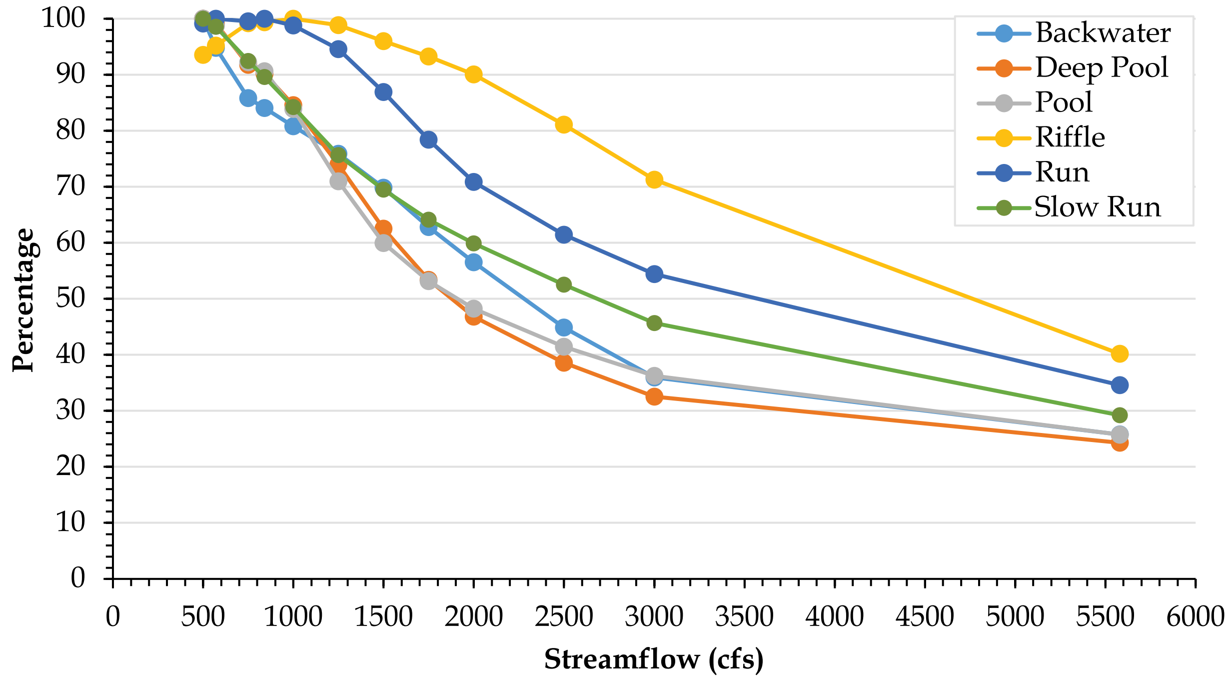


Figure B - 27. Percent maximum of weighted usable area of moderate quality habitat (composite suitability index ≥ 0.5) at the Wildcat Bend study site.

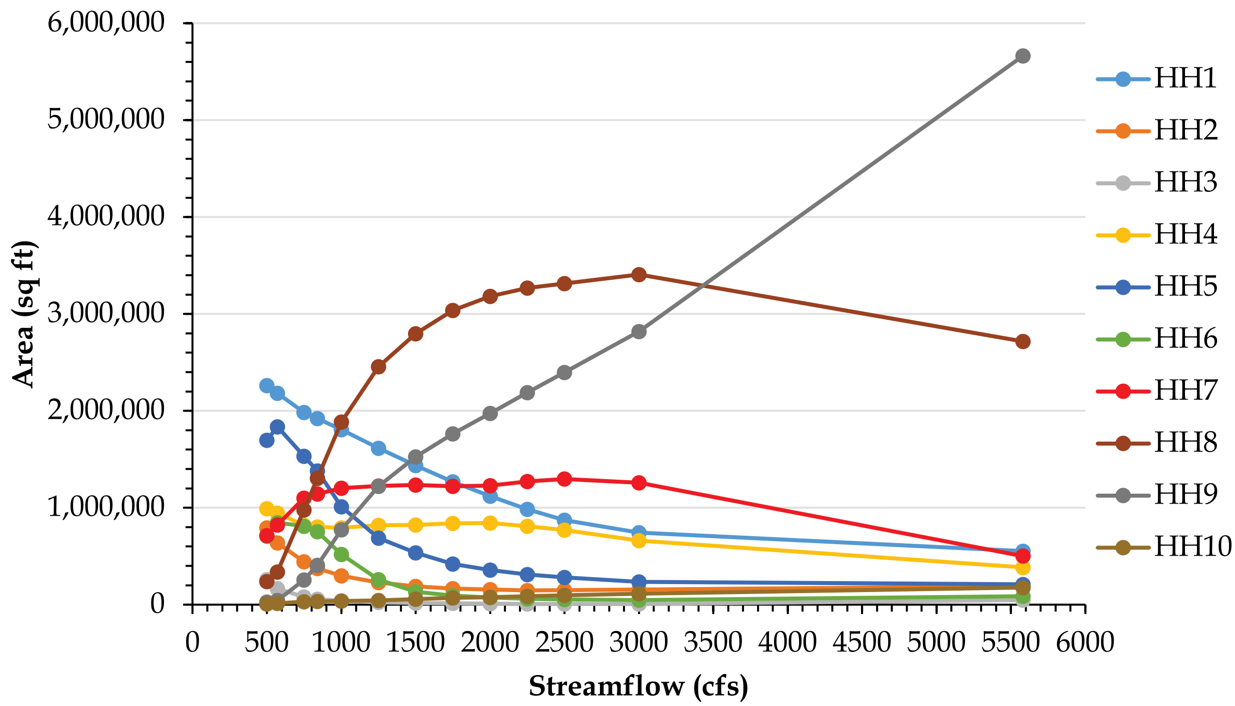


Figure B - 28. Total area of hydraulic habitat criteria versus simulated discharge at the Wildcat Bend study site.

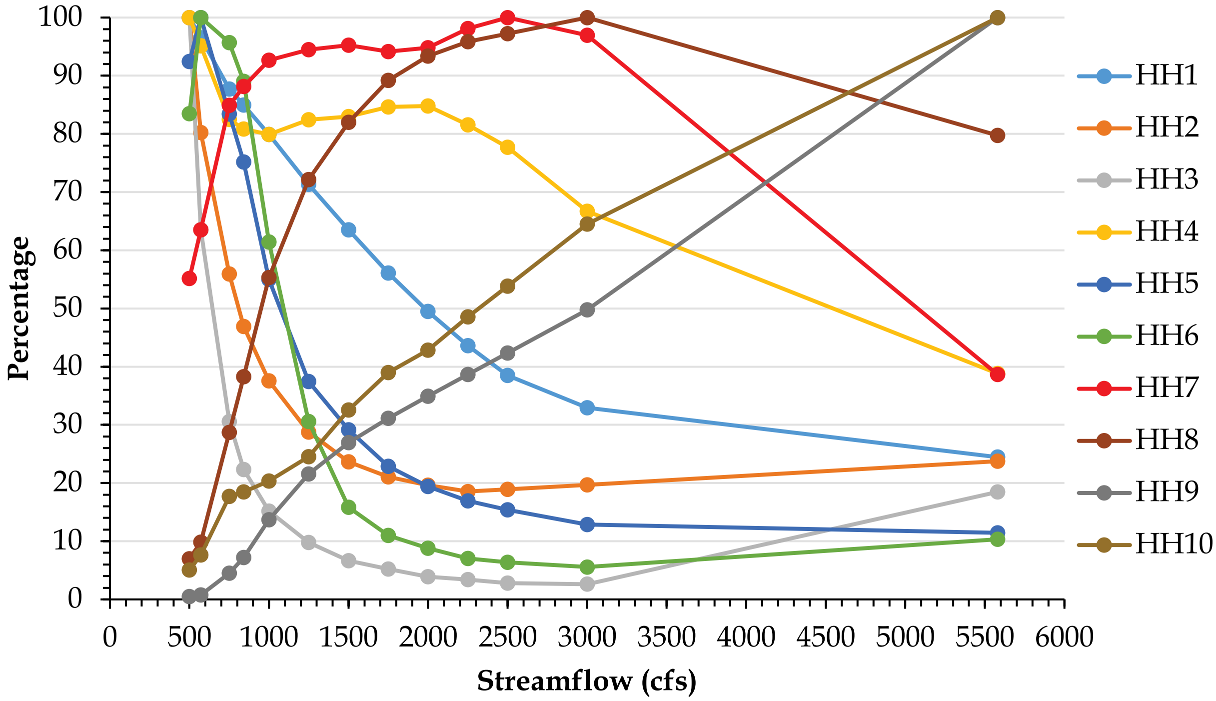


Figure B - 29. Percent maximum of hydraulic habitat criteria at the Wildcat Bend study site.

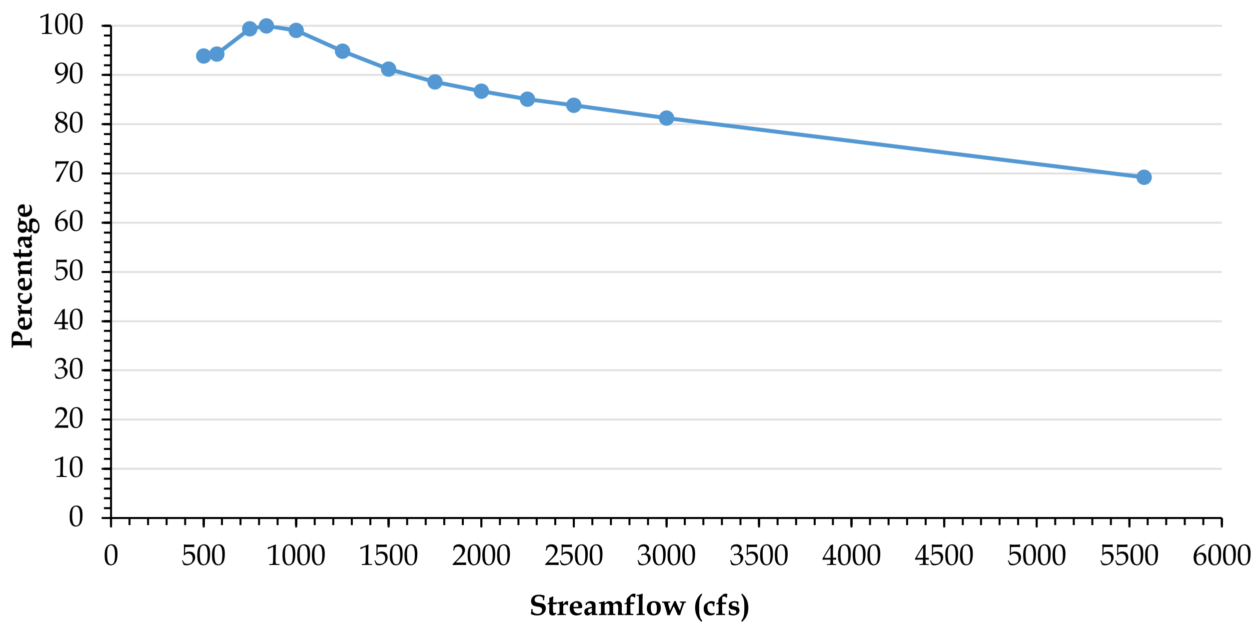


Figure B - 30. Percent maximum of hydraulic habitat diversity (Shannon's H) at the Wildcat Bend study site.

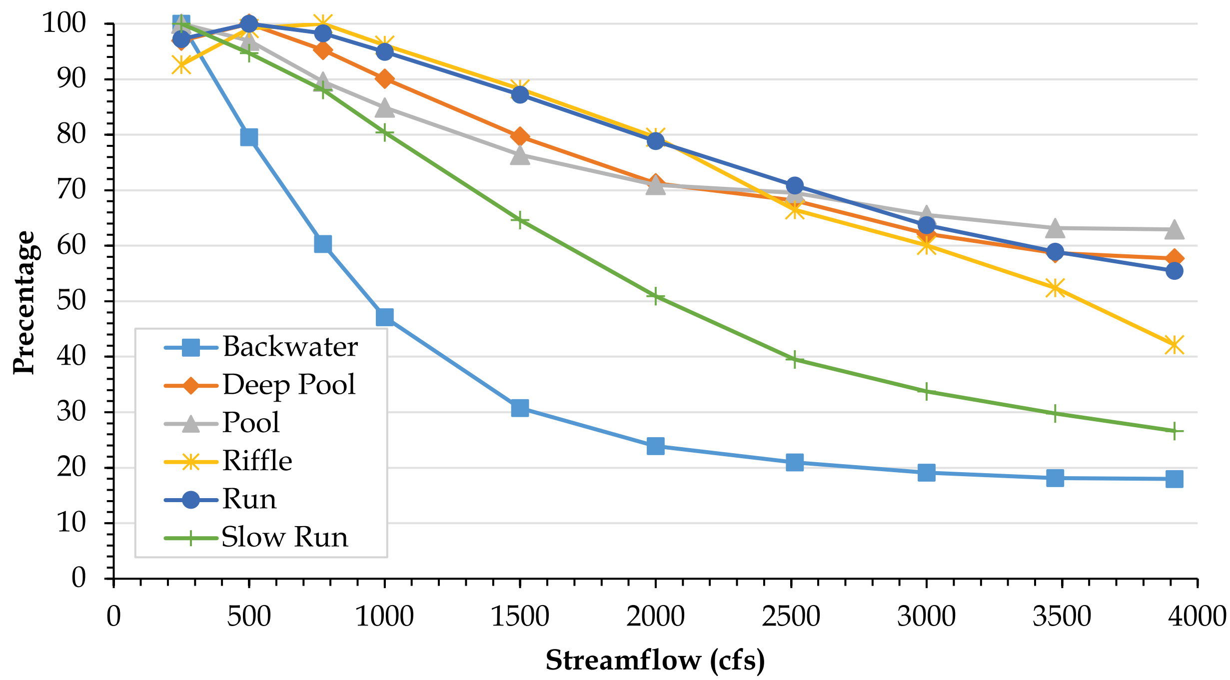


Figure B - 31. Percent maximum of weighted usable area versus simulated discharge for fish habitat guilds at the Allens Creek study site.

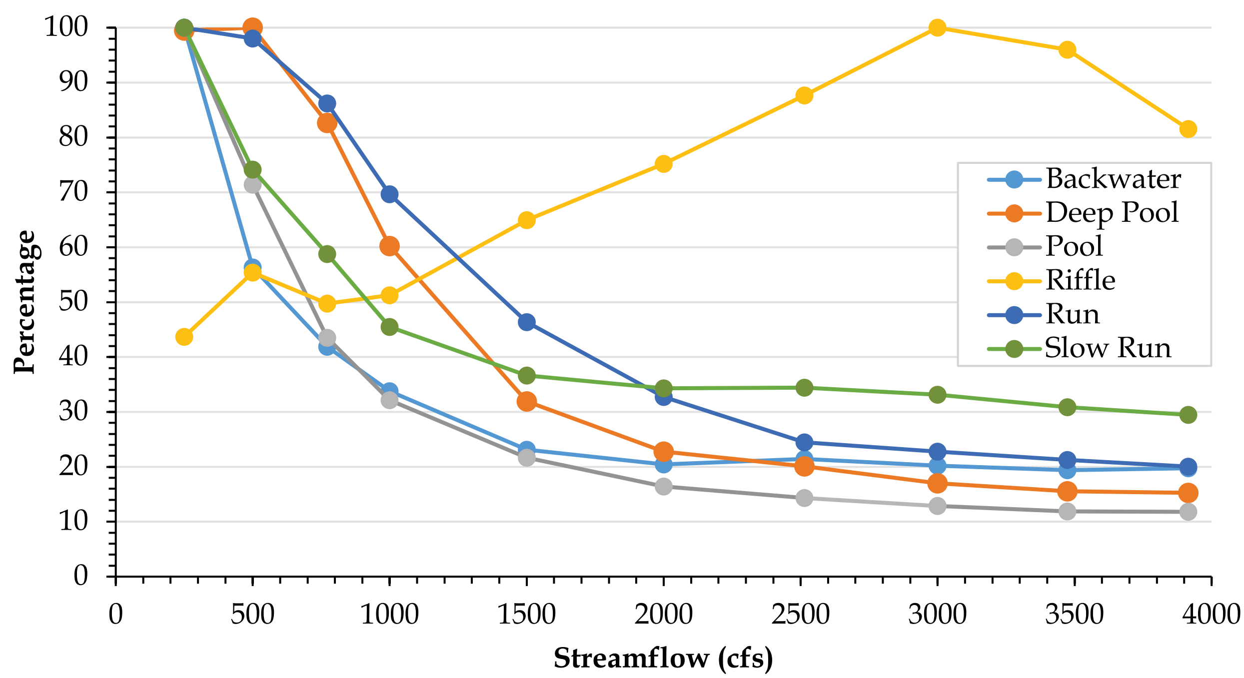


Figure B - 32. Percent maximum of weighted usable area of high quality habitat (composite suitability index ≥ 0.8) at the Allens Creek study site.

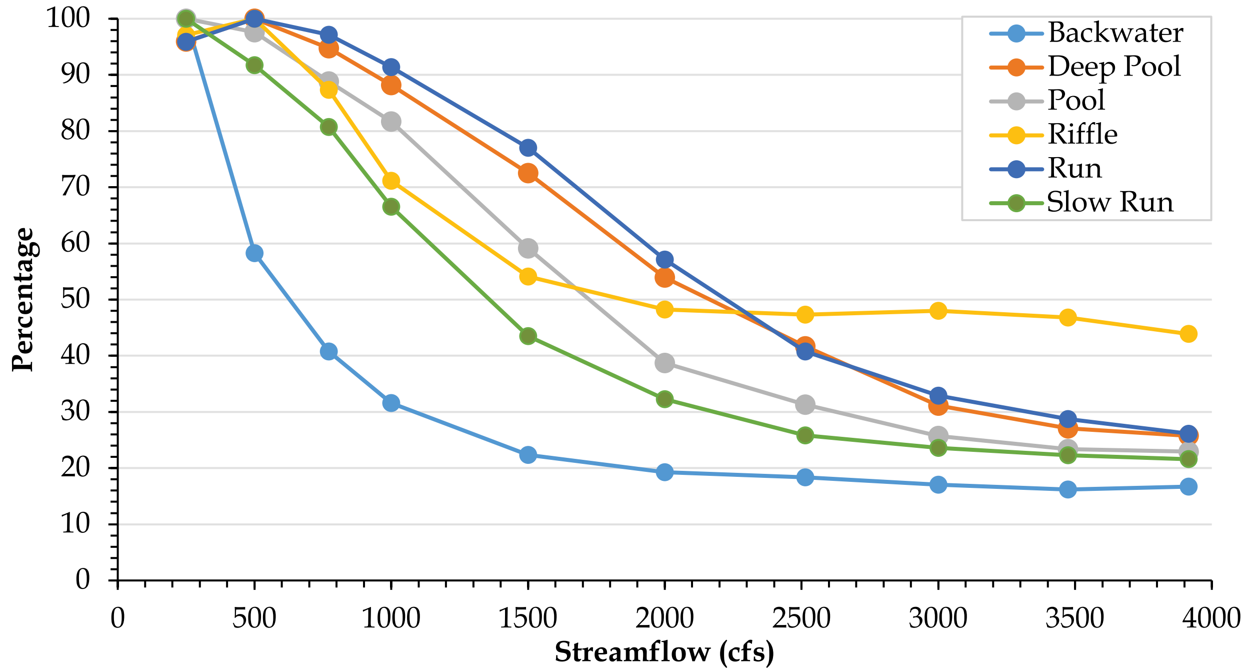


Figure B - 33. Percent maximum of weighted usable area of moderate quality habitat (composite suitability index ≥ 0.5) at the Allens Creek study site.

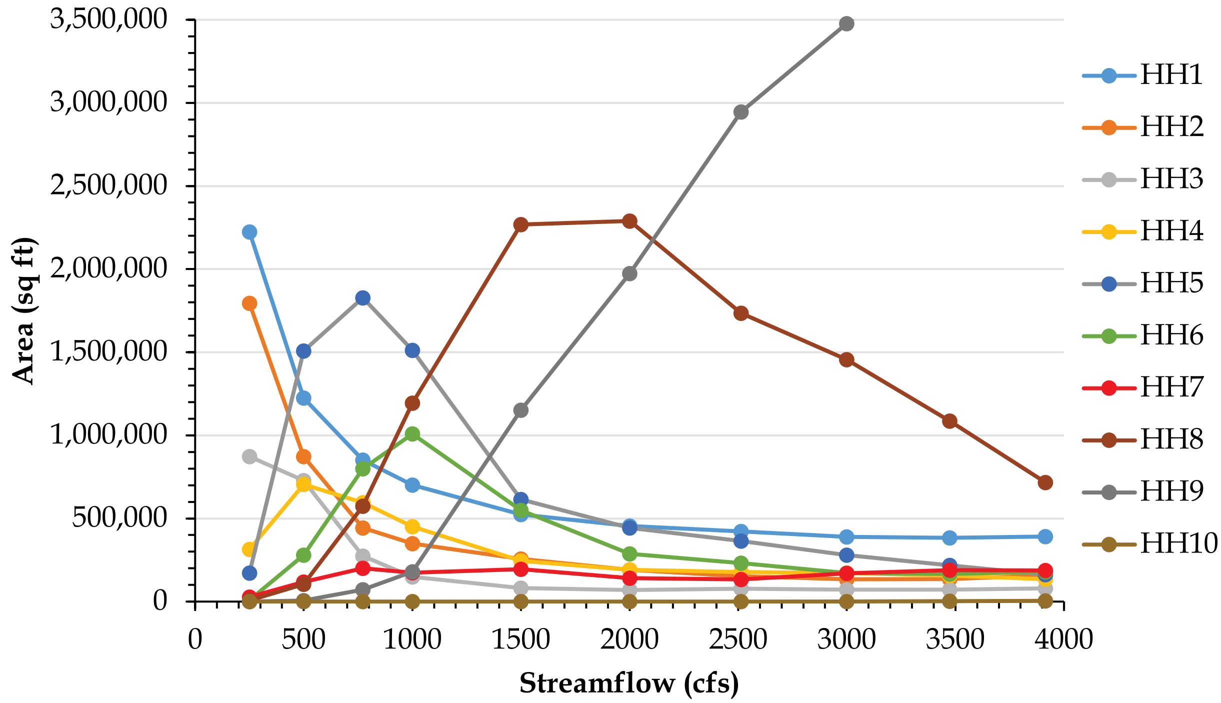


Figure B - 34. Total area of hydraulic habitat criteria versus simulated discharge at the Allens Creek study site.

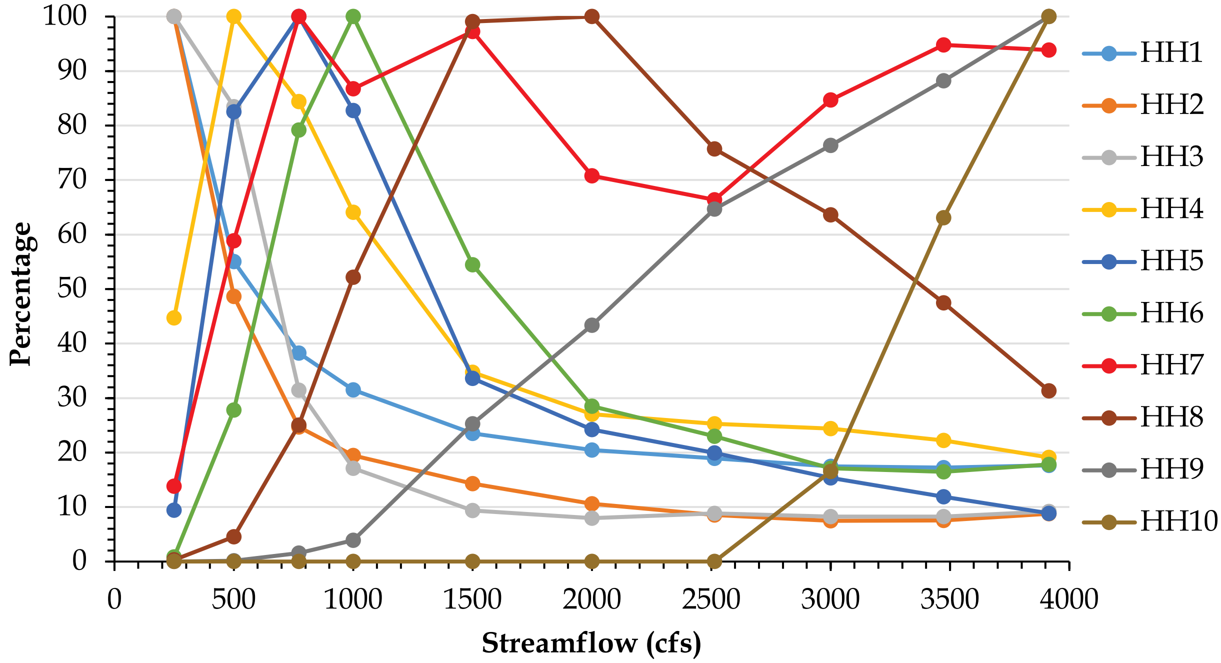


Figure B - 35. Percent maximum of HHC at the Allens Creek study site.

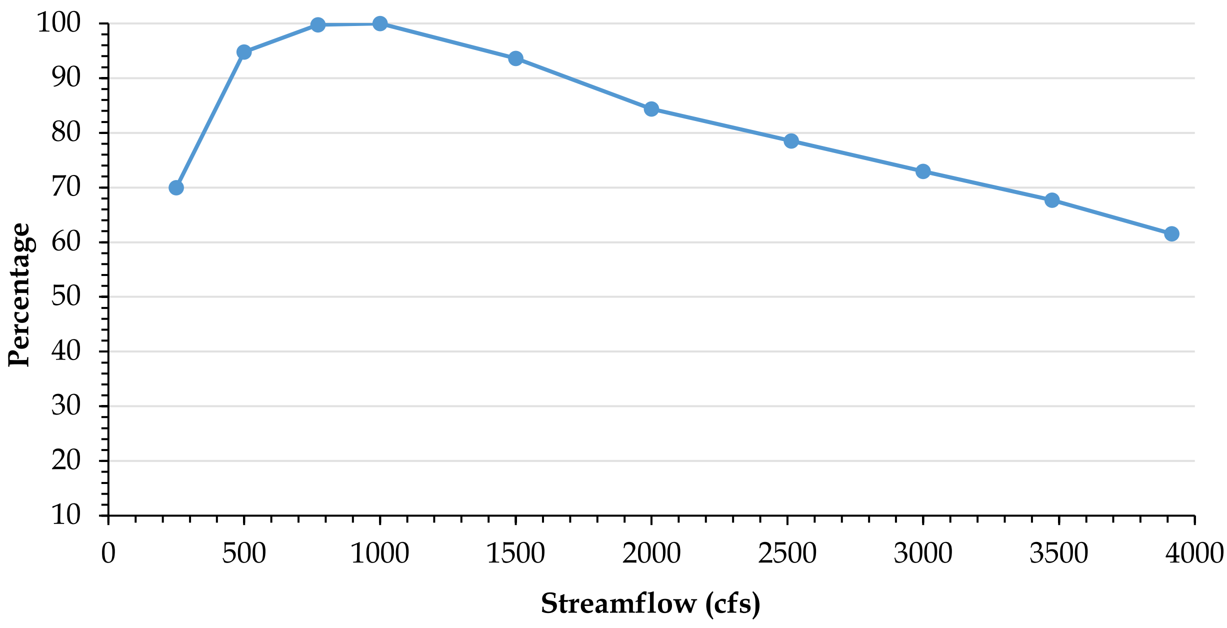


Figure B - 36. Percent maximum of Hydraulic Habitat Diversity (Shannon's H) at the Allens Creek study site.

APPENDIX C
MUSSEL SUITABILITY

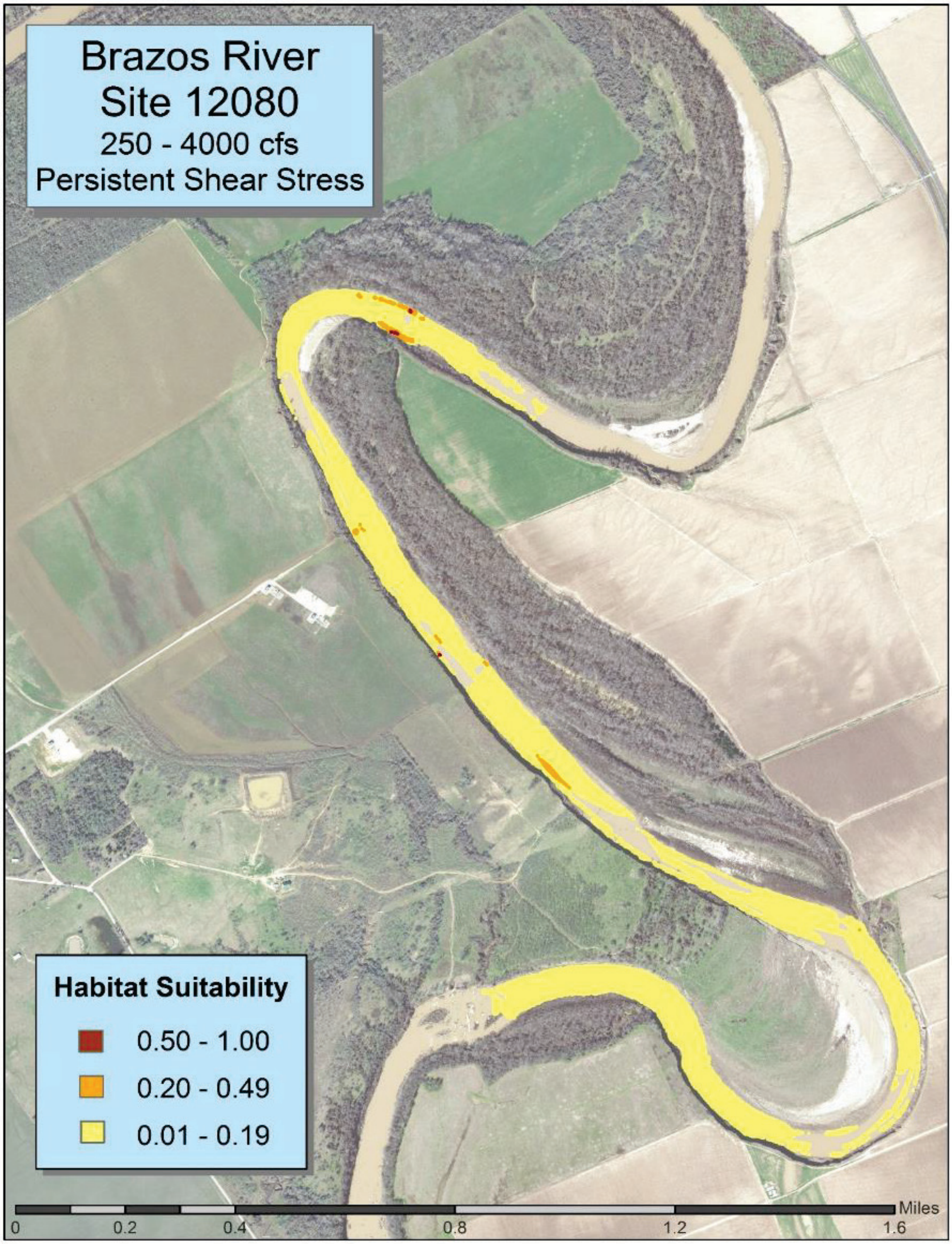


Figure C - 1. Brazos River at Hearne. Mussel habitat suitability quantified as persistent shear stress for flows ranging from 250 to 4000 cubic feet per second.

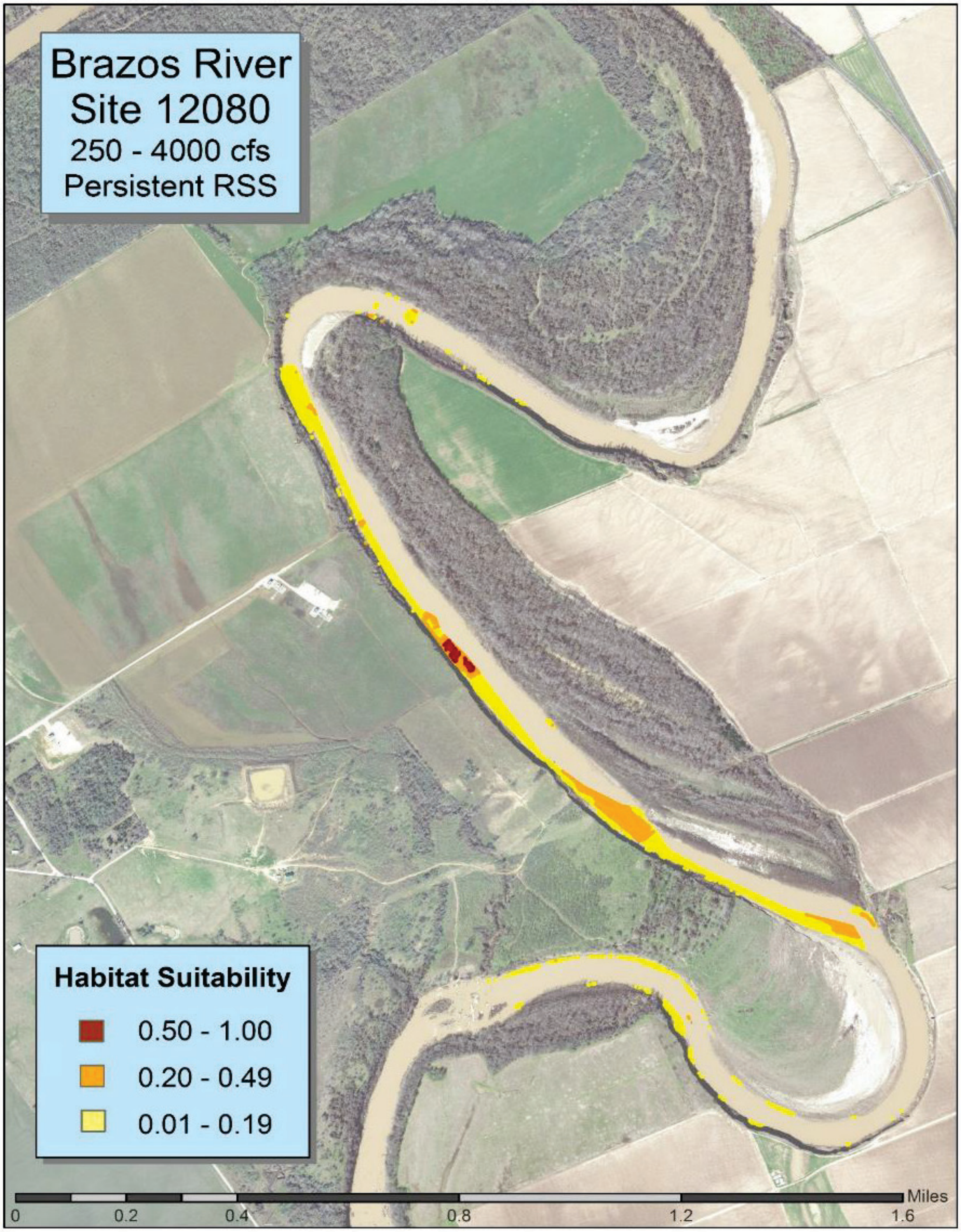


Figure C - 2. Brazos River at Hearne. Mussel habitat suitability quantified as persistent Relative Substrate Stability for flows ranging from 250 to 4000 cubic feet per second.

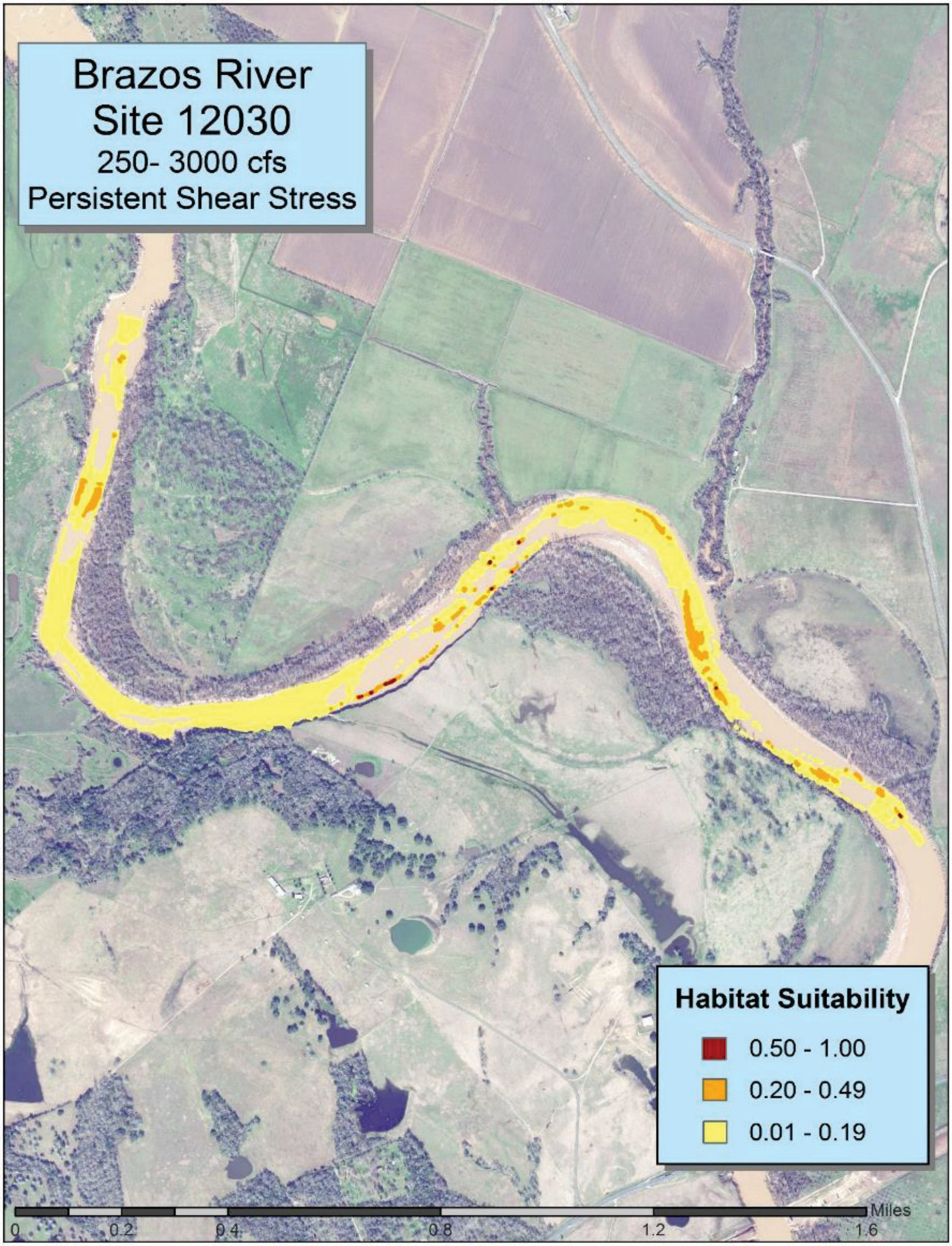


Figure C - 3. Brazos River at Navasota. Mussel habitat suitability quantified as persistent shear stress for flows ranging from 250 to 3000 cubic feet per second.

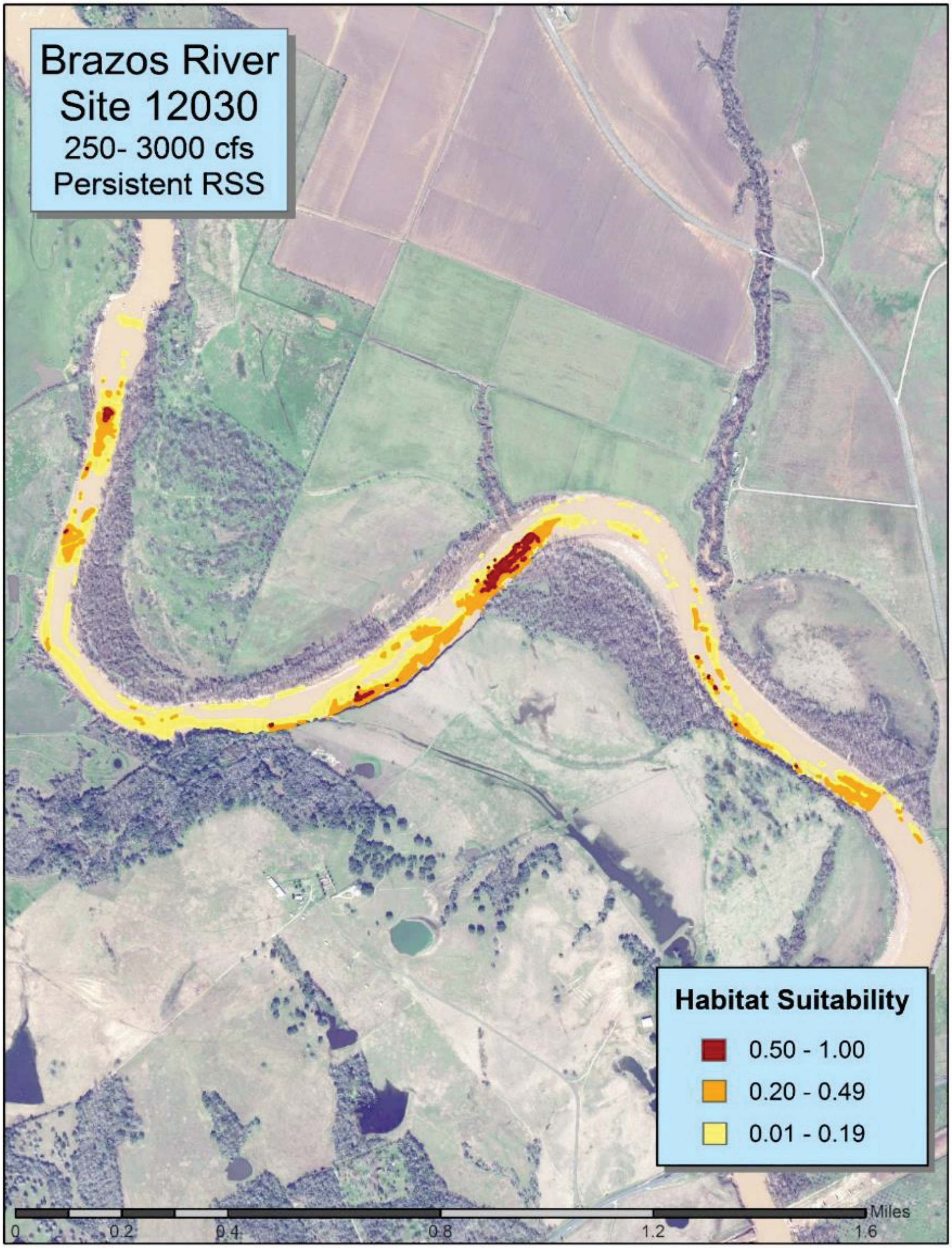


Figure C - 4. Brazos River at Navasota. Mussel habitat suitability quantified as persistent Relative Substrate Stability for flows ranging from 250 to 3000 cubic feet per second.

APPENDIX D
REPRESENTATIVE RIPARIAN SPECIES LIST
MIDDLE AND LOWER BRAZOS RIVER

Table D - 1. Riparian species by site.

Sources (scientific & common names): Ladybird Johnson Wildflower Center 2015 (primary) & USDA, NRCS 2015 (secondary)
Environment codes: A-aquatic, B-bottomland forest, R-riverbank, W-wetland
Growth Form Codes: T-tree, S-shrub, H-herb, WV-woody vine, HV-herbaceous vine
Brazos R. Site Codes: W-Wallis, S-San Felipe, N-Navasota, B-Bryan, H-Hearne, M-Marlin
Abundance Codes: A-abundant, C-common, U-uncomon, R-rare, L-likely but not seen, blank-not found
Wetland indicator status codes (USDA 2015): OBL- Obligate Wetland, FACW- Facultative Wetland, FAC- Facultative,
FACU- Facultative Upland, UPL- Obligate Upland, NA- Not Available

Code	Scientific Name	Common Name	Wetland Indicator Status	Family	Envi	Life Form	Sites Brazos R.					
							W	S	N	B	H	M
ACOS	*Acalypha ostryifolia*	pineland three-seed mercury	UPL	Euphorbiaceae	B	H		R	R			
ACNE	*Acer negundo*	box elder	FAC	Aceraceae	B,R	T	A	A	A	A	A	A
AEPA	*Aesculus pavia*	red buckeye	FACU	Hippocastanaceae	B	S						
	Agalinus sp.	slenderleaf false foxglove	FACU	Scropulariaceae	B	H					R	A
	Allium sp.	onion	NA	Alliaceae	R	H		A	A			R
	Alternanthera philoxeroides	alligator weed	OBL	Amaranthaceae	R,W,A	H	U	U	L			C
	Amaranthus sp.	pigweed	NA	Amaranthaceae	B	H		R				
AMPA	*Amaranthus palmeri*	careless weed	FACU	Amaranthaceae	R	H	U		R			R
	Ambrosia psilostachya	cuman ragweed	FAC	Asteraceae	R	H				R	R	
	Ambrosia trifida	giant ragweed	FAC	Asteraceae	B,R	H	A	C	A	A	A	A
	Ammannia coccinea	valley redstem	OBL	Lythraceae	R,W,A	H		U	L	A	C	
	Amorpha fruticosa	false indigo	FACW	Fabaceae	B	S		R		R	C	U
AMAR	*Ampelopsis arborea*	peppervine	FAC	Vitaceae	R	WV	C	A	A	A	C	U
AMCO	*Ampelopsis cordata*	heart-leaf ampelopsis	FAC	Vitaceae	B,R	WV		A	C	A	U	
	Amphiachyris dracunculoides	prarie broomweed	UPL	Asteraceae	B	H						U
	Anemone heterophylla	tenpetal thimbleweed	UPL	Ranunculaceae	B	H						R
	Apocynum cannabinum	dogbane	FACU	Apocynaceae	B,R	H		U	L	R	R	
	Argomone albiflora	white prickly-poppy	UPL	Papaverae	B,R	H			U			R
	Aster sp.	aster	NA	Asteraceae	B	H		C	A			
	Aster subulatus	hierba del marrano	OBL	Asteraceae	R,W,A	H	A		U	U	C	R
	Baccharis neglecta	poverty weed	FAC	Asteraceae	B,R	S						R
	Bacopia monnieri	coastal water-hyssop	OBL	Scrophulariaceae	R,W	H		U	L	A	C	U
	Berchemia scandens	rattan-vine	FAC	Rhamnaceae	B	WV						
	Bidens frondosa	devil's beggartick	FACW	Asteraceae	R	H		R	U	R		R
	Bignonia capreolata	crossvine	FAC	Bignonaceae	B	WV						
BOCY	*Boerhavia cylindrica*	smallspike false nettle	UPL	Urticaceae	R,W	H	C	C	L		R	
	Brunnichia ovata	American buckwheat vine	FACW	Polygonaceae	B,R	HV		U	A			
	Bumelia sideroxylon	gum bully	UPL	Sapotaceae	B	S/T					R	R
CAAM	*Callicarpa americana*	American beautyberry	FACU	Verbenaceae	B	S		R		R	U	U
CAVI	*Calyptocarpus vialis*	horseherb	FAC	Asteraceae	B	H	U	C	C			C
CARA	*Campsis radicans*	trumpet creeper	FAC	Bignoniaceae	B	WV	A	A	C	A	A	C

Species List.

Table D - 1 (cont). Riparian species by site.

Code	Scientific Name	Common Name	Wetland Indicator Status	Family	Envi	Life Form	Sites Brazos R.					
							W	S	N	B	H	M
	Capsicum annuum	bird pepper	UPL	Solanaceae	B	S		R	R			
	Cardiospermum halicacabum	common balloon vine	FAC	Sapindaceae	B	HV						R
CA sp.	*Carex sp.*	caric sedge	NA	Cyperaceae	B	H						
CAIL	*Carya illinoinensis*	pecan	FACU	Juglandaceae	B	T		A	A	C	C	R
	Carya texana	black hickory	UPL	Juglandaceae	B	T				R		
CELA	*Celtis laevigata*	hackberry	FACW	Ulmaceae	B,R	T	A	A	A	A	A	A
	Cephalanthus occidentallis	buttonbush	OBL	Rubiceae	R,W	S		R				
	Chamaecrista	partridge-pea	NA	Fabaceae	B,R	H			R			
CHLA	*Chasmanthium latifolium*	inland sea oats	FAC	Poaceae	B,R,W	H		A	A	A	A	C
CHAM	*Chenopodium ambrosioides*	epazote	FACU	Chenopodiaceae	B,R	H	C		U			C
	Chenopodium sp.	goosefoot	FACU	Chenopodiaceae	B,R	H					R	
ASSP	*Chloracantha spinosa*	spiny chloracantha	FACW	Asteraceae	B,R	H	A	C	C	A	A	A
CITE	*Cirsium texanum*	Texas thistle	UPL	Asteraceae	B	H						C
	Cissus incisa	ivy tree-bine	UPL	Vitaceae	B	WV		C				
	Clematis pitcheri	Leatherflower	FACU	Ranunculaceae	B	HV		R				
COCA	*Cocculus carolinus*	Carolina snailseed	FAC	Menispermaceae	B	WV		U	C	U	U	
COES	*Colocasia esculenta*	elephant ear, taro	FACW	Araceae	B,R	H						
	Commelina sp.	day-flower	NA	Commelinacae	B	H	U	U	U			
	Conyza canadensis	horseweed	UPL	Asteraceae	B	H	A	C	A	C	A	R
CO sp.	*Cornus sp.*	dogwood	FAC	Cornaceae	B	T	A	A	A	A	A	
CR sp.	*Crataegus sp.*	hawthorn	NA	Rosaceae	B,W	T			R			
	Croton capitatus	hogwort	UPL	Euphorbiaceae	B	H	R		R	R		U
	Croton monanthogynus	prairie tea	UPL	Euphorbiaceae	B	H	R	L	U			A
CUTE	*Cucurbita texana*	Texas gourd	UPL	Cucurbitaceae	B	HV						
	Cucumis melo	muskmelon	UPL	Cucurbitaceae	B	HV						R
	Cynanchum barbigerum	bearded swallow-wort	UPL	Asclepiadaceae	B	HV				R		
	Cynanchum laeve	honeyvine	FAC	Asclepiaceae	B,R	HV			R	C		
	Cynodon dactylon	bermuda grass	FACU	Poaceae	B	H	C	C	C	C	C	C
	Cyperus sp.	flatsedge	NA	Cyperaceae	R,W	H	C	C	C	C	C	C
	Desmanthus illinoensis	bundle-flower	FAC	Fabaceae	B	H				U		
DE sp.	*Desmodium canadense*	showy tick trefoil	FAC	Fabaceae	B,R	H	U	C	U	C	U	
	Desmodium sessilifolium	sissleleaf ticktrefoil	UPL	Fabaceae	B,R	H					R	
	Dichondra sp.	pony-foot	NA	Convolvulae	B	H		C				
	Dicliptera brachiata	branched foldwing	FACW	Acanthaceae	B,R	H	A	C				
	Diodia virginiana	Virginia buttonweed	FACW	Rubiaceae	B,R	H		U	L			

Table D - 1 (cont). Riparian species by site.

Code	Scientific Name	Common Name	Wetland Indicator Status	Family	Envi	Life Form	Sites Brazos R.					
							W	S	N	B	H	M
DITE	*Diospyros texana*	Texas persimmon	UPL	Ebenaceae	B	S/T						
	Dracopis amplexicaulis	clasping-leaf coneflower	FAC	Asteraceae	B	H		L				
	Eclipta prostrata	pie-plant	FACW	Asteraceae	B,R	H		L	L	C	C	
EHAN	*Ehretia anacua*	sandpaper tree	UPL	Boraginaceae	B	T						
	Elephantopus carolinianus	Carolina elephantsfoot	FACU	Asteraceae	B	H	C	U				
ELVI	*Elymus virginicus*	Virginia wild rye	FAC	Poaceae	B	H		A	A	U		C
	Equisetum hyemale	Scouringrush horsetail	FACW	Equisetaceae	R,W,A	H	U					
	Equisetum laevigatum	smooth horsetail	FAC	Equisetaceae	R,W,A	H		U				
	Eryngium hookeri	Hooker's eryngo	FACW	Apiaceae	R	H				R		
	Conoclinium coelestinum	blue-mist flower	FAC	Asteraceae	B	H		R	L	R	R	
	Eupatorium incarnatum	pink boneset	FACU	Asteraceae	B	H	A				C	
EUSE	*Eupatorium serotinum*	lateflowering boneset	FAC	Asteraceae	B	H	C	C	C	A	C	
EUDE	*Euphorbia dentata*	toothed spurge	UPL	Euphorbiaceae	R	H			R			R
EUOS	*Euphorbia sp.*	mot spurge	NA	Euphorbiaceae	R	H						R
FLIN	*Fleischmannia incarnata*	pink thoroughwort	FACU	Asteraceae	B	H					A	
FOAC	*Forestiera acuminata*	eastern swamp-privet	OBL	Oleaceae	R,W,A	S		R	U	R	R	U
FRPE	*Fraxinus pennsylvanica*	green ash	FACW	Oleaceae	B,R	T	U	A	A	A	A	
	Funastrum cyanochoides	vine milkweed	FACU	Apocynaceae	B	HV						U
	Gaura parviflora	velvetweed	UPL	Onagra	B	H				R		
GLTR	*Gleditsia triacanthos*	honey locust	FAC	Fabaceae	B	T		R		R	U	R
	Grindelia sp.	gumweed	NA	Asteraceae	R	H				R		
	Helianthus annus	common sunflower	FAC	Asteraceae	B,R	H		R	U	C	R	
	Heliotropum indicum	turnsole	FAC	Boraginaceae	B,R	H		R	R		R	
	Heterantheca subaxillaris	camphorweed	UPL	Asteraceae	B	H			U	C	U	C
	Heteranthera dubia	grassleaf mudplantain	OBL	Pontederiaceae	R,W,A	H				R		
	Hibiscus laevis	halberdleaf rosemallow	OBL	Malvaceae	R,W	H		U				
	Hydrocotyle sp.	pennywort	NA	Umbelliferae	R	H		R				C
HYVE	*Hydrocotyle verticillata*	whorled marshpennywort	OBL	Umbelliferae	R	H		C	L			
ILDE	*Ilex decidua*	deciduous holly	FACW	Aquifoliaceae	B	T	A			U	U	A
ILVO	*Ilex vomitoria*	yaupon holly	FAC	Aquifoliaceae	B	T	R	A	A		U	
	Ipomoea sp.	morning-glory	NA	Convolulaceae	B,R	HV		C		R		
	Ipomoea cordatotriloba	tievine	FACU	Convolulaceae	B,R	HV						U
	Ipomoea wrightii	Wright morning-glory	FACW	Convolulaceae	B,R	HV		R	R			
IVAN	*Iva annua*	annual marshelder	FAC	Asteraceae	R	H		C	C	A	C	U
	Juniperus virginiana	eastern red cedar	FACU	Cupressaceae	B	T			U		C	
	Lactuca floridana	woodland lettuce	FACU	Asteraceae	B	H		U				

Table D - 1 (cont). Riparian species by site.

Code	Scientific Name	Common Name	Wetland Indicator Status	Family	Envi	Life Form	Sites Brazos R.					
							W	S	N	B	H	M
LEMU	*Leucospora multifida*	narrowleaf paleseed	OBL	Scrophulariaceae	R,W	H	C	U	C	A	A	
	Ligustrum sinenese	Chinese ligustrum	FAC	Oleaceae	B,R	S/T	R	U		U		
	Lindernia dubia	yellowseed false pimpernel	OBL	Scrophulariaceae	R,W	H	R		R			
	Lonicera japonica	common garden honeysuckle	FACU	Caprifoliae	B	WV		A				
	Ludwigia decurrens	wingleaf primrose-willow	OBL	Onagraceae	R,W	H				R		
	Ludwigia octovalvis	Mexican primrose-willow	OBL	Onagraceae	R,W	H	R					
	Ludwigia peploides	water-primrose	OBL	Onagraceae	R,W,A	H	C			R	R	
	Lythrum californicum	California loosestrife	OBL	Lythraceae	W	H				R		
MAUN	*Macfadyena unguis-cati*	cat-claw vine	UPL	Bignoniaceae	B	HV						
MAPO	*Maclura pomifera*	osage orange	FACU	Moraceae	B	T		U	C	R	U	
	Malachra capitata	malva de caballo	UPL	Malvaceae	B	H	R					
	Malvastrum coromandelianum	threelobe false mallow	FACU	Malvaceae	B,R	H	C					
MAAR-I	*Malvaviscus arboreus* var. *drummondii*	Turk's cap	UPL	Malvaceae	B	H		U	U			
	Marsilea macropoda	bigfoot water clover	OBL	Marsileaceae	R,W	H				R		
	Marsilea vestita	hairy water clover	OBL	Marsileaceae	R,W,A	H	U	R	L	R		
	Matelea sp.	milk-vine	NA	Ascleferaceae	B	HV					R	
GOGO	*Matelea gonocarpos*	angularfruit milkvine	FACW	Asclepiaceae	B,R	HV	U	R	R			
MEAZ	*Melia azedarach*	Chinaberry	UPL	Meliaceae	B	T		R	U	R	C	C
MEPE	*Melothria pendula*	speckled gourd	FAC	Cucurbitaceae	B,R	H	U	C	A	C	R	
	Mikania scandens	climbing hempweed	FACW	Asteraceae	B	HV	A	R	R	U		
	Mimosa latidens	Kairn's sensitive-briar	UPL	Fabaceae	B,R	H				R		
	Mimosa strigillosa	powderpuff	FAC	Fabaceae	B,R	H		U	L	U		
	Monarda sp.	bee-balm	NA	Lam	B	H			U			R
MOAB	*Morus alba*	white mulberry	FACU	Moraceae	B,R	T				R		
MORU	*Morus rubra*	red mulberry	FACU	Moraceae	B,R	T			U	R	C	C
	Myrica cerifera	wax myrtle	FAC	Myricaceae	B	S/T		R				
	Nicotiana glauca	tree-tobacco	FAC	Solanaceae	B	H			R			
	Nicotiana repanda	fiddle-leaf	FAC	Solanaceae	B	H						
OPHI	*Oplismenus hirtellus*	basketgrass	FAC	Poaceae	B,W	H		C				
OXDI	*Oxalis dillenii*	slender yellow woodsorrel	FACU	Oxalidaceae	B	H	C	U	U			C
PAPE	*Parietaria pensylvanica*	Pennsylvania cucumber plant	FACU	Urticaceae	B	H						
	Parkinsonia aculeata	retama	FAC	Fabaceae	B,R	T						
PAHY	*Parthenium hysterophorus*	false ragweed	FAC	Asteraceae	R	H		L	U			C
PAQU	*Parthenocissus quinquefolia*	Virginia creeper	FACU	Vitaceae	B	V	C	A	A	A	A	U

Table D - 1 (cont). Riparian species by site.

Code	Scientific Name	Common Name	Wetland Indicator Status	Family	Envi	Life Form	Sites Brazos R.					
							W	S	N	B	H	M
PA sp.	*Paspalum langei*	rustyseed paspalum	UPL	Poaceae	B	H						
	Passiflora incarnata	purple passionflower	UPL	Pasifloraceae	B,R	HV			L	R	C	
	Phoradendron tomentosum	mistletoe	UPL	Viscacea	B	H			C			
	Phyla incisa	Texas frogfruit	FAC	Verbenaceae	B,R,W	H						R
PHLA	*Phyla lanceolata*	lanceleaf frogfruit	OBL	Verbenaceae	R,W	H		A	R			
PH sp.	*Physalis sp.*	yellow ground cherry	NA	Solanaceae	B	H		R	R	R	R	U
PHAM	*Phytolacca americana*	pigeonberry	FACU	Phytolaccaceae	B	H		U	A		U	
	Plantago rhodosperma	redseed plantain	UPL	Plantanaceae	B,R	H						C
PLOC	*Platanus occidentalis*	sycamore	FACW	Plantanaceae	B,R	T	A	A	C	R	R	U
	Pluchea sp.	stinkweed	NA	Asteraceae	R,W	H	U			R		R
	Polygonum ramosissimum	bushy knotweed	FACU	Polygonaceae	B	H/S		R	R	R	R	
	Polygonum lapathifolium	Pennsylvania smartweed	FACW	Polygonaceae	R,W	H		C	A			
PO sp.	*Polygonum sp.*	smartweed	NA	Polygonaceae	R,W	H	C	C	C	C	C	C
POTI	*Poncirus trifoliata*	trifoliate orange	UPL	Rutaceae	B,W	S						
	Populus deltoides	eastern cottonwood	FAC	Salicaceae	B,R	T	A	A	A	A	A	A
	Portulaca olerocea	common purslane	FACU	Portlulacaceae	B	H			R			
PRGL	*Prosopis glandulosa*	honey mesquite	UPL	Fabaceae	B,R	T				R		R
PTTR	*Ptelea trifoliata*	wafer ash	FACU	Rutaceae	B	S/T				R		
QUMA	*Quercus macrocarpa*	overcup oak	FACU	Fagaceae	B	T						
	Quercus virginiana	coastal live oak	FACU	Fagaceae	B	T			R			
	Ranunculus sceleratus	cursed buttercup	OBL	Ranunculaceae	R,W	H				R	C	
RARU	*Rapistrum rugosum*	bastard cabbage	UPL	Brassicaceae	B	H	U		R		R	C
	Ratibida columnifera	mexican hat	UPL	Asteraceae	B	H						R
	Rhynchosia minima	least snoutbean	UPL	Fabaceae	B	HV	C	U	U			
RICO	*Ricinus communis*	castor bean	FACU	Euphorbiaceae	B,R,W	H						
RIHU	*Rivina humilis*	pigeonberry	UPL	Phytolaccaceae	B,R	H	U	U	U	R	U	
	Rorippa palustris	bog yellowcress	OBL	Brassicaceae	R,W	H		R	L			
ROBR	*Rosa bracteata*	Macartney rose	UPL	Rosaceae	B,W	S						
RUTR	*Rubus trivialis*	dewberry	FACU	Rosaceae	B	S	A	A	A	A	A	A
	Rudbeckia hirta	back-eyed Susan	FACU	Asteraceae	B	H		R	R			
RU sp.	*Ruellia humilis*	fringeleaf wild petunia	FACU	Acanthaceae	B	H						
	Ruellia strepens	limestone ruellia	FAC	Acanthaceae	B	H			C			
	Sabal minor	palmetto	FACW	Araceae	B,R	S						
	Sabal texana	Texas palm	UPL	Araceae	B,R	T						
	Sagittaria graminea	grassy arrowhead	OBL	Alismataceae	R,W	H		U				
	Sagittaria platyphylla	delta arrowhead	OBL	Alismataceae	R,W	H		U		R		U

Table D - 1 (cont). Riparian species by site.

Code	Scientific Name	Common Name	Wetland Indicator Status	Family	Envi	Life Form	Sites Brazos R.					
							W	S	N	B	H	M
SAIN	*Salix interior*	sand-bar willow	OBL	Salicaceae	B,R,W	T				A		
SANI	*Salix nigra*	black willow	OBL	Salicaceae	R,W,A	T	A	A	A	A	A	U
SACO	*Salvia coccinea*	scarlet sage	UPL	Lamiaceae	B	H						
	Salvia roemeriana	cedar sage	UPL	Lamiaceae	B	H						U
	Sambucus nigra var. canadensis	common elderberry	UPL	Caprifoliaceae	X	X	A	C	A	A		U
	Samolus parviflorus	thin-leaf brookweed	OBL	Primulaceae	R,W,A	H		R			U	
	Sanicula canadensis	Canadian blacksnakeroot	FACU	Apiaciae	B	H		C	A	C		
SASA	*Sapindus saponaria*	Wingleaf soapberry	FACU	Sapindaceae	B	T	A		A	A	A	A
SASE	*Sapium sebiferum*	Chinese tallow	FAC	Euphorbiaceae	B,R	T		R				
	Saururus cernuus	lizard's tail	OBL	Saururaceae	R,W	H		R				
	Sesbania drummondii	rattlebox	FACW	Fabaceae	R,W	H	U			R		R
	Sesbania herbacea	bigpod sesbania	NA	Fabaceae	R,W	H	U			R	A	U
	Sesbania vesicaria	bagpod	FAC	Fabaceae	R,W	H				R		U
SILA	*Sideroxylon lanuginosum*	gum bumelia	FACU	Sapotaceae	B	T	R	U		C	C	U
	Smilax bona-nox	saw greenbrier	FAC	Smilacaceae	B,R	WV	A		C	A	A	
	Smilax tamnoides	bristly greenbrier	FAC	Smilacaceae	B,R	WV	U	U	U	R	U	R
	Solanum americanum	American black nightshade	FACU	Solanaceae	B,R	H			U			
	Solanum dimidiatum	western horsenettle	UPL	Solanaceae	B,R	H						R
SOEL	*Solanum elaeagnifolium*	silverleaf nightshade	UPL	Solanaceae	B,R	H						
SOAL	*Solidago altissima*	Canadian goldenrod	FACU	Asteraceae	B	H	A			C	C	A
	Spermacoce glabra	smooth buttonweed	FACW	Rubiaceae	B,R	H		C				
SPTE	*Spigelia texana*	Texas pinkroot	UPL	Loganiaceae	B	H						
	Sphenoclea zeylanica	chickenspike	FACW	Sphenocleaceae	B,R	H				R	R	
STHE	*Strophostyles helvola*	amberique-bean	FAC	Fabaceae	B	H	R	R		A	C	R
SOAF	*Styphnolobium affine*	eve's necklace	UPL	Fabaceae	B	S/T						U
	Symphoricarpos orbiculatus	coralberry	FACU	Oleaceae	B	S	U				C	U
	Symphyotrichum lanceolatum	white panicle aster	FACW	Asteraceae	B,R	H					R	C
	Tamarix sp.	tamarisk	NA	Tamaricaceae	R	S/T						U
TADI	*Taxodium distichum*	bald cypress	OBL	Cupressaceae	R,W,A	T						
TECA	*Teucrium canadense*	Canada germander	FACW	Lamiaceae	B,R	H		A	A		C	U
TECU	*Teucrium cubense*	coast germander	UPL	Lamiaceae	B	H		R	R			
	Tillandsia recurvata	ball moss	UPL	Bromeliaceae	B	H		A				
	Tillandsia usenoides	Spanish moss	FAC	Bromeliaceae	B	H		A				
	Torilis arvensis	hedge parsely	UPL	Apiaciae	B	H	C	A	A	C		A
	Toxicodendron radicans	poison ivy	FAC	Anacardiaceae	B,R	S/V	A	A	A	A	A	C
	Tragia sp.	noseburn	NA	Euphorbiaceae	B	H			U			

Table D - 1 (cont). Riparian species by site.

Code	Scientific Name	Common Name	Wetland Indicator Status	Family	Envi	Life Form	Sites Brazos R.					
							W	S	N	B	H	M
	Typha sp.	cat-tail	NA	Typhaceae	R,W,A	H						
	Ulmus americana	American elm	FAC	Ulmaceae	B	T				R	A	U
ULCR	*Ulmus crassifolia*	cedar elm	FAC	Ulmaceae	B	T				R	A	U
ULRU	*Ulmus rubra*	slippery elm	FAC	Ulmaceae	B	T		A	A		A	C
UNSP	*Ungnadia speciosa*	Mexican buckeye	UPL	Sapindaceae	B,R	T						
	Verbena halei	Texas verain	UPL	Verbenaceae	B	H	U			U	R	C
	Verbena urticifolia	White vervain	FAC	Verbenaceae	B	H		U	C			
	Verbena xutha	gulf vervain	UPL	Verbenaceae	B	H	U	L	R			
VEEN	*Verbesina encelioides*	cowpen daisy	FAC	Asteraceae	B,W	H	R		R			
VEVI	*Verbesina virginica*	frostweed	FACU	Asteraceae	B,W	H		C	U	C	C	
	Vernonia baldwinii	Baldwin's ironweed	UPL	Asteraceae	B	H			R			
	Viburnum rufidulum	rusty blackhaw	UPL	Caprifoliaceae	B,R	S/T	R				R	
VI sp	*Viola sp.*	violet	NA	Violaceae	B	H	R					
	Vitex agnus-castus	Lavender Chaste Tree	UPL	Verbenaceae	B	S/T					R	
	Vitis aestivalis	long grape	FACU	Vitaceae	B, R	WV		A	A		A	
	Vitis cinerea	winter grape	FAC	Vitaceae	B, R	WV	C	A	A	A	A	
VIMU	*Vitis mustangensis*	mustang grape	UPL	Vitaceae	B, R	WV	U	A	A	A	A	
	Vitis vulpina	frost grape	FAC	Vitaceae	B, R	WV					R	
XAST	*Xanthium strumarium*	rough cocklebur	FAC	Asteraceae	B, R	H	A	C	C	A	A	
	Zanthoxylum clava-herculis	Hercules' club	FAC	Rutaceae	B	T						R
	Zanthoxylum hirsutum	Toothache tree	UPL	Rutaceae	B	S		U	R			
	Zizaniopsis miliacea	giant cutgrass	OBL	Poaceae	R,W,A	H						U

APPENDIX E
RIPARIAN TRANSECT PLOTS AND INDICATOR SPECIES SPECIFIC ANALYSES

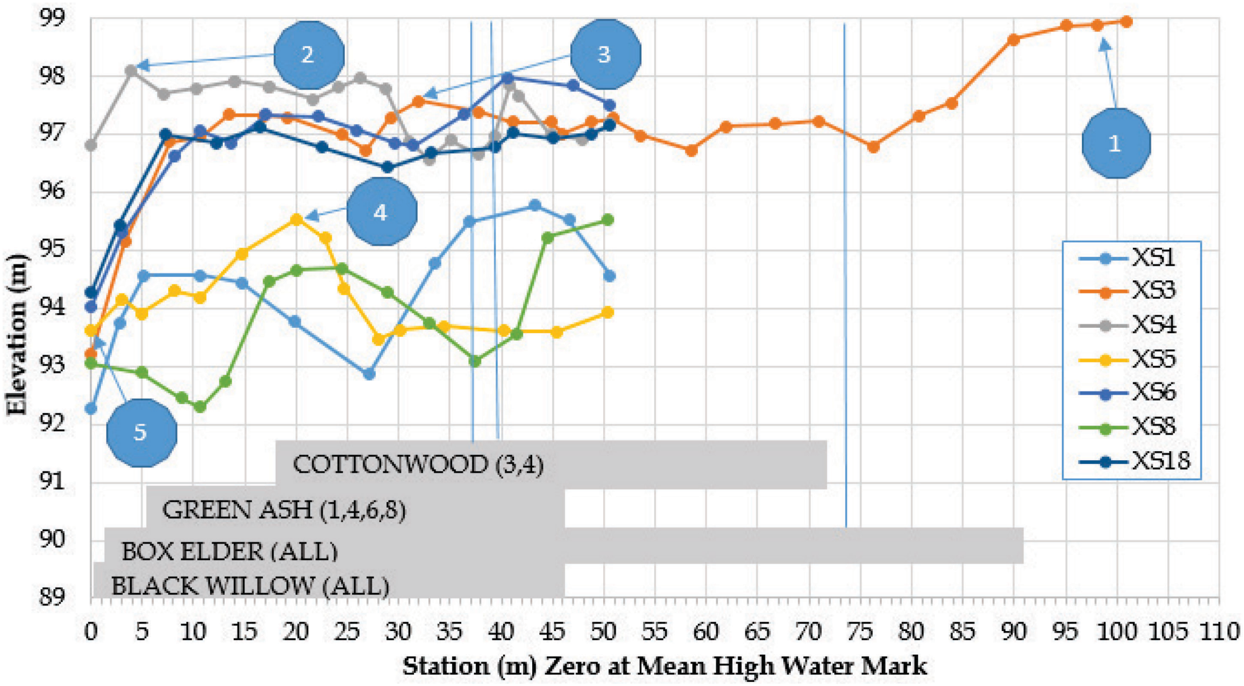


Figure E - 1. Riparian transect profiles at the Marlin riparian study site. (1) Elevation of 98.9 meters to inundate maximum extent of box elder. (2) Elevation 98.1 meters to inundate 80% extent of green ash on Transect 4. (3) Elevation of 97.6 meters to inundate 80% extent of cottonwood (Transect 3), box elder, black willow, and green ash. (4) Elevation of 95.5 meters to inundate 80% black willow on lower transects. (5) Elevation of 93.6 meters, estimate of average mean high water mark, needed for routine channel maintenance.

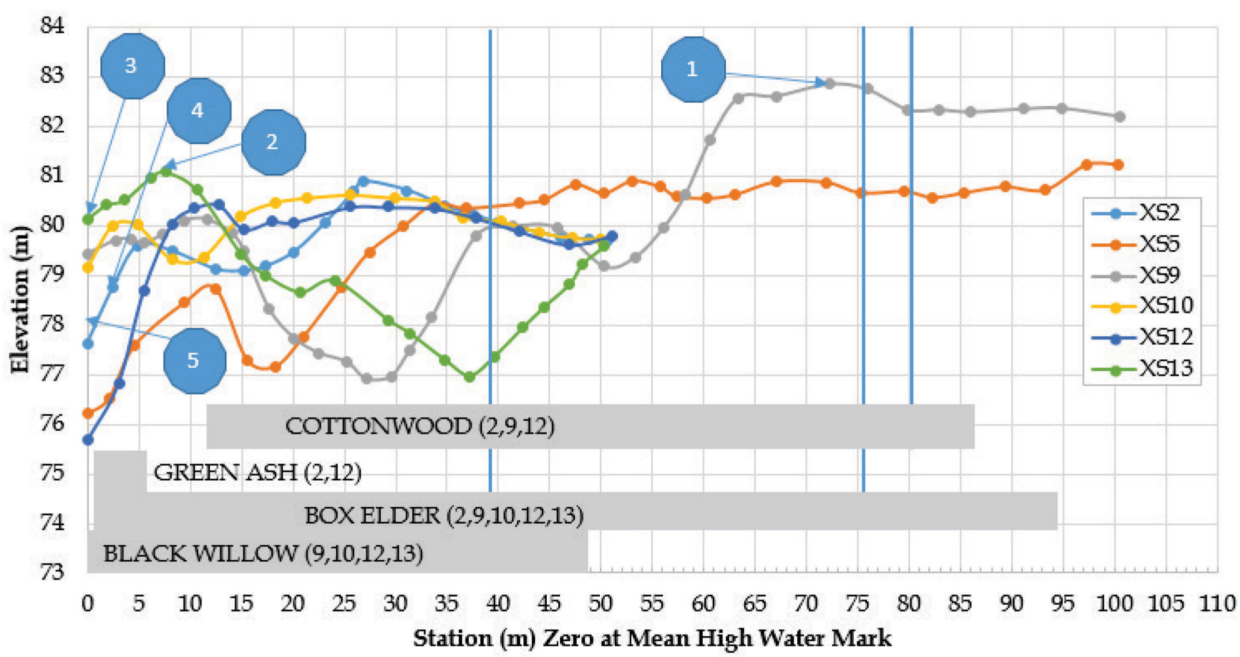


Figure E - 2. Riparian transect profiles at the Hearne riparian study site. (1) Elevation of 82.85 meters to inundate 80% extent of box elder and cottonwood (Transect 9). (2) Elevation 81.1 meters to inundate 80% extent of black willow on Transect 13. (3) Elevation of 80. 12 meters maximum extent of black willow recruitment. (4) Elevation of 78.74 meters to inundate minimum extent of green ash. (5) Elevation of 78.2 meters, estimate of average mean high water mark, for routine channel maintenance and black willow recruitment.

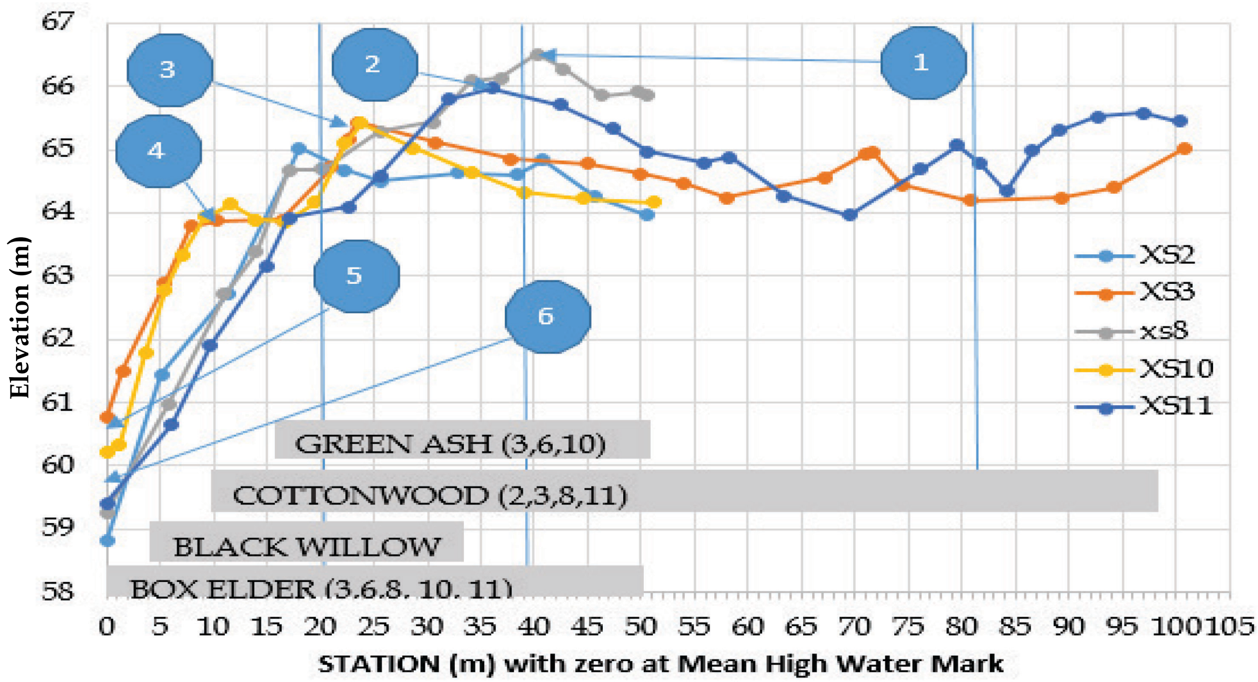


Figure E - 3. Riparian transect profiles at the Bryan riparian study site. (1) Elevation of 66.5 meters to inundate 80% extent of box elder (Transect 8). (2) Elevation 66 meters to inundate maximum extent of cottonwood. (3) Elevation of 65.5 meters to inundate 80% extent of black willow. (4) Elevation of 64 meters to inundate lower terraces for green ash, black willow, box elder, and cottonwood. (5) Elevation of 60.75 meters to inundate maximum extent of black willow recruitment. (6) Elevation of 60 meters, estimate of average mean high water mark, for routine channel maintenance and black willow recruitment.

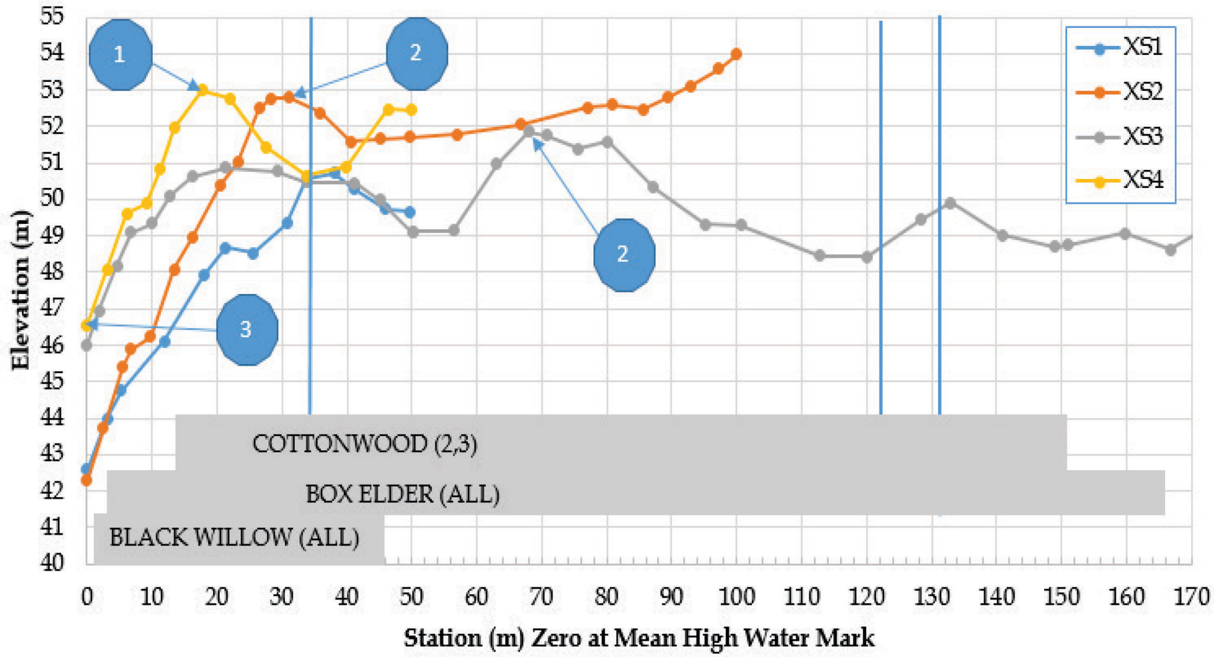


Figure E - 4. Riparian transect profiles at the Navasota riparian study site. (1) Elevation of 53 meters to inundate 80% extent of box elder and black willow. (2) Elevation 52.8 meters to inundate 80% extent of cottonwood on Transect 2. (3) Elevation of 46.5 meters to inundate maximum extent of black willow recruitment. (4) Elevation of 44.4 meters, estimate of average mean high water mark, needed for routine channel maintenance.

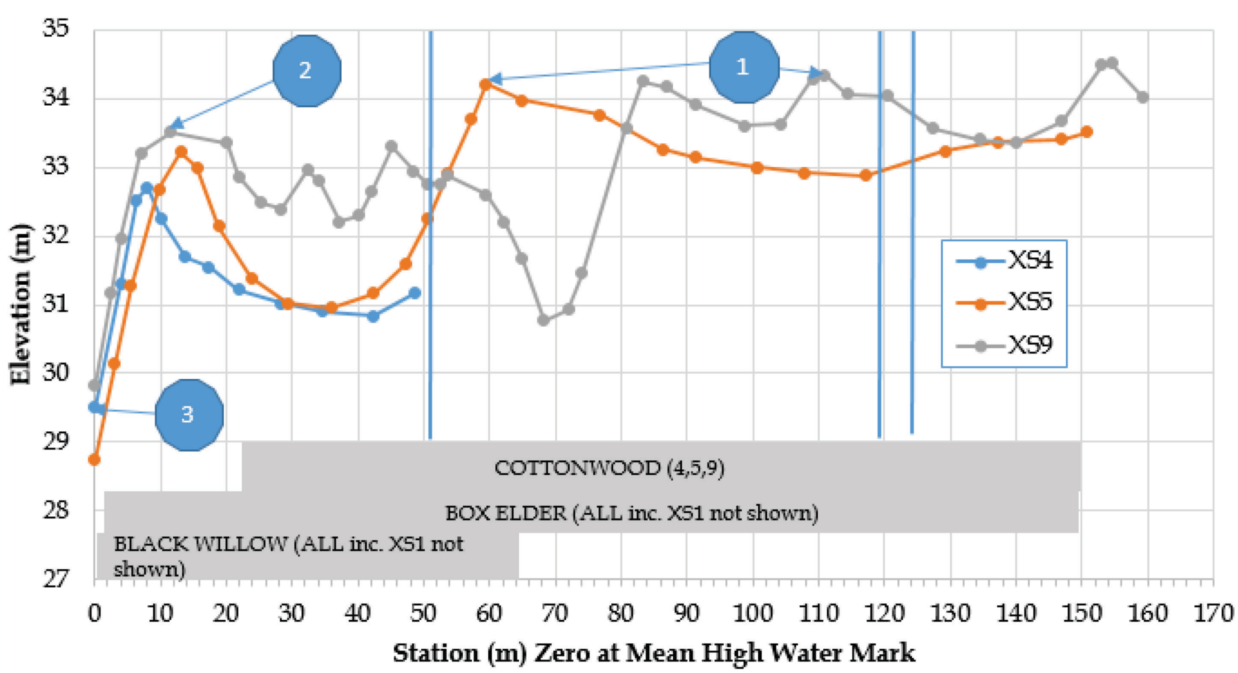


Figure E - 5. Riparian transect profiles at the San Felipe riparian study site. (1) Elevations of 34.35 and 34.21 meters to inundate 80% extent of box elder and cottonwood (Transects 5 and 9). (2) Elevation 33.5 meters to inundate 80% extent of black willow on Transect 9.

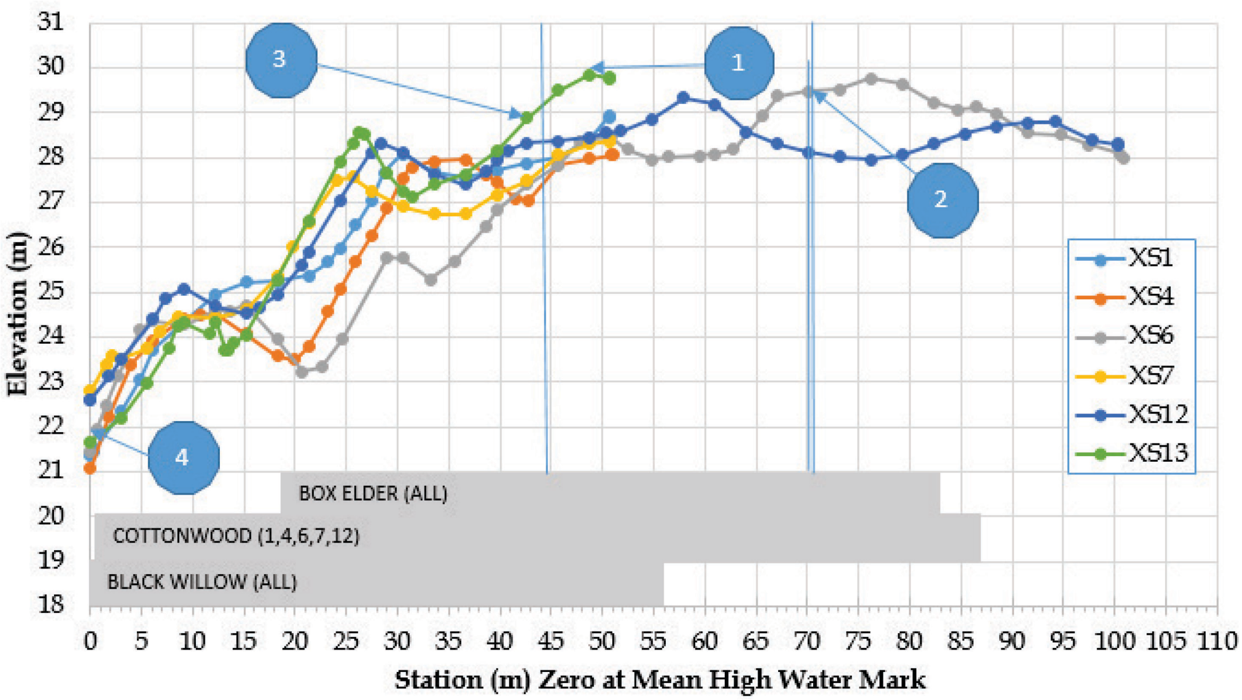


Figure E - 6. Riparian transect profiles at the Wallis riparian site. (1) Elevation of 29.8 meters to inundate 80% extent of box elder. (2) Elevation 29.47 meters to inundate 80% extent of cottonwood. (3) Elevation of 28.88 meters to inundate 80% extent black willow. (4) Elevation of 22 meters, estimate of average mean high water mark, needed for routine channel maintenance.

APPENDIX F
SEDIMENT TRANSPORT ANALYSIS

Introduction

The channel shape (geometry or bathymetry) of an alluvial river adjusts in response to the range of flows that mobilize the boundary sediments. It has been observed that in many rivers, a single representative discharge from the range of flows that have occurred historically can be used to determine a stable channel shape. A stable channel shape is important because it maintains habitat conditions that support biological resources both within the channel and in near channel riparian areas. Flow recommendations will only be successful if they support the long-term creation and maintenance of desired aquatic and riparian habitats. Changes in the flow regime of a stable channel can cause unstable conditions due to changes in the rate of:

- Erosion,
- Sediment transport, and/or
- Sediment deposition.

While these processes are at work in any river and channel shape is always adjusting somewhat, a stable channel exhibits what river engineers call "dynamic equilibrium." Once dynamic equilibrium is disrupted, the channel will be unstable while these processes work to reestablish equilibrium by changing the channel geometry (width, depth), width-depth ratio, sinuosity, and slope (Schumm 1969). Such changes in channel geometry have the potential to alter the amount and nature of aquatic and riparian habitats and, therefore, biological communities.

There is some scientific literature regarding the flows required to maintain the physical characteristics/habitats of river systems. Biedenharn *et al.* (2000) report that channels should remain dynamically stable if the sediment transport capacity of a reach is within 10 percent of the sediment supplied to the reach. Acreman *et al.* (2010) report that environmental standards adopted in the United Kingdom were developed with consideration of biology (macro-invertebrates, fish, and macrophytes) and geomorphology. Those standards allow diversion of from 7.5 to 30 percent, depending on geomorphology, flow conditions, and desired ecological status. In addition, at least some of the reported impacts on biologic communities due to flow alterations are probably due to changes in river geomorphology (and therefore habitat). Poff and Zimmerman (2010) found that a 50% change or greater in flow magnitudes (including peak, total or mean, base or hourly discharge) had a negative impact on fish communities. They could not precisely identify the level of flow alteration when fish were likely to be impacted, however, because of limited data related to systems with flow alterations in the range of 0 to 50%. Carlisle *et al.* (2010) found that a 60% decrease in the mean annual maximum flow was likely to lead to degraded fish communities. In most systems, mean annual maximum flows significantly affect the channel's shape or morphology. The impact on fish communities related to changes in mean annual maximum flow may be directly related to changes in habitat, though disruptions to spawning cues, access to floodplain habitats, or other factors may also play a role.

When significant changes to a river's flow regime are proposed, a geomorphic analysis should be conducted to determine if the proposed regime can be expected to maintain the current channel shape. The need for performing such a geomorphic analysis is discussed in the SAC guidance document "Fluvial Sediment Transport as an Overlay to Instream Flow Recommendations for the Environmental Flows Allocation Process" (SAC 2009). The foundation of the SAC guidance is the use of effective discharge to estimate if a future hydrologic regime is capable of maintaining the existing channel shape. The effective discharge is the (relatively narrow) range of flows from the entire range of flows associated with some hydrologic condition that transport the most sediment over time. Effective discharge incorporates the principles prescribed by Wolman and Miller (1960) that channel-forming discharge is a function of both the magnitude of an event and its frequency of occurrence. In addition to the analysis outlined in SAC (2009), the effects of the proposed Environmental Flow Regimes were analyzed using the sediment module of the U.S. Army Corps of Engineers Hydrologic Engineering Center River Analysis System computer program (HEC-RAS) version 5.0.3 (USACE 2016a). The sediment module of HEC-RAS allows analysis of how proposed environmental flow regimes would affect channel bathymetry and hydraulic properties such as wetted perimeter, depth, width, area, and bottom slope.

Special Consideration for Sediment Transport Analysis

As discussed in the physical process and connectivity sections of this report, the Brazos River downstream of Waco is an actively degrading/incising channel. One characteristic of a degrading channel is changes in the stage-discharge relationships at USGS gaging stations along the length of the river. Figure F-1 shows changes in the stage-discharge relationship at the USGS gage at Richmond. This figure shows that flows of 10,000 cfs would have occurred at a stage of 52.5 feet NGVD in the early 1940's, but occur at a stage of about 45 feet NGVD today.

Channel incision has the potential to result in the loss of productive agricultural land and valuable infrastructure such as bridges, pipelines and other structures that are near or cross the river. Incising channels are known to follow a pattern of development that may take many years, from an originally stable condition (relatively constant geometry) to an unstable, actively incising condition, and ultimately to a final stable (but with different geometry from the original) condition. Simon (1989) developed a six stage Channel Evolution Model. The six stages, also shown in Figure F-2, are as follows:

Stage I: The waterway is a stable, undisturbed natural channel.

Stage II: The channel is disturbed by some drastic change such as forest clearing, urbanization, dam construction, or channel dredging.

Stage III: Instability sets in with scouring of the bed.

Stage IV: Destructive bank erosion and channel widening occur by collapse of bank sections.

Stage V: The banks continue to cave into the stream, widening the channel. The stream also begins to aggrade, or fill in, with sediment from eroding channel sections upstream.

Stage VI: Aggradation continues to fill the channel, re-equilibrium occurs, and bank erosion ceases. Riparian vegetation once again becomes established.

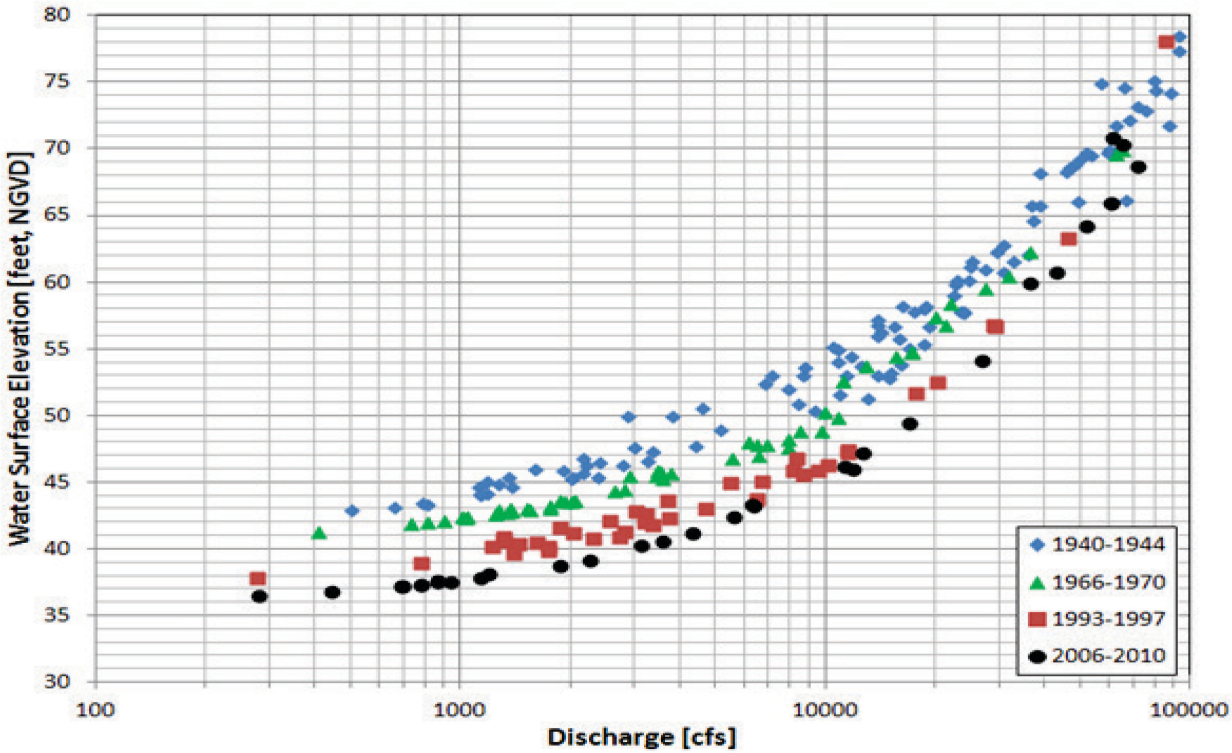
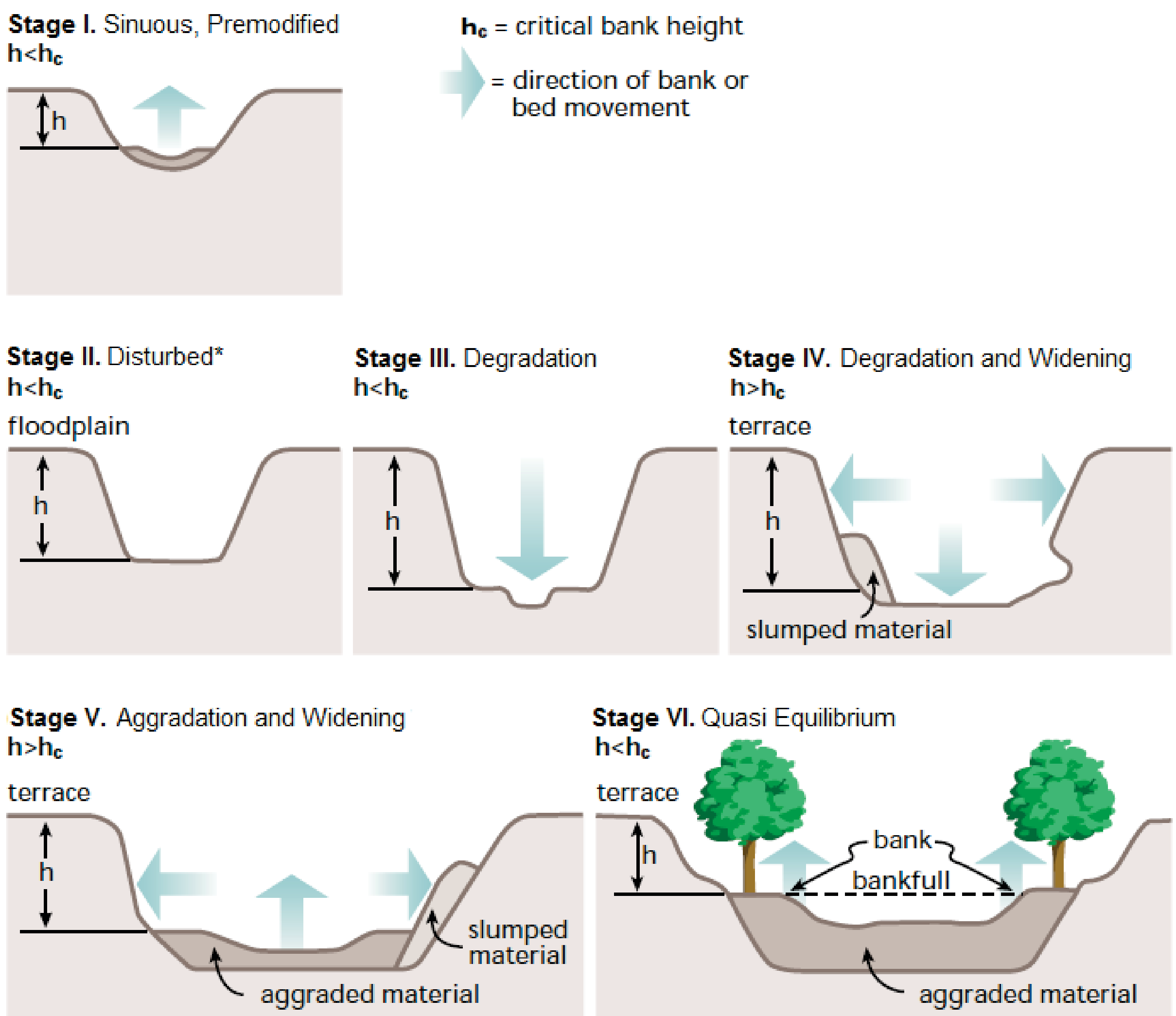


Figure F-1. Stage-discharge measurements for United States Geological Survey Gage No. 08114000 Brazos River at Richmond (data from USGS).



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

Figure F-2. Simon's Channel Evolution Diagram (modified from FISRWG 1998).

The impact of flow alteration on an unstable channel is very difficult to determine and it is highly unlikely that the sediment transport analysis performed for the Allens Creek study site described in the following sections will accurately forecast future channel bathymetry. The future configuration of the channel at this study site will depend on the disturbance causing the incision, changes to the flow regime, sediment input to the channel, and the stage of evolution that the channel is undergoing.

Large reservoir and diversion projects have the potential to impact both the flow regime and the sediment delivered to the channel downstream of the project. When the parameters of a proposed impoundment or diversion project are being defined, a detailed and thorough investigation should be conducted to evaluate their potential impact. Once those impacts are determined, measures can be taken to maintain or promote the desired downstream channel condition.

The basic purpose of this section of the report is to outline the analysis and procedures that can be used to determine the flows required to maintain a healthy ecological system once the channel has stabilized. Ecological parameters such as in-channel fish habitat, water quality, and riparian flow needs have been established. This section of the report should be used as an example for future calculations. The results of the analysis presented in the report should not be viewed as flows needed to develop or maintain a stable channel or even flows that protect the existing fish habitat, riparian or overbank connectivity. Guidance on the planning, analysis and design of systems to maintain stable channels and restore incising channels can be found in Watson *et al.* (2002).

Study Location

The Brazos River, located predominantly within the state of Texas, has the highest water and sediment discharge of all rivers in the state, and ranks second behind the Mississippi River in terms of sediment load delivered to the Gulf of Mexico (Carlin 2013). The Allens Creek Study site was selected for this sediment transport analysis. The downstream boundary is located at approximately river mile 125.5 near the city of Simonton, Texas. A complete data set for performing a detailed sediment analysis was not available for the six TIFP study sites. At the Allens Creek study site, however, the bathymetric data collected for fish habitat analysis can be used. Because flow recommendations at all six study sites were developed using the same methodology, lessons learned from the results of the sediment transport analysis at this study site are generally applicable to the remaining study sites.

Frequency Curves

An understanding of the basic hydrology of a stream is necessary when performing geomorphic studies. The basic assumption of the effective discharge approach is that channel shape is a function of the flow in the channel. The stability of a channel in a study reach can also be judged by the frequency of occurrence of the effective discharge. The effective discharge of a stable alluvial channel is usually associated with peak flows that occur every 1 to 3 years (Biedenharn *et al.* 1999). In reaches where the channel bed is composed of material larger than sand (gravel, cobble, and/or bedrock), effective discharges are expected to occur less often. For the Llano River at Llano, Heitmuller (2009) found that floods with return periods ranging from about 10 to 40 years play an important role in shaping the channel. The Llano River at Llano is a bedrock channel with sands and gravels found in the overbank areas. Because the banks and bed of the Brazos River are composed principally of sand and gravel sized material, an effective discharge with a return period of 1 to 3 years is expected for a stable channel condition at the Allens Creek study site.

Annual frequency curves were developed using the U.S. Army Corps of Engineers Hydrologic Engineering Center Statistical Software Package, HEC-SSP (USACE 2016b). This software allows the user to perform a variety of statistical analyses of hydrologic data. The current version of HEC-SSP can perform flood flow frequency analysis based on "Bulletin 17B - Guidelines for Determining Flood Flow Frequency" (IACWD 1982), a generalized frequency analysis suitable for flow and other hydrologic data, and a volume-duration frequency analysis on high and low flows. HEC-SSP uses annual peak flows to develop the flood frequency curves. Langbein (1949) showed that the Annual Flood flow frequency analysis underestimates the return interval of flows by about 0.5 years, which is important on the lower end of the frequency analysis. Because of this underestimation, the 1-year event calculated from the annual flood series can be expected to occur about every six months. Frequency curves for the Brazos River at Richmond for the period 1996-2015 were developed for the historical flows observed at the gage (Figure F-3), specific environmental flow recommendations only (Figure F-4), specific environmental flows recommendations plus 75% of flows above 5,000 cfs (Figure F-5), and specific environmental flow recommendations plus 95% of flows above 5,000 cfs (Figure F-6). Table F-1 shows both annual flood frequency calculations and the frequency when adjusted as recommended by Langbein (1949) for the four flow scenarios.

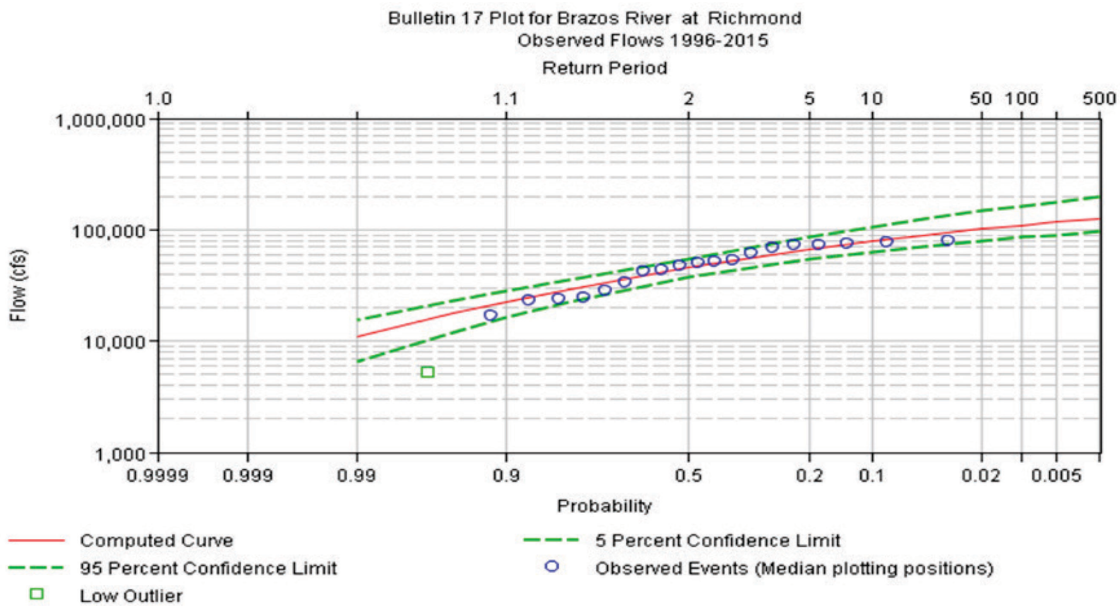


Figure F-3. Annual flow frequency curve for the Brazos River at Richmond – Observed flows.

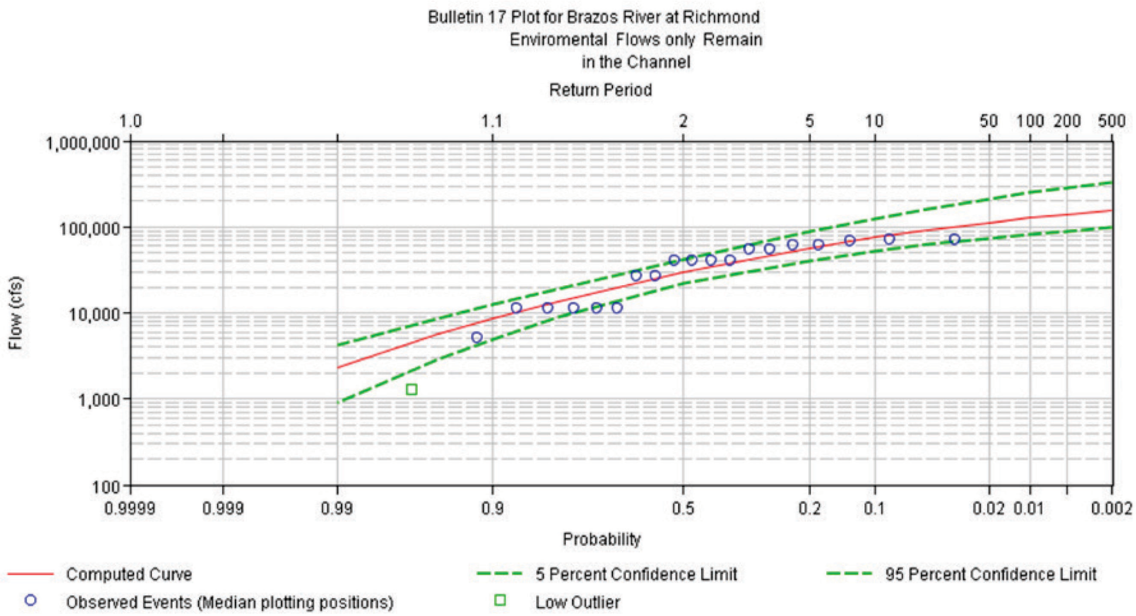


Figure F-4. Annual flow frequency curve for the Brazos River at Richmond – Specific environmental flow recommendations only.

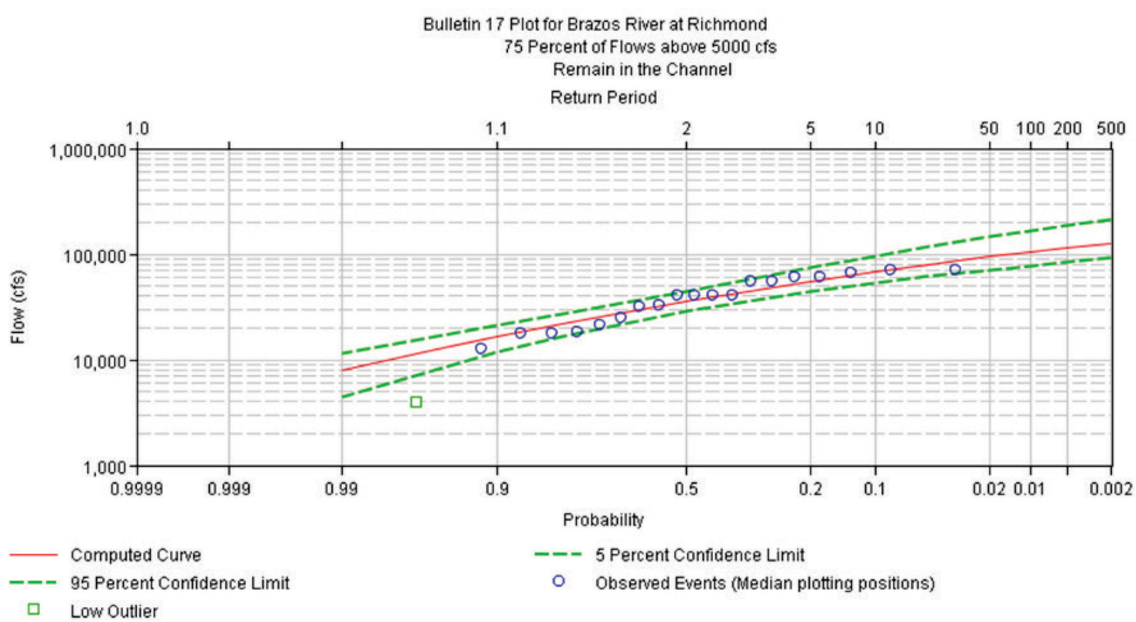


Figure F-5. Annual flow frequency curve for the Brazos River at Richmond – Specific environmental flow recommendations plus 75% of flow above 5,000 cubic feet per second.

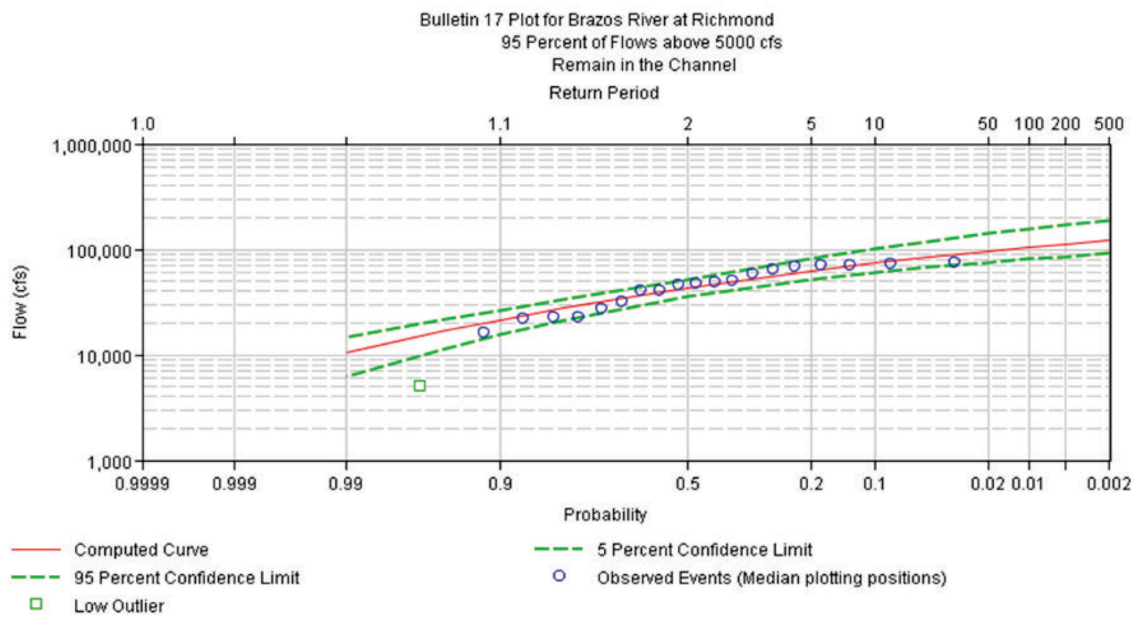


Figure F-6. Annual flow frequency curve for the Brazos River at Richmond – Specific environmental flow recommendations plus 95% of flow above 5,000 cubic feet per second.

Table F-1. Selected flow frequencies for the Brazos River at Richmond for four flow scenarios.

Corresponding Return Period in Years for Annual and Partial Series (Langbein, 1949)							
Partial Series	0.5	1	1.45	2	5	10	50
Annual Series	1.16	1.58	2	2.54	5.52	10.5	50.5
Annual Return Period in Years			10	5	2	1.25	1.11
Estimate Partial Return Periods in Years				4.5	1.5	0.7	0.5
Percent Chance of Exceedance in 1 Year			10	20	50	80	90
Scenario		Time Period	Flow (cfs)	Flow (cfs)	Flow (cfs)	Flow (cfs)	Flow (cfs)
Observed		1996-2015	45,500	57,800	73,080	82,360	101,500
Specific environmental flow recommendations only		1996-2015	29,980	38,070	62,615	78,770	112,950
Specific environmental flow recommendations plus 75% of flow above 5,000 cfs		1996-2015	36,020	45,750	61,310	71,520	94,150

Table F-1 (cont). Selected flow frequencies for the Brazos River at Richmond for four flow scenarios.

Scenario	Time Period	Flow (cfs)	Flow (cfs)	Flow (cfs)	Flow (cfs)	Flow (cfs)
Specific environmental flow recommendations plus 95% of flow above 5,000 cfs	1996-2015	43,240	54,910	69,520	78,400	96,700

Discharge Rating Curves

The existing channel should be analyzed to ensure that it is reasonably stable and has adjusted to the existing hydrologic regime for the effective discharge calculations to be meaningful and to provide guidance on how a future hydrologic regime might affect channel stability. One relatively simple and quick way to do this for a gage site is to analyze how the long-term stage-discharge curve (also known as the "rating curve") has changed over time. For the Brazos River at Richmond, the USGS has collected field measurements for an adequate period of record to analyze for channel stability. A rating curve that remains stable over time is one indication that a channel is stable. An alluvial channel that is either degrading or aggrading will show a distinct change in the stage-discharge relationship over time. For the same discharge, incising (degrading) channels will exhibit a decreasing gage height while an aggrading channel will exhibit an increasing gage height.

The amount of data available for this site allowed the data to be separated into various time periods to detect any potential changes over time. Figure F-7 contains rating curves developed for the Brazos River at Richmond for three separate time periods beginning from 1921 and ending in 2015. Figure F-7 shows that the channel has degraded approximately six feet from the earliest decade to the most recent time period. It also indicates that there has been an increase in the rate of degradation since 1980.

To definitively determine if channel degradation is occurring at this site would require studies outside the scope of this work, including, but not limited to, looking at how gages upstream and downstream of this gage have changed during this same time period, examining changes in cross-section and channel shape in this reach of the Brazos River, and consulting with the USGS to determine if changes in field measurement techniques or locations may be causing the gage to appear to be reflecting lower stages for the same discharge.

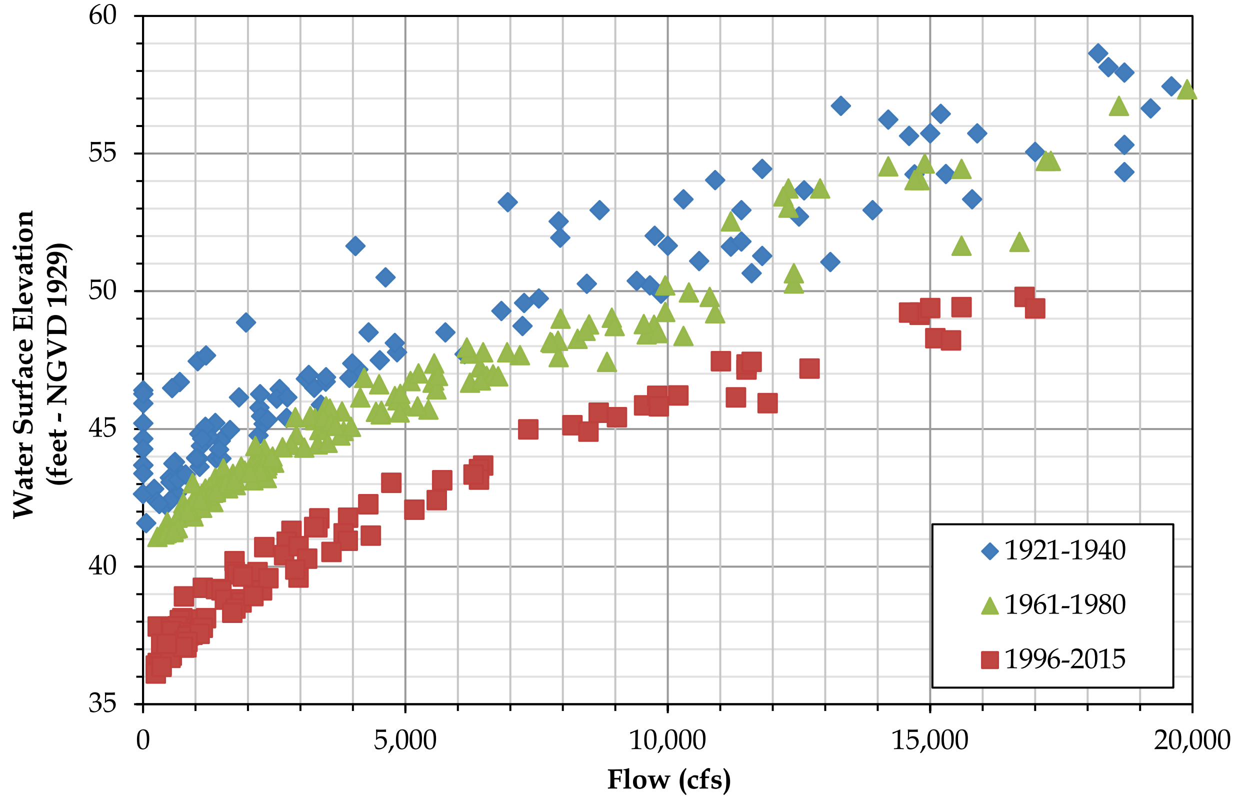


Figure F-7. Discharge rating curve for the Brazos River at Richmond.

Sediment Rating Curves

Like many rivers in Texas, the lower Brazos River has been sampled very infrequently for suspended sediment load and almost never for bedload. No sediment data are available at the Allens Creek study site. However, a limited amount of data has been collected by the USGS at the Richmond gage about 29 miles downstream.

Sediment rating curves estimate the amount of sediment moved by flows of various sizes and are required as input to the HEC-RAS and SAMWIN computer programs (Thomas *et al.*, 2002). Suspended sediment load data collected by USGS between 1961 and 1995 and by the University of Houston (Strom 2013) between 2011 and 2012 at the Richmond gage were used to develop the sediment rating curves at the Allens Creek.

Channel parameters (velocity, discharge, channel width, channel depth, computed energy slopes and bed gradation) at the gage site were input into SAMwin and a sediment rating curve was computed. Several sediment functions were applied and the function that fit the measured data most closely was chosen for developing the sediment rating curve used in the effective discharge calculation. Figure F-8 shows the measured sediment data and the sediment rating curve used to compute sediment transport rate and effective discharge for the Brazos River at Richmond. Note the extreme non-linearity of the relationship between discharge and sediment load, which is typical for river systems. Because of this non-linearity, large flows have a more significant role in moving sediment than lower flows. For example, from Figure F-8 we see that a flow of 10,000 cfs for one day would move about 3,500 tons of bed material. In contrast, a flow of 1,000 cfs for one day would only move a total of about 14 tons of bed material.

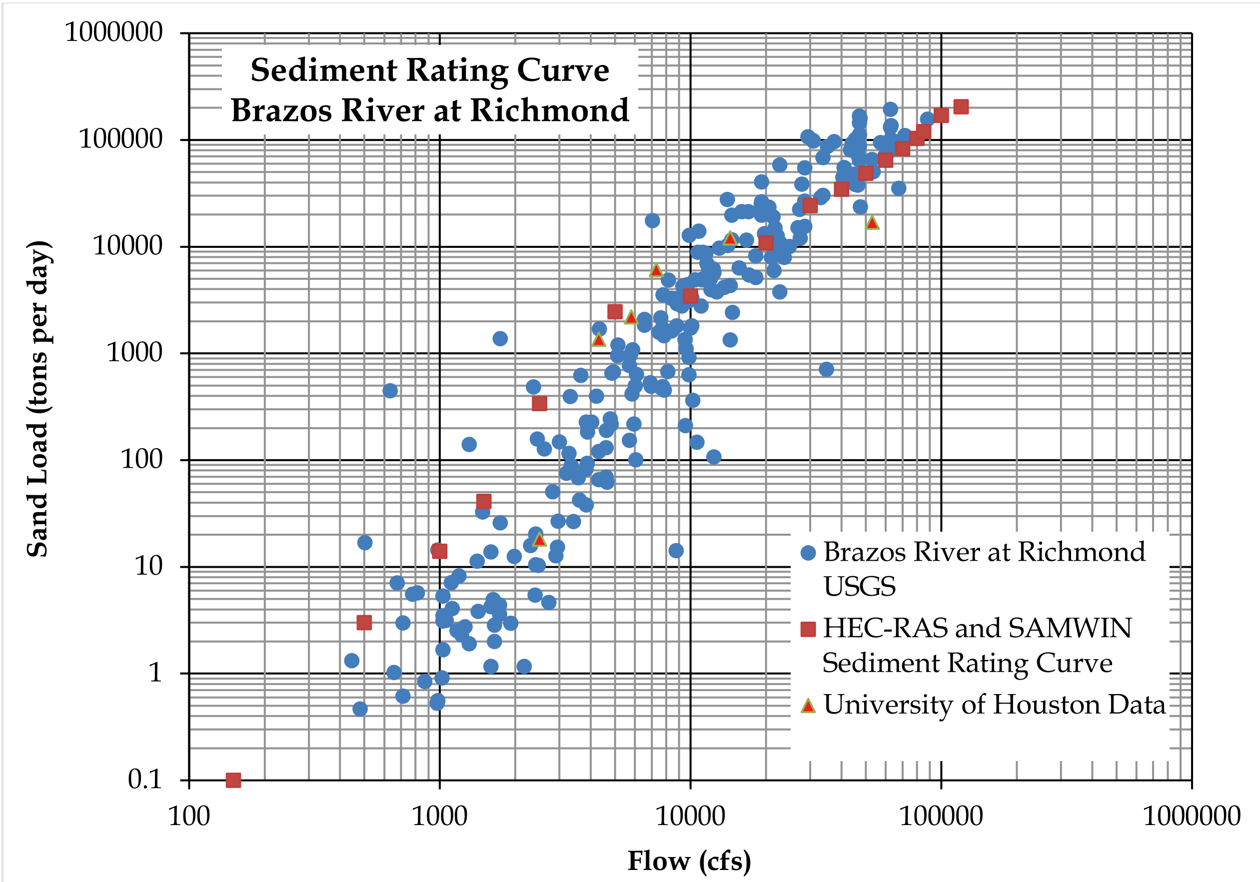


Figure F-8. Sediment rating curve for the Brazos River at Richmond.

Bed Material

Like suspended load, very little sampling has been performed to determine the type and size of bed materials found in the lower Brazos River basin. For this sediment analysis effort, no bed material samples are available for the Allens Creek study site and only a few bed material samples are available for the Brazos River at Richmond. The most recent bed sampling data for the Brazos River at Richmond are the data collected by Strom (2013). Bed material samples collected at the Richmond gage by Strom, shown in Figure F-9 (Strom's data are labeled "U of H"), were used to develop the bed material input to both HEC-RAS and SAMWIN computer programs. Gravel was added to bed material data collected at the Richmond gage by Strom because visual observation in the field showed parts of the river bed contained fine and very fine gravels. The HEC-RAS sediment analysis at the Allens Creek study site showed the Brazos River has the capacity to transport limited amounts of fine and very fine gravels at flows greater than 40,000 cfs and almost no capacity to move fine and very fine gravels at flow less than 20,000 cfs.

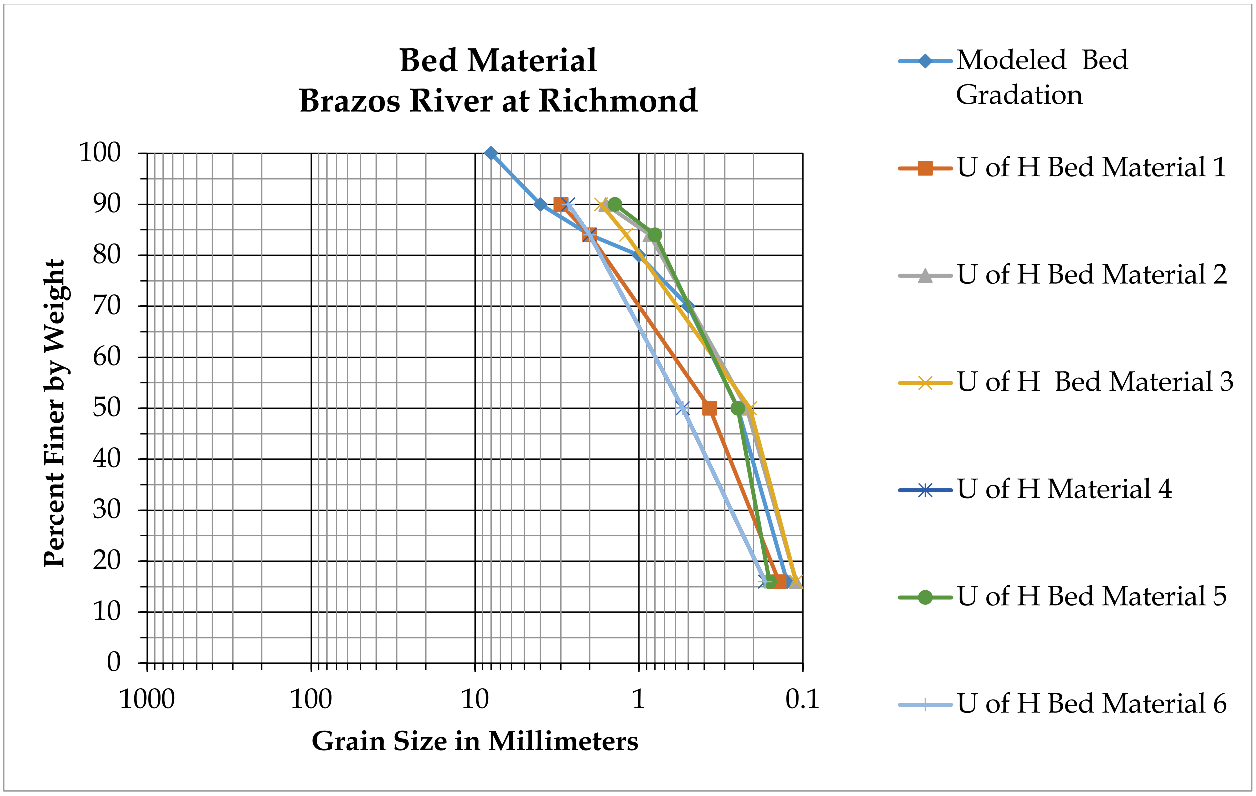


Figure F-9. Sediment rating curve for the Brazos River at Richmond.

Hydrology

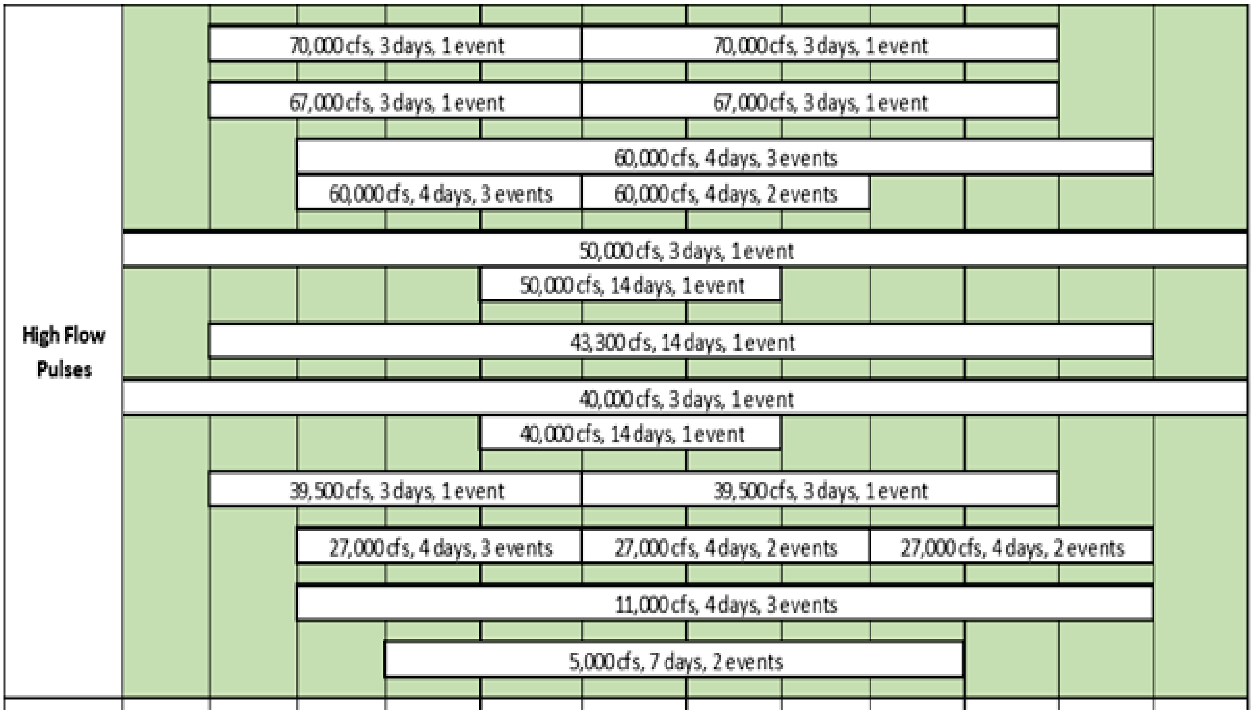
In addition to the sediment rating curves and bed material data, a third input variable, hydrology, is needed for the sediment analysis. In a typical hydrologic analysis, a base hydrology is developed, followed by proposed alternatives. Base and alternative hydrologies evaluated to see how well they meet the objectives of the proposed project (water supply, flood reduction, water quality improvement, etc.). For this study, proposed environmental flow regimes are being evaluated to determine their ability to transport flow and sediment without aggrading or degrading the channel while maintaining its dimension, pattern, and profile. A flow time series is needed for performing this analysis using HEC-RAS. SAMWIN can use times series input but most applications of SAMWIN use a flow duration curve as the hydrologic input when calculating sediment yield and determining the effective discharge. The hydrologic time series can be daily, hourly, 15-minute, etc., depending on flow characteristics of the stream. Smaller time steps are required when flow events rise and fall within a short time span and are not accurately reflected in average daily flow data. Daily data were available for the Brazos River at Richmond with 15-minute stage and discharge data available from about 1999 to present. The drainage area of the Brazos River at Richmond is 45,107 squares miles. There are no high slope tributaries with small drainage areas entering the river near the Richmond gage. In addition, the channel bed slope of the river is very small at this location. It was therefore determined that daily flows provide a sufficiently accurate description of the flow regime. Observed gaged data at Richmond were used as the "base flow condition" for the Allens Creek study site. The Richmond gage is about 29 miles downstream of the Allens Creek study site with no major tributaries entering the Brazos River between the Allens Creek study site and the Richmond gage.

Four hydrologic scenarios were included in the sediment analysis. Scenario 1 was the gaged or observed flow that occurred from January 1, 1996 to December 31, 2015 for the Brazos River at Richmond. This scenario represents current conditions and is the regime most responsible for sculpting the shape of the current Brazos River channel.

Scenario 2 is a "specific flow recommendations only" scenario based on gaged daily flows (1996 to 2015) reduced to the minimum values protected by subsistence, base habitat, high flow pulse and overbank flows described in Sections 3.1, 3.2, 3.3.1, and 3.3.2 and shown in Figure F-10.

Two additional flow scenarios were developed by adding additional water to the "specific flow recommendations only" scenario. In these scenarios, in addition to the pulse and overbank flows specified in Section 3.3.1 and 3.3.2, a percentage of all flows in the gaged record above a flow threshold were included in the flow recommendations. In other words, after the flow threshold was achieved, only a limited percentage of water could be diverted from the river, with the remainder reserved in the channel to carry out sediment transport and channel maintenance. For both additional scenarios, the flow threshold was 5,000 cfs. The percentage of flow that remained in the channel was 75 and 95 percent for Scenarios 3 and 4, respectively.

Flow duration curves associated with the four flow scenarios are shown in Figure F-11. Table F-2 shows annual flow volumes for observed gage flows (Scenario 1) and the specific flow recommendations only (Scenario 2) for 1996 to 2015. The average annual volume of gaged flow from 1996 to 2015 is 5.2 million acre-feet. The average annual volume of the "specific flow recommendation only" scenario (Scenario 2) for 1996 to 2015 is 1.8 million acre-feet, or about 35% of the observed flows.



BASE FLOWS (cfs) - Aquatic Habitat protection (intra- and interannual variability)									Key Indicators: Aquatic Habitat, Water Quality			
Base Wet	2,739	3,027	3,881	3,358	5,297	5,074	1943*	1943*	1943*	1,312	1,622	1,766
Base Average	1,587	1,754	2,249	1,946	3,069	2,940	1,115	946*	946*	760	940	1,023
Base Dry	563	622	798	691	1,089	1,043	626*	626*	626*	517**	517**	517**
SUBSISTENCE FLOWS (cfs) - Water quality protection and maintainence of limited aquatic habitat									Key Indicators: Aquatic Habitat, Water Quality			
Subsistence	517	517	517	517	626*	626*	626*	626*	626*	517	517	517
MONTH	January	February	March	April	May	June	July	August	September	October	November	December

* - mussel thermal tolerance flows

** - subsistence overlay on base

ALLENS CREEK

Figure F-10. Specific flow recommendations for the Brazos River at Allens Creek study site.

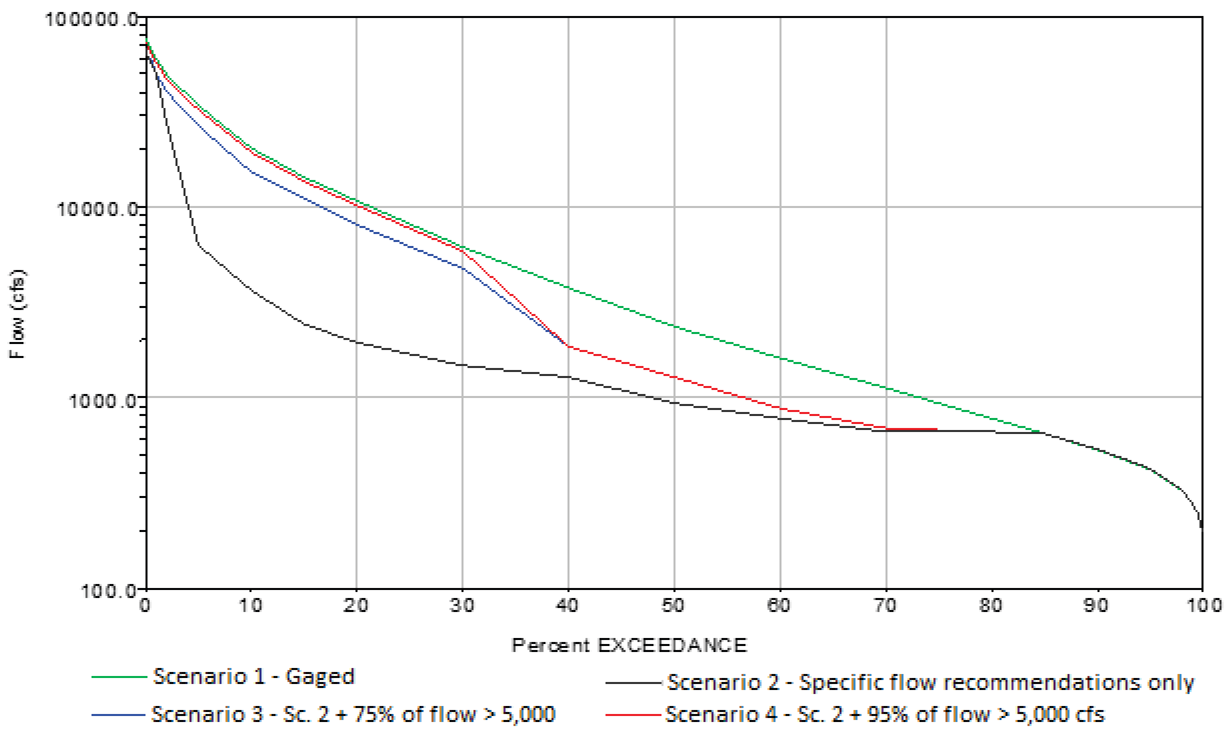


Figure F-11. Flow duration curves for four hydrologic scenarios for the Brazos River at Richmond.

Table F-2. Annual flow volumes the Brazos River at Richmond for gaged flows (Scenario 1) and specific environmental flow recommendations only (Scenario 2).

Annual Flow Volumes for Brazos River at Richmond (1996-2015)			
	Gaged	**Specific Flow Recommendations Only**	
Year	**Flow (acre-feet)**	**(acre-feet)**	**(Percentage of Gaged Flow)**
1996	1,835,976	721,449	39.30%
1997	9,974,232	2,902,267	29.10%
1998	8,476,119	2,934,198	34.62%
1999	2,220,561	999,696	45.02%
2000	1,966,069	591,755	30.10%
2001	7,487,655	2,132,354	28.48%
2002	5,005,223	1,711,866	34.20%
2003	4,055,862	1,836,506	45.28%
2004	10,135,609	4,198,810	41.43%
2005	4,901,938	1,585,875	32.35%
2006	1,220,602	593,411	48.62%
2007	15,258,610	5,056,188	33.14%
2008	2,123,876	1,138,448	53.60%
2009	3,571,895	1,153,450	32.29%
2010	6,082,864	1,939,473	31.88%
2011	521,436	445,945	85.52%
2012	3,172,062	1,007,521	31.76%

Table F-3 (cont). Annual flow volumes the Brazos River at Richmond for gaged flows (Scenario 1) and specific environmental flow recommendations only (Scenario 2).

Year	Gaged Flow (acre-feet)	Specific Flow Recommendations Only (acre-feet)	(Percentage of Gaged Flow)
2014	1,357,209	699,876	51.57%
2015	13,071,789	4,051,192	30.99%
Average	5,211,112	1,820,456	34.93%

Effective Discharge Calculations

SAMWIN calculates the annual sediment yield by integrating the flow duration and sediment rating curves discussed in previous sections. The effective discharge is determined from analyzing the results of the "bin" computations created by SAMWIN, which are output during computation of the annual sediment yield. The effective discharge is the mid-point flow of the bin (also called class or interval) that transports the largest sediment load. The following example describes how bin size is determined. If the minimum flow for the hydrologic period of record is 0 cfs, the maximum is 100,000 cfs, and 50 bins are chosen for the analysis, each bin would be 2,000 cfs. Bin one would bracket flows from 0 to 2,000 cfs, bin two from 2,000 to 4,000 cfs, and so forth until bin 50, which would encompass the range from 98,000 to 100,000 cfs. There are no definite rules for selecting the bin size (or interval) to be used in effective discharge computation (Biedenharn *et al.* 2000). Hey (1997) found that in rivers with a high incidence of very low flows, a large number of bins (thus small intervals) can bias the computed effective discharge towards the lowest discharge class (bin). Hey (1997) also found that in channels where the effective discharge corresponded relatively closely to the bankfull flow, 25 bins produced a continuous flow frequency distribution with a smooth sediment load histogram while using more than 25 bins produced inconsistent results. Experience has shown that in some cases, 25 bins produce unsatisfactory results and that up to 250 bins may be required (Biedenharn *et al.* 2000).

There is no standard method to validate or check the results of an effective discharge calculation. As a first step, the bed material load histogram can be analyzed to insure the computed effective discharge does not occur in the first bin (the bin with the lowest discharge class). An effective discharge taken from the lowest discharge bin is most likely erroneous according to Biedenharn *et al.* (2000).

The second step to determine the reasonableness of the computed effective discharge value is to determine the return period of the computed value. Both Hey (1994 and 1997) and Biedenharn *et al.* (2000) have reported that effective discharge return periods are normally in the one to three-year return frequencies. Discharges outside the one to three year return frequency range should be queried (Biedenharn *et al.* 2000).

Effective Discharge Results

The results of the SAMWIN computations for all hydrologic scenarios investigated are shown in Table F-3.

Table F-4. Results of sediment analysis for the Brazos River at Richmond for four flow scenarios.

Flow Scenario	Average Annual Water Volume (ac-ft/ year*)	Average Annual Sediment Transport Rate (tons/year)	Effective Discharge (cfs**)	Sediment Load in Effective Discharge Bin (tons/year)	Annual Frequency of Effective Discharge (years)	Partial Duration Frequency of Effective Discharge (years)
1. 1996-2015 Gaged	5,207,000	1,635,000	35,800	51,400	1.5	1.00
2. Specific Flow Recommendations Only	1,783,000	430,000	58,300	33,700	5.0	5.00
3. Sp. Flows + 75% of flow > 5,000 cfs	3,928,000	1,121,000	27,600	38,000	1.2	0.75
4. Sp. Flows + 95% of flow > 5,000 cfs	4,665,000	1,458,000	34,000	48,130	1.8	1.30

* ac-ft/year – acre-feet per year
** cfs – cubic feet per year

The first scenario achieves an average annual sediment transport rate for the period 1996-2015 of 1,635,000 tons per year. This number compares favorably with the figure of 31.6 million cubic feet per year that Mathewson and Minter (1976) report as the average annual volume of sand transported by the river past the Richmond gage location from 1952 to 1972. At a specific weight of 100 pounds per cubic foot, the volume calculated by Mathewson and Minter (1976) would equate to 1.58 million cubic tons per year, within about 3% of the average sediment transport rate calculated for 1996 to 2015. According to the guidelines of Biedenharn *et al.* (2000), if the channel were stable in 1952-1972 and no other disturbances impacted the system, the transition from the 1952-1972 hydrology (which averaged 4.89 million acre-feet of flow volume per year) to the 1996-2015 hydrology (which averaged about 6.5% more) should not have caused the channel to become unstable.

By the same criteria, assuming the 1996-2015 channel was stable, a transition from the 1996-2015 hydrology to the "specific flow recommendations only" scenario would not maintain stability. According to Biedenharn *et al.* (2000), a 10% or less reduction or increase in sediment transport should not cause instability and rapid changes in channel configuration. The "specific flow recommendations only" scenario reduces the sediment transport by much more than 10% during the 20 years analyzed (1996 to 2015). During the 1996 to 2015 time period, the Brazos River downstream of Waco has been unstable with more substantial degradation occurring in the lower reaches. The reduction of sediment transport at Richmond would reduce the sediment supplied to the Brazos below Richmond and exacerbate channel degradation and its related problems in that reach. The number of high flow pulses and overbank events provided by the "specific flow recommendations only" scenario is not sufficient to move a significant fraction of the sediment moved by the historical flows.

If the "specific flow recommendations only" scenario were achieved, it would result in major channel instabilities including incision in some areas and aggradation in others and the likely narrowing of the entire channel. Incision could cause bank failure due to over steepening of banks. Increased rates of channel meandering could occur in other areas where channel aggradation occurs. The current aquatic habitats and flow ecology relationships would not be maintained.

Scenarios 3 and 4 provide additional flow and corresponding sediment transport by protecting a percentage of flows above a flow threshold. The additional flow results in the movement of more sediment. In addition, because the additional flow is at the higher end of the flow spectrum (and sediment transport increases exponentially with flow rate), additional sediment is moved with a minimal increase in flow volume. Scenario 4 provides the specific flow recommendations as well as 95 percent of flows greater than 5,000 cfs and moves about 90 percent of the sediment moved by the historical 1996-2015 hydrology. Scenario 4 also had an effective discharge very similar to that of the gaged data and, in the event that the current channel were stable, should prove adequate for maintaining the current channel shape.

HEC-RAS Sediment Computations

In recent years, computer programs have been developed to assist river engineers to analyze how changing flow and/or sediment regimes impact the geomorphic role of rivers. HEC-RAS computes/predicts changes in basic hydraulic parameters such as channel width, depth, velocity, wetted perimeter and longitude slope. HEC-RAS is a computer program developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center and is commonly used to perform:

- River analysis for steady flow water surface profile computations,
- One and two-dimensional unsteady flow simulations,
- Movable boundary sediment transport computations including the ability to model the effects of dredging on channel hydraulics and channel bathymetric changes, and
- Water quality analysis.

A key element is that all four components of HEC-RAS use a common geometric data representation and common geometric and hydraulic computation routines. For this study, HEC-RAS was used to perform sediment routing and mobile bed computations. The primary advantage of using HEC-RAS in addition to SAMWIN is that HEC-RAS is designed to simulate long-term trends of scour and deposition in a stream channel that might result from modifying the frequency and duration of the water discharge and stage, or modifying the channel geometry.

HEC-RAS Input Data

HEC-RAS requires three basic data inputs: 1) channel and overbank geometric data, 2) hydrologic data, and 3) sediment data, including a sediment transport function.

Channel-Geometry Data

For this study, geometric data were collected from several sources:

- A hydrographic survey completed in 2015,
- Terrestrial surveys, also completed in 2015, at locations where the channel was dry or water depth was insufficient to operate boats to complete the hydrographic survey, and
- Airborne LIDAR data of above water and overbank areas collected in 2011.

The combined geometric data collected for the Allens Creek study site are shown in Figure F-12 and a three-dimensional rendering of a portion of the data is shown in Figure F-13.

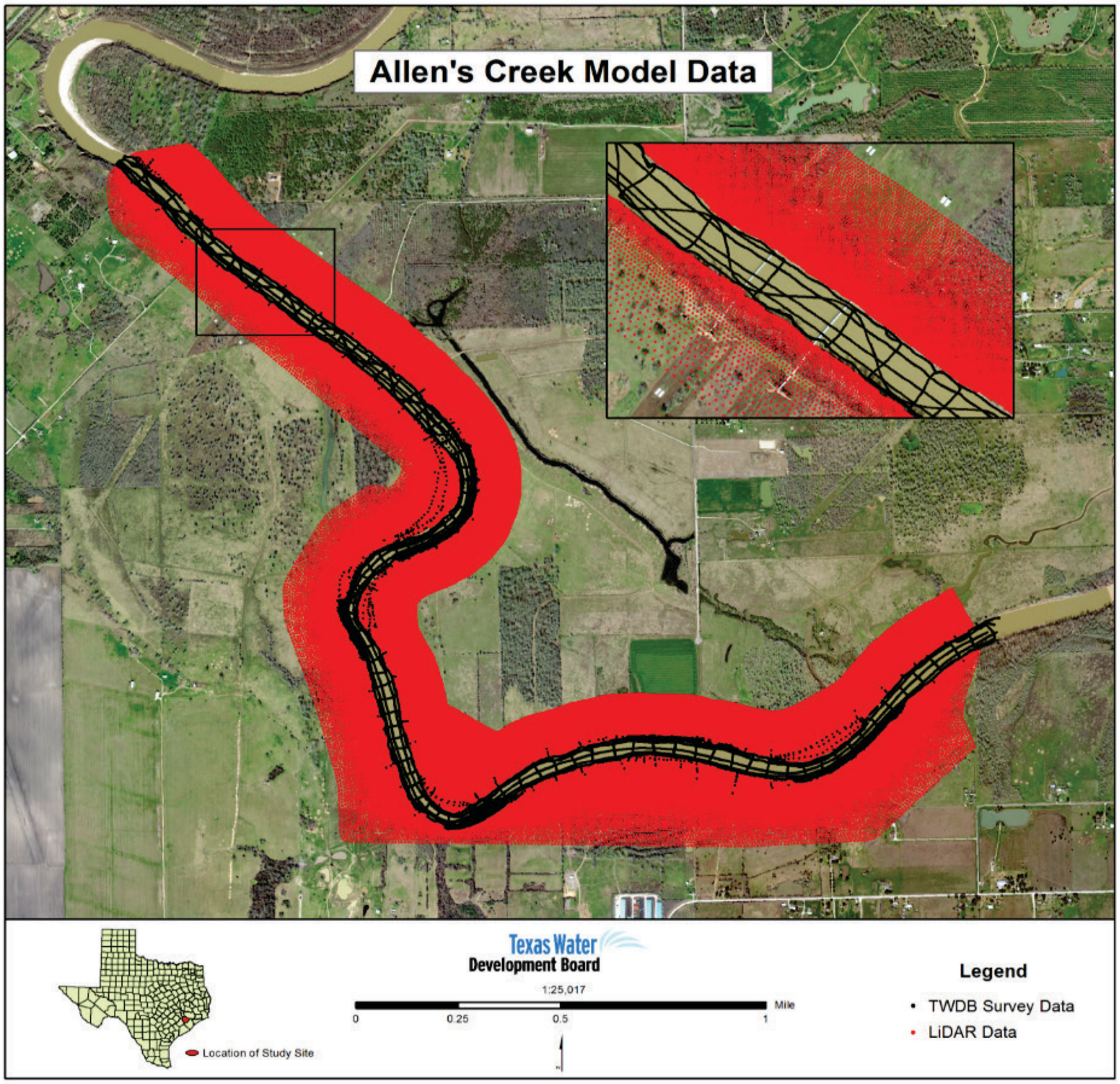


Figure F-12. Bathymetric and terrestrial surveys and LiDAR data used for model development for Allens Creek study site.

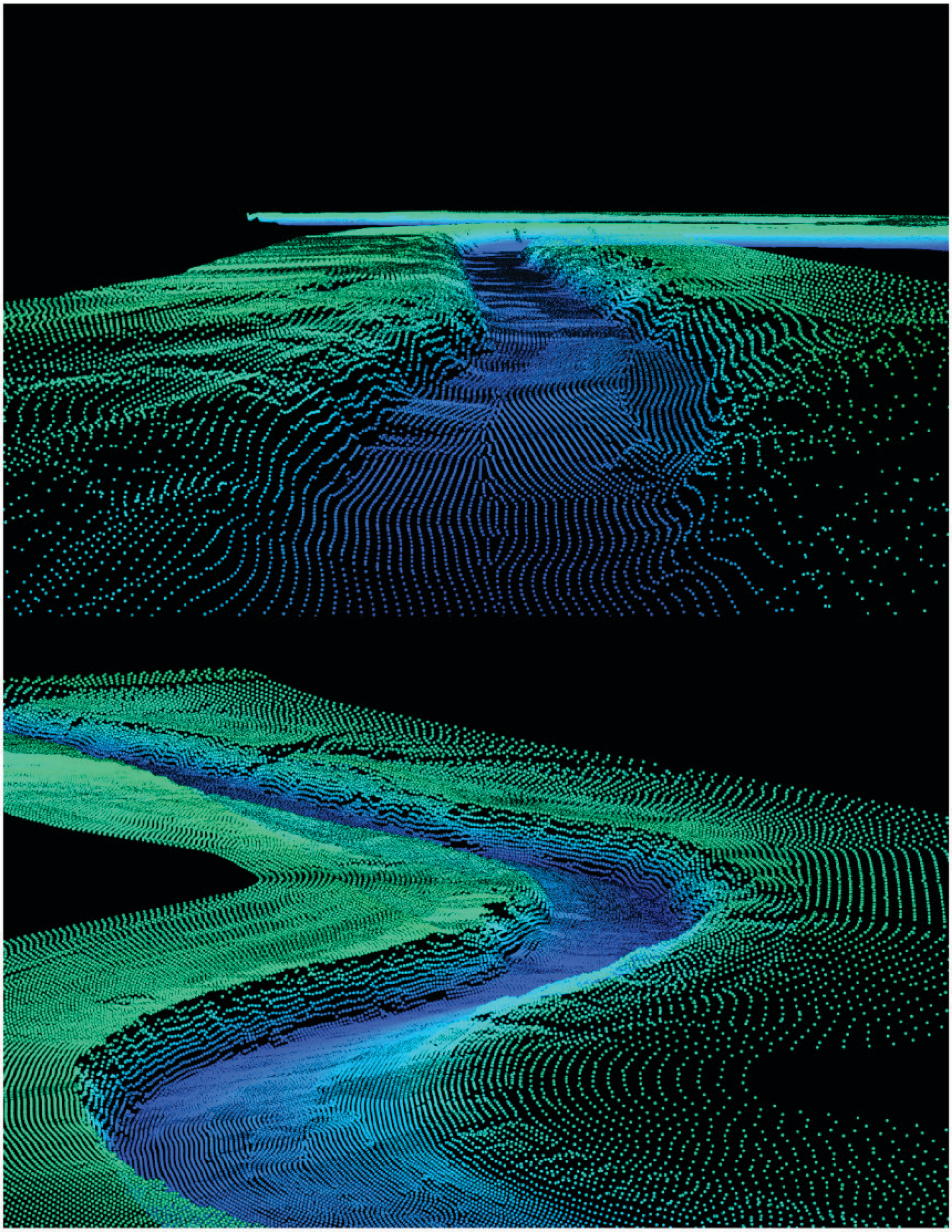


Figure F-13. Three dimensional rendering of the Allens Creek study site.

Hydrology

The hydrologic data used in this study were collected at USGS Gage No. 08114000 Brazos River at Richmond between January 1, 1996 and December 31, 2015. More discussion of available hydrologic data can be found in Section 2.2 (Hydrology and Hydraulics). This same base hydrology was used for the SAMWIN analysis discussed previously.

Sediment data

HEC-RAS requires two sediment inputs. The first is data describing the upstream inflow sediment load and the second is the bed material at each cross-section. The user has three options for the upstream boundary condition: 1) an inflow sediment-load series, 2) a rating curve, or 3) an equilibrium load. For this study, the rating curve option was chosen. As discussed in the SAMWIN section of this appendix, the sediment rating curve was developed from field measurements collected at the Richmond gage by the USGS from 1961 to 1995 and suspended sediment load collected by the University of Houston in 2011 to 2012 (Strom 2013). The bed material (sometimes referred to as "streambed material") is defined as a mixture of sediment found in the streambed. This material is available for transport and, when combined with the flow regime, generally determines the hydraulic properties of a stream such as width, depth, sinuosity and channel slope. A second component of the sediment in a stream is suspended sediment or "wash load."" This is the material found suspended in the water column but not found in appreciable quantities in the streambed. This material is usually very fine, originates from overland flow in the watershed, stays in suspension, and is not deposited in the streambed.

Sediment Transport Function

The HEC–RAS sediment-transport model requires the user to choose a sediment transport equation (sometime referred to as a "sediment transport function") to be used for the entire simulation time period and at all cross-sections within the computation grid. Seven different transport equations are available in HEC-RAS: Toffaleti (1968), Ackers and White (1973), Engelund and Hansen (1967), Laursen (1958) and Copeland and Thomas (1989), Meyer-Peter and Muller (1948), Yang (1973), and Wilcock (2001).

The Laursen-Copeland transport function was chosen to perform the HEC-RAS sediment analysis of the Allens Creek study site. The Laursen-Copeland function is especially well suited for the lower Brazos River because the function was originally developed for sand bed rivers (Laursen 1958) and later extended by Copeland and Thomas (1989) to include gravel size material. Because visual observations of the streambed at the Allens Creek study site indicated that a small percentage of gravel was found in the bed, there was a possibility that stream armoring could occur. Modeling of gravel movement on the bed is necessary to predict the development of an armored layer on the streambed. A partially or fully armored bed reduces the amount of sediment material available for transport and thus can limit bed degradation at a cross-section. During a simulation, bed armoring can be episodic with coarser size particles armoring the channel bed at lower flows but transported downstream at higher flows.

Development of a Stable Channel

As stated earlier in this report, the Brazos River near the Allens Creek study site appears to be a degrading/incising channel. Under these conditions, environmental flow recommendations would be sufficient for a healthy ecologic environment only for a brief period of time.

A degrading reach is defined as one that experiences a net lowering of bed elevations, with the bed profile tending to become flatter over time (Thomas 1977). This condition persists when the capacity of the river to transport sediment exceeds sediment supply. The river then picks up material stored in the channel and banks, resulting in degradation or lateral erosion (Flynn 2011). The erosion of the streambed lowers the stage for a given flow, increases bank height, and causes the flood plain to be abandoned.

For the HEC-RAS study, a stable channel geometry was developed for the Allens Creek study site using the channel bathymetry collected in 2015, flows that occurred from 1996-2015, and constant downstream and upstream boundaries. This channel, along with a fixed downstream boundary and fixed sediment inflow boundary, means that any channel changes computed by the HEC-RAS are results of changes in flow regime only and not biased by the ongoing channel incision.

Sediment Analysis vs. Sediment Modeling

The HEC-RAS model was used to simulate flow and sediment movement in the Allens Creek study site for a 20-year period from January 1, 1996 to December 31, 2015. This study should be considered a sediment analysis and not sediment modeling of the Allens Creek study site. A sediment analysis uses the best available data and engineering judgement to predict how the river will adjust to changes in flow regime. Development of a full-fledged sediment model requires several orders of magnitude more data than is required to perform a sediment analysis. To develop a sediment model, an intensive field data collection effort is usually required. Field data collection includes:

- Bathymetric data collected at two or more times (typically with a year or more between data sets),
- Continuous stage and discharge measurements at the upstream and downstream boundaries,
- Daily water temperature,
- Suspended sediment measurements at the model boundaries that cover the range of flows that will be modeled, and
- Bed material gradations of the streambed in the study area.

HEC-RAS Simulation of Flow-Sediment Transport

HEC–RAS contains four one-dimensional components for analysis of rivers:

1. Computations of water-surface profiles of steady flow,
2. Simulation of unsteady flow,
3. Computations for movable-boundary transport of sediment; and
4. Analysis of water quality (Flynn 2011).

HEC–RAS, version 5.0.3 (USACE 2016a) was used in this study to model flow and sediment transport.

For this study, the daily flows from January 1, 1996 to December 31, 2015 where used in the quasi-unsteady state flow model to simulate the hydraulic conditions found at the Allens Creek study site. Quasi-unsteady flow computation time steps ranged from six hours at flows less than 2,000 cfs to five minutes at flows above 50,000 cfs. The hydraulic parameters calculated in the quasi-unsteady flow computations are used in the Lausen-Copeland sediment transport function to determine total bed material capacity at each of the models 110 cross-sections. Using the bed gradation at each Cross section and applying the selected sorting and armoring technique, total bed material capacity is converted to total bed material load. After the bed material load is calculated, HEC-RAS solves the sediment-continuity equation to determine the volume of deposition or erosion.

For this effort, four different hydrologic scenarios were modeled. Scenario 1 represents the base condition: a 7,305-day simulation of the observed flows that where measured from January 1, 1996 to December 31, 2015. Sediment input used in HEC-RAS sediment analysis was the rating curve shown Figure F-8, and is the same sediment rating curve used with SAMWIN to calculate sediment yield and effective discharge (discussed previously). Bed material gradations for the HEC-RAS analysis are shown in Figure F-9 and labeled "Modeled Bed Gradation." The downstream boundary for this analysis is the rating curve (water surface elevation versus discharge) developed for this location. It must be pointed out that for all four scenarios modeled, the boundary conditions where constant upstream sediment input and constant downstream stage-discharge boundaries, which would imply a channel that is in dynamic equilibrium. As stated in Section 2.4.2, geomorphic analysis of the Brazos River at this location indicates the channel is not in dynamic equilibrium but instead is currently degrading at a rate of about 1.5 feet per decade.

The results of this analysis indicate that the Brazos river channel, with the input adjusted to represent a channel in dynamic equilibrium, changes very little during the 20-year simulation. Figure F-14 shows the upstream and downstream boundaries of the HEC-RAS model and the location of three representative cross-sections that are shown in Figures F-15 through F-17. The initial geometry for all four scenarios is the dark blue line labeled "Start of all Simulations." Scenario 1 is the red "base" line in Figures F-15 through F-17. In addition, the channel invert on day 1 (January 1, 1996) and day 7,305 (December 31, 2015) is shown on Figure F-18, again as the dark blue and red line, respectively. The difference between the dark blue and red lines shows only a minimum amount of change, reflecting the properties of a stable channel.

Scenario 2 is a 7,305-day simulation of the specific environmental flow recommendations only, as shown in Figure F-10. This Scenario represents how the channel would adjust if the only flows in the river were those shown in Figure F-10. To model this scenario, the observed inflows from January 1, 1996 to December 31, 2015 were input at the upstream boundary, as was done in Scenario 1. At cross-section 21,769.34, about 900 feet downstream from the upstream boundary, all flow not required to satisfy the subsistence, base, pulse or overbank flows as depicted in Figure F-10 were diverted from the channel. This left only the flows represented by Figure F-10 in the remainder of the model. Obviously, a real-world diversion of this magnitude would require significant infrastructure, which may not be cost effective. In reality, there are an infinite number of possible diversion plans that could be developed. However, assuming that multiple flow diversion structures were used to reduce the flow in the channel to the flows shown in Figure F-10, the results would be similar. These results are shown in Figures F-15 through F-17 as the green line labeled "Dec 31 2015 E-Flows Only." This scenario would result in significant loss of channel depth and flow area. These results should be viewed as an indication that significant channel stability issues would develop in the channel downstream of the flow diversion. This analysis is not designed to completely predict the geomorphic changes one would expect from such a major change in flow regime.

Scenario 3 provides the specific environmental flow recommendations plus 75% of all flows greater than 5,000 cfs. This flow regime is modeled like Scenario 2 except the diversion from the main channel is limited to 25% of in-channel flow when channel flows exceed 5,000 cfs unless a greater flow is required to meet a specific flow recommendation. The results of flow-sediment routing are shown in Figures F-15 through F-17 for the three representative cross-sections as the purple line labeled "Dec 31, 2015 75% in Channel." Figure F-18 shows the channel invert (lowest point of each cross-section) along the length of the study reach after the 20-year simulation, again as the purple line.

Scenario 4 provides the specific environmental flow recommendations when in-channel river flows are less than 5,000 cfs. However, when flow exceeds 5,000 cfs, at least 95% of the flow remains in the channel. This flow regime is modeled like Scenario 2 except the diversion from main channel is limited to 5% of in-channel flow when in-channel flows exceed 5,000 cfs unless a greater flow required to meet a specific flow recommendation. The results of flow-sediment routing are shown in Figures F-15 through F-17 as the light blue line labeled "Dec 31, 2015 95% in Channel." Figure F-18 shows the channel invert changes that occur during the 20-year simulation, again as the light blue line.

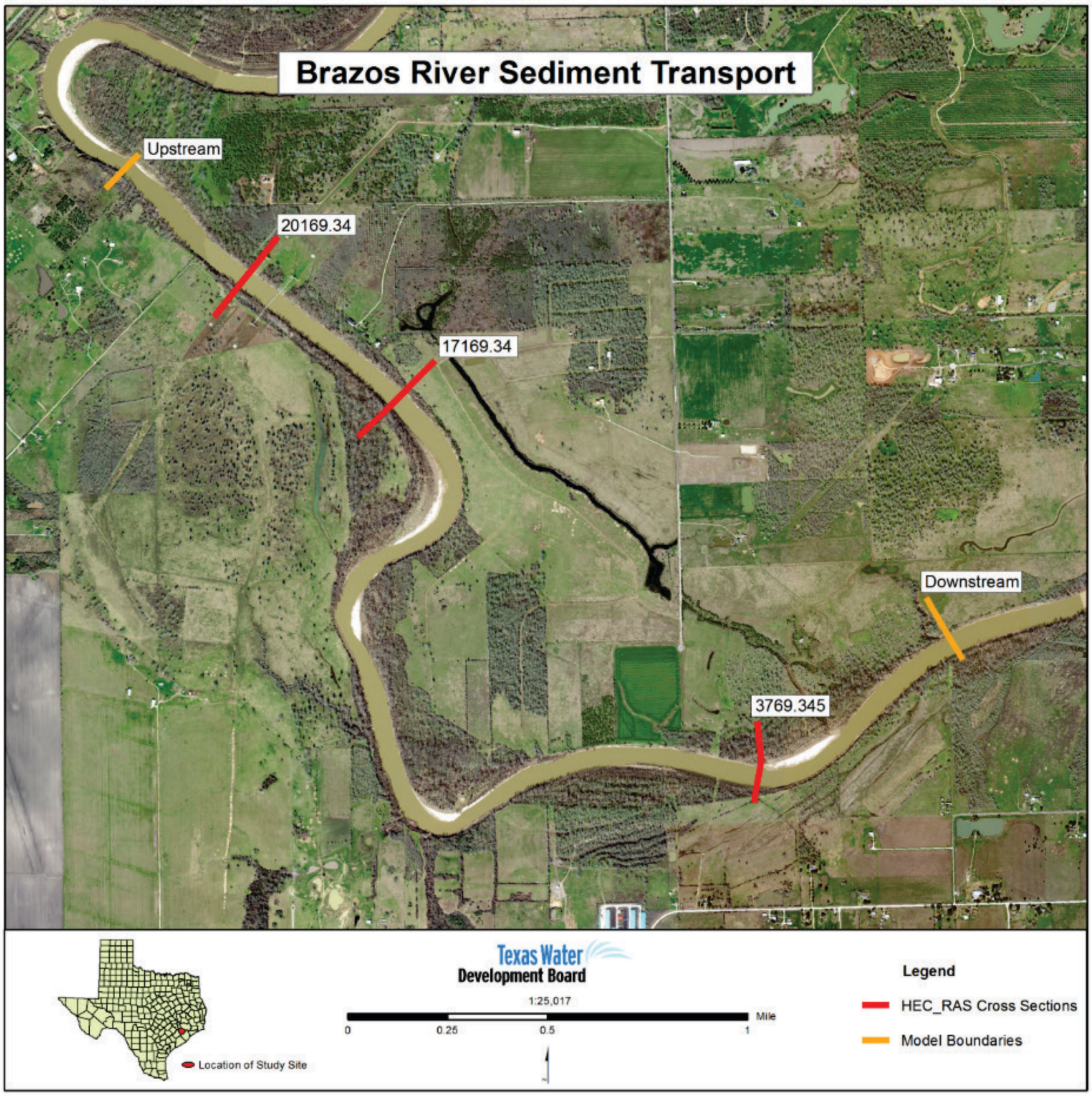


Figure F-14. Location of representative Hydrologic Engineering Center's River Analysis System cross-sections.

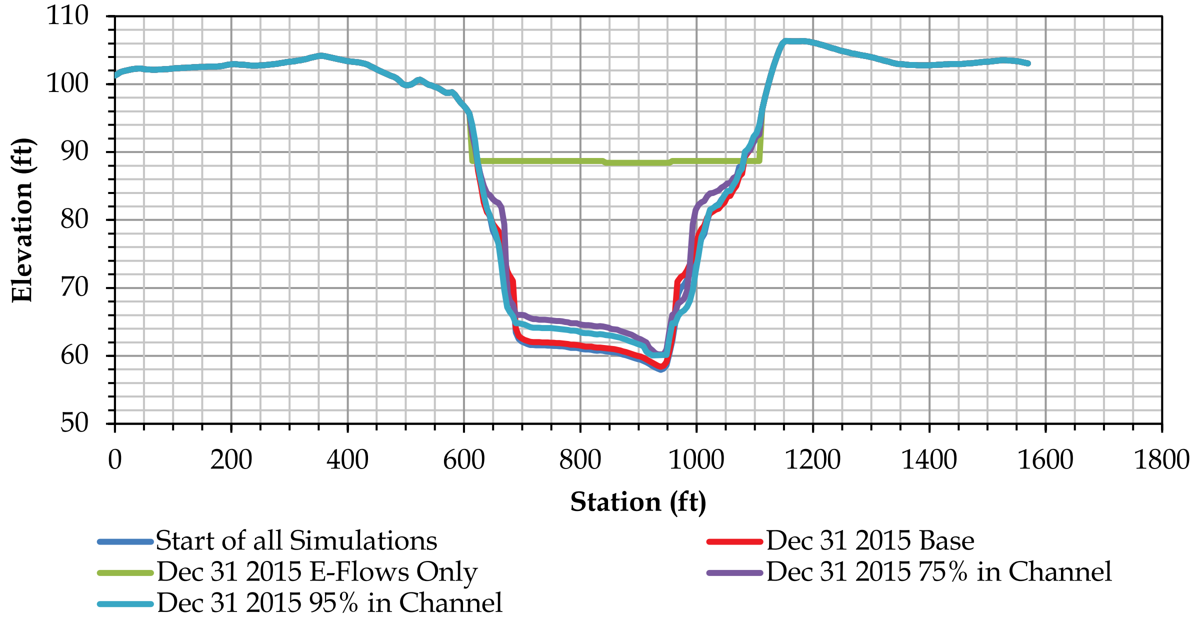


Figure F-15. Brazos River-Allens Creek cross-section 20,169.34. Station location and elevation are in feet.

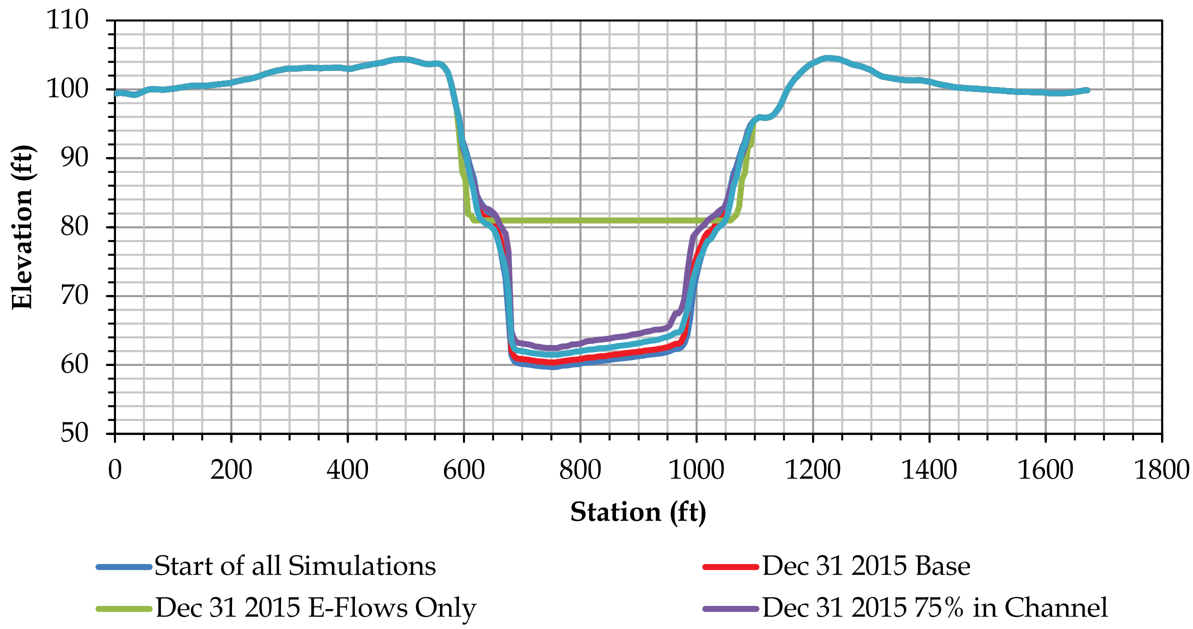


Figure F-16. Brazos River-Allens Creek cross-section 17,169.34. Station location and elevation are in feet.

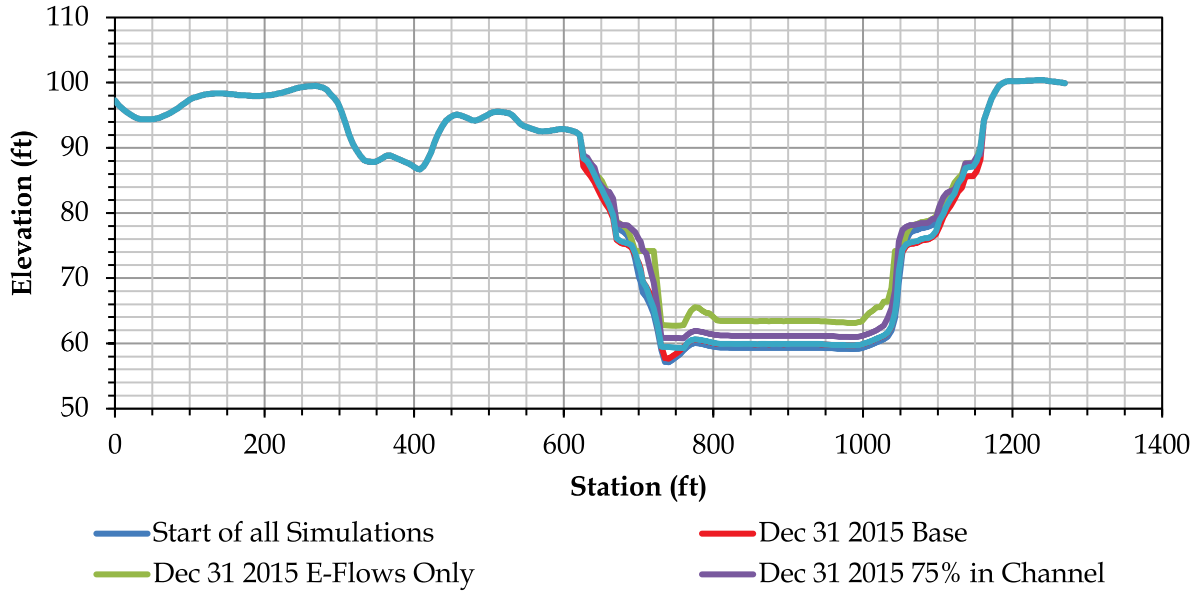


Figure F-17. Brazos River-Allens Creek cross-section 3,769.345. Station location and elevation are in feet.

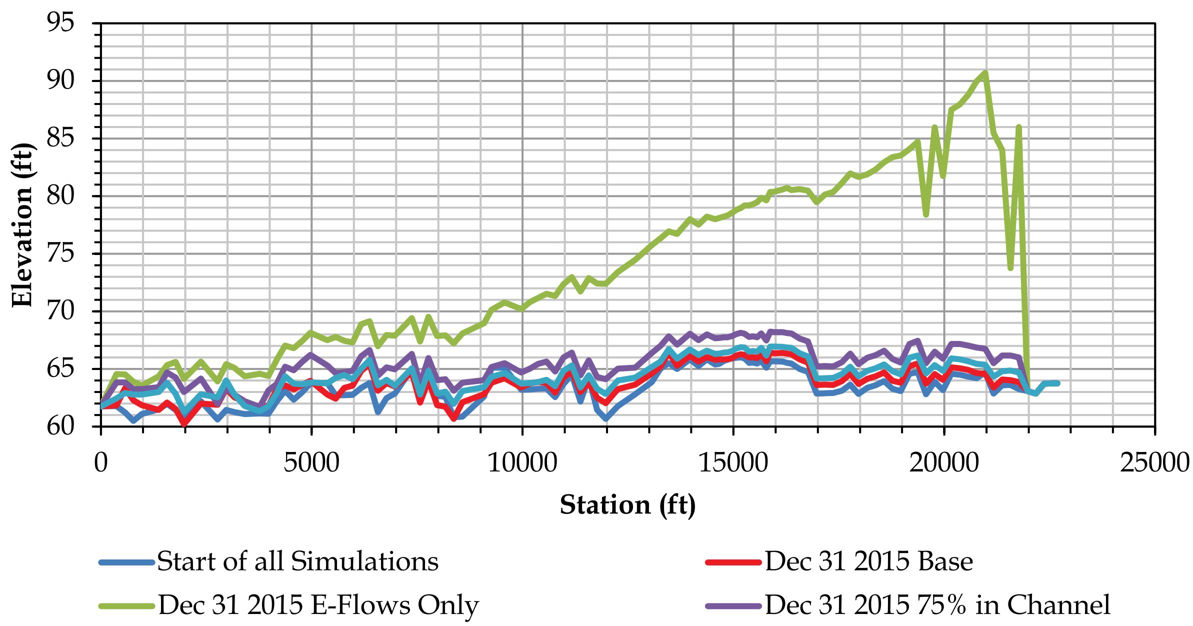


Figure F-18. Mean effective invert for model of Allens Creek study site. Station location and elevation are in feet.

Conclusions

The sediment transport analysis reached the following conclusions:

1. The Brazos River at the Allens Creek study site and the USGS gage at Richmond is a degrading channel. Analysis of the stage-discharge relationship at the Richmond gage shows this degradation trend has existed for more than 60 years. The current rate of degradation appears to be a fairly constant incision of 1.5 feet per decade. A stable channel might have periods when the stream is degrading slightly, but would rebound during subsequent periods and maintain a fairly constant channel invert overall.
2. Assuming the channel does stabilize at some future time in a configuration similar to the existing channel, the specific environmental flow recommendations only scenario will not provide the flows needed to maintain the stability of that channel. This flow regime would result in major channel instabilities including incision in some areas and aggradation in others. Incision could cause bank failure due to over- steepening of banks. Increased rates of channel meandering could occur in other areas where channel aggradation occurs. The current aquatic habitats and flow-ecology relationships would not be maintained.

The effective discharge and desktop computational methods provide a means to rapidly compare the geomorphic impacts of current and proposed flow regimes. In this analysis for the Brazos River at the Allens Creek study site, these techniques have been utilized to the full extent that they can reasonably be expected to provide useful, valid guidance. As noted by Shafroth *et al.* (2010), approaches that account for geomorphic processes (including models of sediment transport, channel migration and sediment budgets) hold great potential for advancing efforts to link changes in flow regimes to changes in channel geometry, aquatic habitats, and biotic responses, thereby strengthening the scientific basis of environmental flow assessments and recommendations. The development of basin-wide sediment transport models should be considered to more accurately account for geomorphic processes during future study efforts.

The HEC-RAS sediment analysis shows:

1. The HEC-RAS model confirmed the SAMWIN analysis and provided some quantitative predictions as to how the channel geometry, sediment transport capacity, and channel invert would change if four different flow regimes were applied to the Allens Creek study site.
2. Review of the base condition (Scenario 1) showed that only minor changes in Cross section geometry and channel invert had occurred by the end of the 20 year simulation. One should remember the channel geometry, channel bed material gradations, and upstream and downstream flow sediment boundaries were slightly adjusted from data collected at Richmond to produce a channel in "dynamic equilibrium."
3. Scenario 2, which kept everything the same as the base condition (Scenario 1) with the exception that flows not required to meet specific environmental flow recommendations prescribed in Figure F-10 were removed from the model. This scenario showed significant channel filling would occur, along with an increase in the

bottom slope of the channel. The increase in bottom slope (or channel gradient) and decrease in depth is consistent with potential alterations in channel characteristics due to changes in transport variables as described in Table 8-3 of the Texas Instream Flow Studies Technical Overview (TIFP 2008).

4. Scenario 3 maintains the same flows as Scenario 2 when daily flows are less than 5,000 cfs. When inflow exceeds 5,000 cfs, flow in river is the greater of: a) flows required to meet the pulse flows as shown on Figure F-10 or b) 75% of the observed river flow. Results of the 20 year flow-sediment simulation for this scenario are shown on Figures F-15 through F-17. The data shows that at the end of the 20 year simulation, a moderate amount of sediment deposition has occurred at the three selected cross-sections. This will lead to a smaller channel and an increase in the channel invert elevation. More analysis would be needed to predict exactly how the channel would change. However, this amount of deposition would probably increase the channel meander rate and decrease flow depth and width.
5. Scenario 4 maintains the same flows as Scenario 2 when daily flows are less than 5,000 cfs. When the daily flow is above 5,000 cfs, the flow remaining in the channel is the greater of flows required to meet the pulse flows as shown on Figure F-10 or 95% of the observed river flow. As seen in Figures F-15 through F-17, Scenario 4 results in only small amounts of sediment deposition in-channel and a very small increase in channel inverts above the baseline 20-year simulation. The channel Cross section and channel invert changes appear no greater than those you would expect in a stable channel. The SAMwin model computed the sediment transport rate for Scenario 4 to be about 90% of the sediment transport rate for the base condition, indicating this flow-sediment regime would most likely maintain a stable channel.

To accurately model the effect of future flow regimes on the physical characteristics of a channel, the future flow regime must be accurately portrayed. The details of how environmental flow recommendations will be implemented are currently unknown. Those details may greatly influence the flow regimes (particularly the pulse and overbank flow components) that are achieved at locations within the basin and, therefore, the extent to which channel change may or may not occur.

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APPENDIX G
WATER QUALITY

United States Geological Survey Gage and Surface Water Quality Monitoring Station Locations

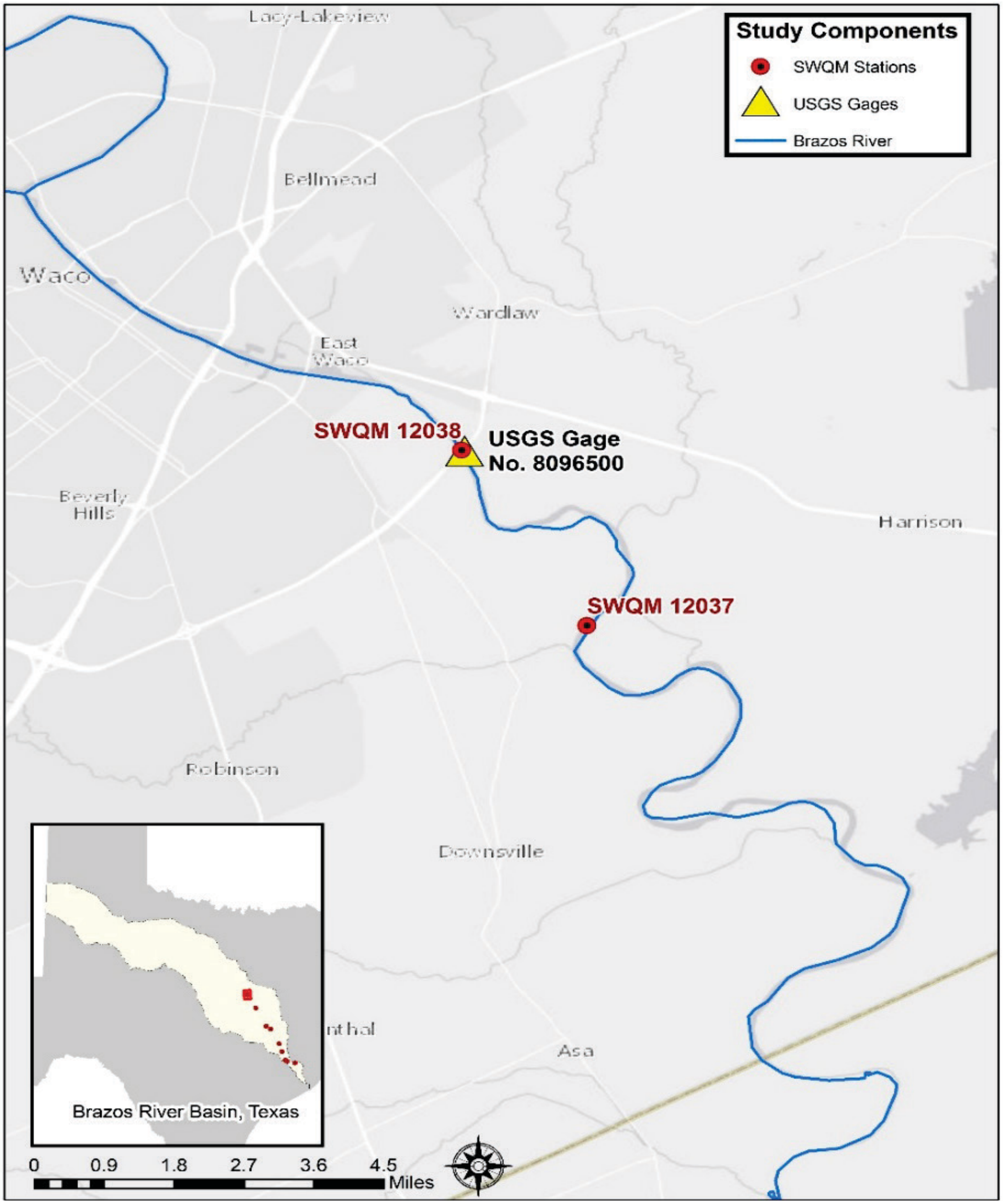


Figure G - 1. Surface water quality monitoring stations near United States Geological Survey Gage No. 08096500 (Waco).

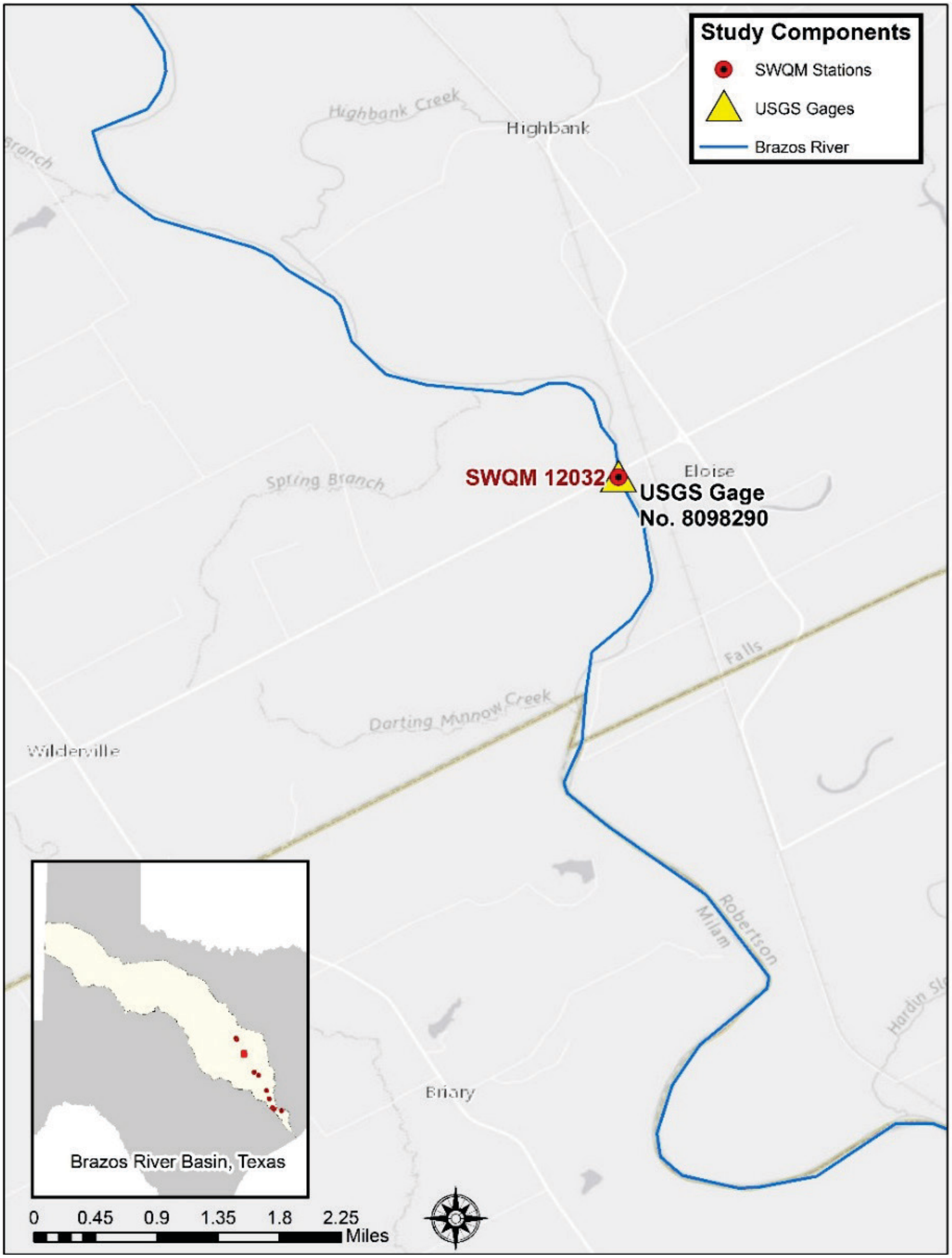


Figure G - 2. Surface water quality monitoring stations near United States Geological Survey Gage No. 08098290 (Highbank).

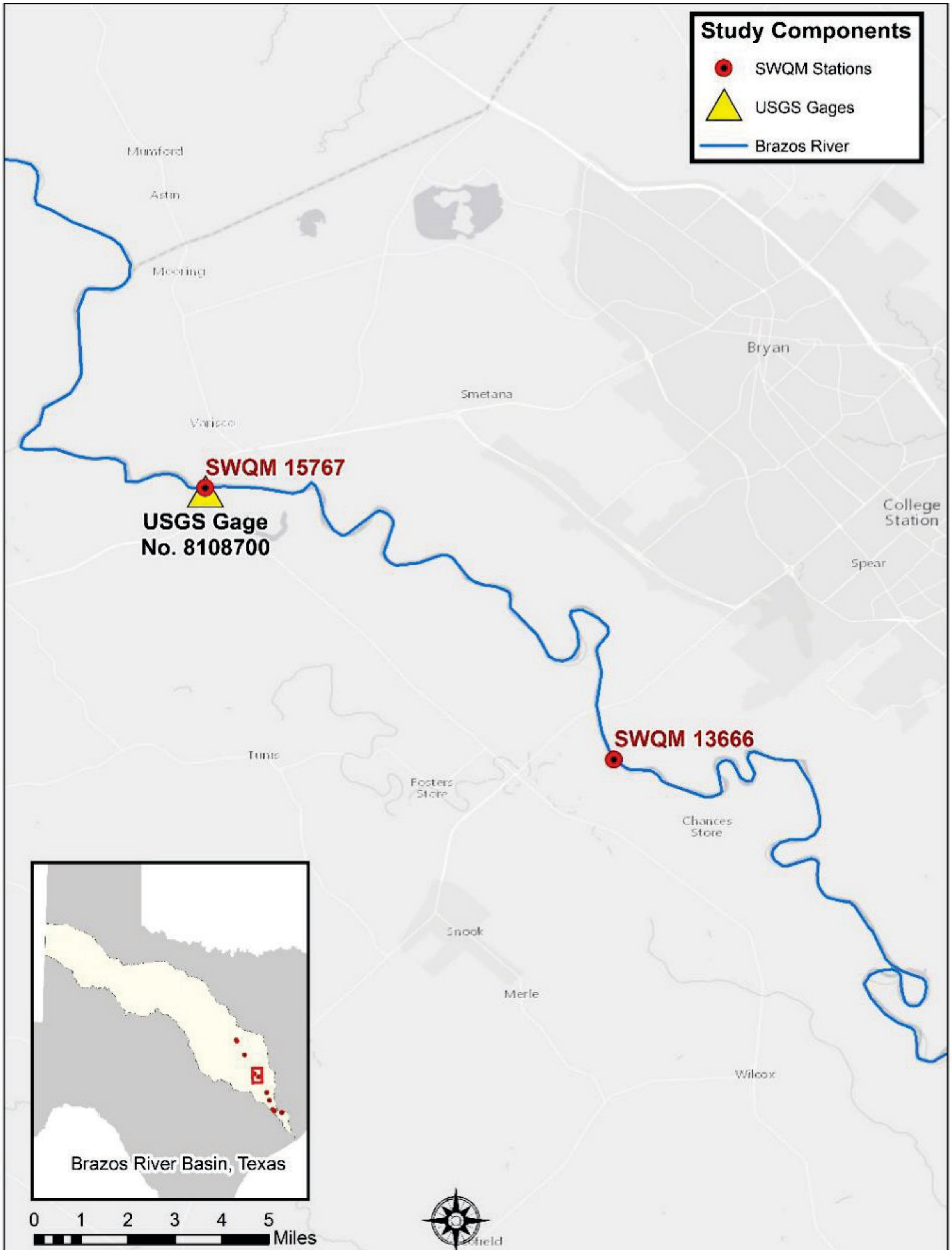


Figure G - 3. Surface water quality monitoring stations near United States Geological Survey Gage No. 08108700 (Bryan).

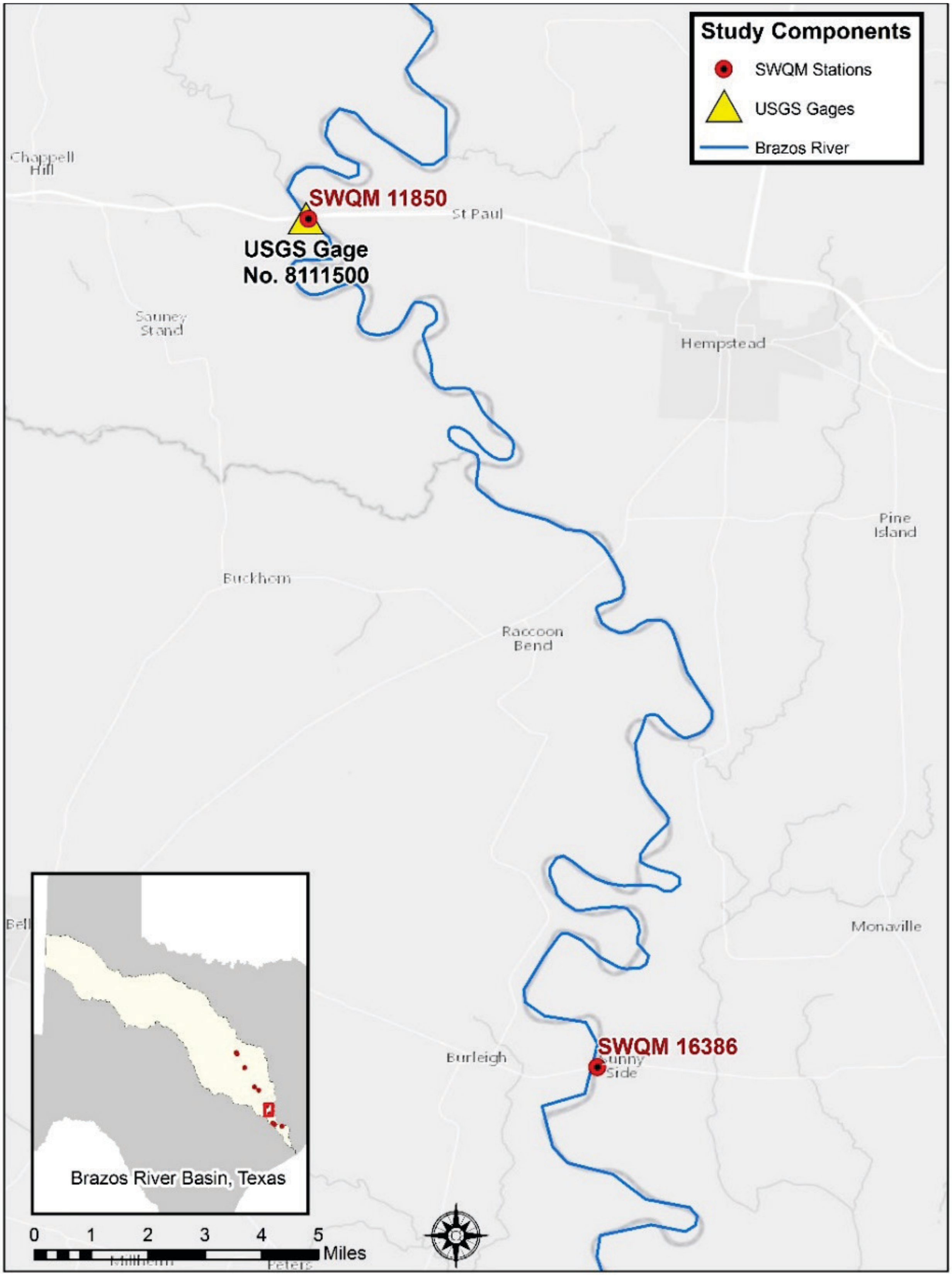


Figure G - 4. Surface water quality monitoring stations near United States Geological Survey Gage No. 08111500 (Hempstead).

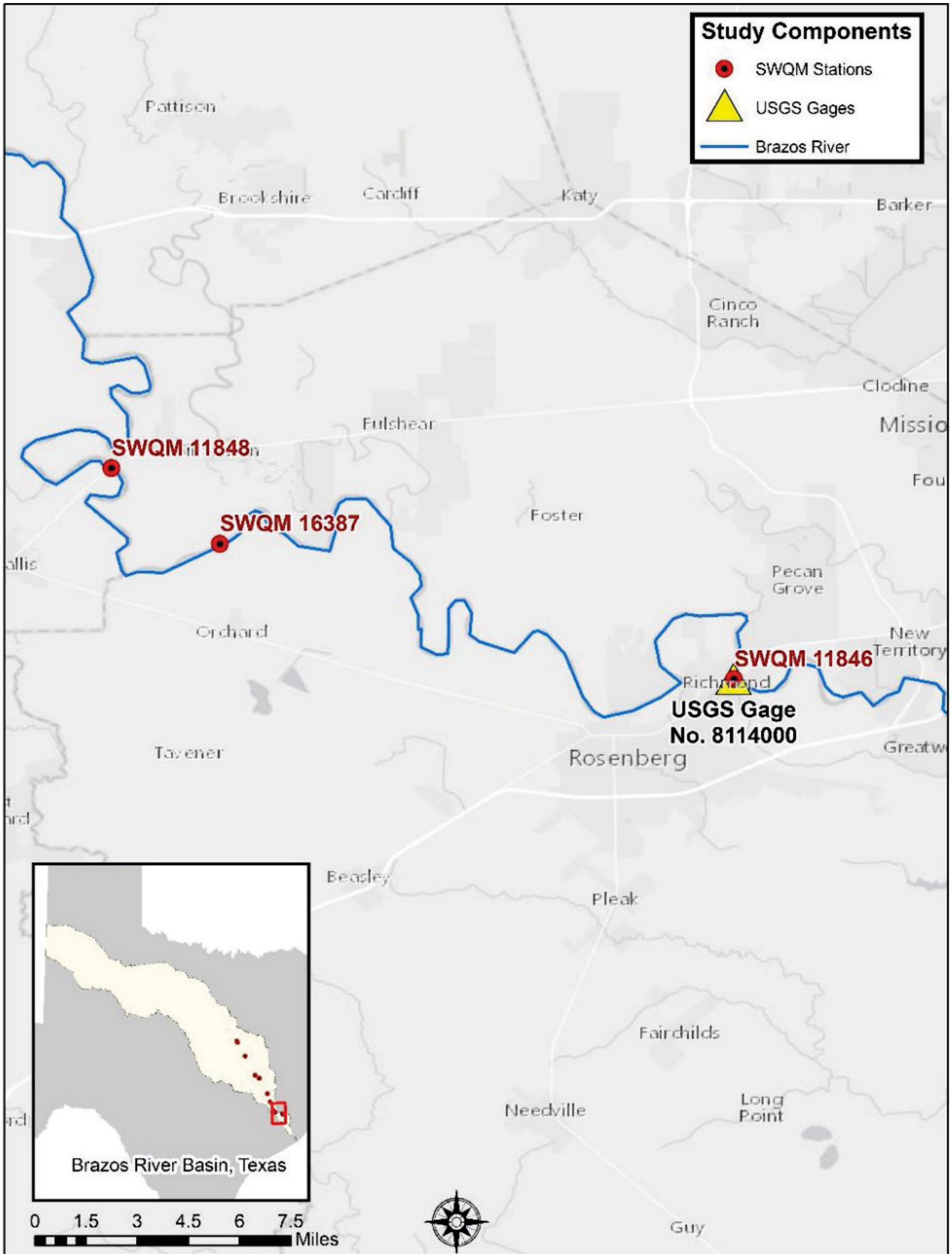


Figure G - 5. Surface water quality monitoring stations near United States Geological Survey Gage No. 08114000 (Richmond).

Primary Priority Goal
Temperature (35 degrees C)

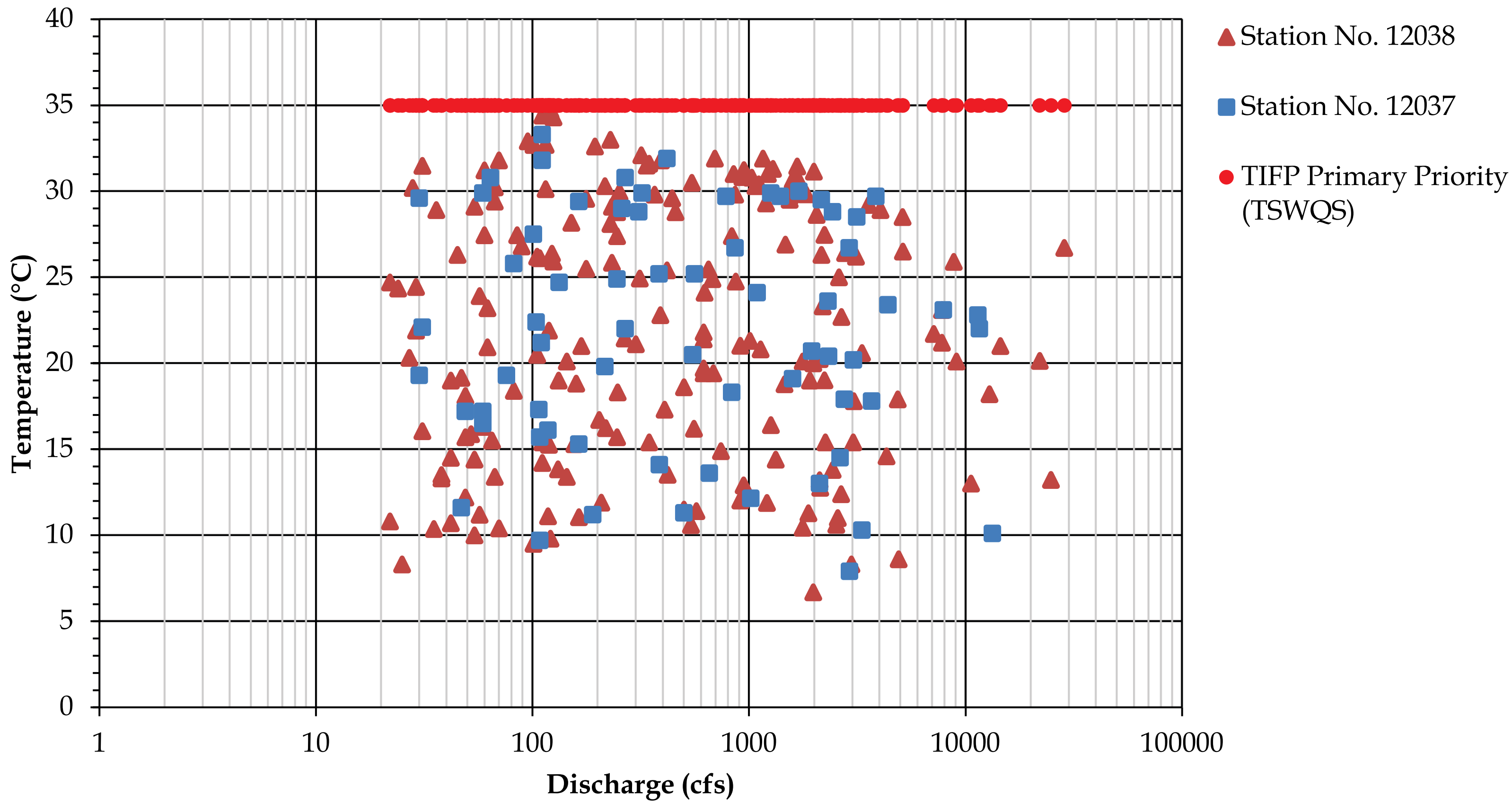


Figure G - 6. Temperature data for surface water quality monitoring stations near United States Geological Survey Gage No. 08096500 (Waco) TIFP primary priority (all dates).

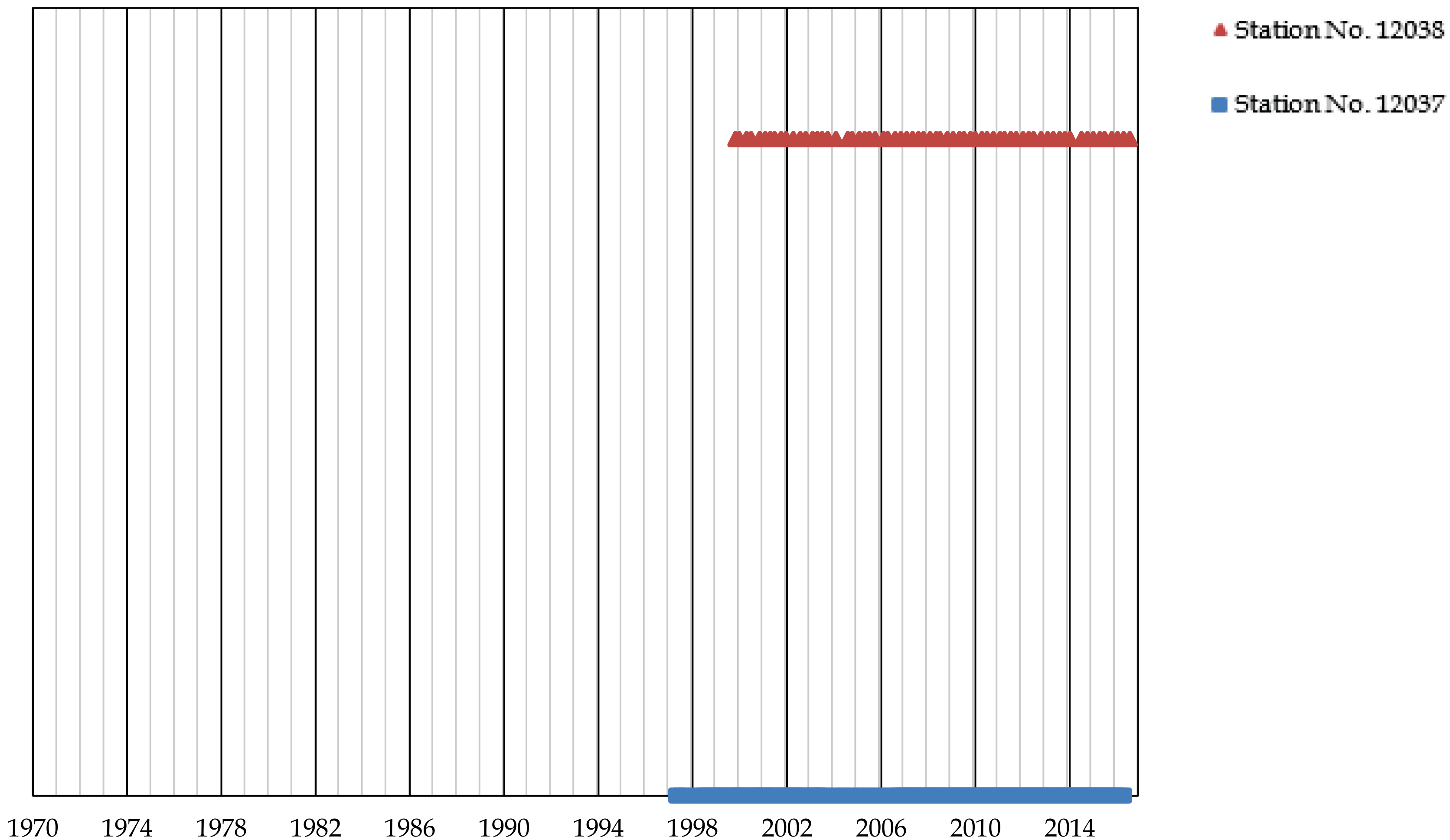


Figure G - 7. Temperature sampling dates surface water quality monitoring stations near United States Geological Survey Gage No. 08096500 (Waco) TIFP primary priority (all dates).

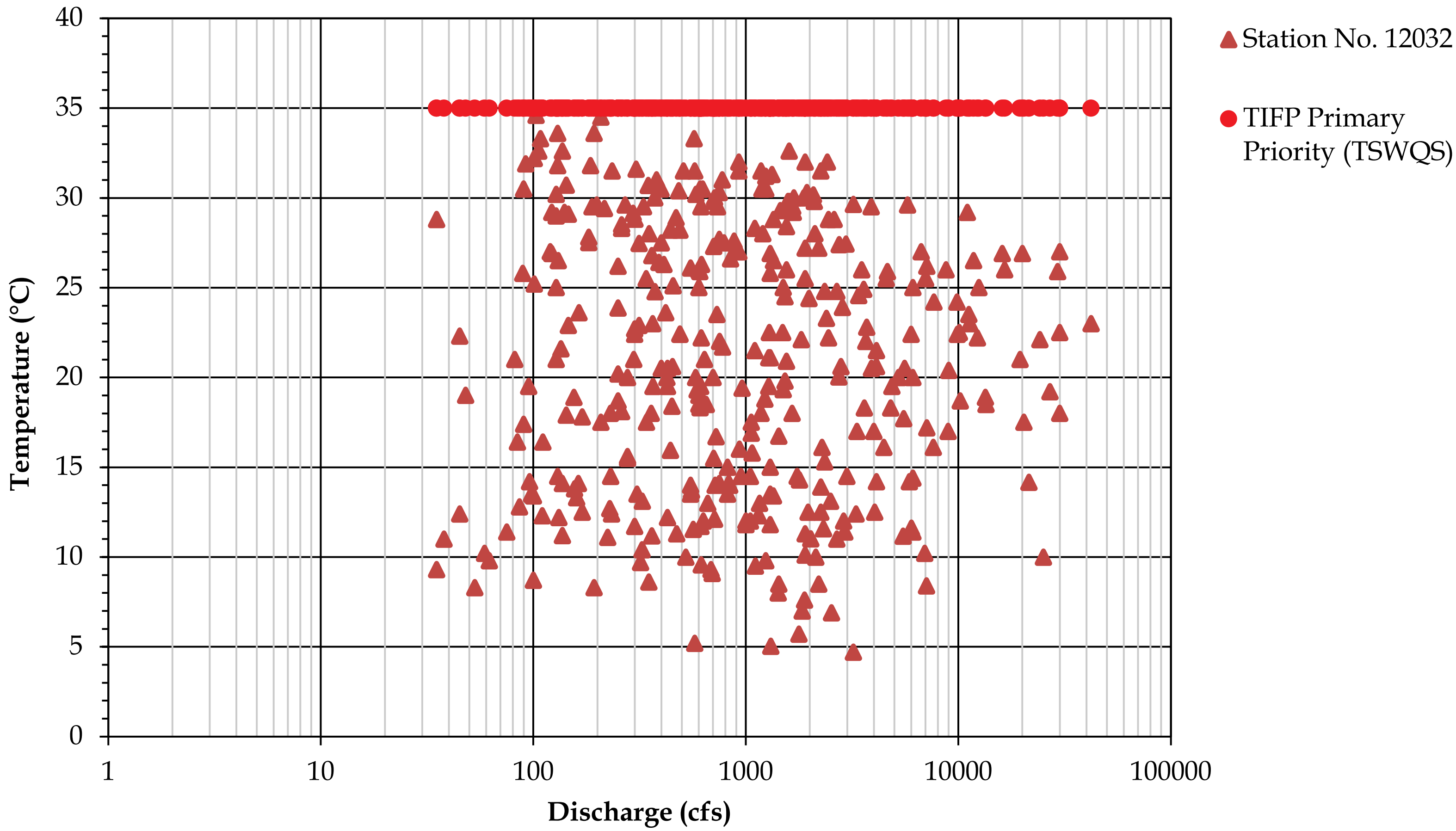


Figure G - 8. Temperature data for surface water quality monitoring stations near United States Geological Survey Gage No. 08098290 (Highbank) TIFP primary priority (all dates).

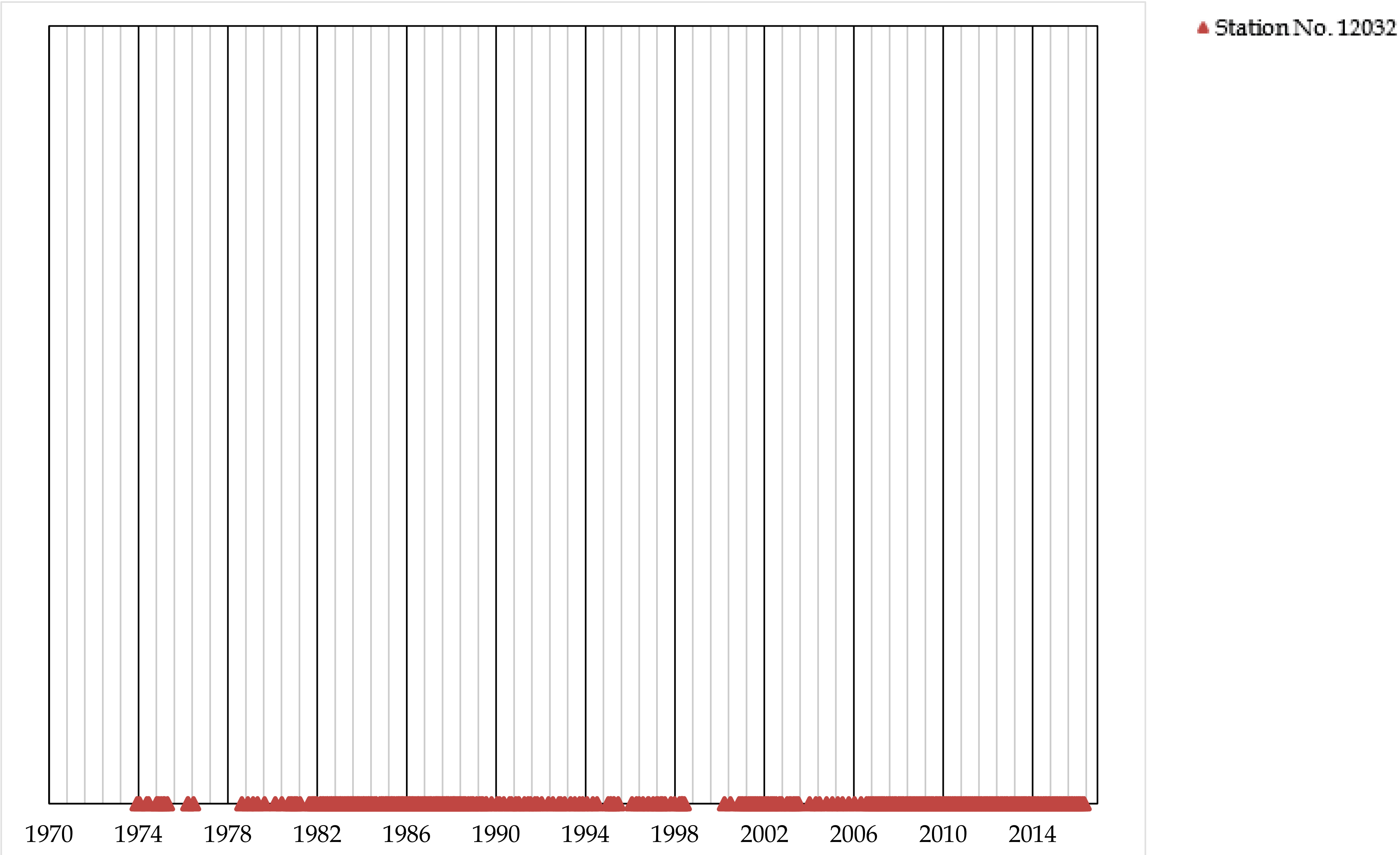


Figure G - 9. Temperature sampling dates for surface water quality monitoring stations near United States Geological Survey Gage No. 08098290 (Highbank) TIFP primary priority (all dates).

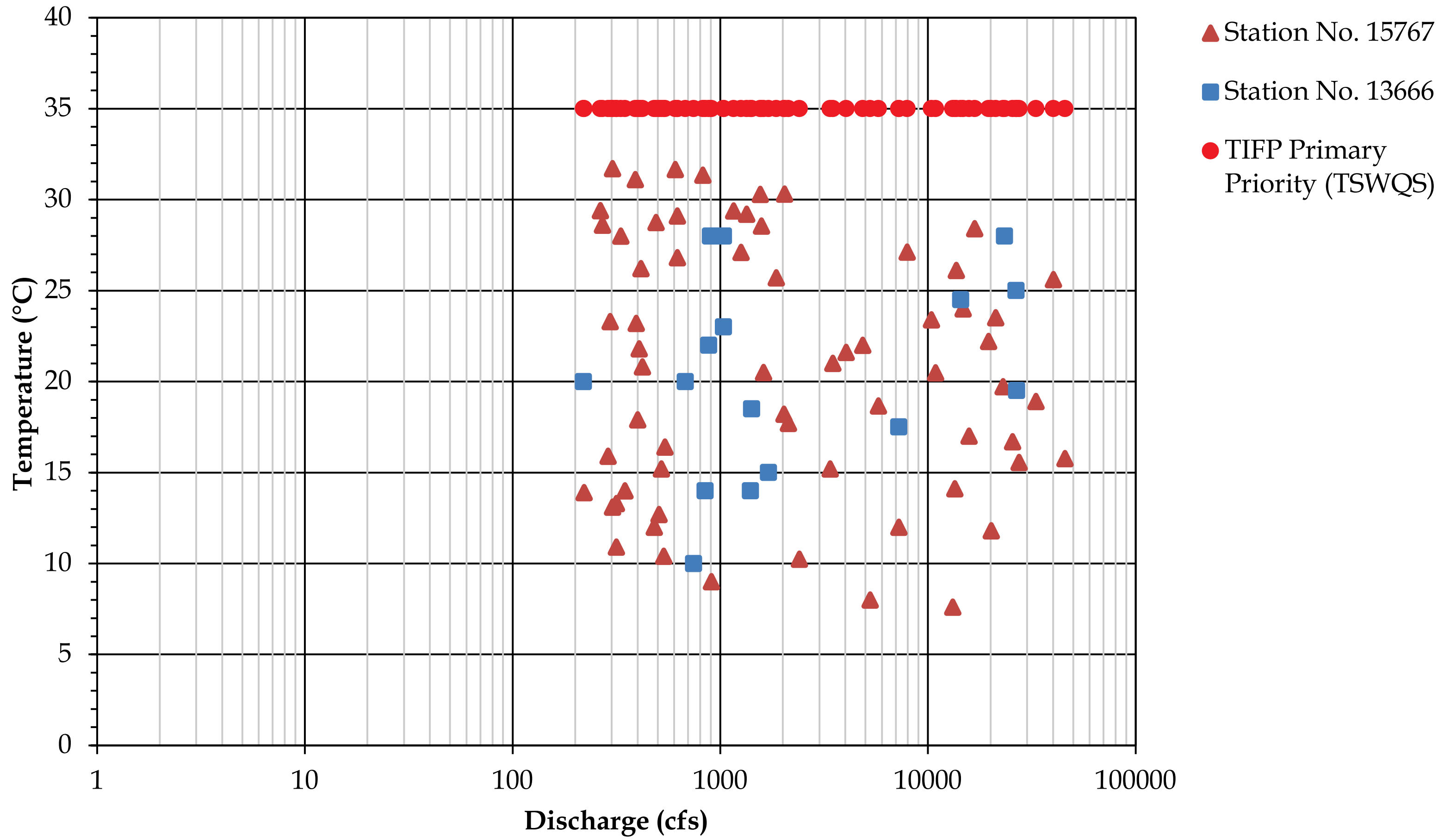


Figure G - 10. Temperature sampling data for surface water quality monitoring stations near United States Geological Survey Gage No. 08108700 (Bryan) TIFP primary priority (all dates).

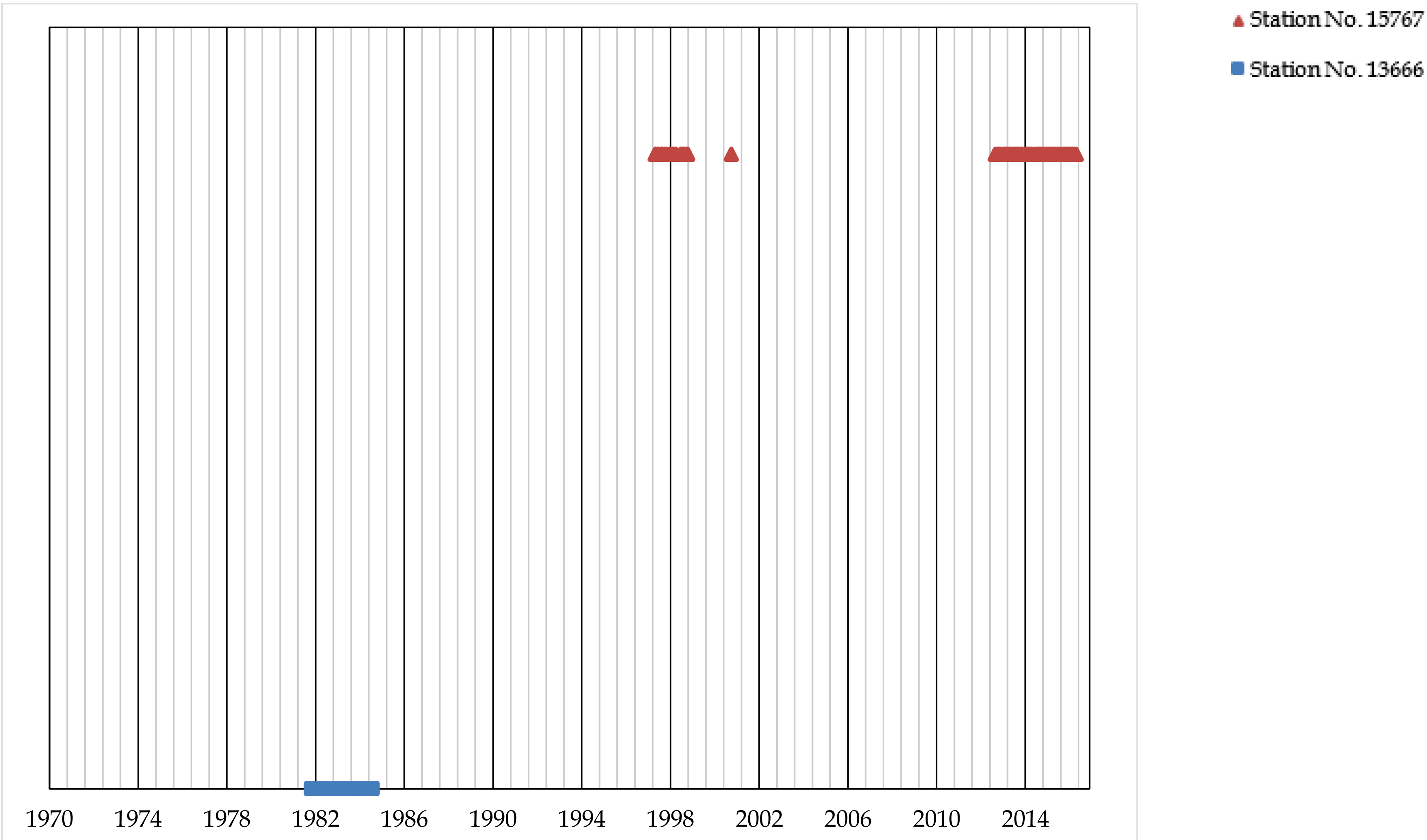


Figure G - 11. Temperature sampling dates for surface water quality monitoring stations near United States Geological Survey Gage No. 08108700 (Bryan) TIFP primary priority (all dates).

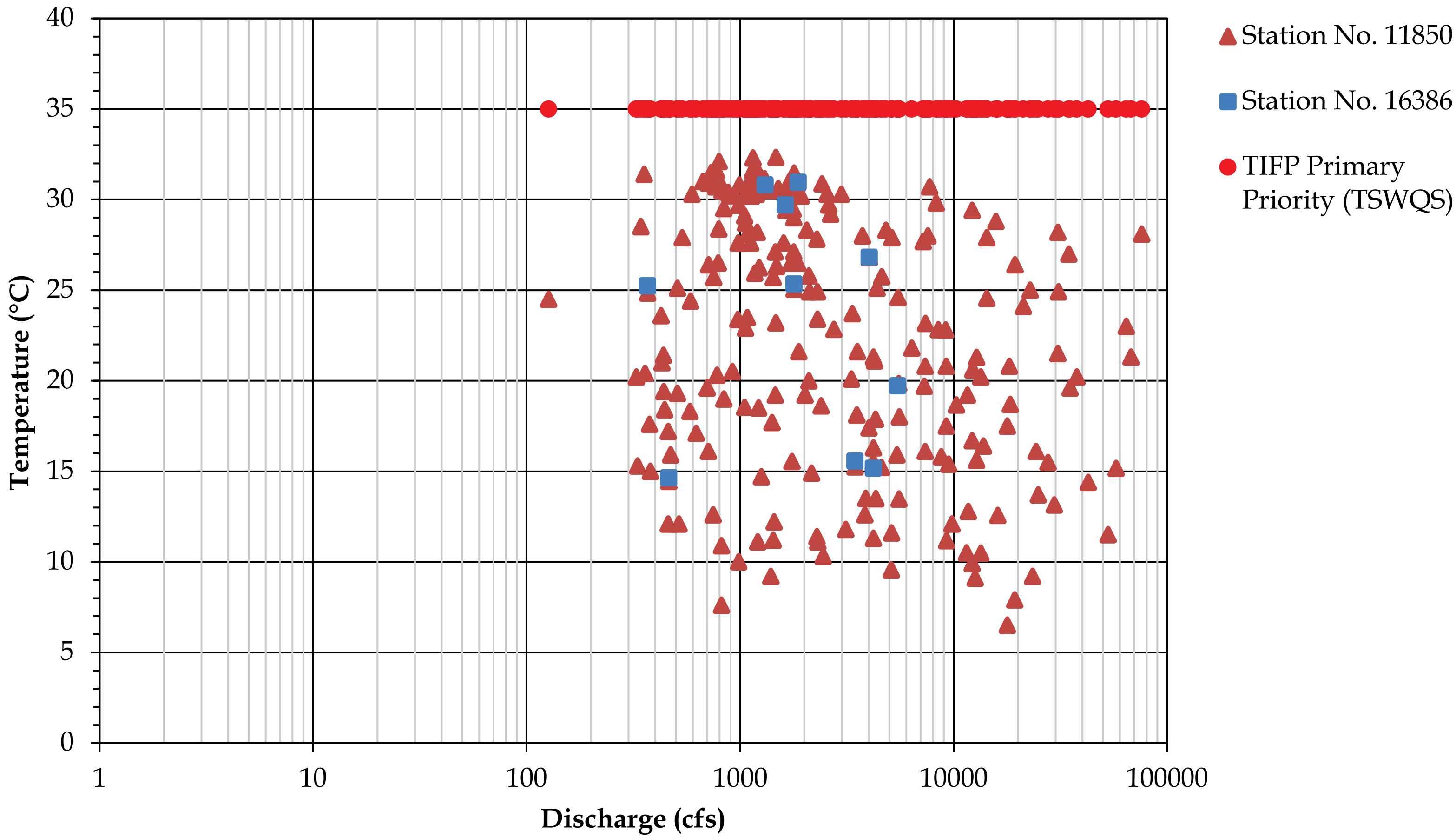


Figure G - 12. Temperature data for surface water quality monitoring stations near United States Geological Survey Gage No. 08111500 (Hempstead) TIFP primary priority (all dates).

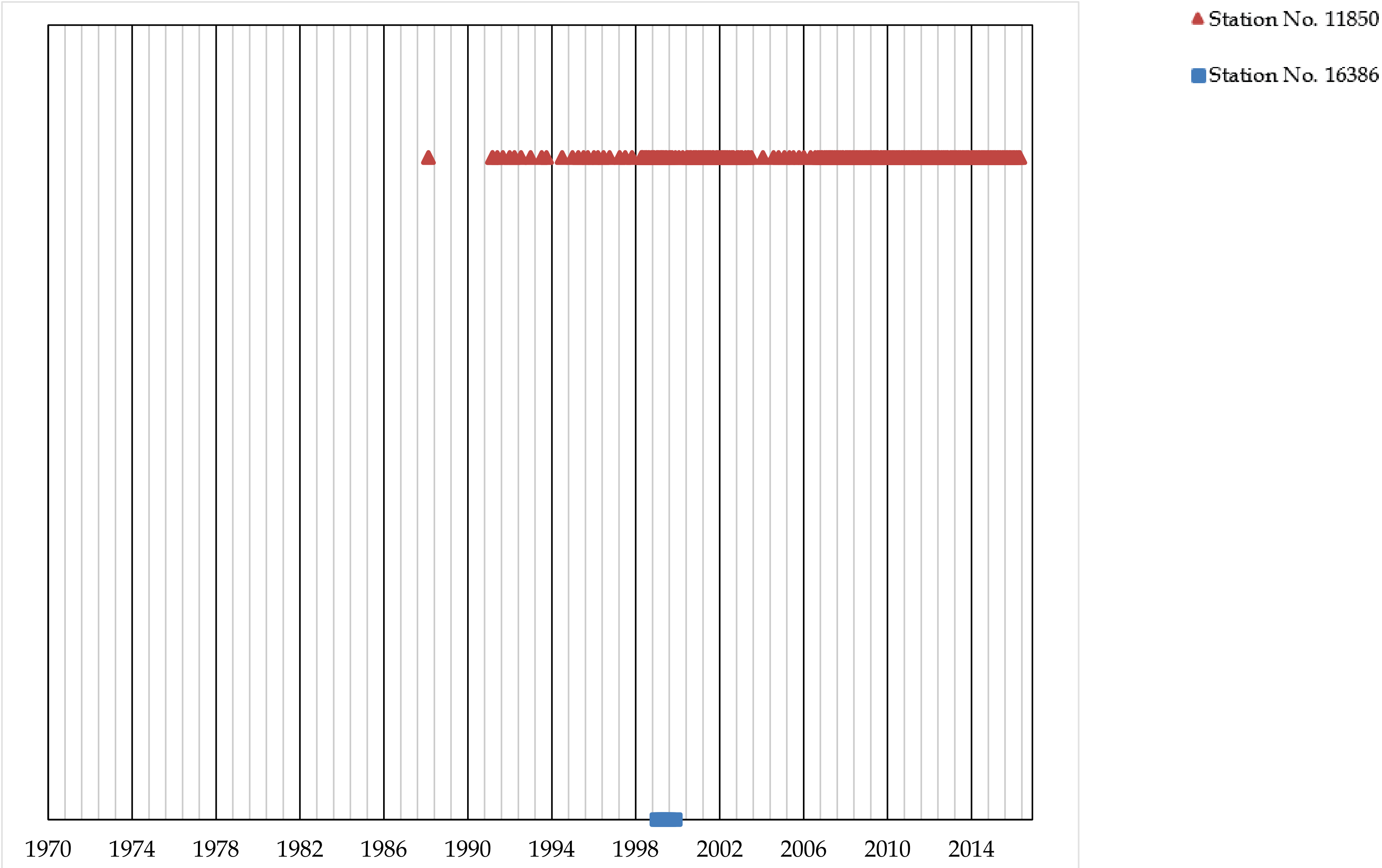


Figure G - 13. Temperature sampling dates for surface water quality monitoring stations near United States Geological Survey Gage No. 08111500 (Hempstead) TIFP primary priority (all dates).

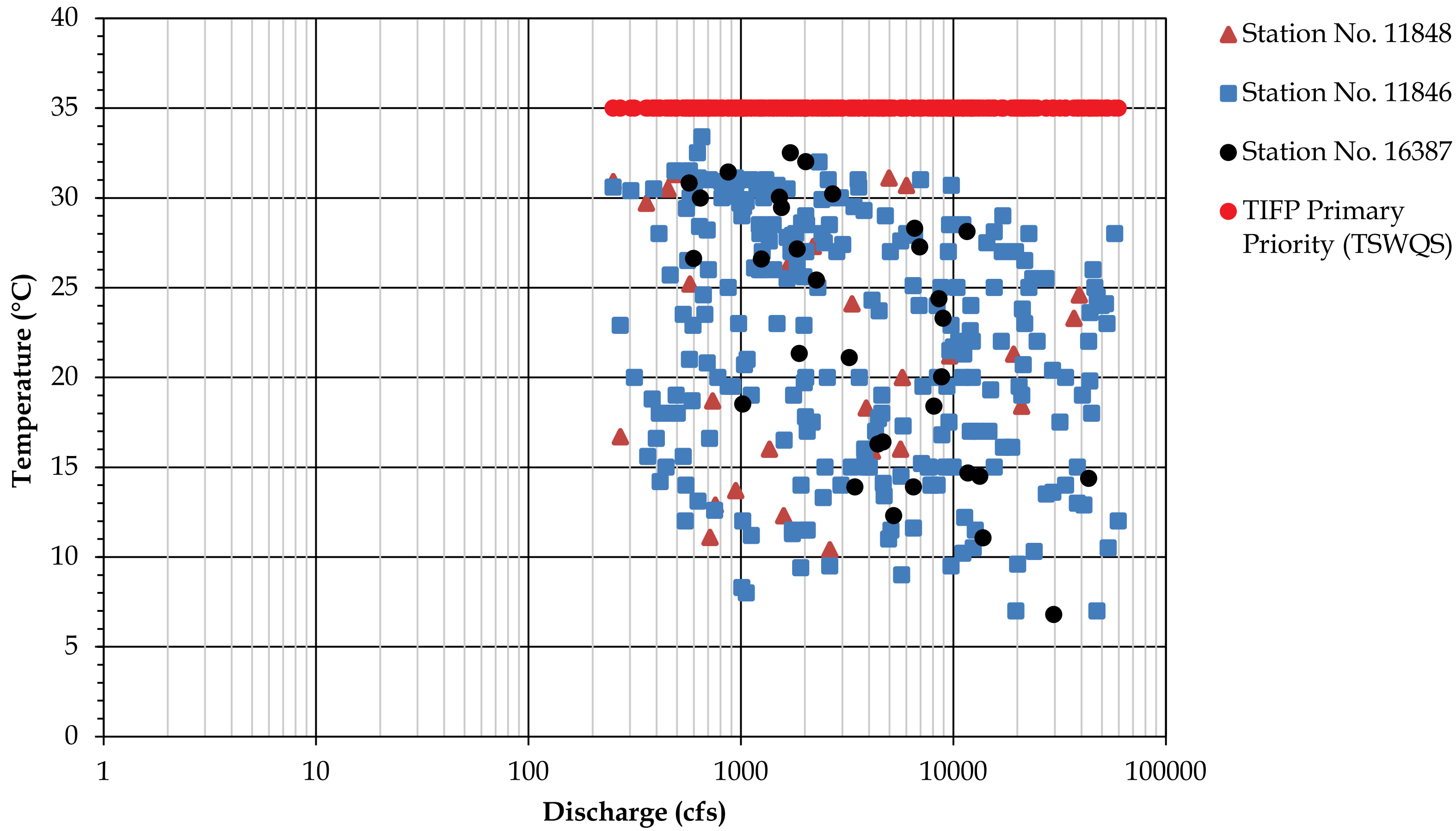


Figure G - 14. Temperature data for surface water quality monitoring stations near United States Geological Survey Gage No. 08114000 (Richmond) TIFP primary priority (all dates).

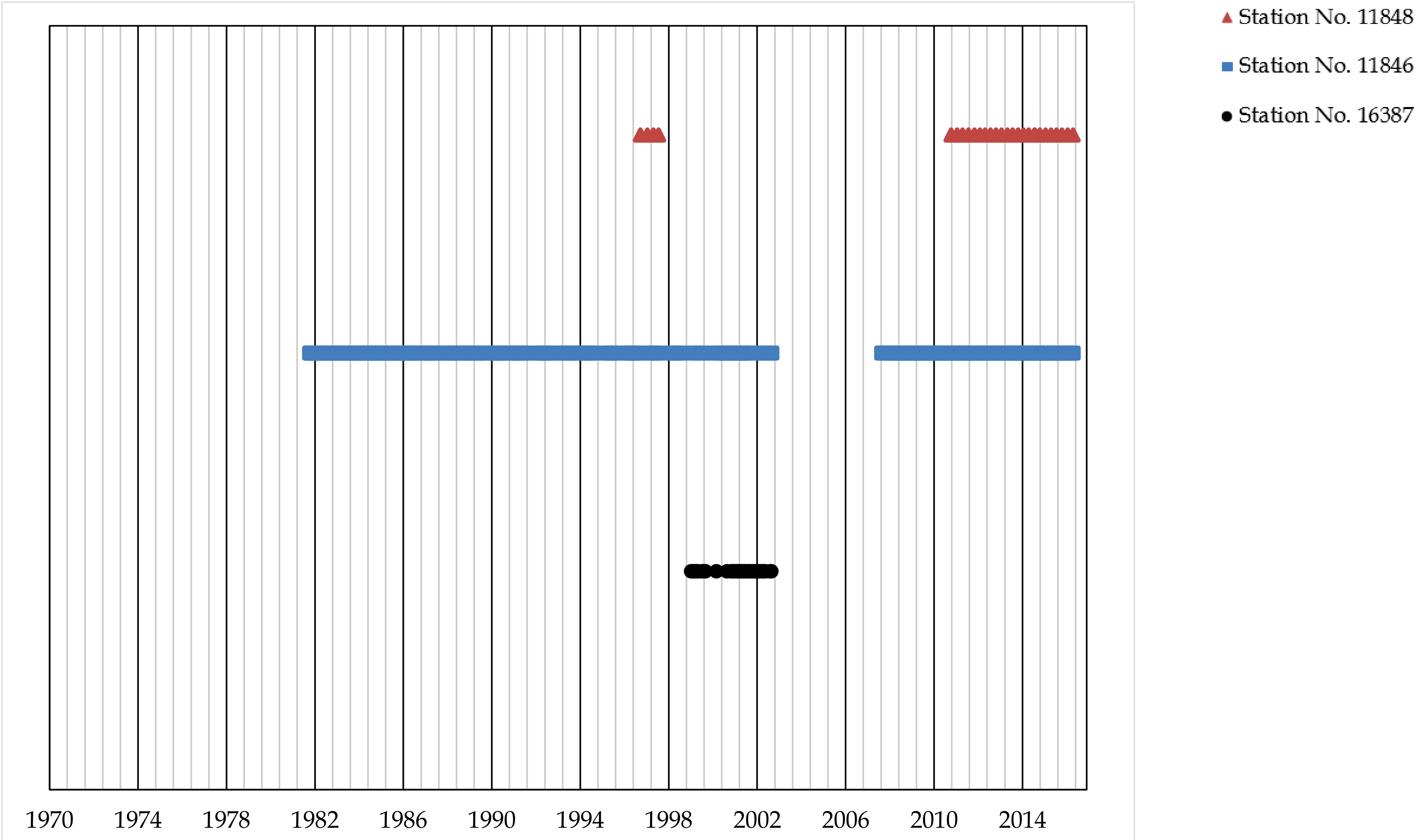


Figure G - 15. Temperature sampling dates for surface water quality monitoring stations near United States Geological Survey Gage No. 08114000 (Richmond) TIFP primary priority (all dates).

Primary Priority Goal
Dissolved Oxygen

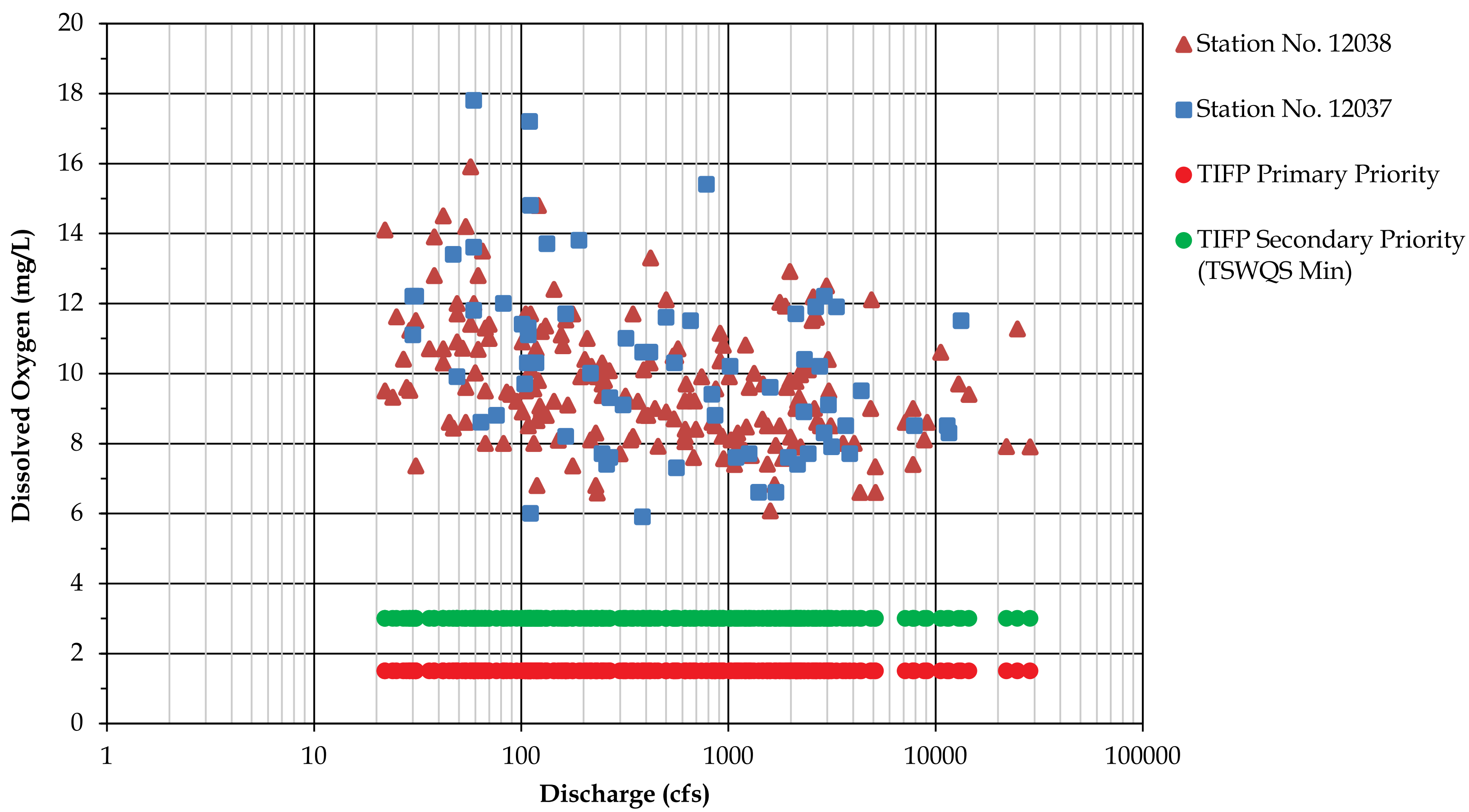


Figure G - 16. Dissolved oxygen data for surface water quality monitoring stations near United States Geological Survey Gage No. 08096500 (Waco) TIFP primary priority (all dates).

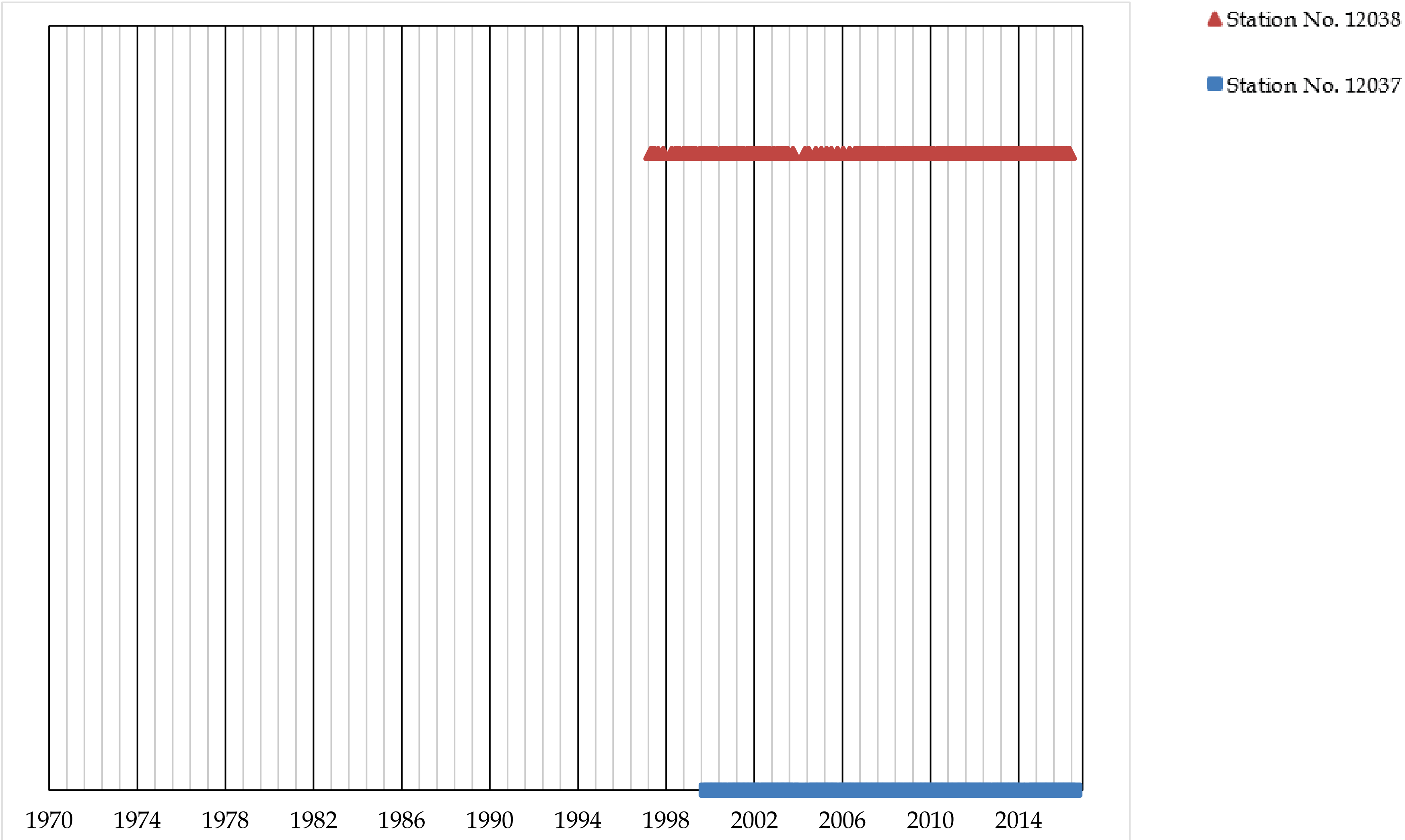


Figure G - 17. Dissolved oxygen sampling dates for surface water quality monitoring stations near United States Geological Survey Gage No. 08096500 (Waco) TIFP primary priority (all dates).

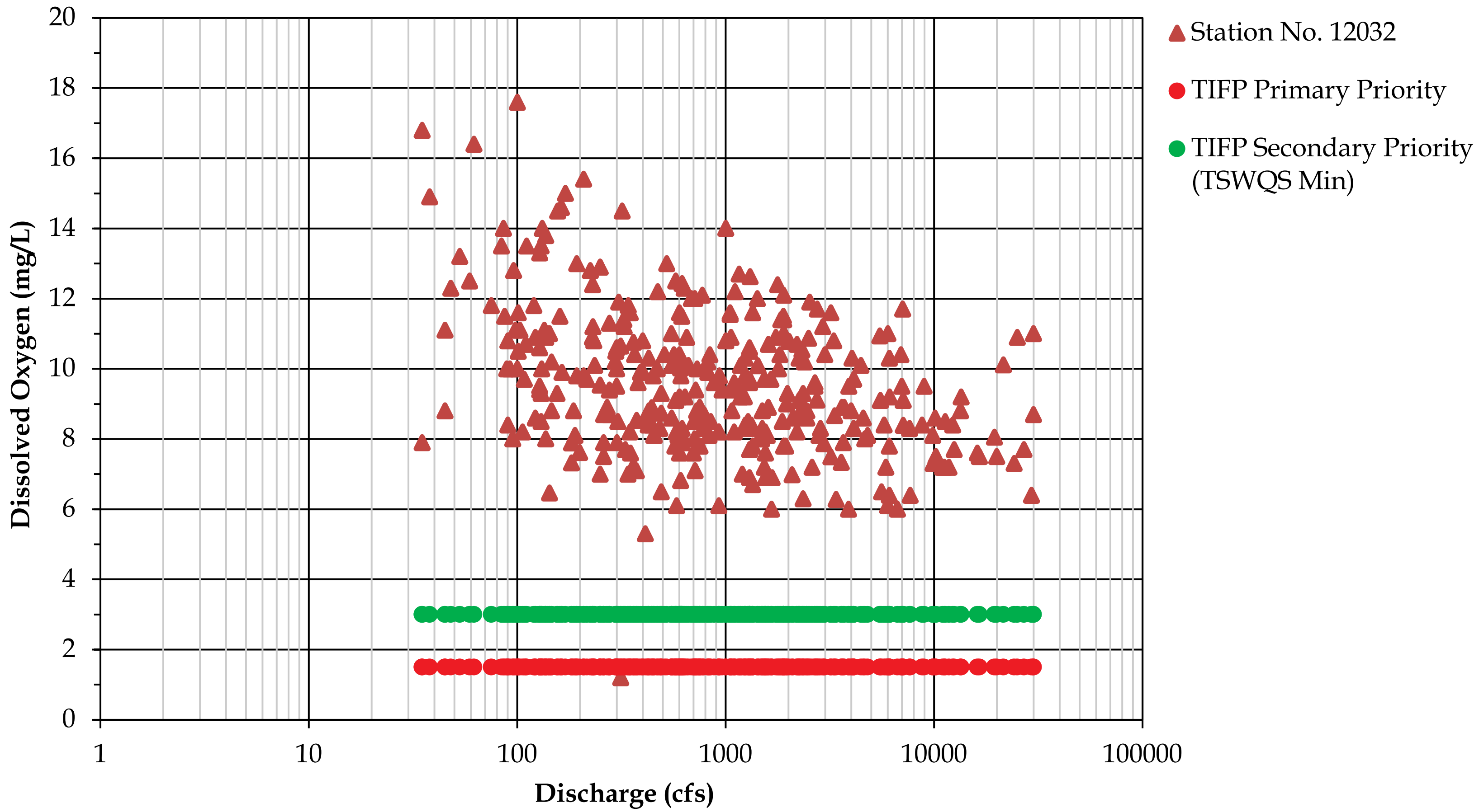


Figure G - 18. Dissolved oxygen data for surface water quality monitoring stations near United States Geological Survey Gage No. 08098290 (Highbank) TIFP primary priority (all dates).

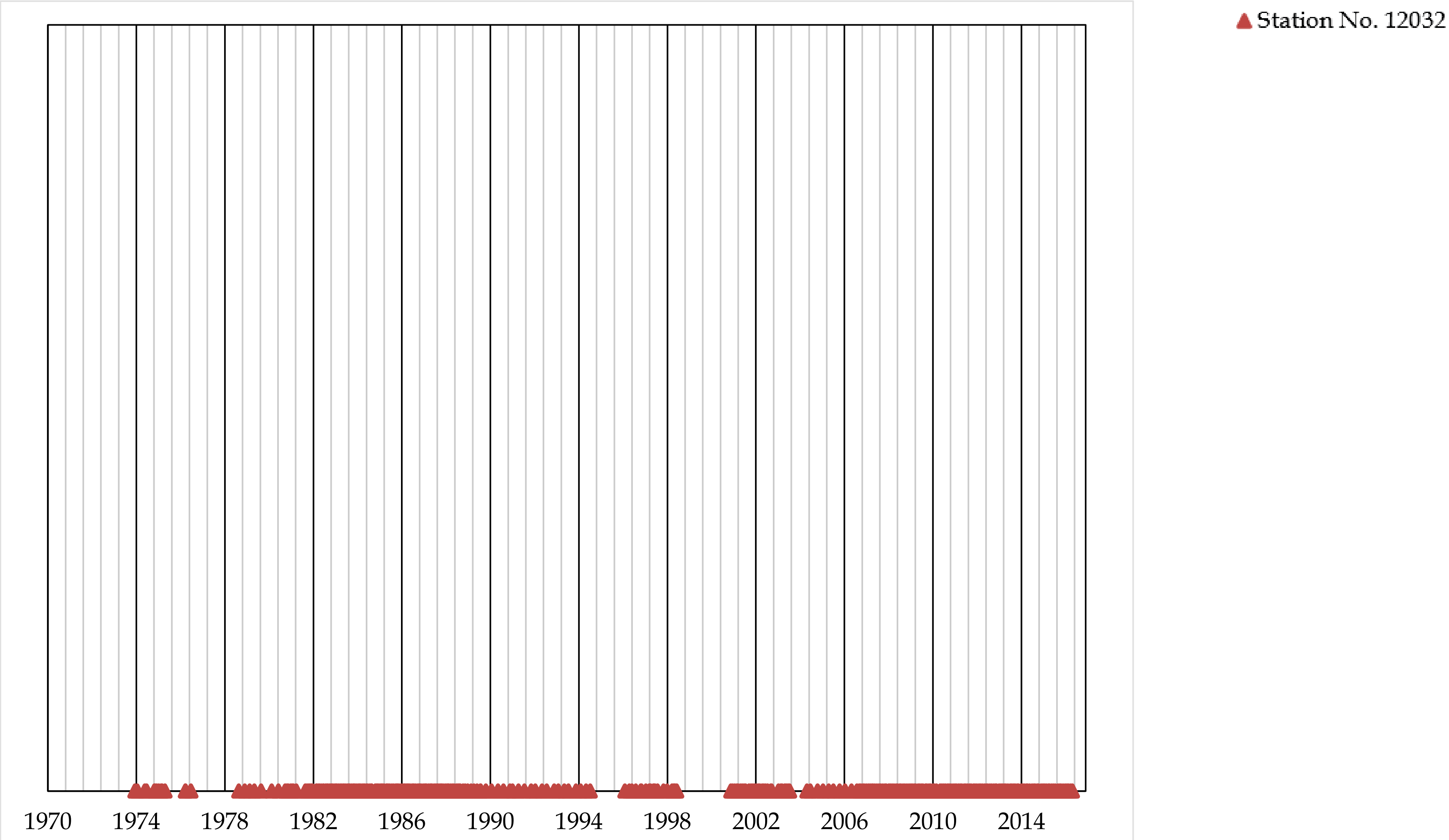


Figure G - 19. Dissolved oxygen sampling dates surface water quality monitoring stations near United States Geological Survey Gage No. 08098290 (Highbank) TIFP primary priority (all dates).

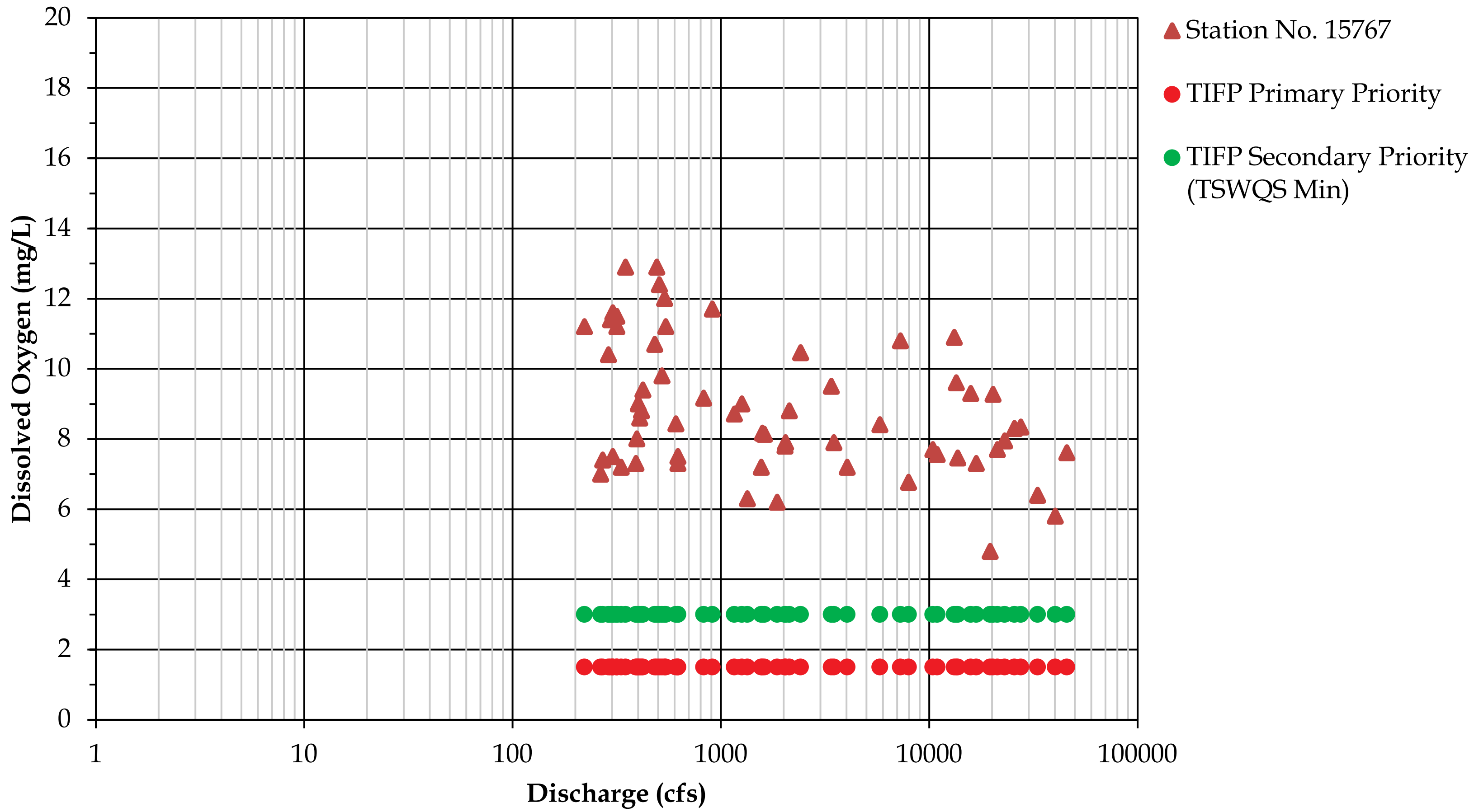


Figure G - 20. Dissolved oxygen data for surface water quality monitoring stations near United States Geological Survey Gage No. 08108700 (Bryan) TIFP primary priority (all dates).

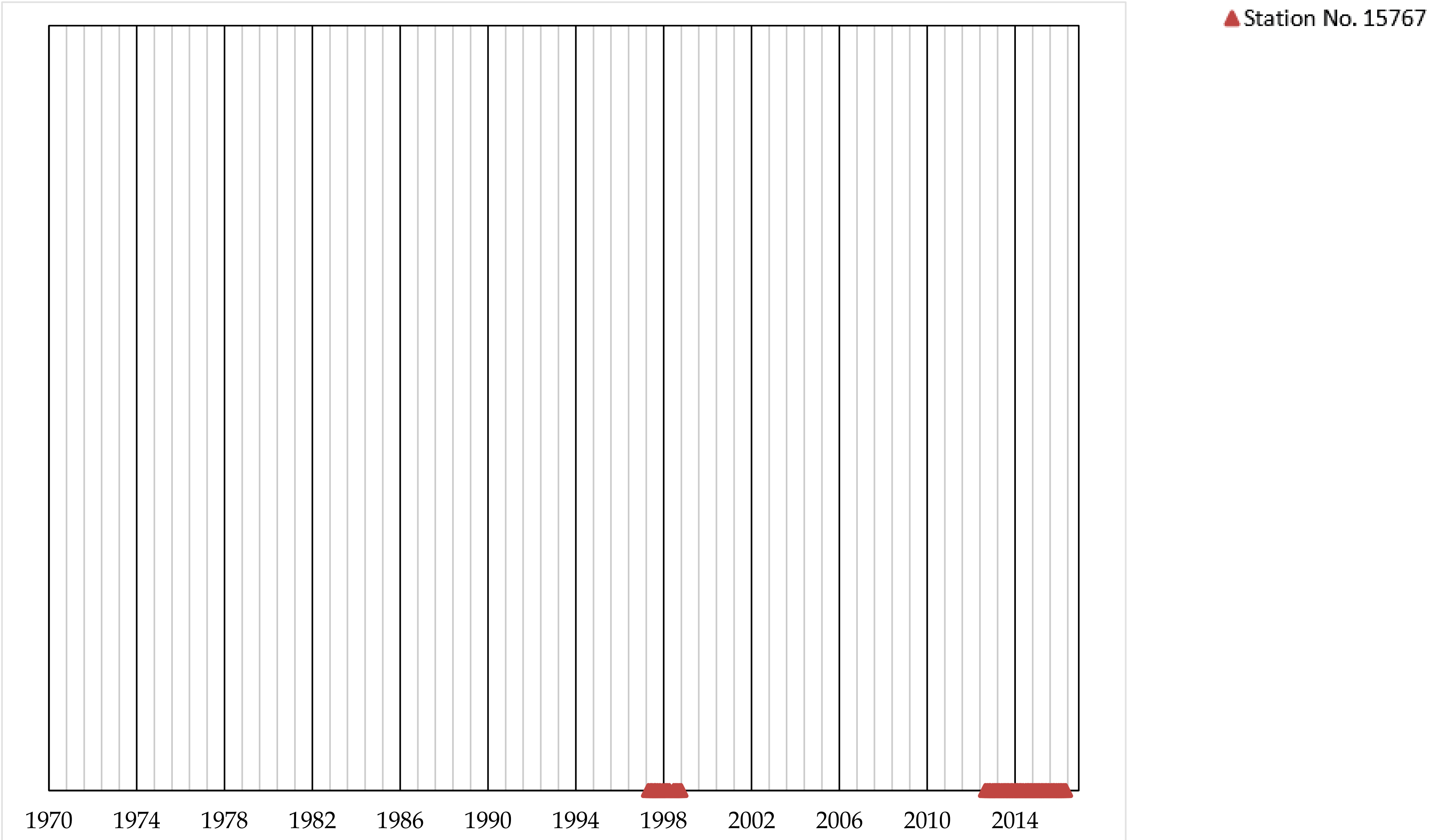


Figure G - 21. Dissolved oxygen sampling dates for surface water quality monitoring stations near United States Geological Survey Gage No. 08108700 (Bryan) TIFP primary priority (all dates).

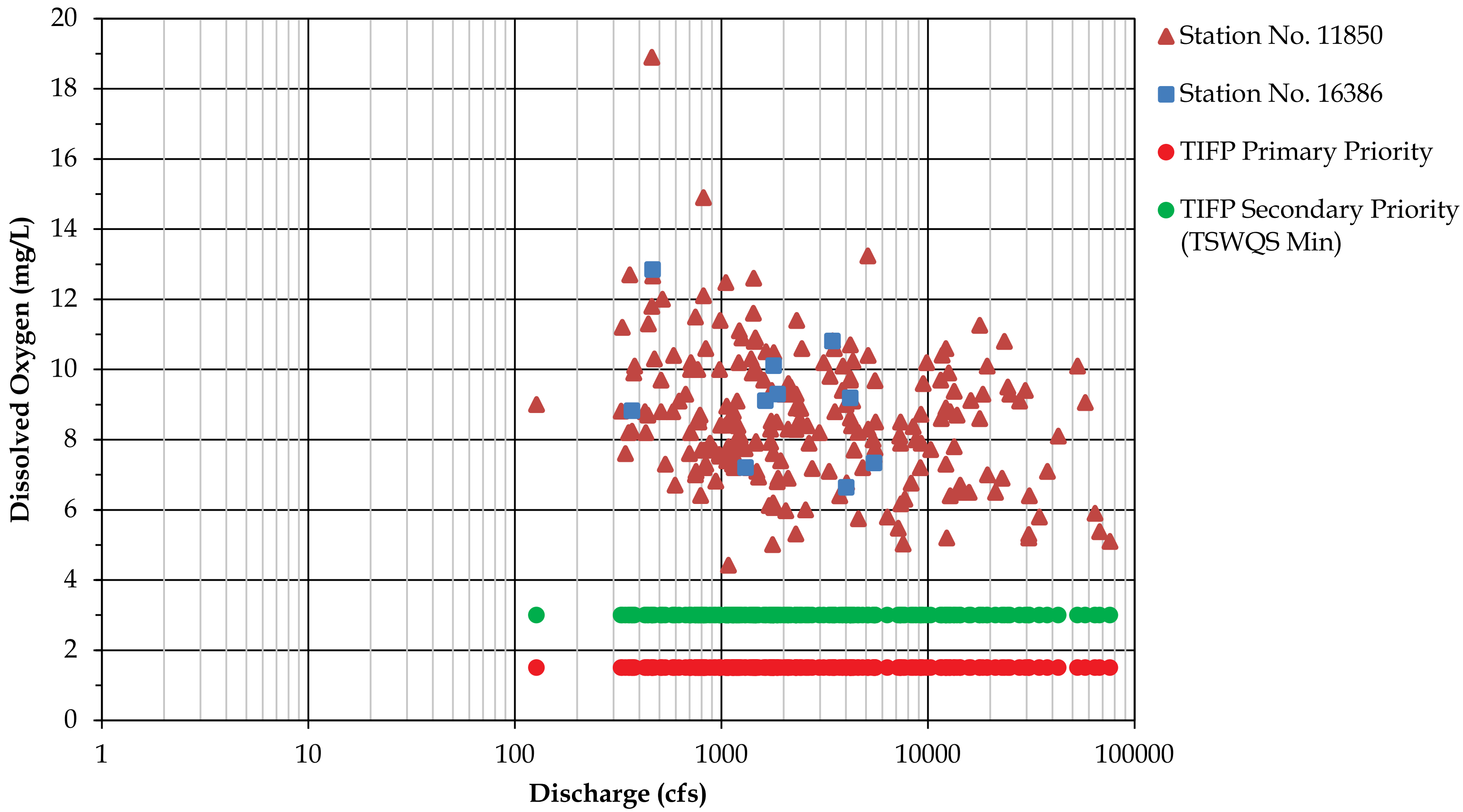


Figure G - 22. Dissolved oxygen data for surface water quality monitoring stations near United States Geological Survey Gage No. 08111500 (Hempstead) TIFP primary priority (all dates).

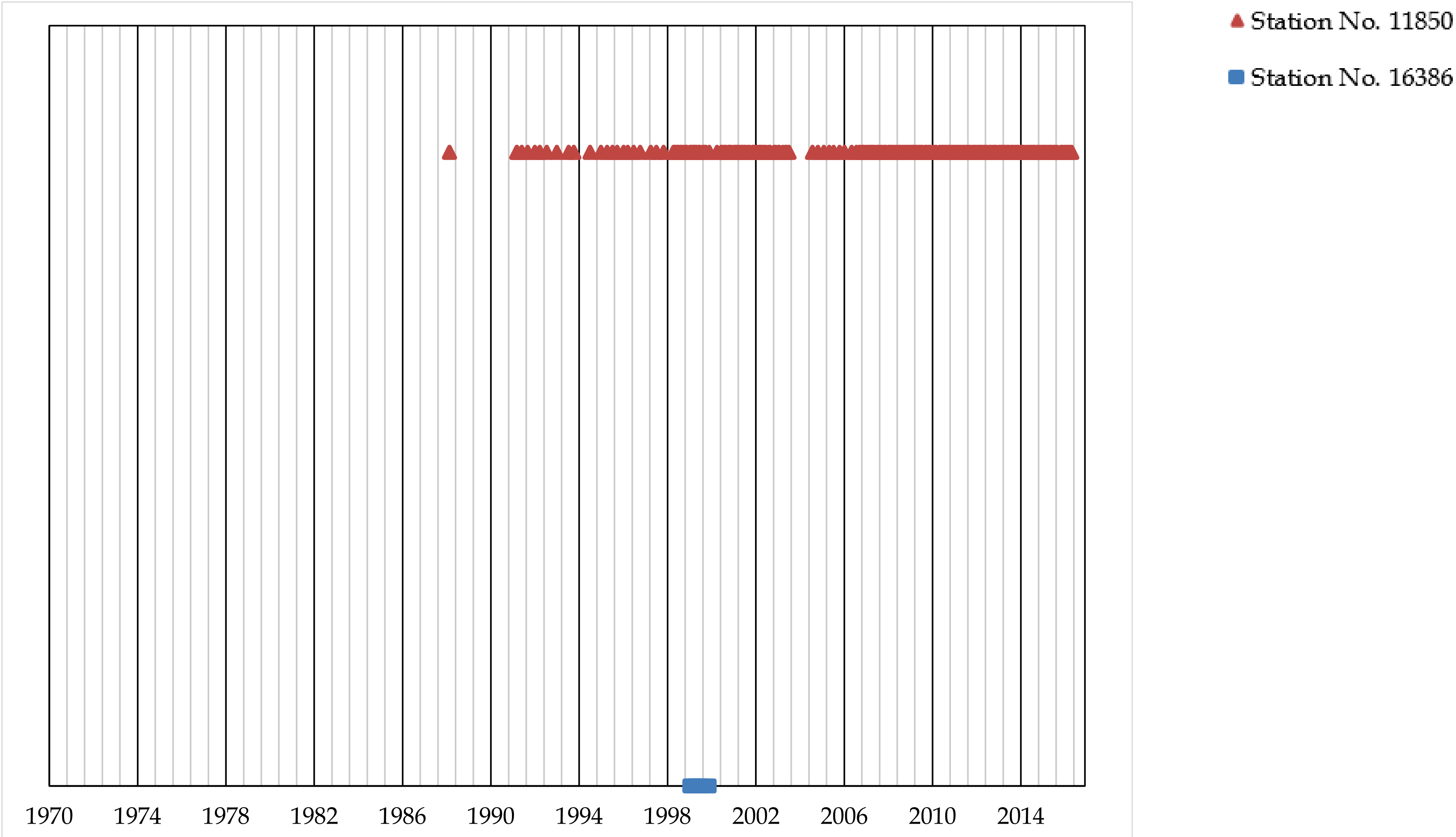


Figure G - 23. Dissolved oxygen sampling dates for surface water quality monitoring stations near United States Geological Survey Gage No. 08111500 (Hempstead) TIFP primary priority (all dates).

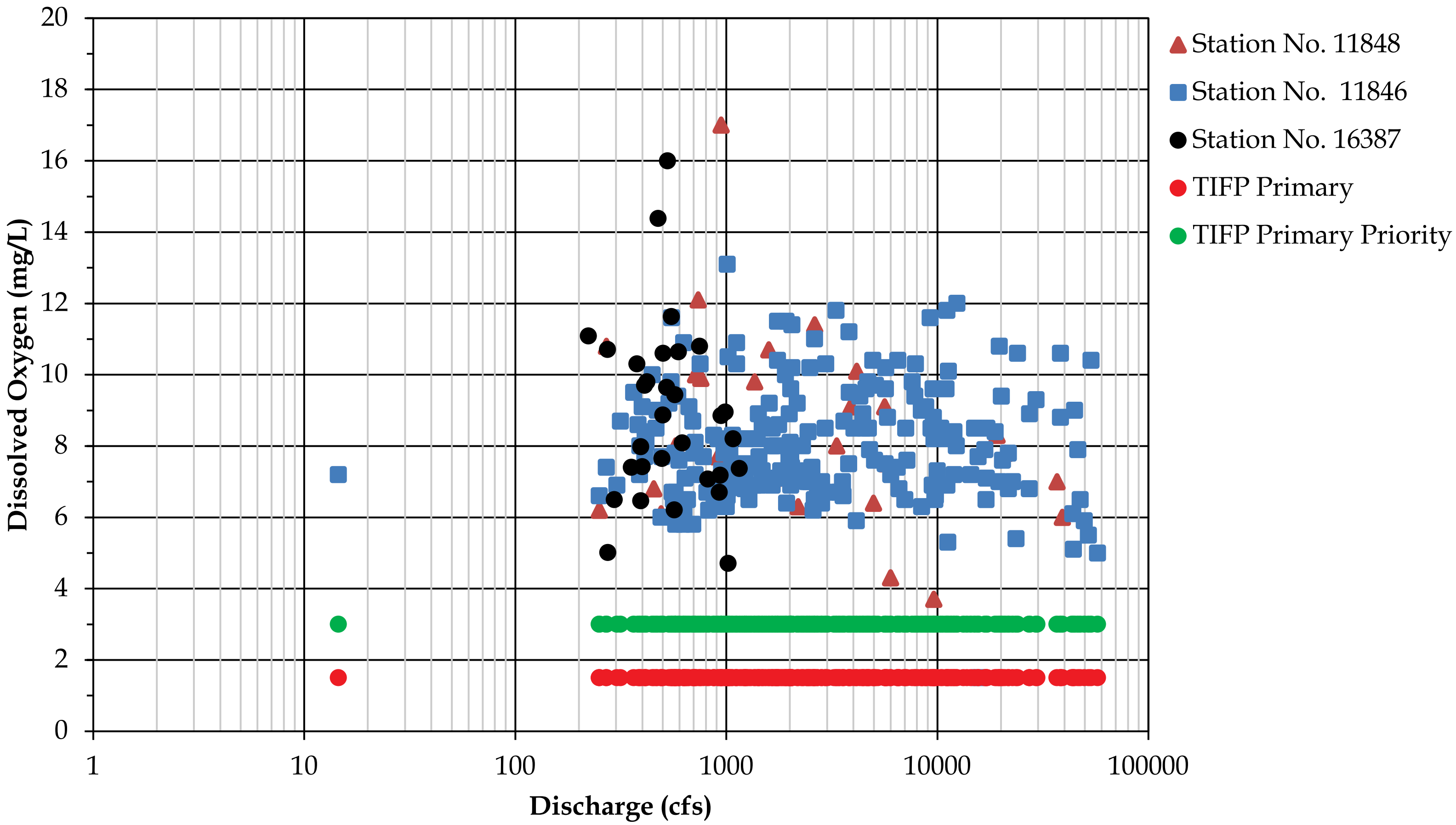


Figure G - 24. Dissolved oxygen data for surface water quality monitoring stations near United States Geological Survey Gage No. 08114000 (Richmond) TIFP primary priority (all dates).

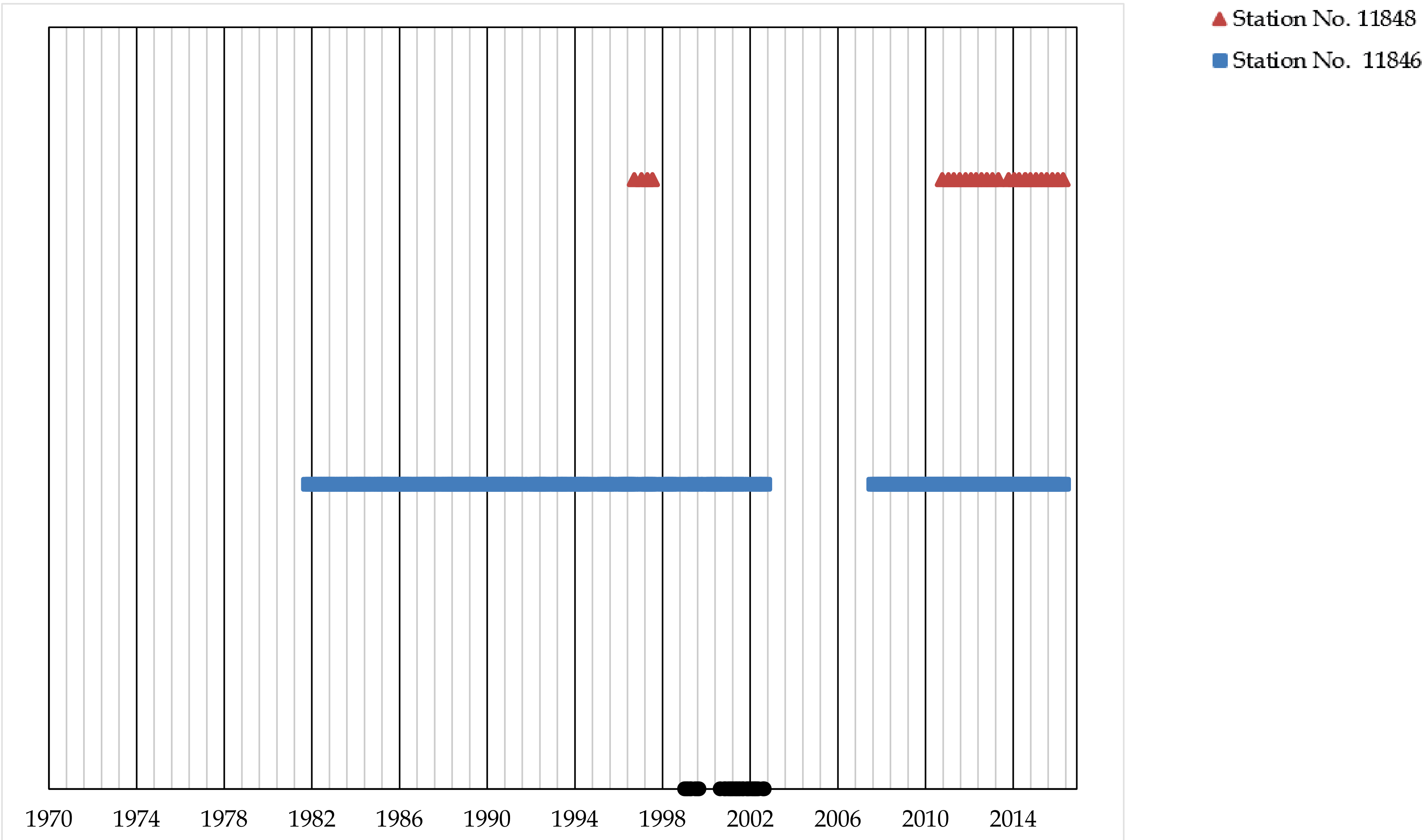


Figure G - 25. Dissolved oxygen sampling dates for surface water quality monitoring stations near United States Geological Survey Gage No. 08114000 (Richmond) TIFP primary priority (all dates).

Tier 2 and Tier 3 Goals
Between Marlin and Allens Creek TIFP Study Sites

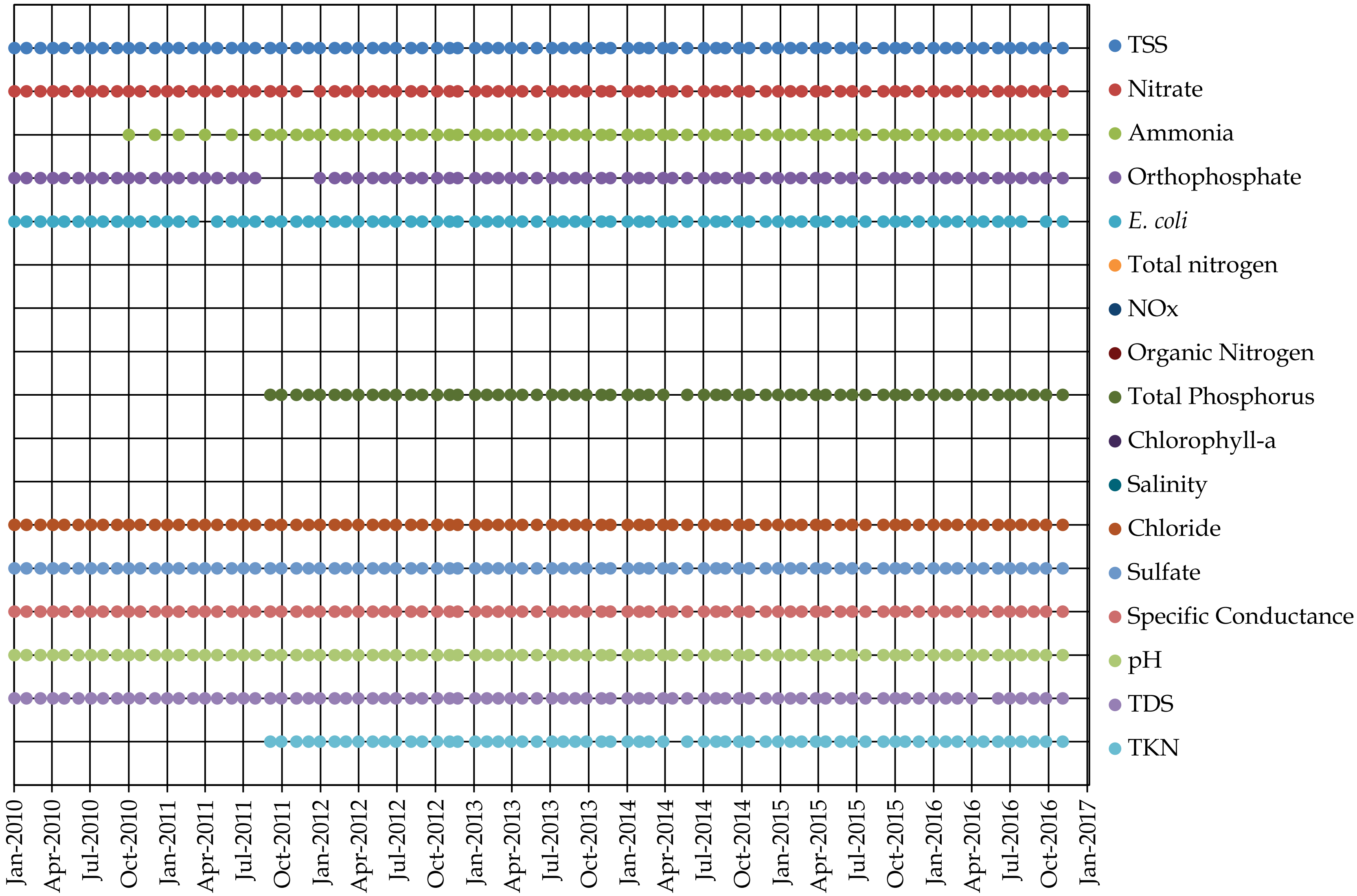


Figure G - 26. Surface water quality monitoring station data availability near Highbank (January 2010 – December 2016).

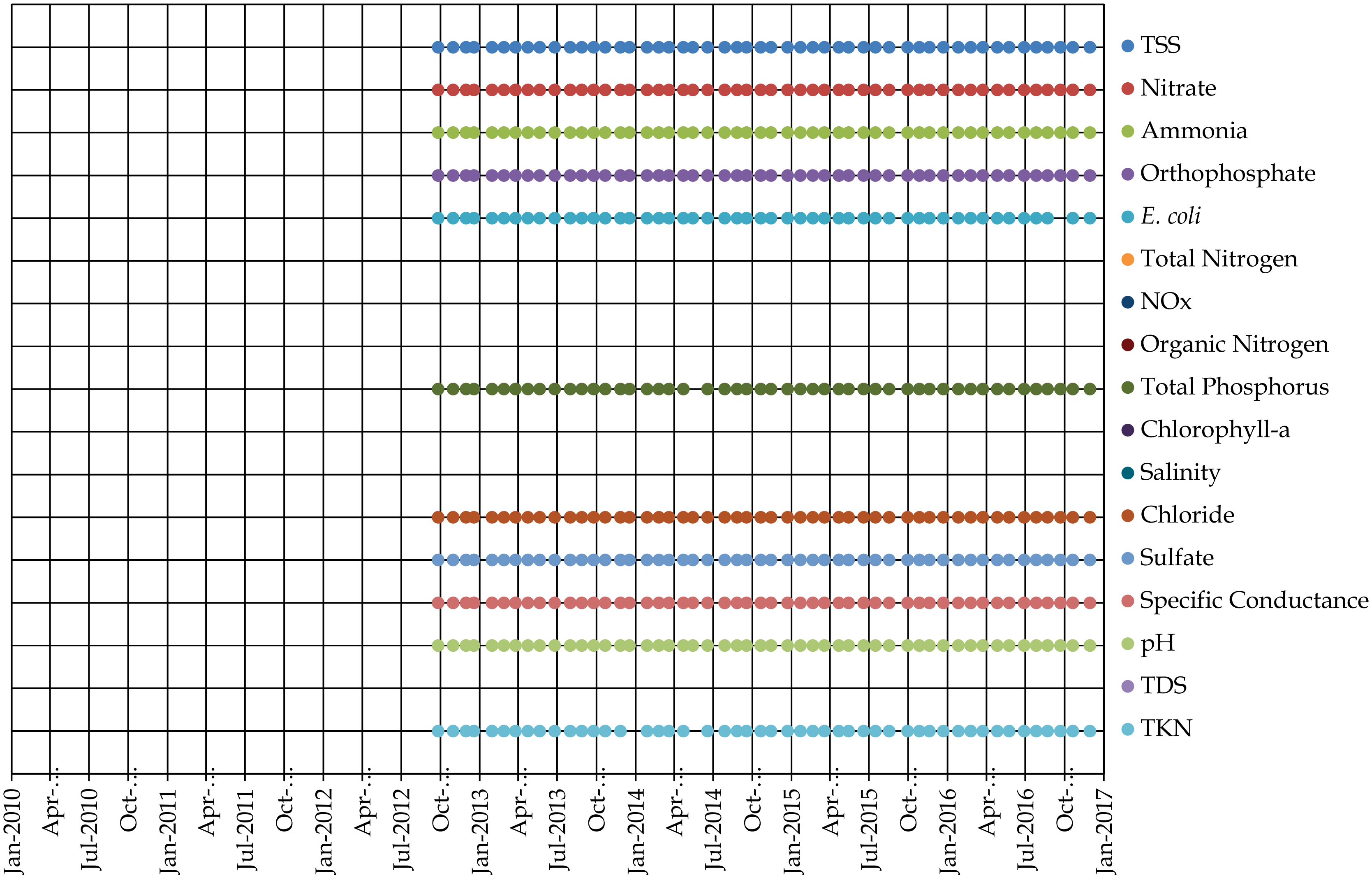


Figure G - 27. Surface water quality monitoring station data availability near Bryan (January 2010 – December 2016).

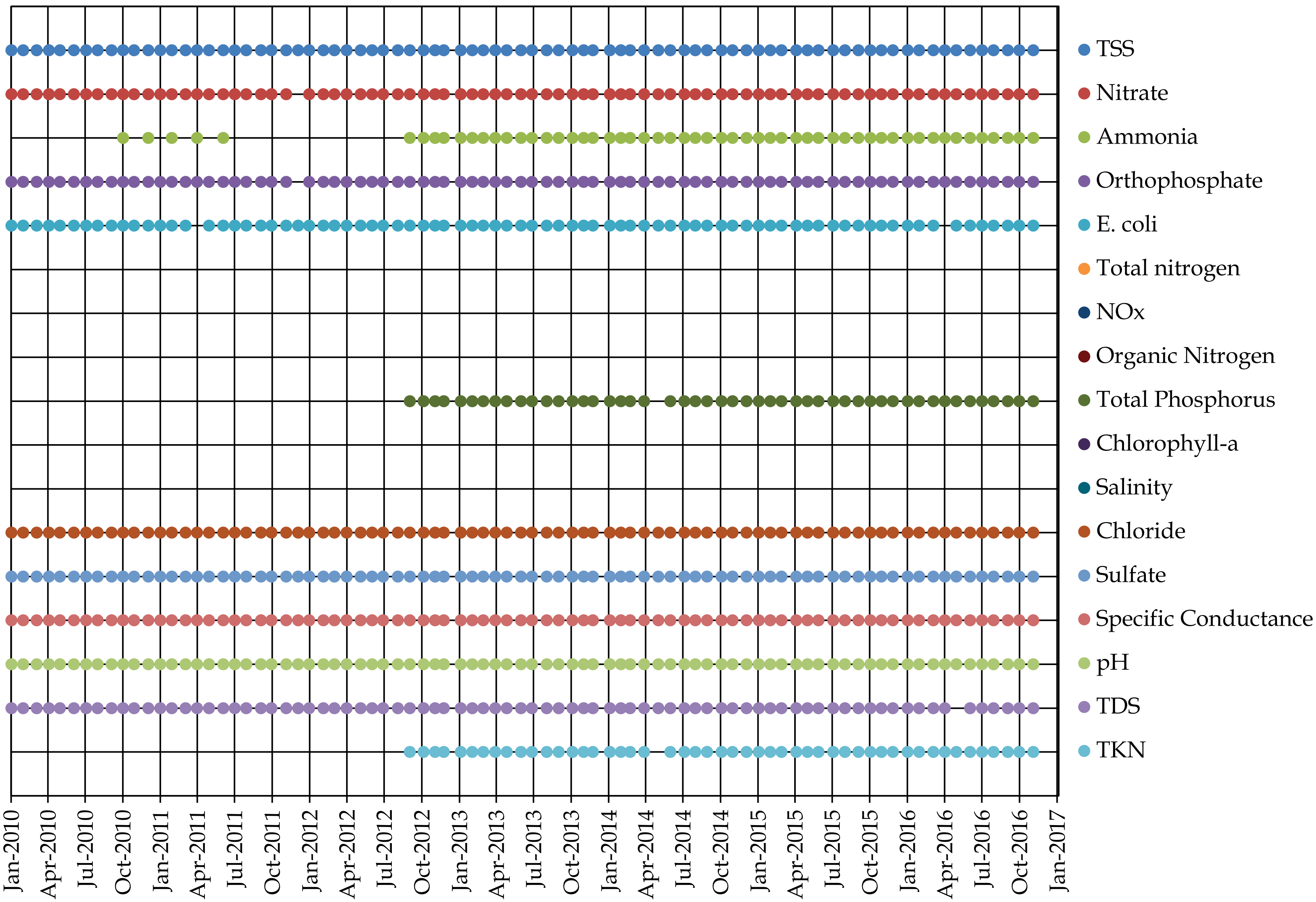


Figure G - 28. Surface water quality monitoring station data availability near Hempstead (January 2010 – December 2016).

Table G - 1. Summary of goal attainments for Tier 2 and Tier 3 parameters (January 2010 – December 2016).

Parameter	SWQM Station 12032 Near Highbank	SWQM Station 15767 Near Bryan	SWQM Station 11850 Near Hempstead
TSS	pGNA	pGNA	pGNA
Nitrate	pGA	pGA	pGA
Ammonia	pGA	pGA	pGA
Orthophosphate	pGA	pGA	pGA
E. coli	pGA	pGA	pGA
Total nitrogen	No data	No data	No data
NO_x	No data	No data	No data
Organic nitrogen	No data	No data	No data
Total phosphorus	pGA	pGA	pGA
Chlorophyll-*a*	No data	No data	No data
Salinity	No data	No data	No data
Chloride	pGA	pGA	pGA
Sulfate	pGA	pGA	pGA
Specific conductance	pGA	pGA	pGA
pH	pGA	pGA	pGA
TDS	pGA	No data	pGA
TKN	No criteria	No criteria	No criteria

Field codes: GA = goal achievement; pGA = preliminary assessment of goal achievement
GN = goal non-achievement; pGNA = preliminary assessment of goal non-achievement

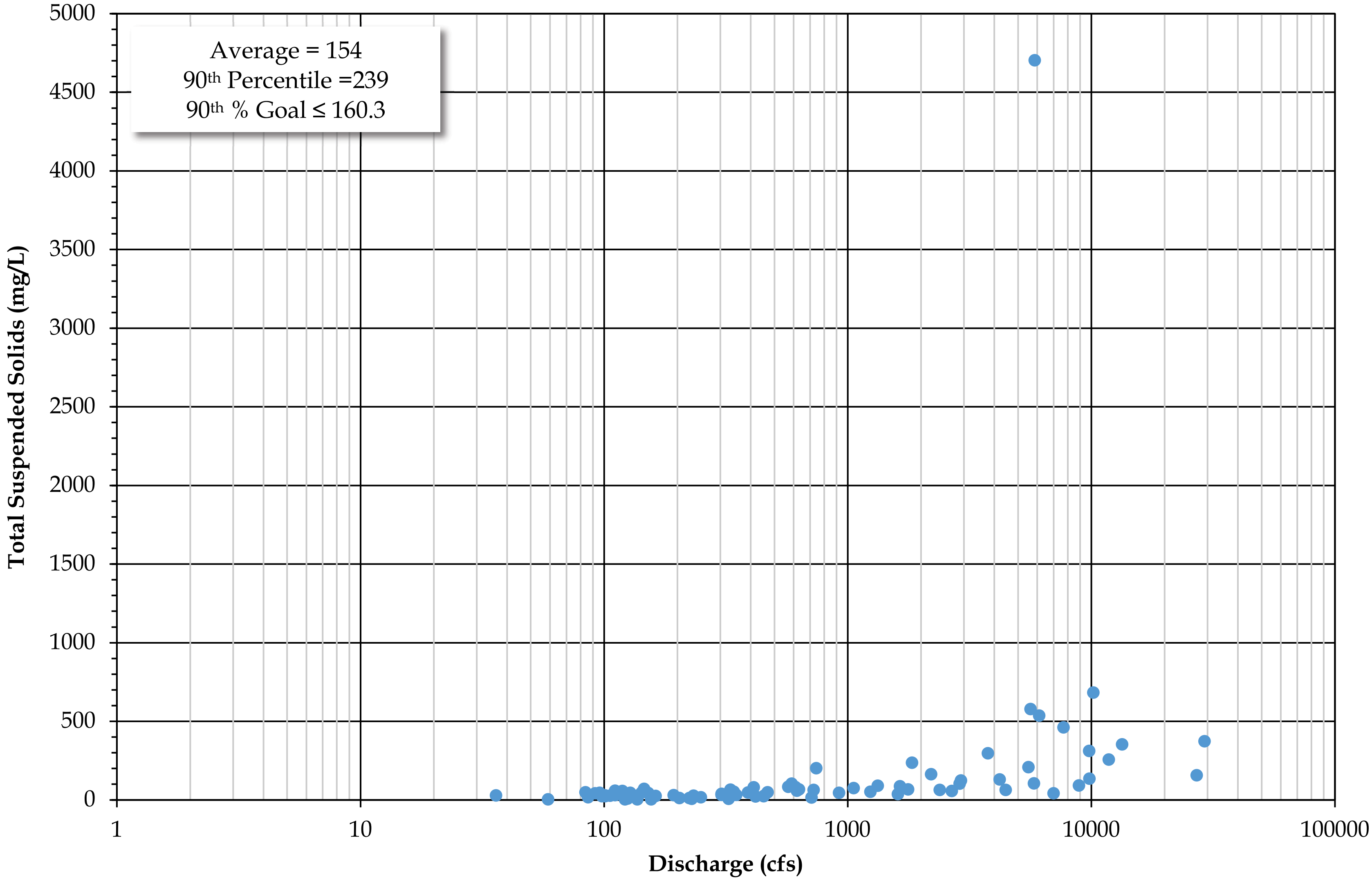


Figure G - 29. Total suspended solids for surface water quality monitoring Station 12032 near Highbank.

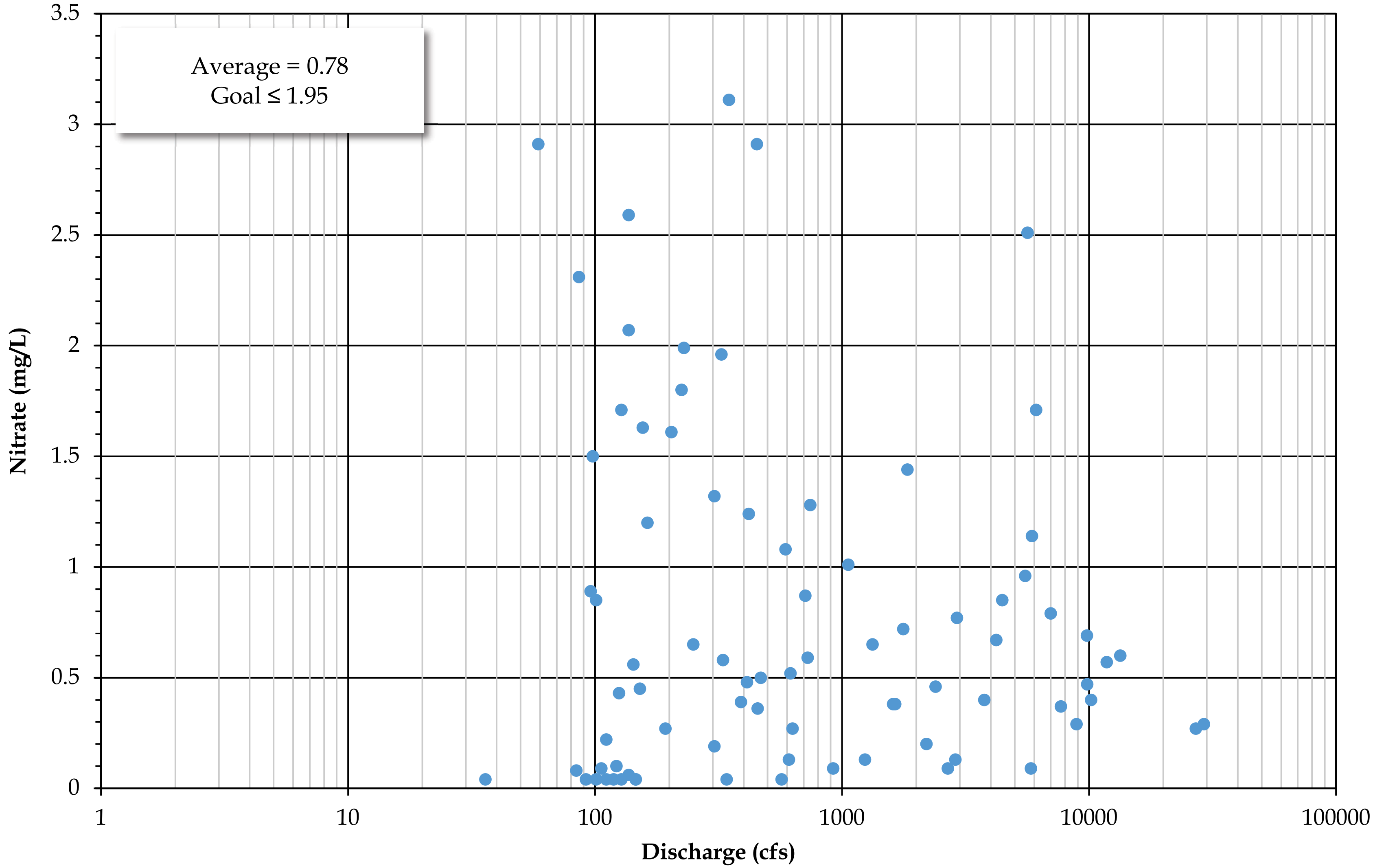


Figure G - 30. Nitrate for surface water quality monitoring Station 12032 near Highbank.

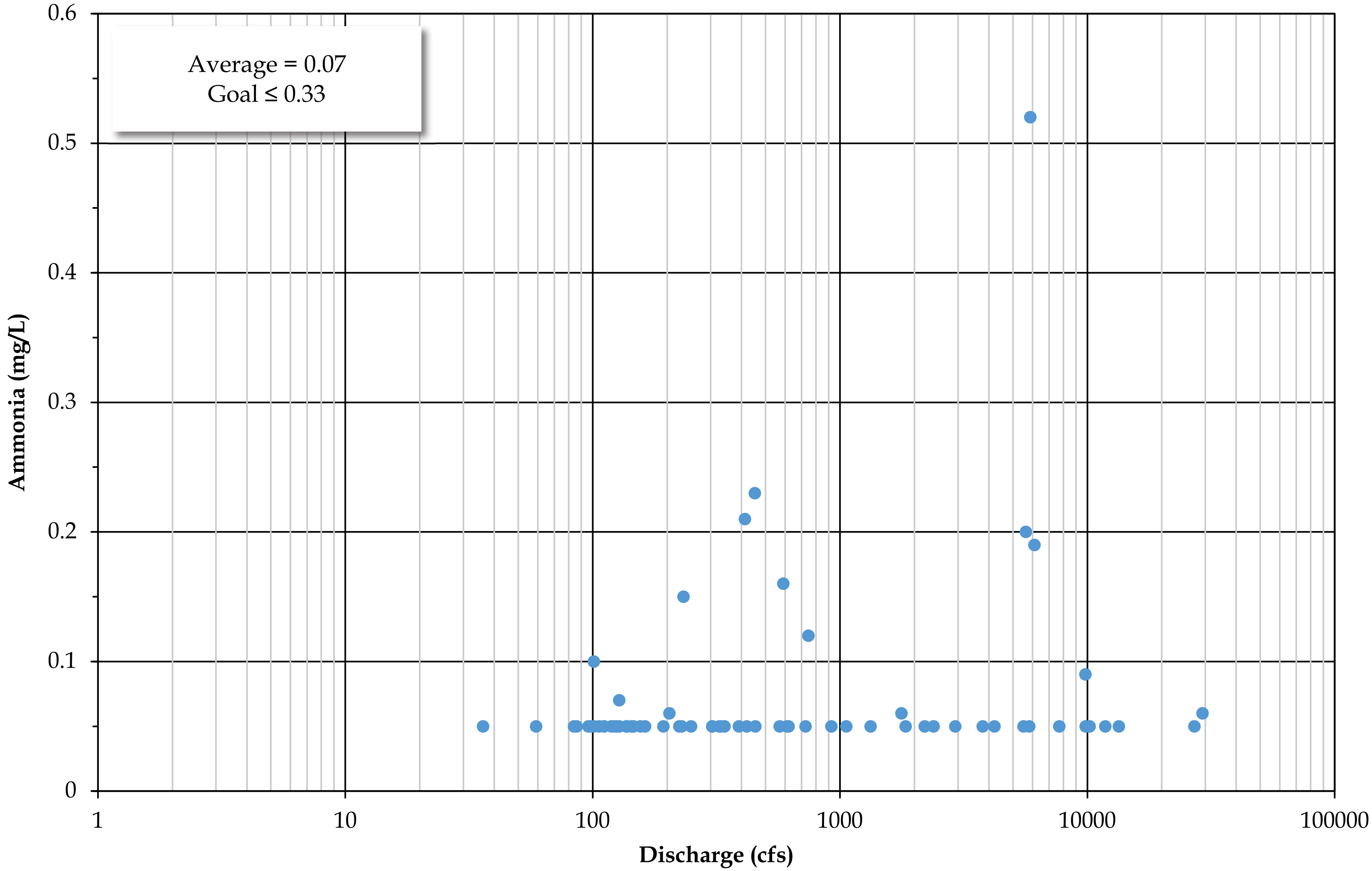


Figure G - 31. Ammonia for surface water quality monitoring Station 12032 near Highbank.

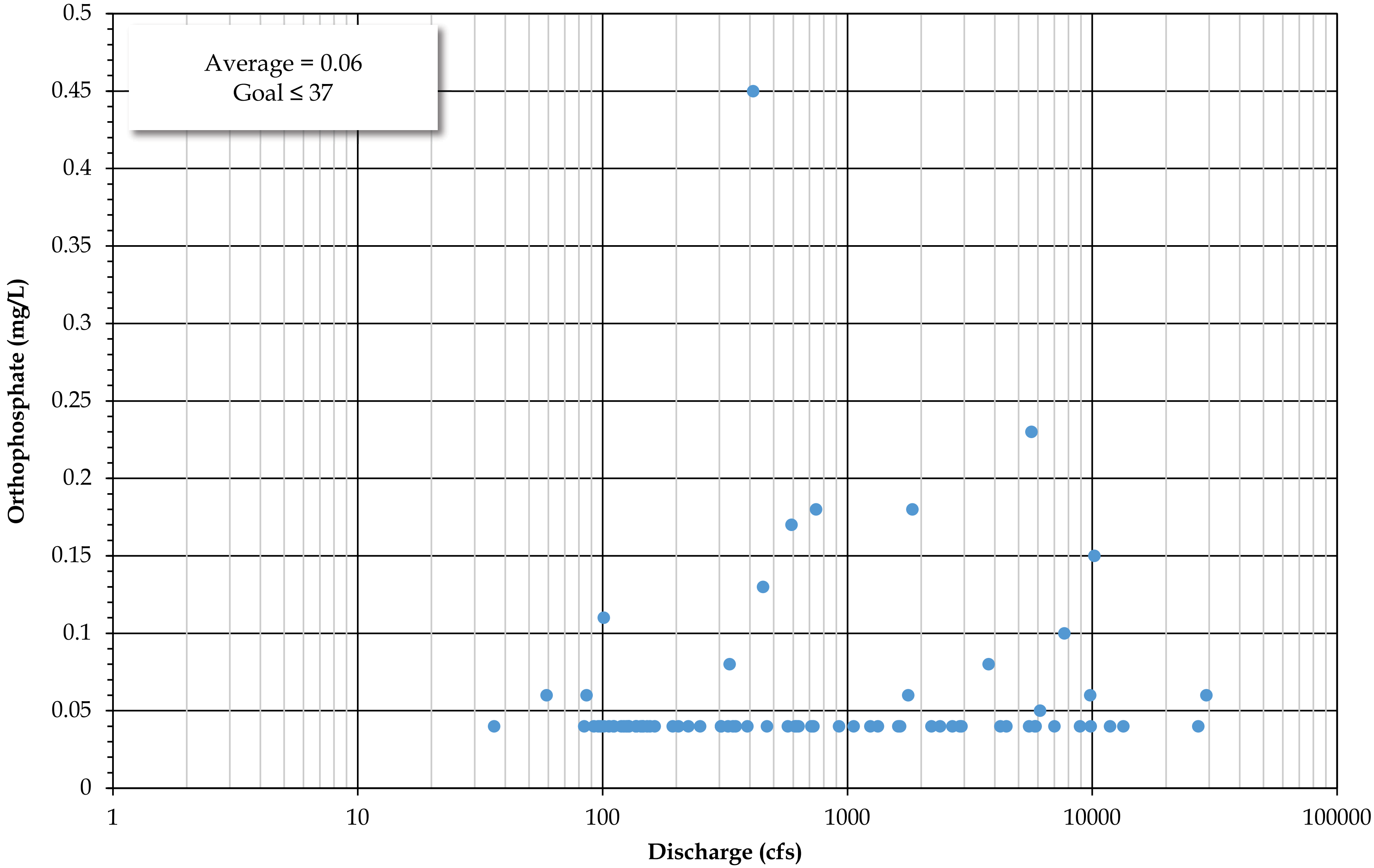


Figure G - 32. Orthophosphate for surface water quality monitoring Station 12032 near Highbank.

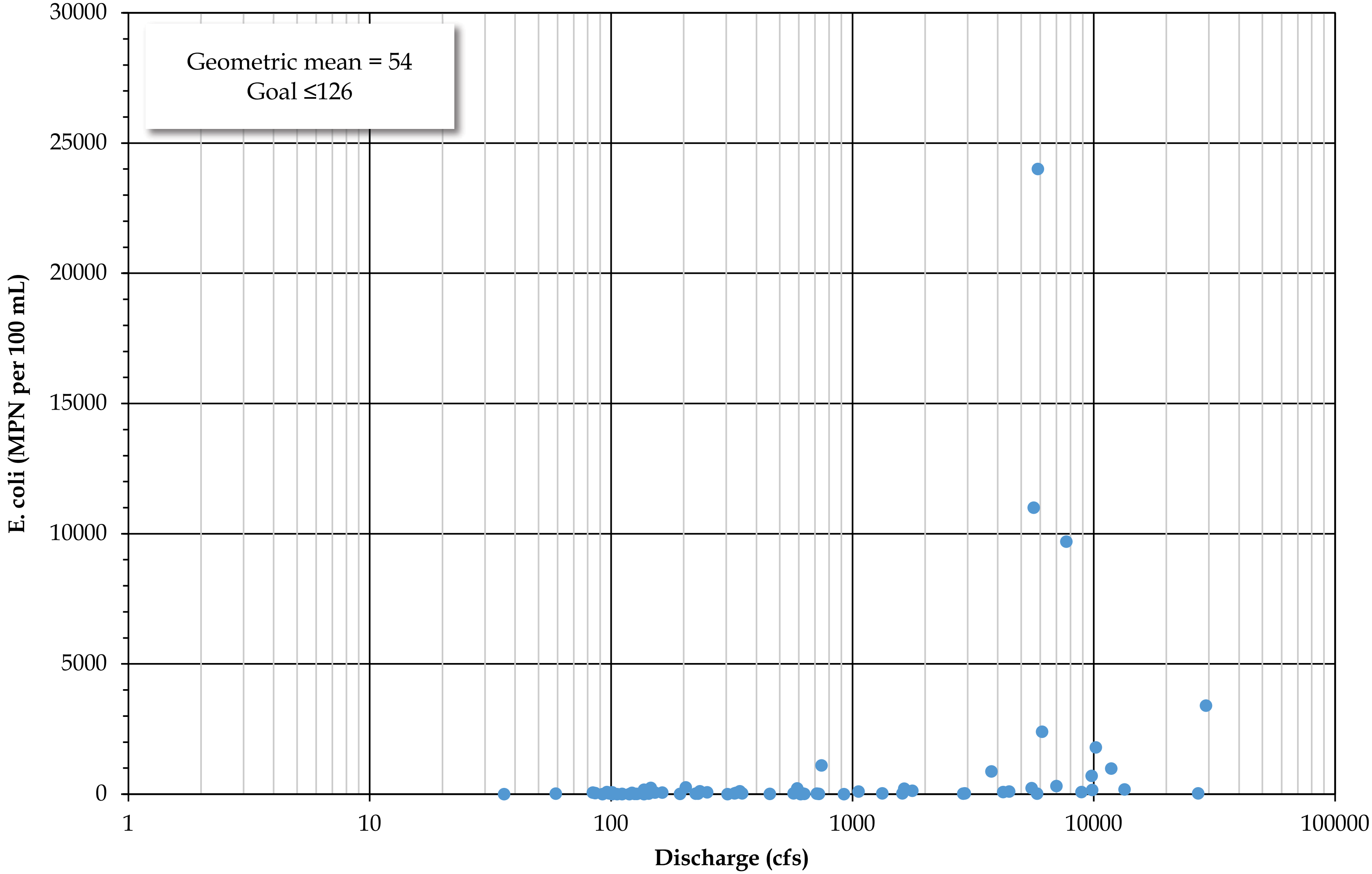


Figure G - 33. *E. coli* for surface water quality monitoring Station 12032 near Highbank.

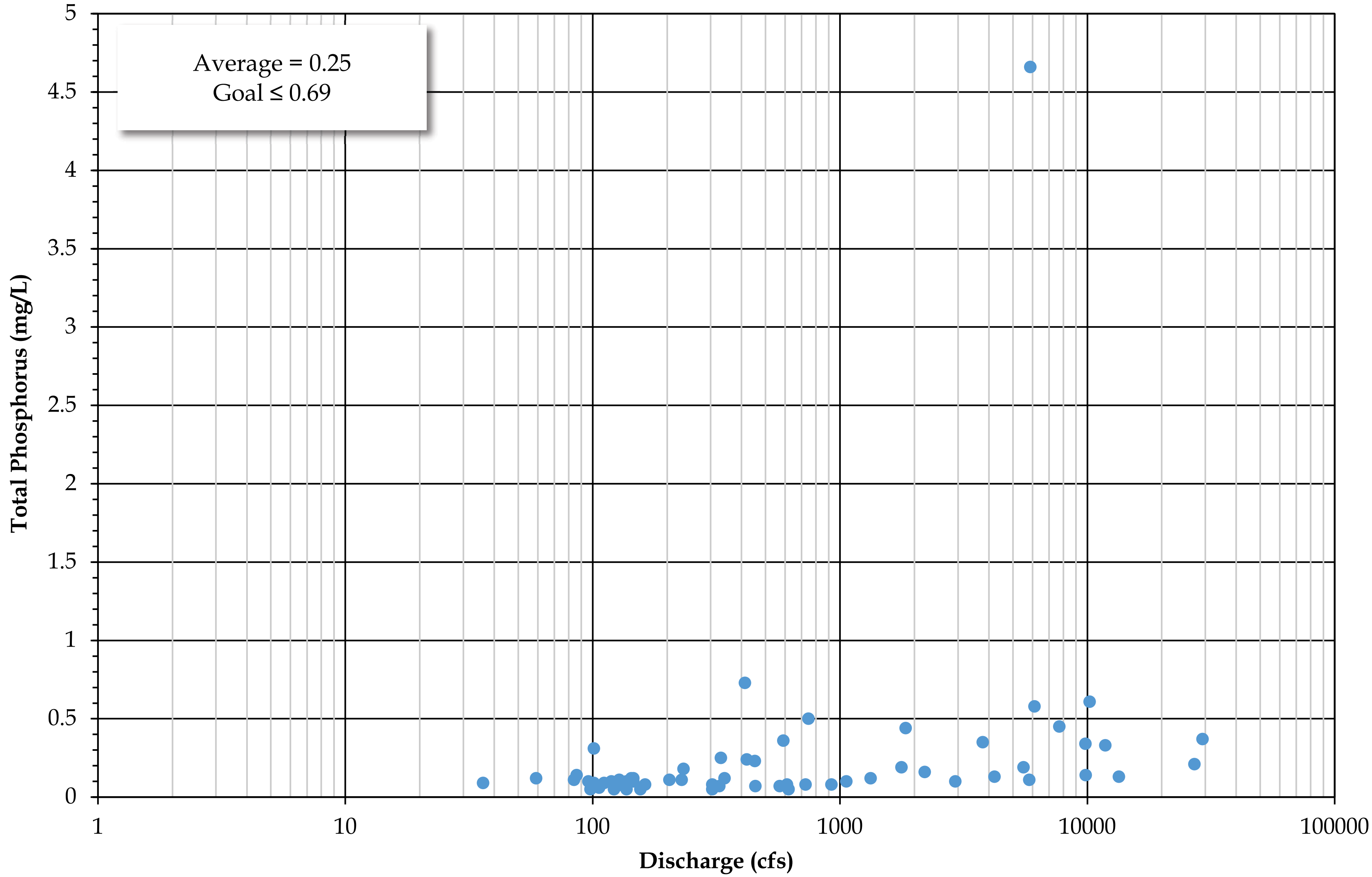


Figure G - 34. Total phosphorus for surface water quality monitoring Station 12032 near Highbank.

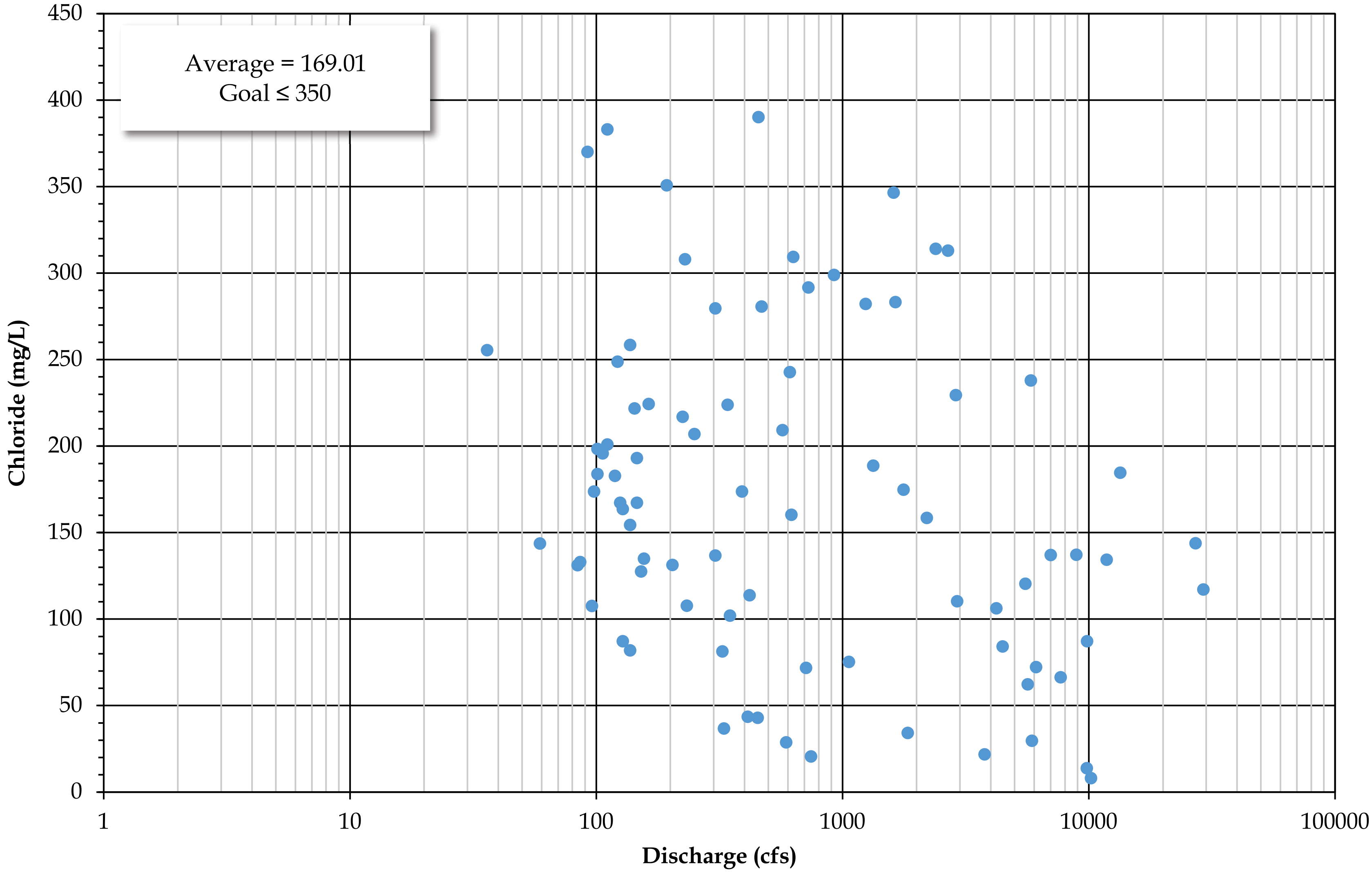


Figure G - 35. Chloride for surface water quality monitoring Station 12032 near Highbank.

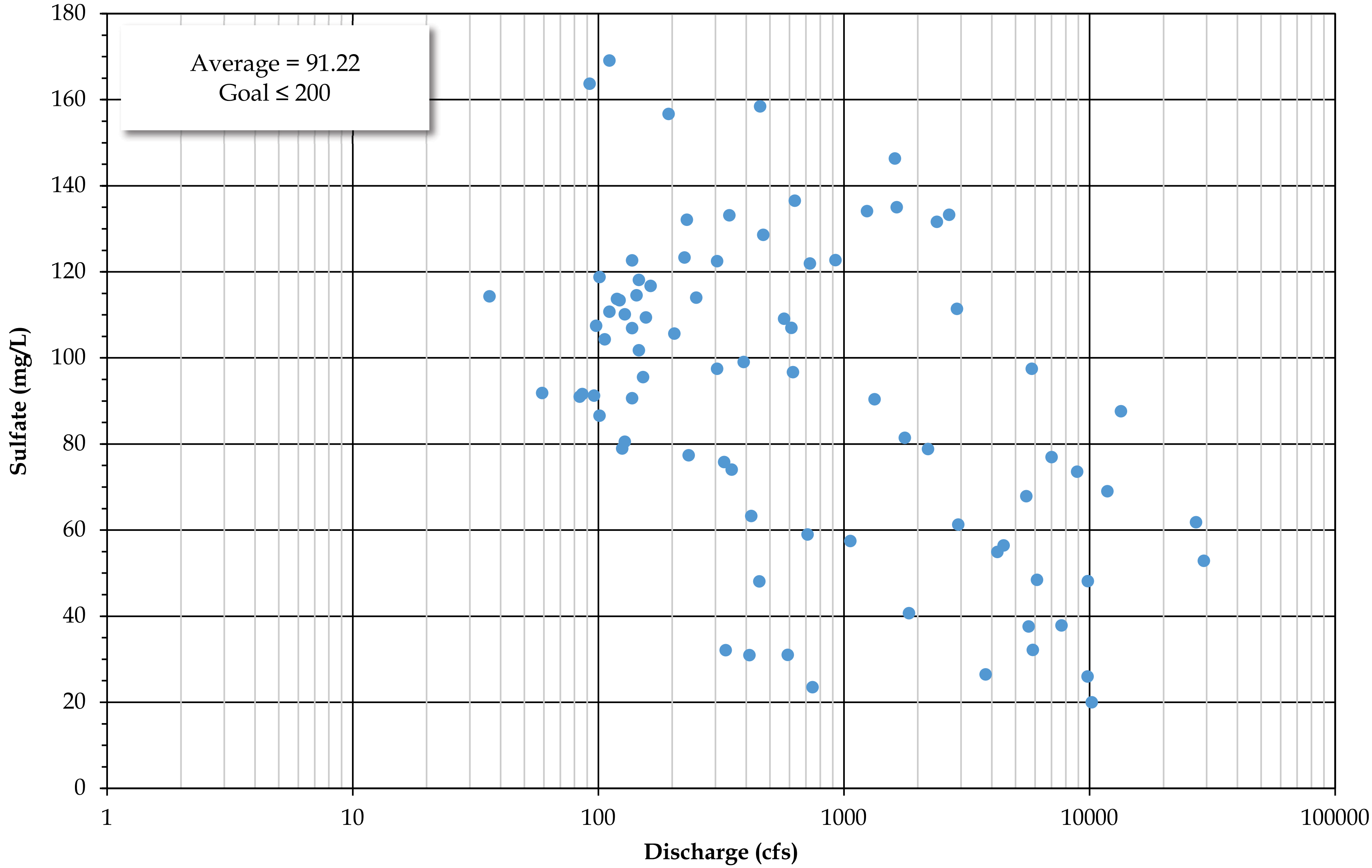


Figure G - 36. Sulfate for surface water quality monitoring Station 12032 near Highbank.

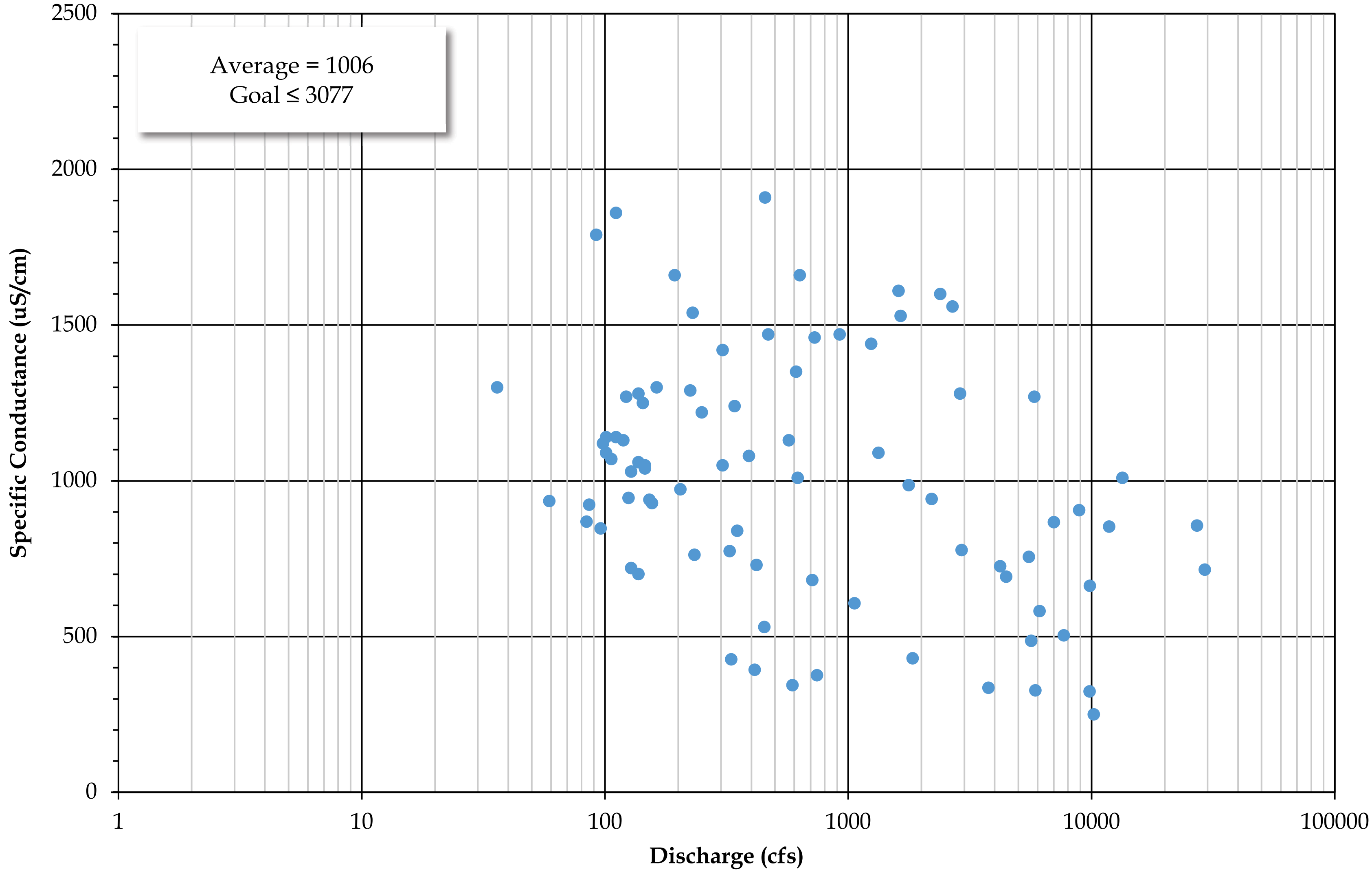


Figure G - 37. Specific conductance for surface water quality monitoring Station 12032 near Highbank.

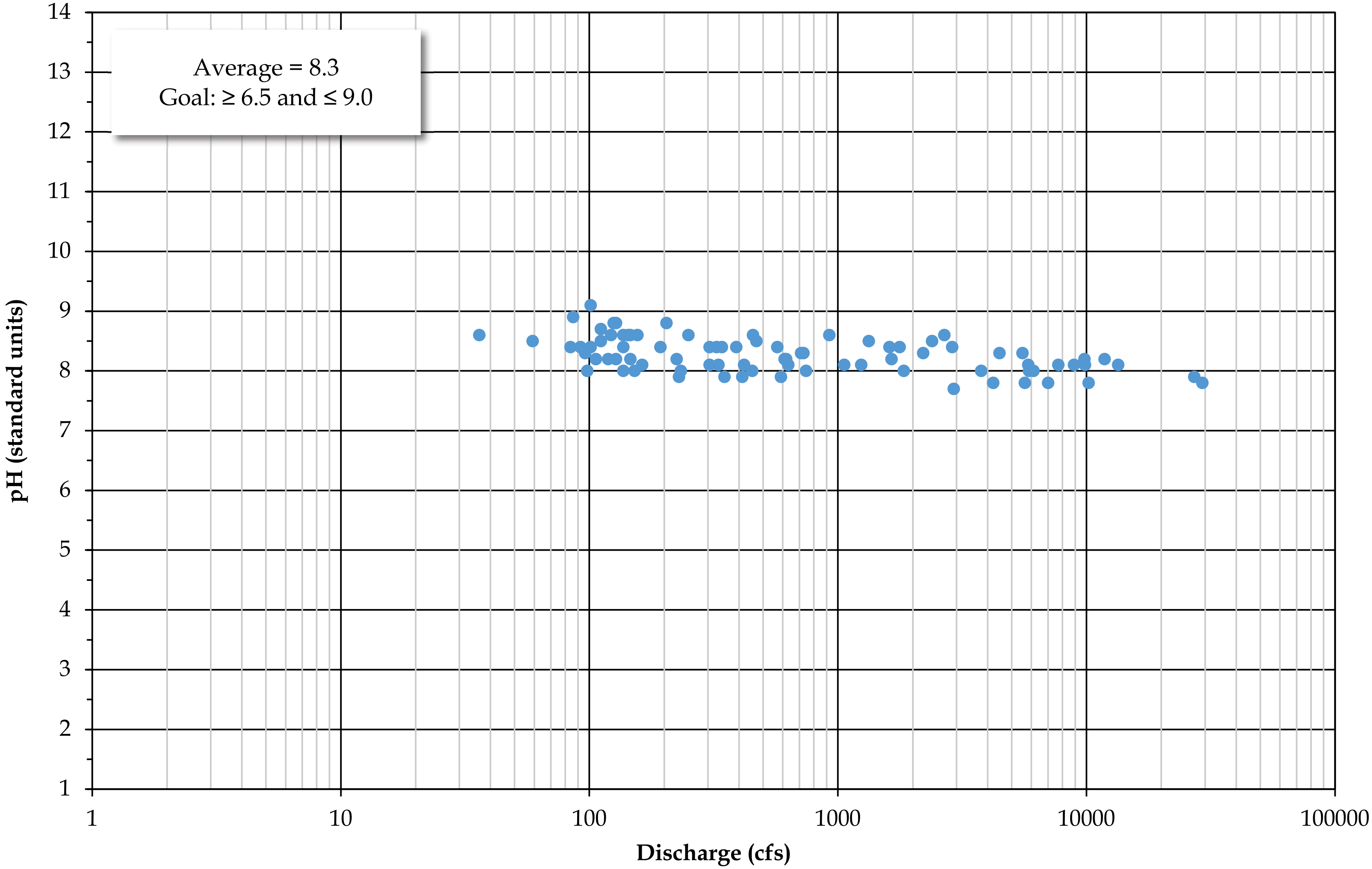


Figure G - 38. pH for surface water quality monitoring Station 12032 near Highbank.

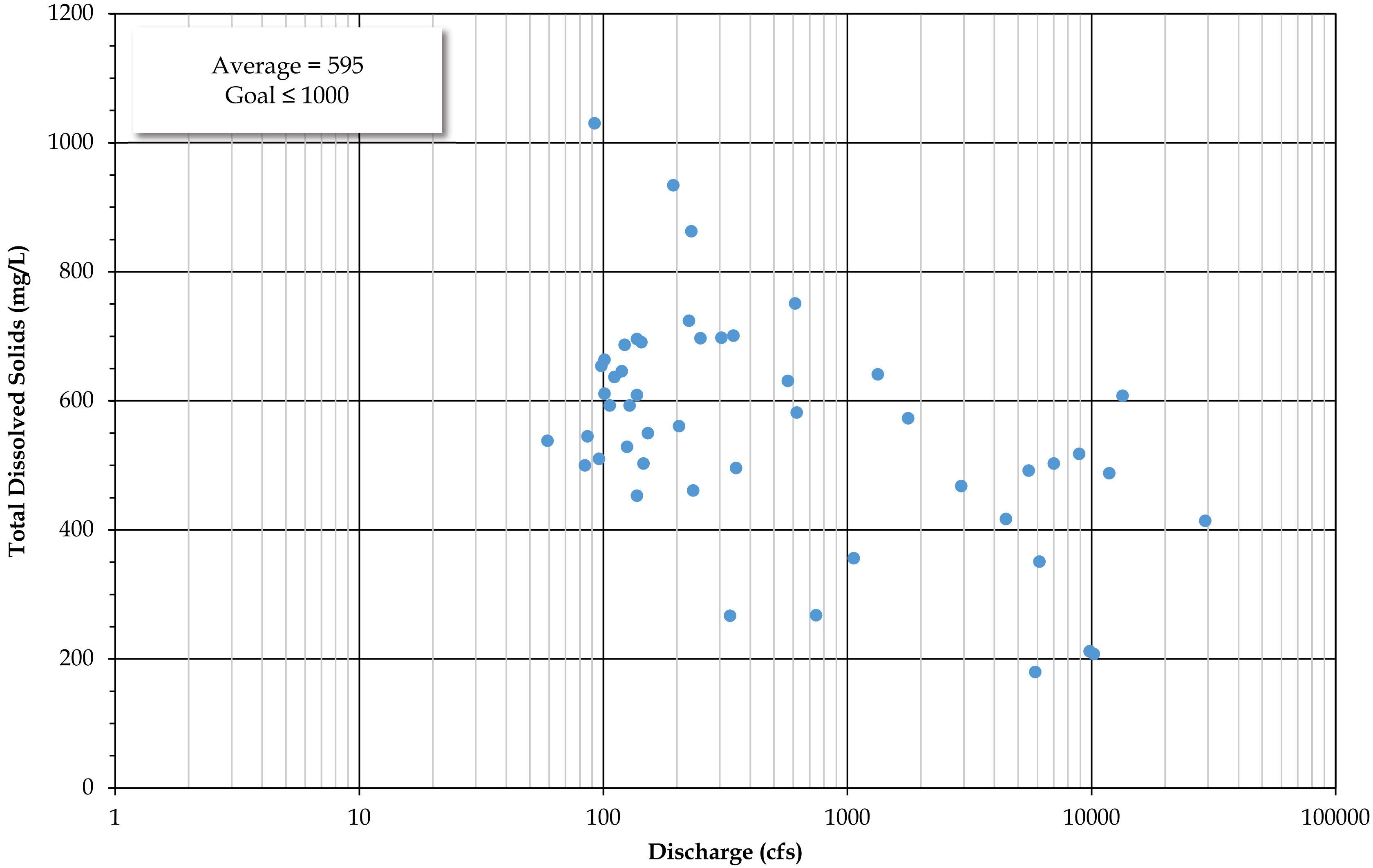


Figure G - 39. Total dissolved solids for surface water quality monitoring Station 12032 near Highbank.

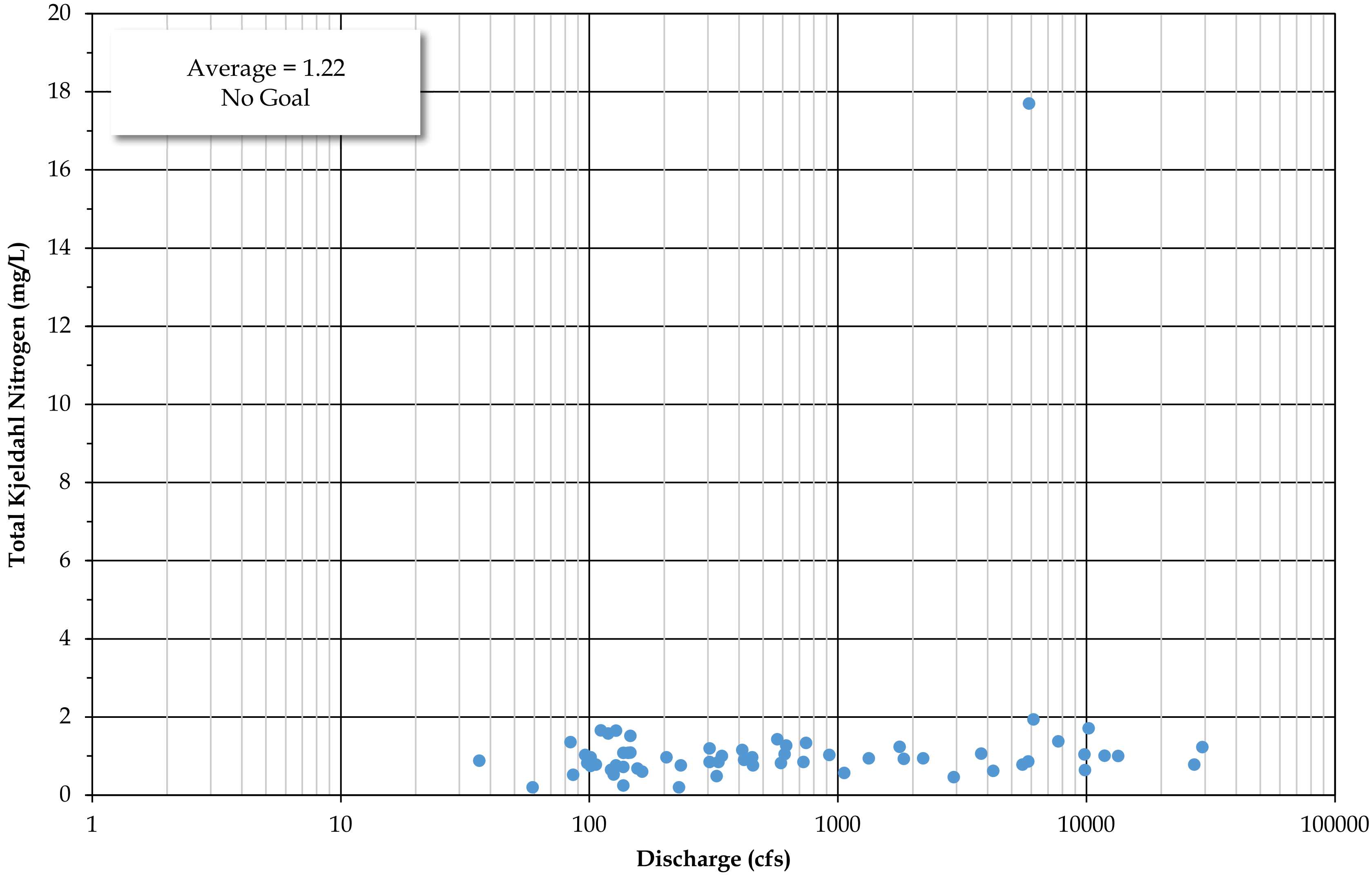


Figure G - 40. Total kjeldahl nitrogen for surface water quality monitoring Station 12032 near Highbank.

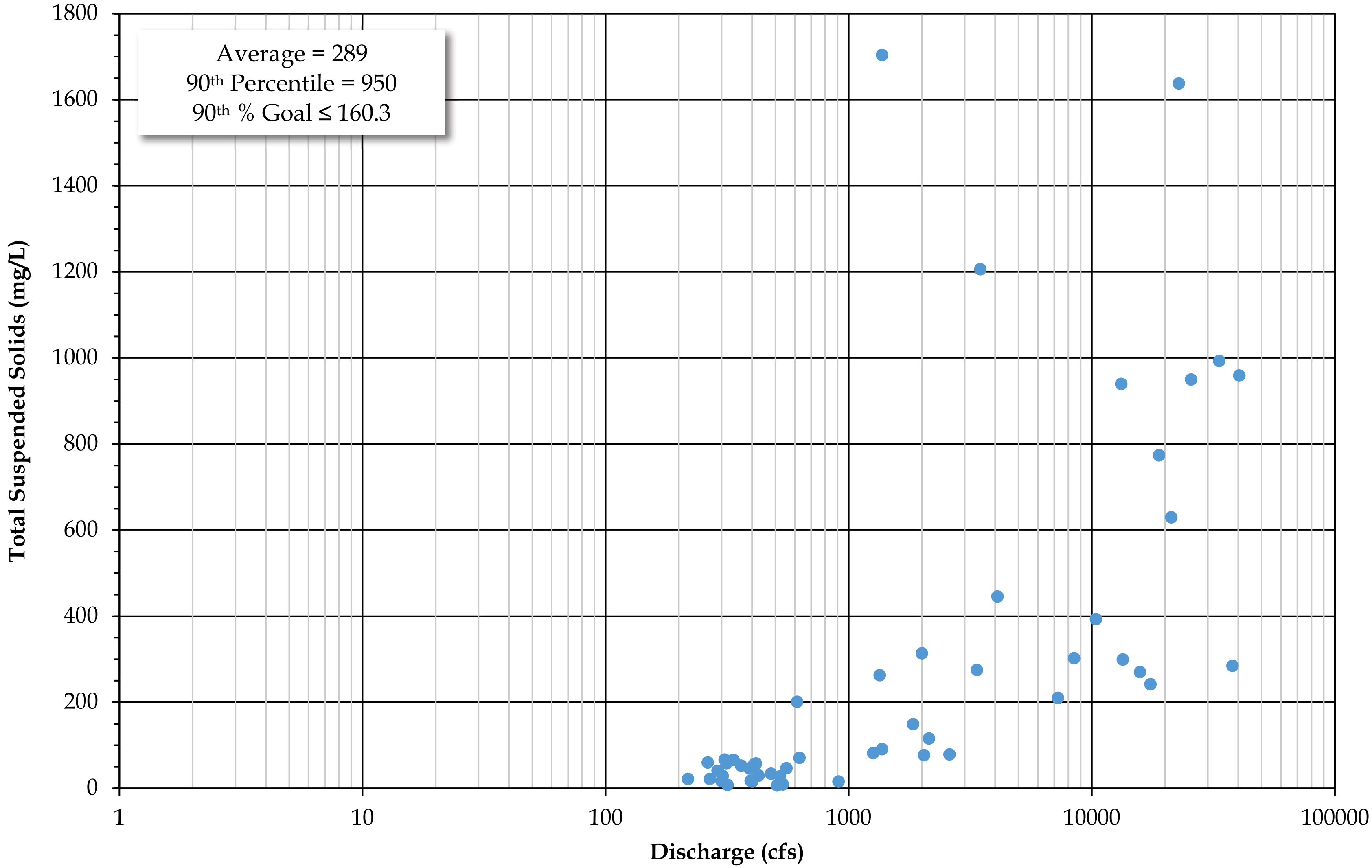


Figure G - 41. Total suspended solids for surface water quality monitoring Station 15767 near Bryan.

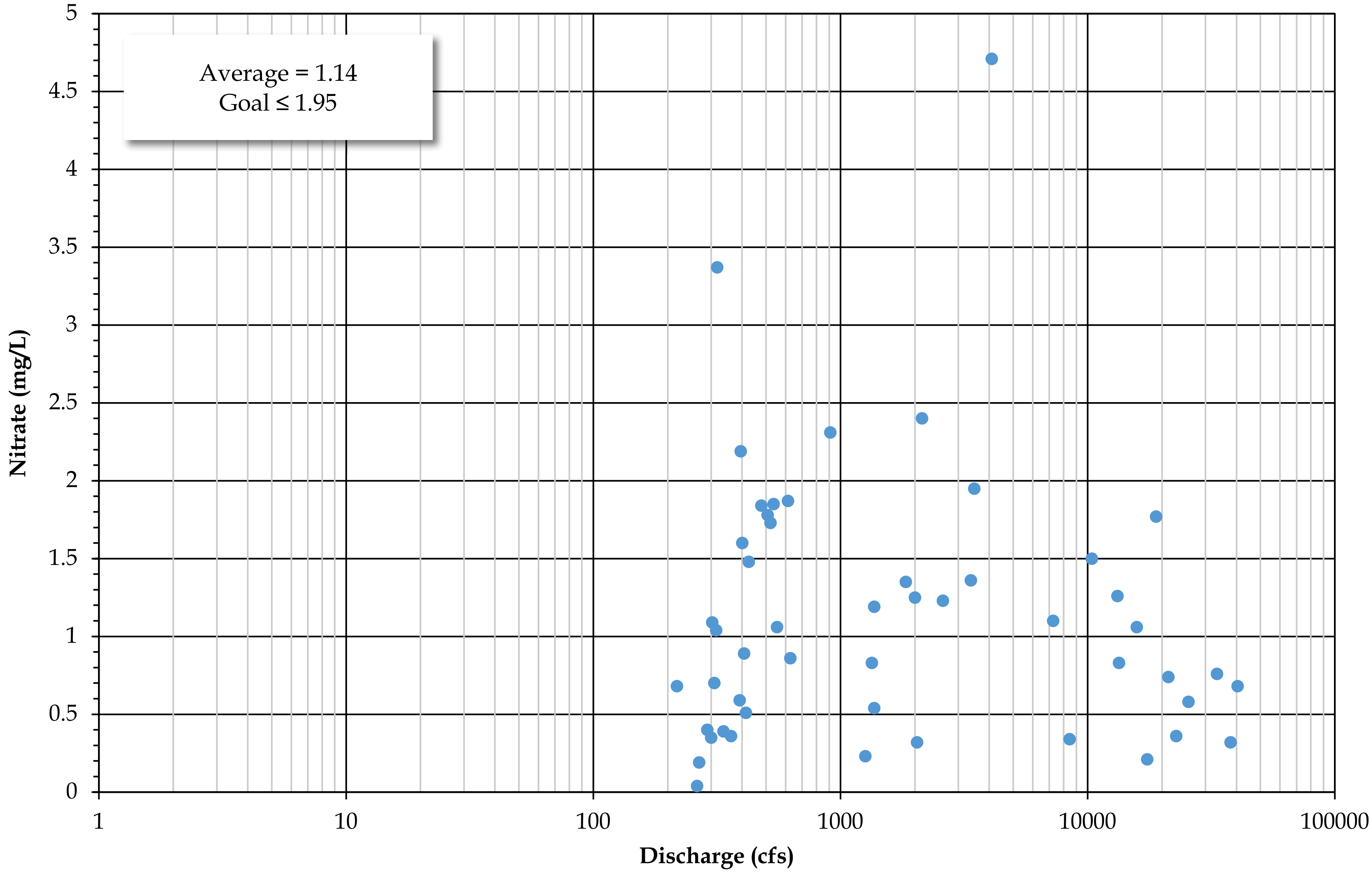


Figure G - 42. Nitrate for surface water quality monitoring Station 15767 near Bryan.

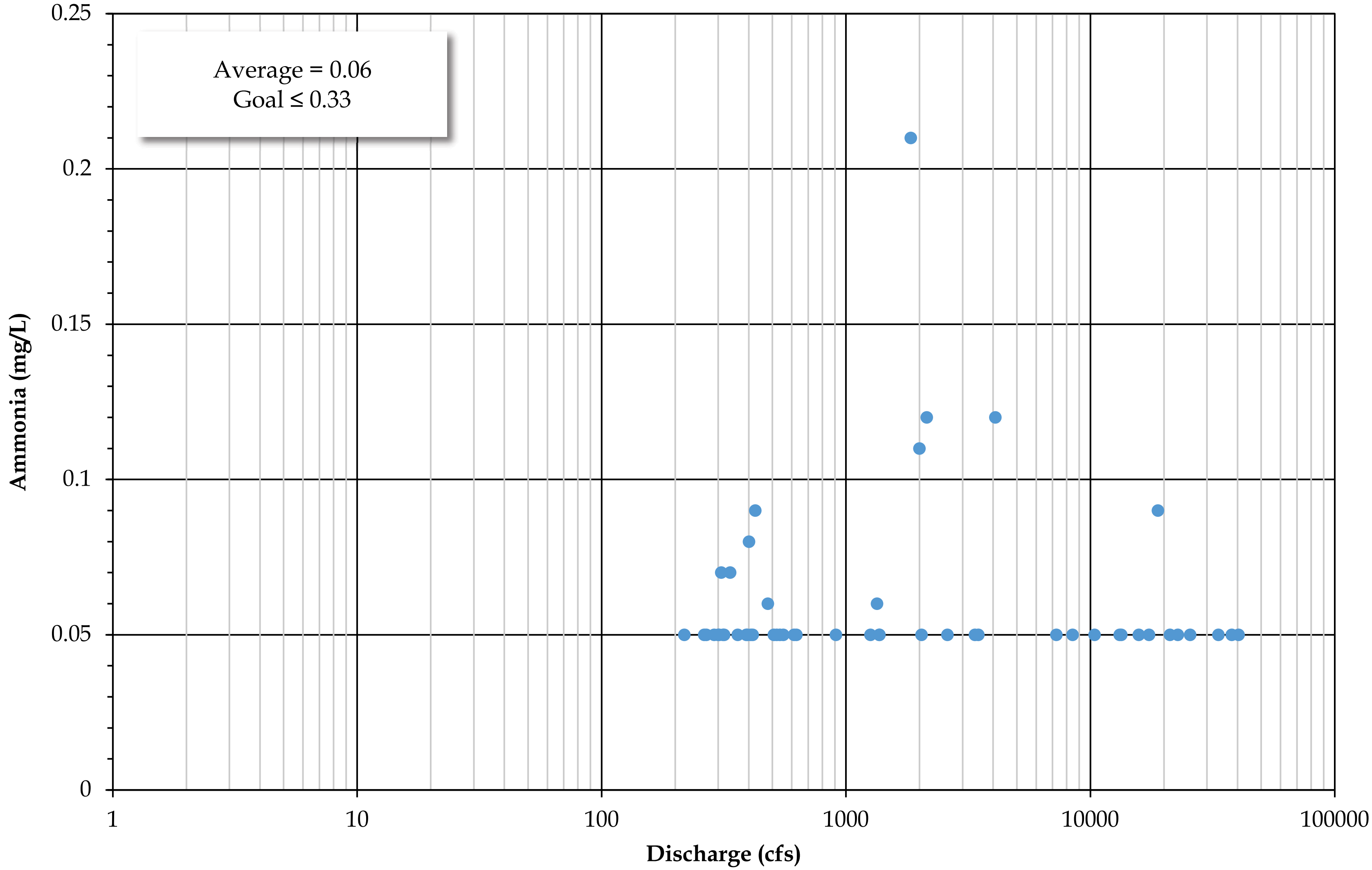


Figure G - 43. Ammonia for surface water quality monitoring Station 15767 near Bryan.

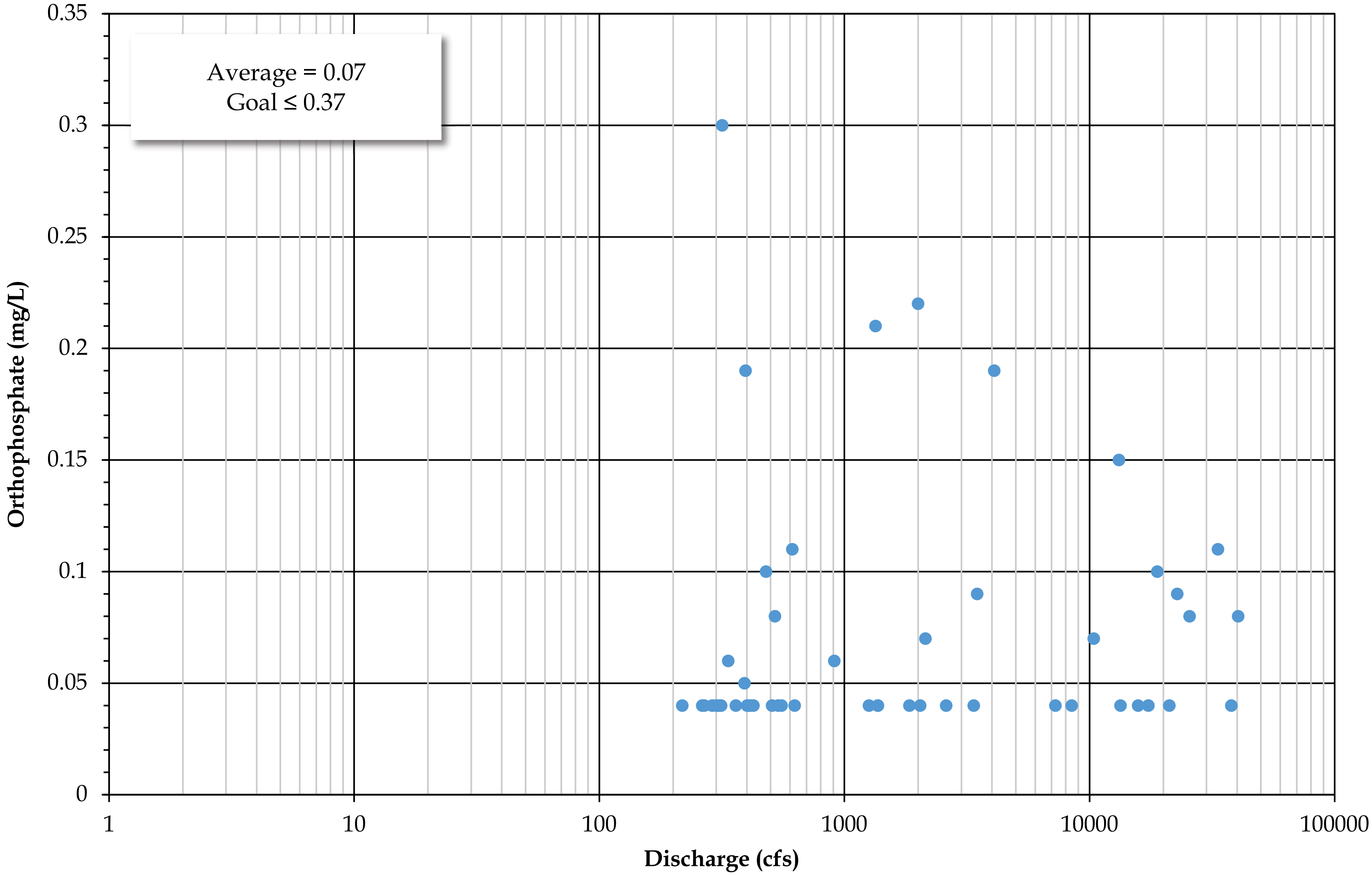


Figure G - 44. Orthophosphate for surface water quality monitoring Station 15767 near Bryan.

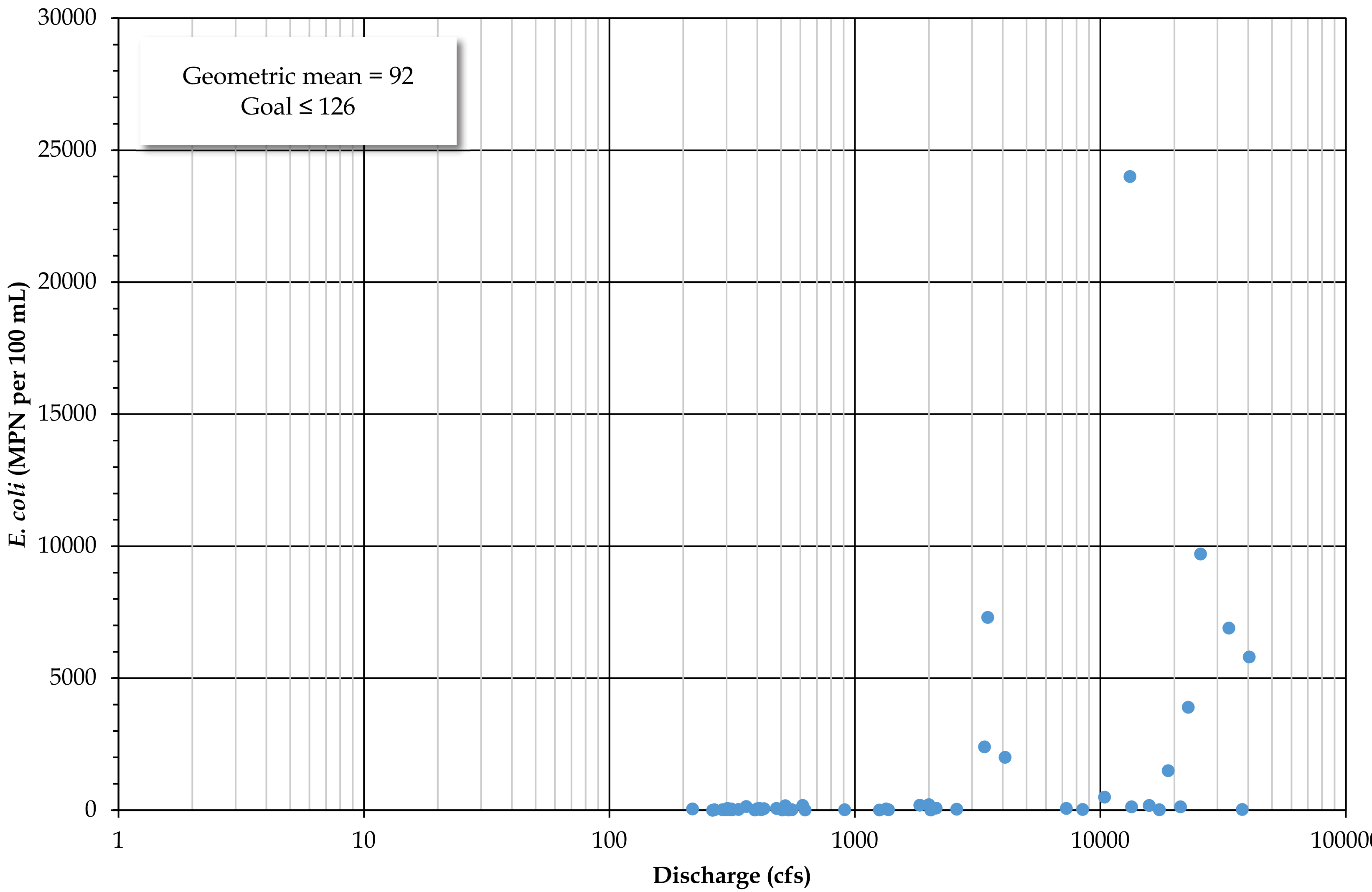


Figure G - 45. *E. coli* for surface water quality monitoring Station 15767 near Bryan.

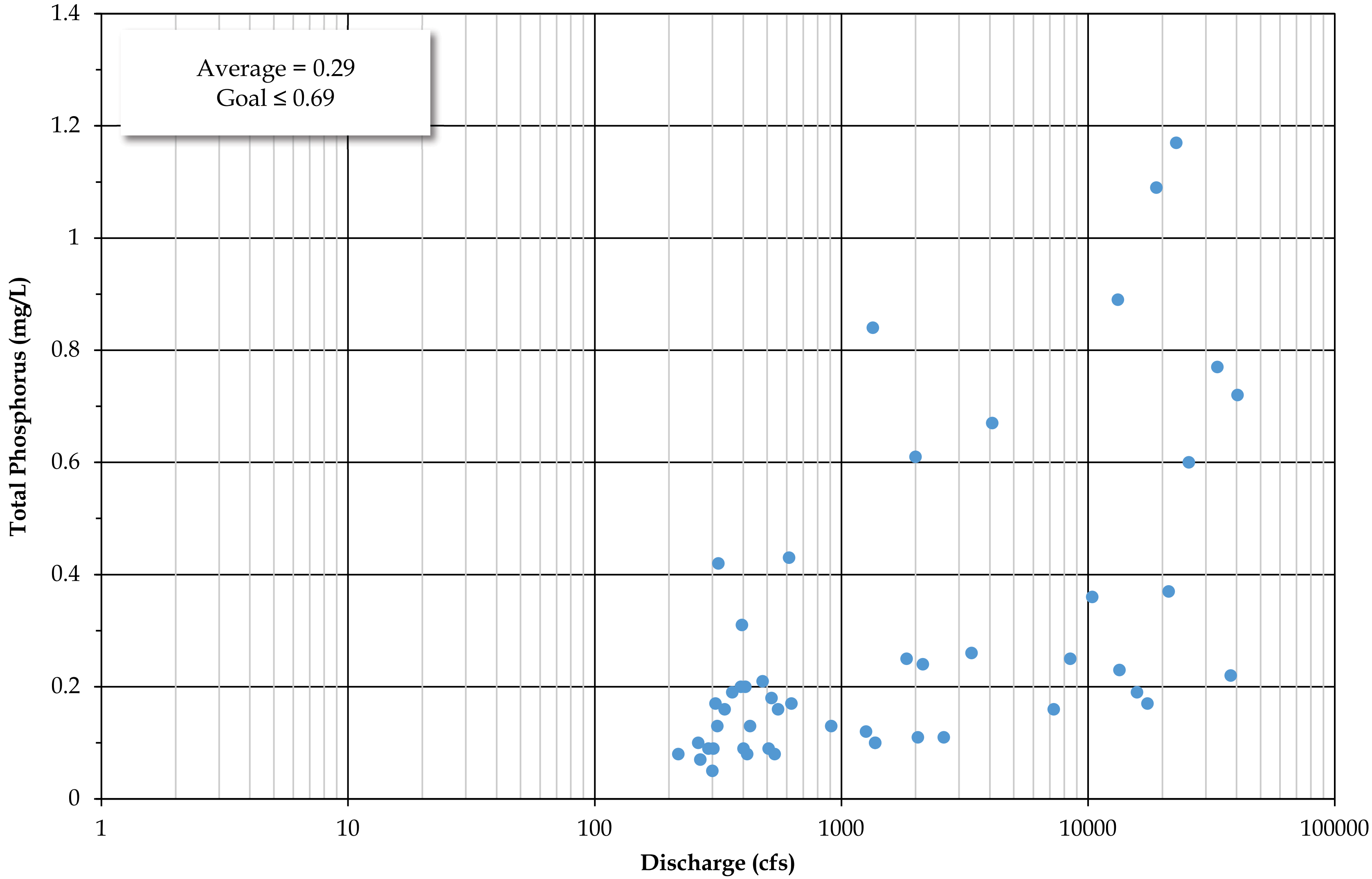


Figure G - 46. Total phosphorus for surface water quality monitoring Station 15767 near Bryan.

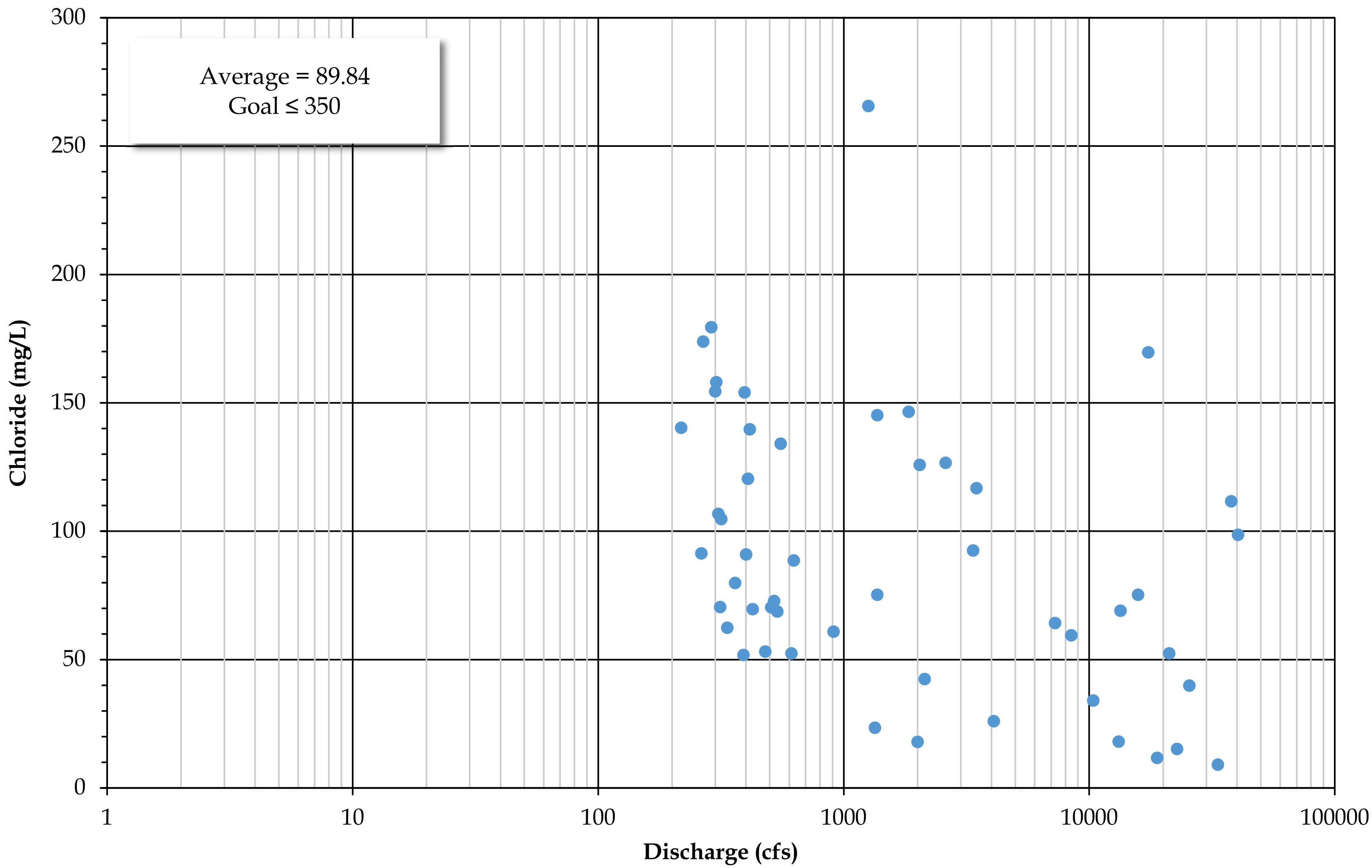


Figure G - 47. Chloride for surface water quality monitoring Station 15767 near Bryan.

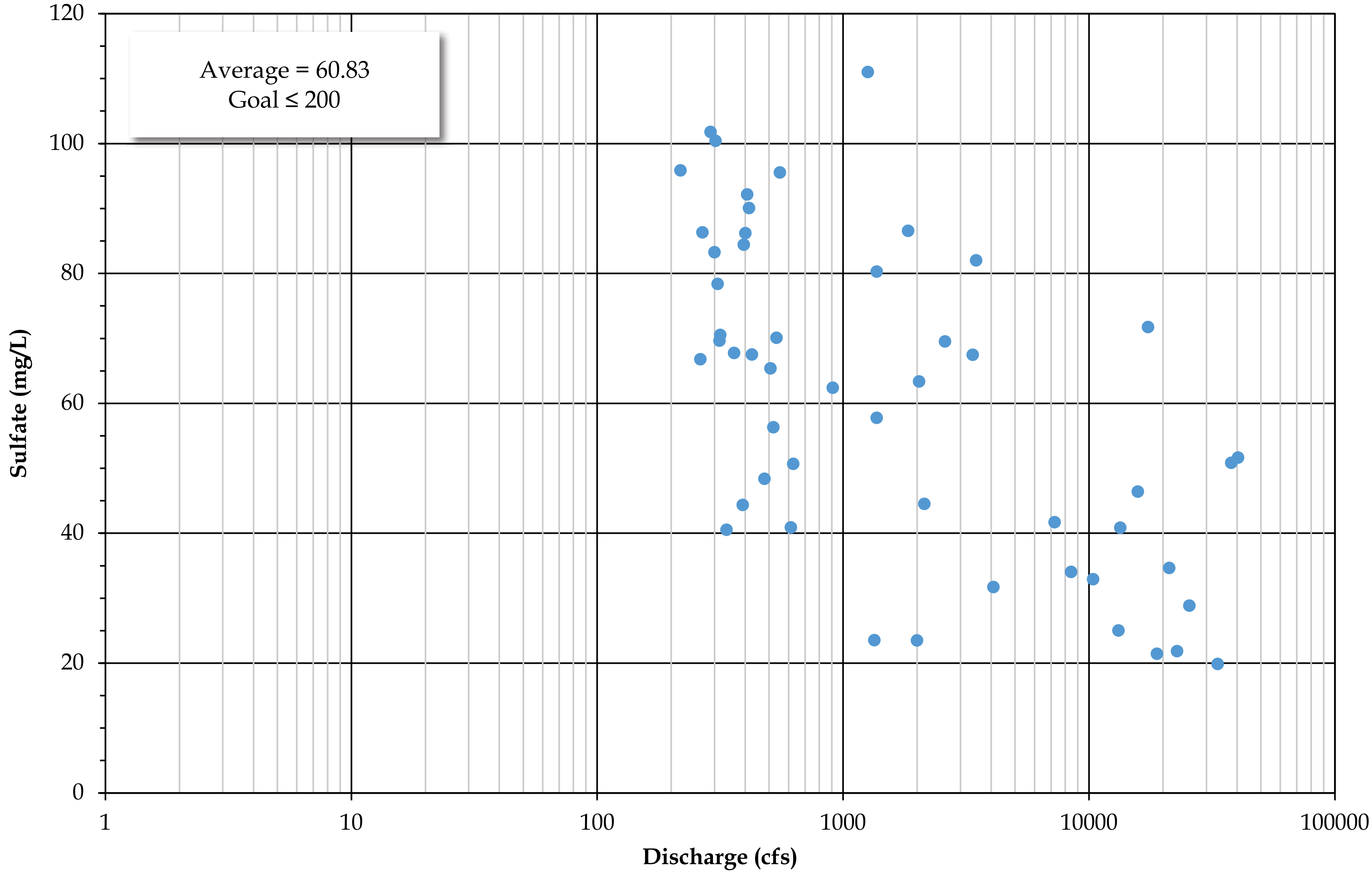


Figure G - 48. Sulfate for surface water quality monitoring Station 15767 near Bryan.

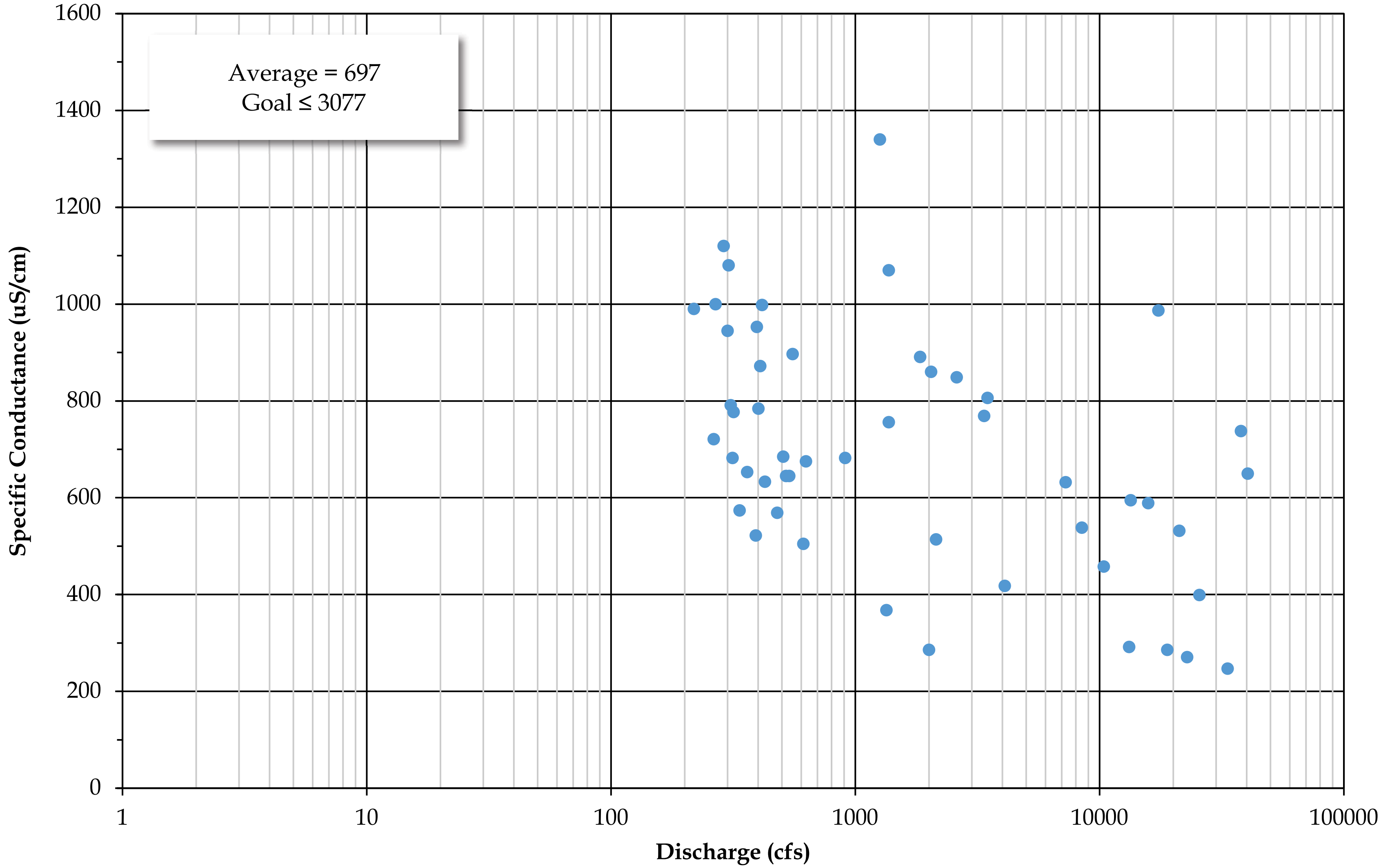


Figure G - 49. Specific conductance for surface water quality monitoring Station 15767 near Bryan.

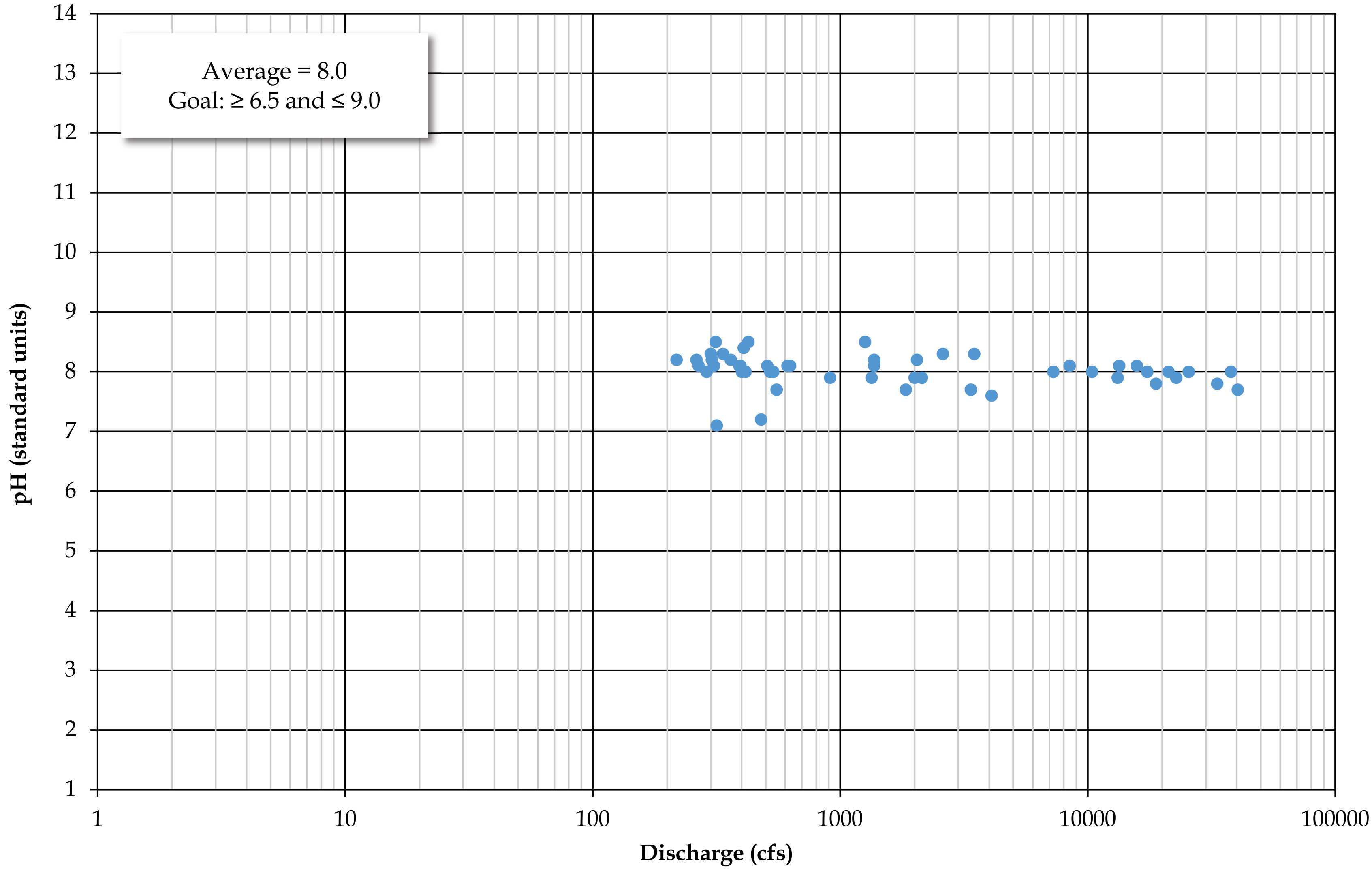


Figure G - 50. pH for surface water quality monitoring Station 15767 near Bryan.

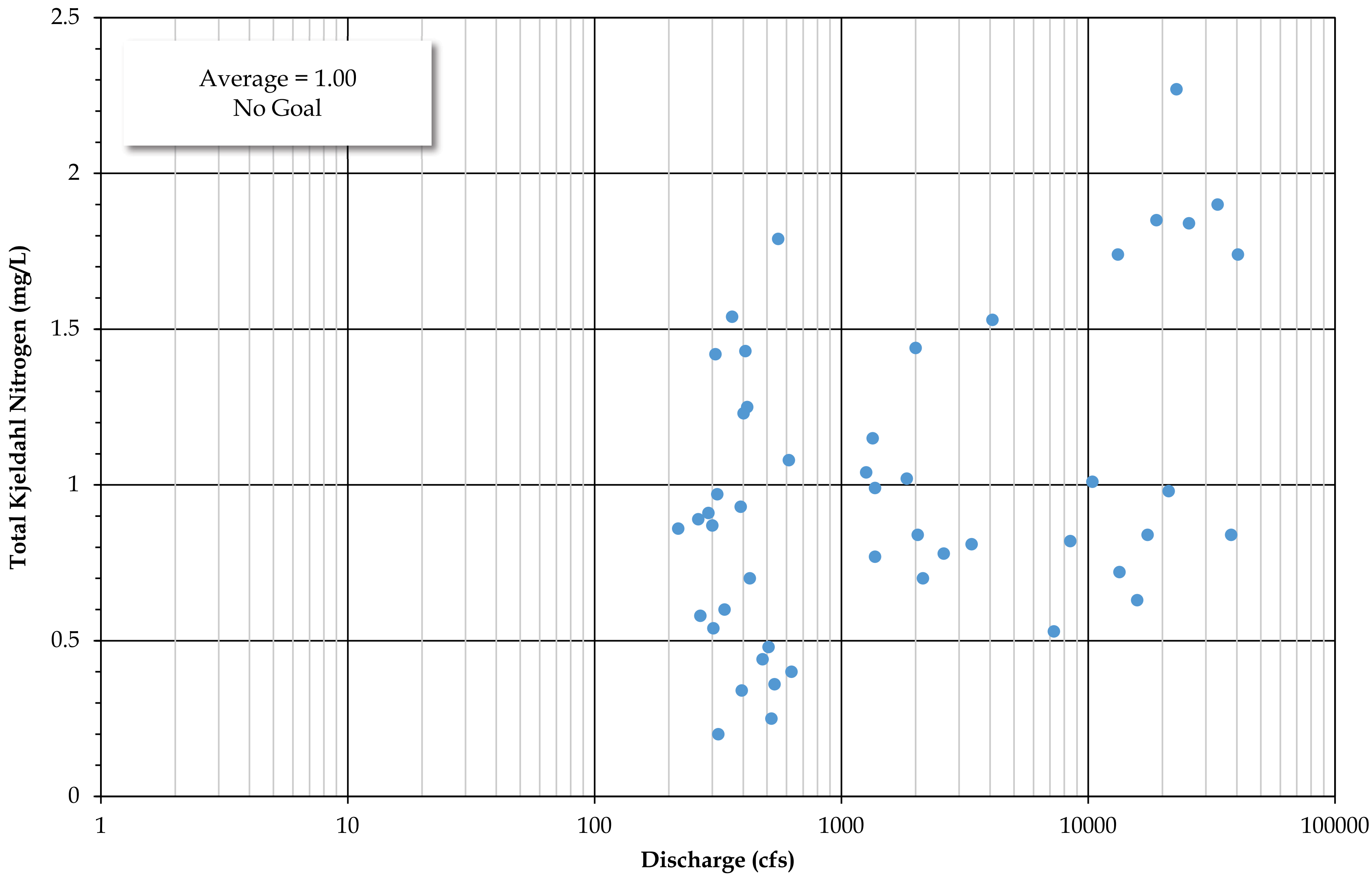


Figure G - 51. Total kjeldahl nitrogen for surface water quality monitoring Station 15767 near Bryan.

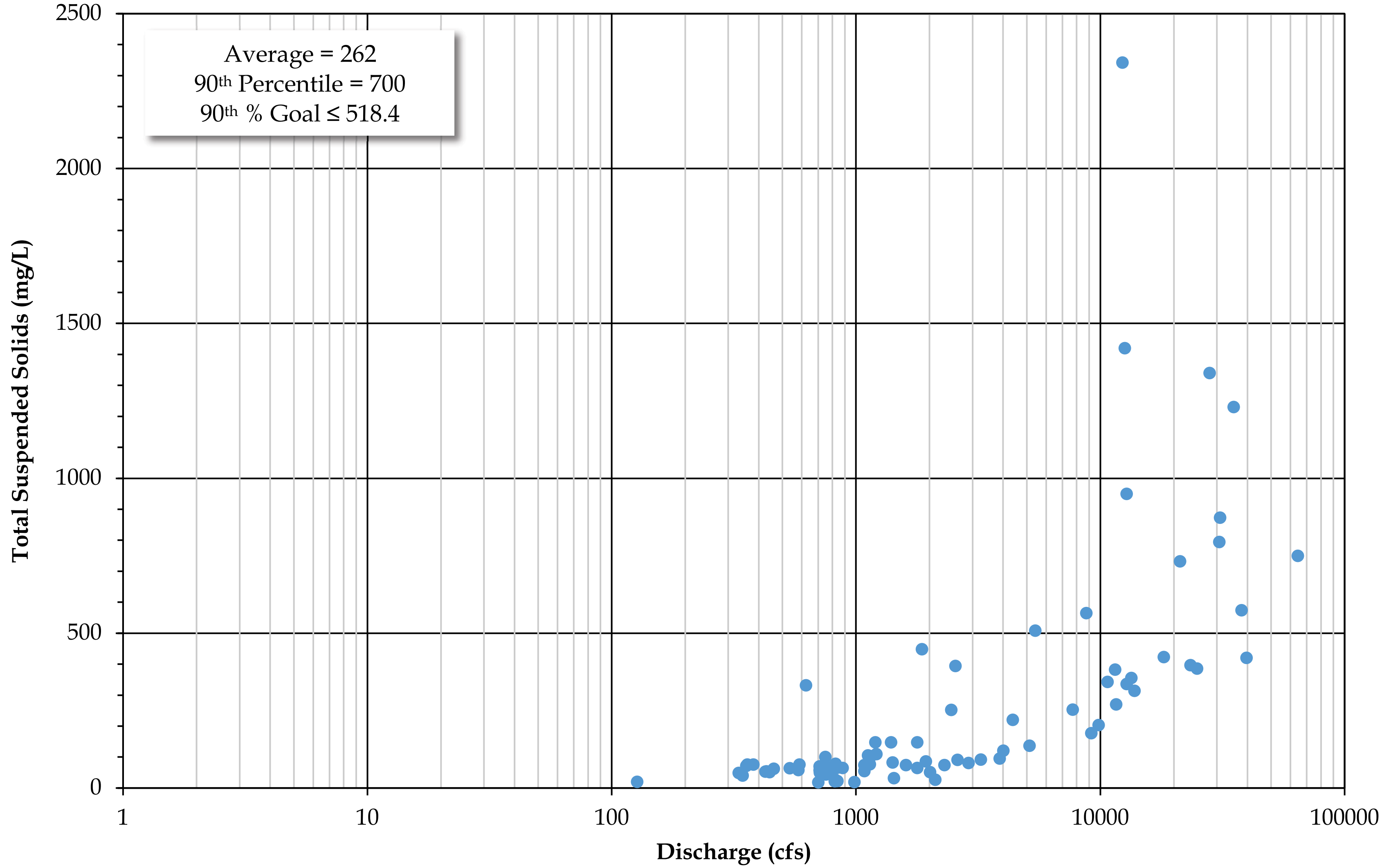


Figure G - 52. Total suspended solids for surface water quality monitoring Station 11850 near Hempstead.

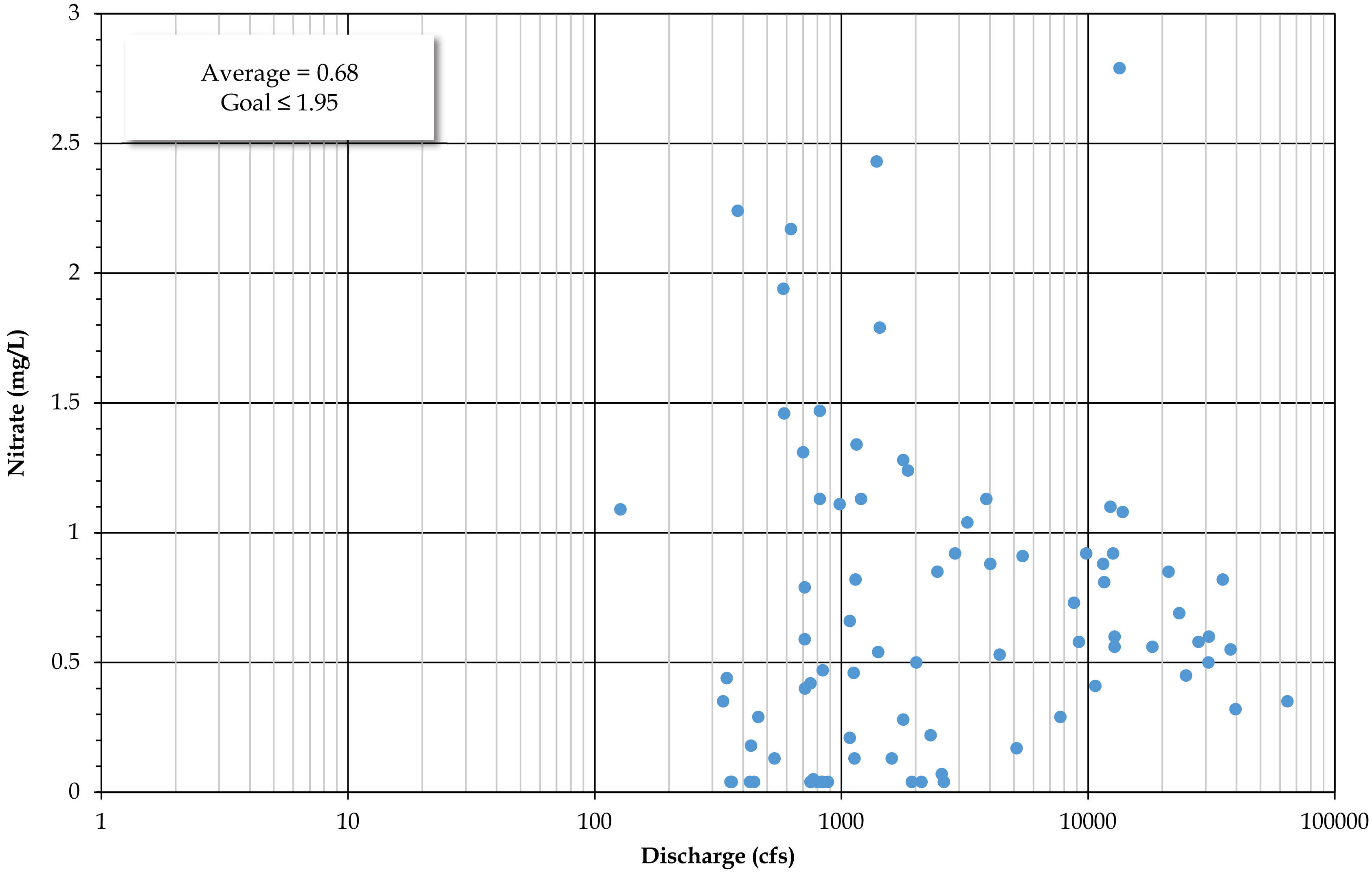


Figure G - 53. Nitrate for surface water quality monitoring Station 11850 near Hempstead.

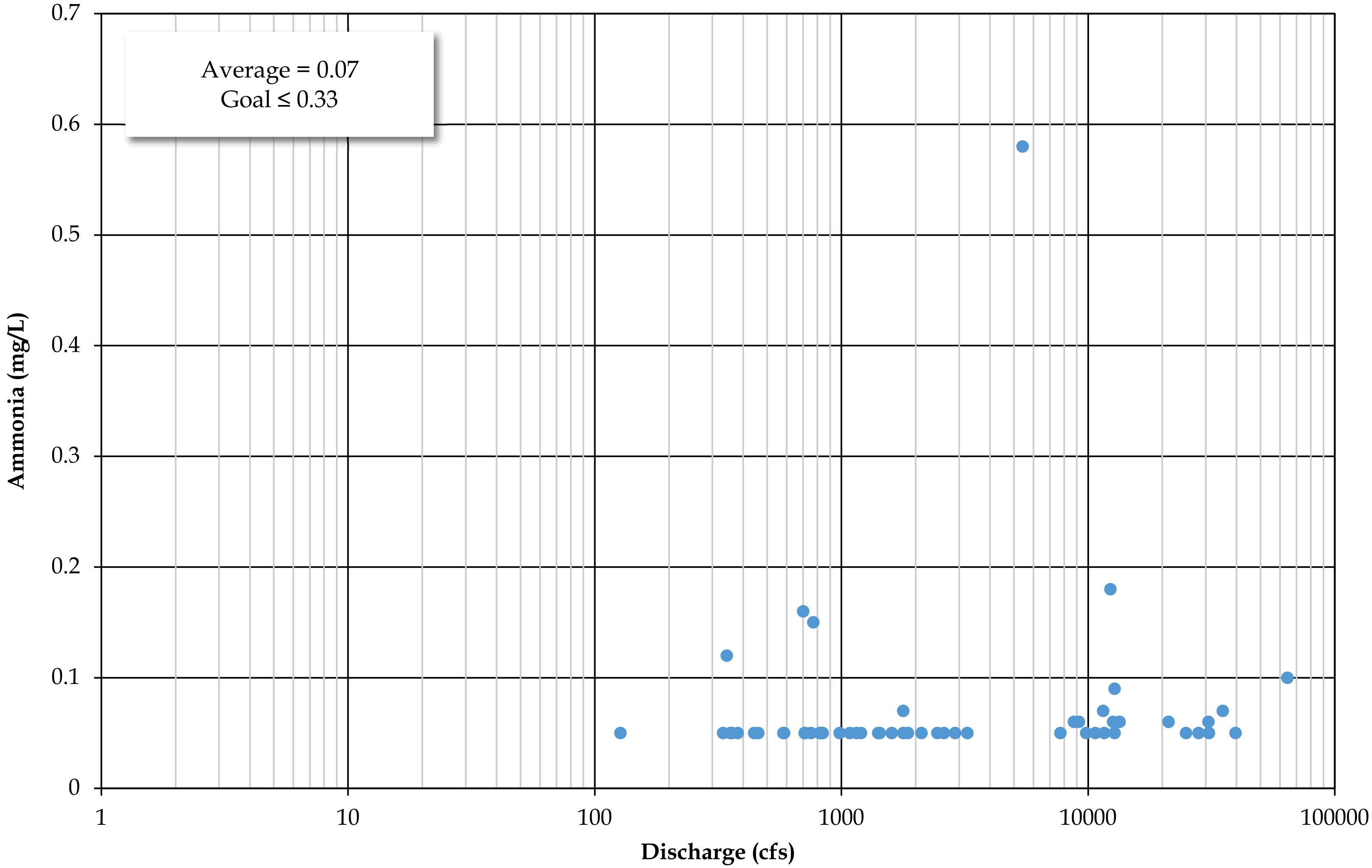


Figure G - 54. Ammonia for surface water quality monitoring Station 11850 near Hempstead.

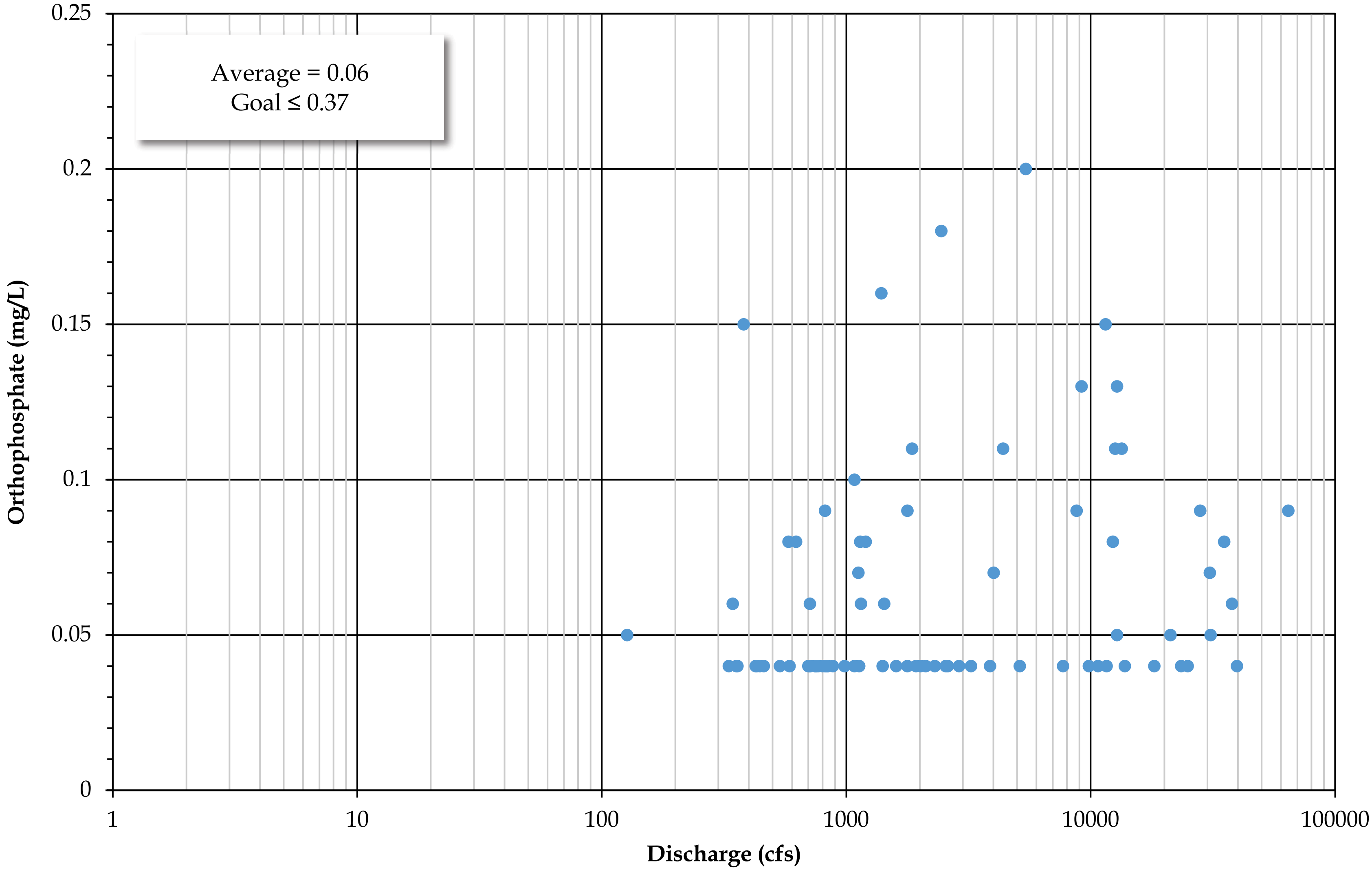


Figure G - 55. Orthophosphate for surface water quality monitoring Station 11850 near Hempstead.

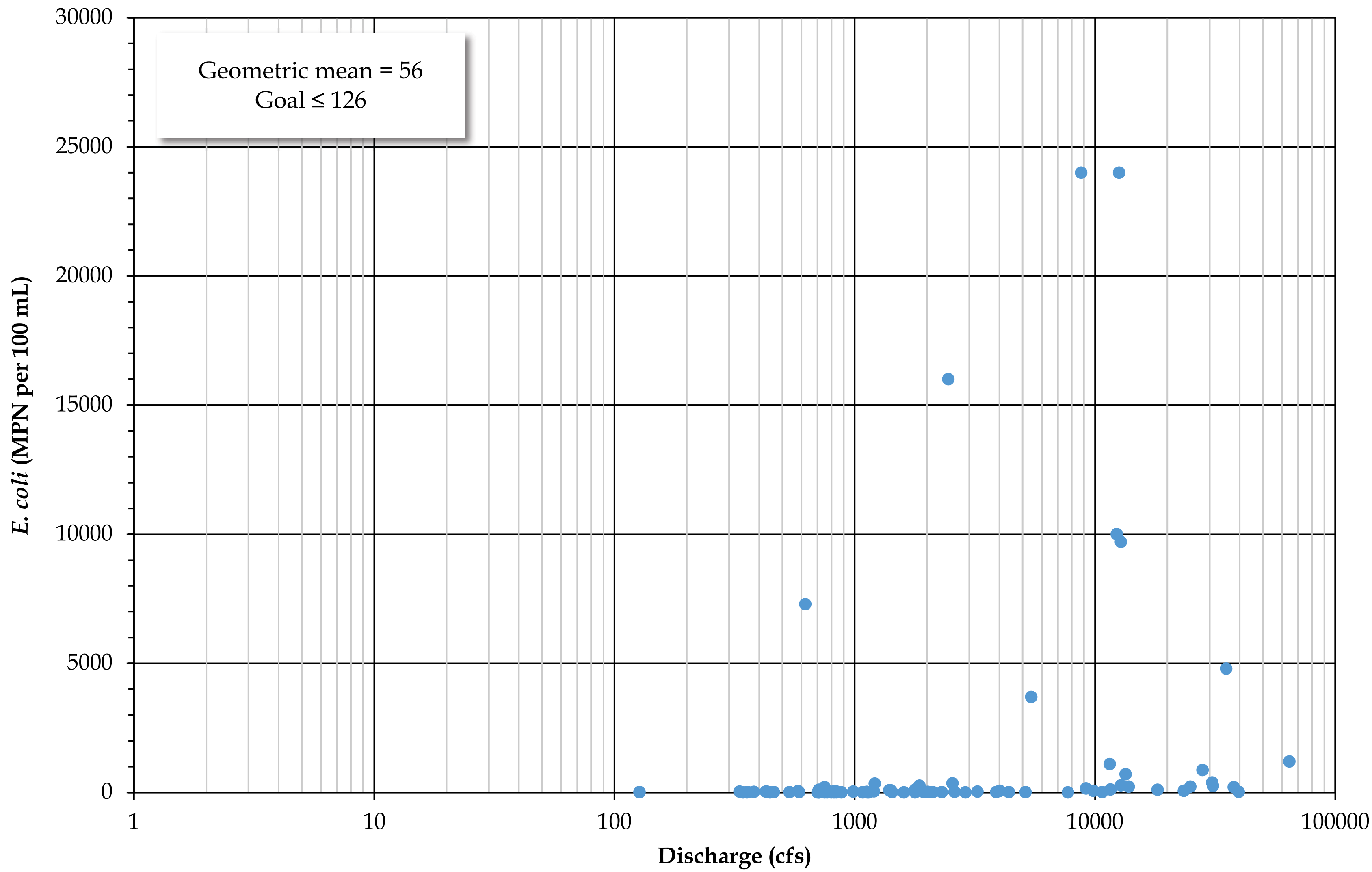


Figure G - 56. *E. coli* for surface water quality monitoring Station 11850 near Hempstead.

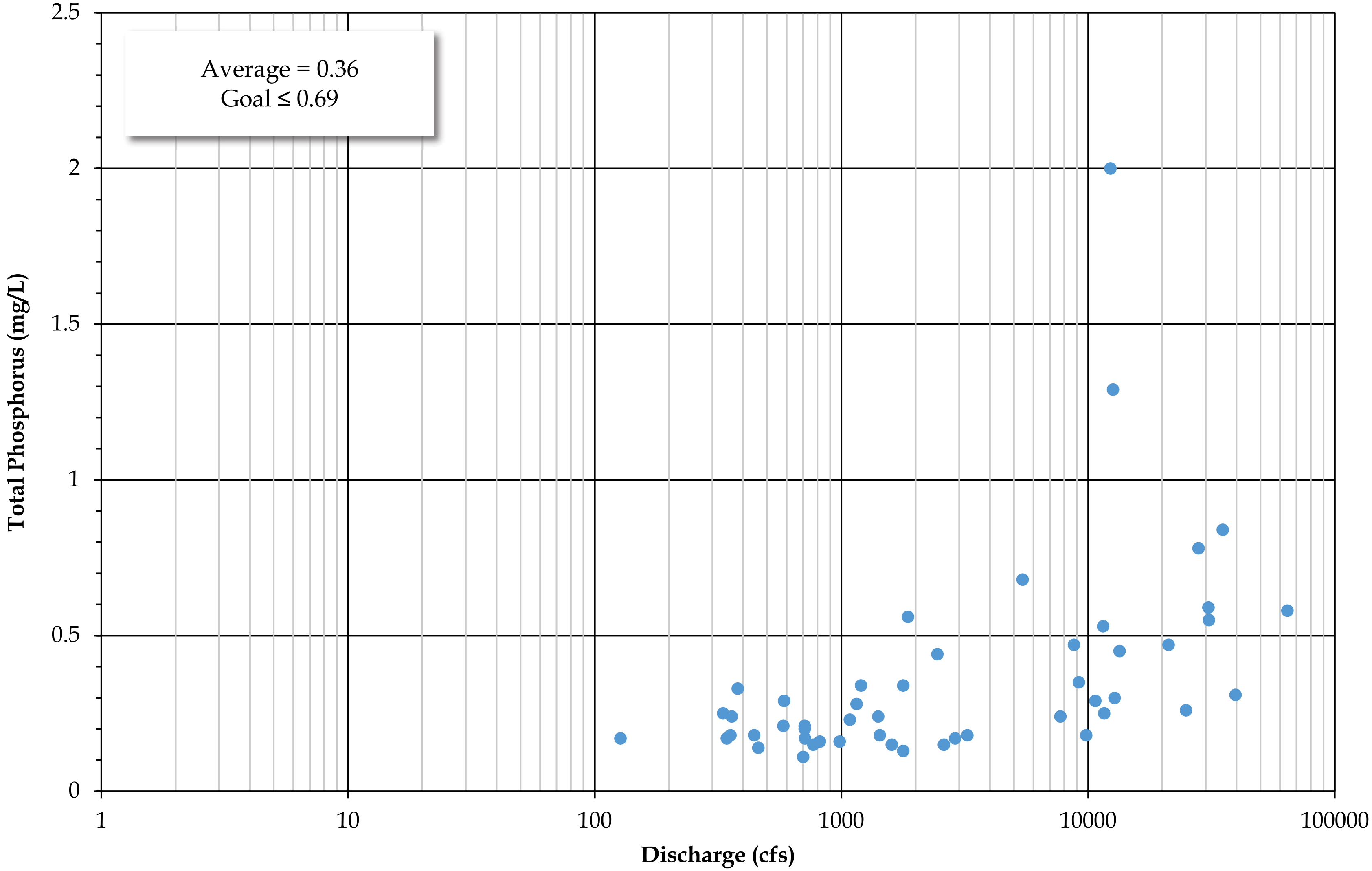


Figure G - 57. Total phosphorus for surface water quality monitoring Station 11850 near Hempstead.

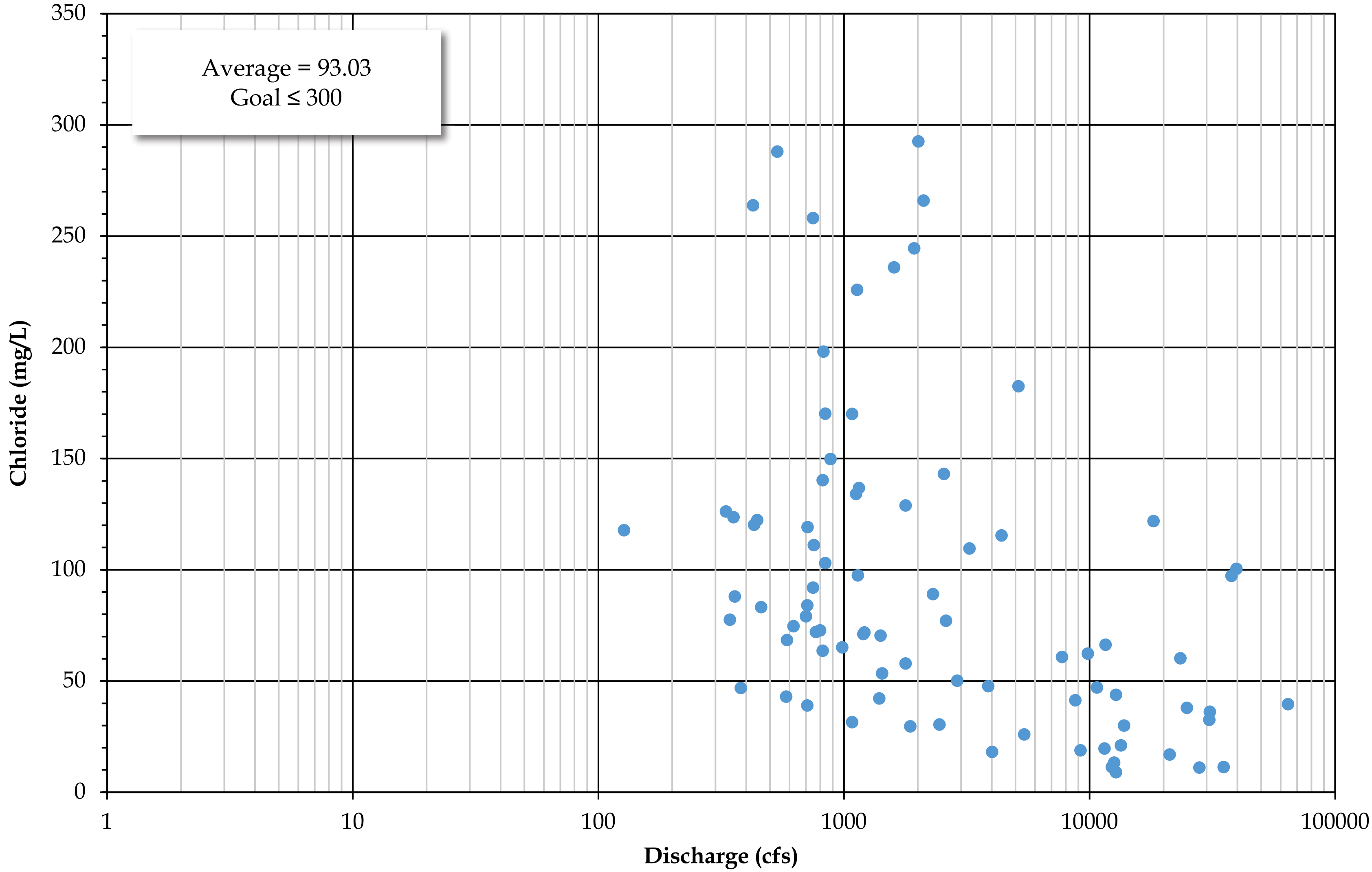


Figure G - 58. Chloride for surface water quality monitoring Station 11850 near Hempstead.

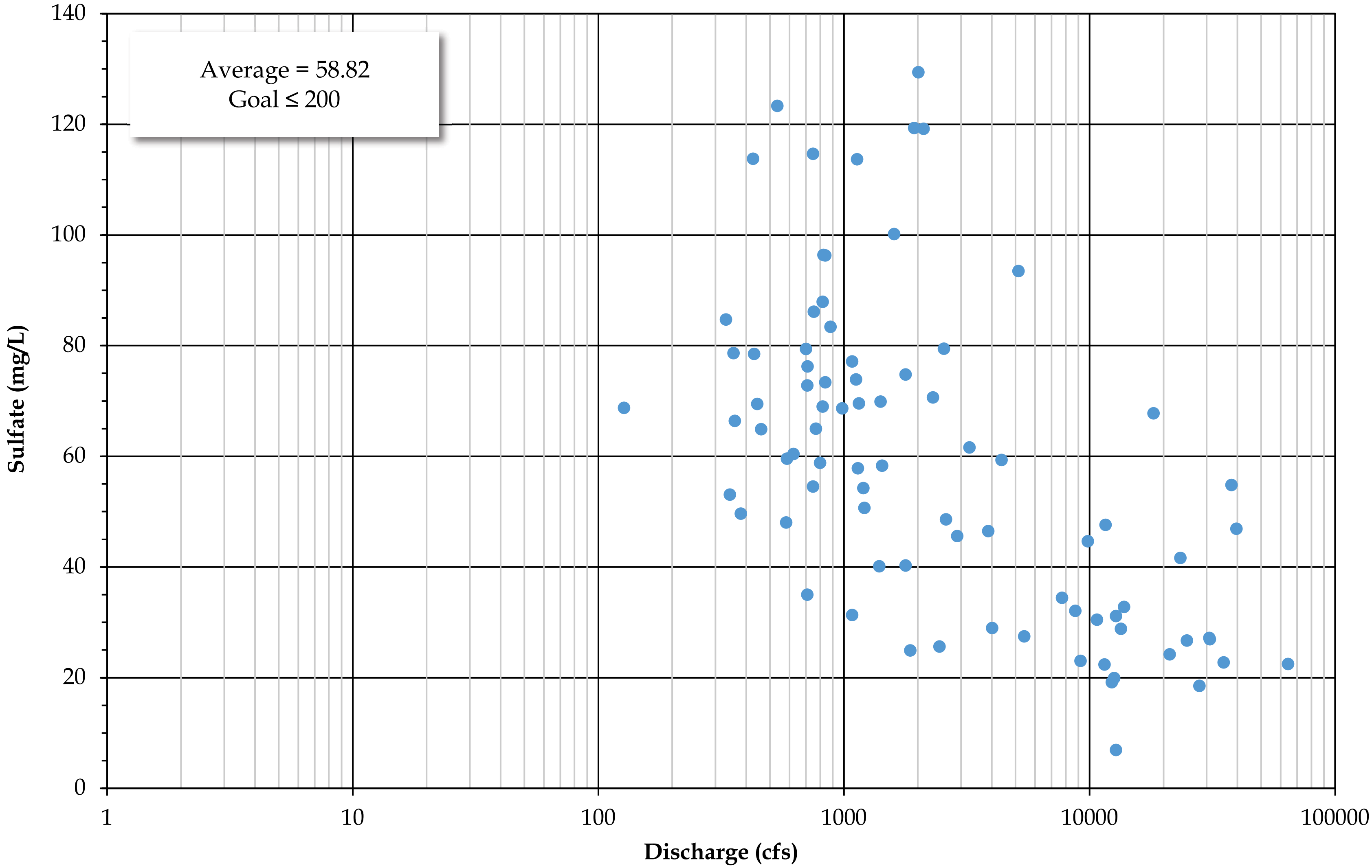


Figure G - 59. Sulfate for surface water quality monitoring Station 11850 near Hempstead.

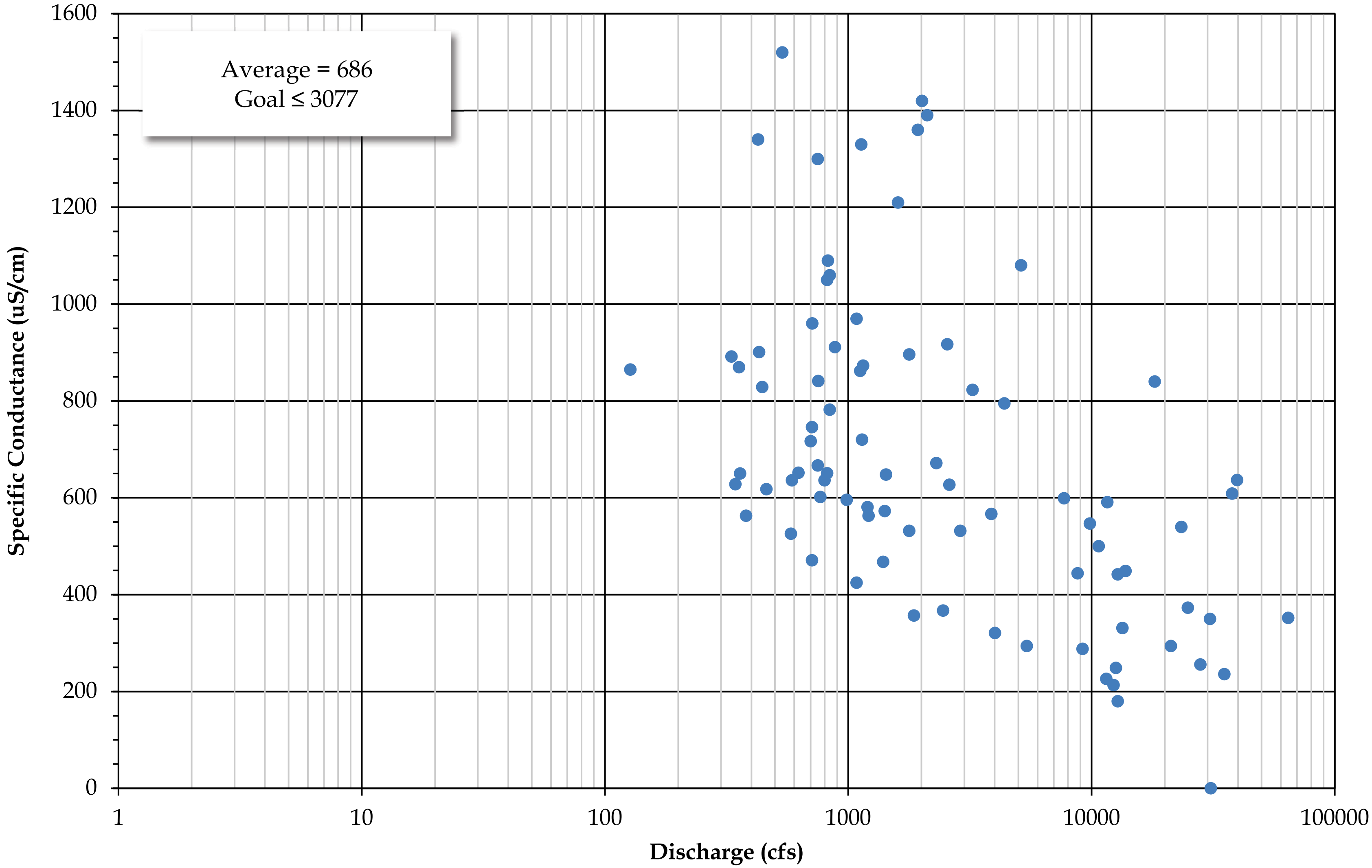


Figure G - 60. Specific conductance for surface water quality monitoring Station 11850 near Hempstead.

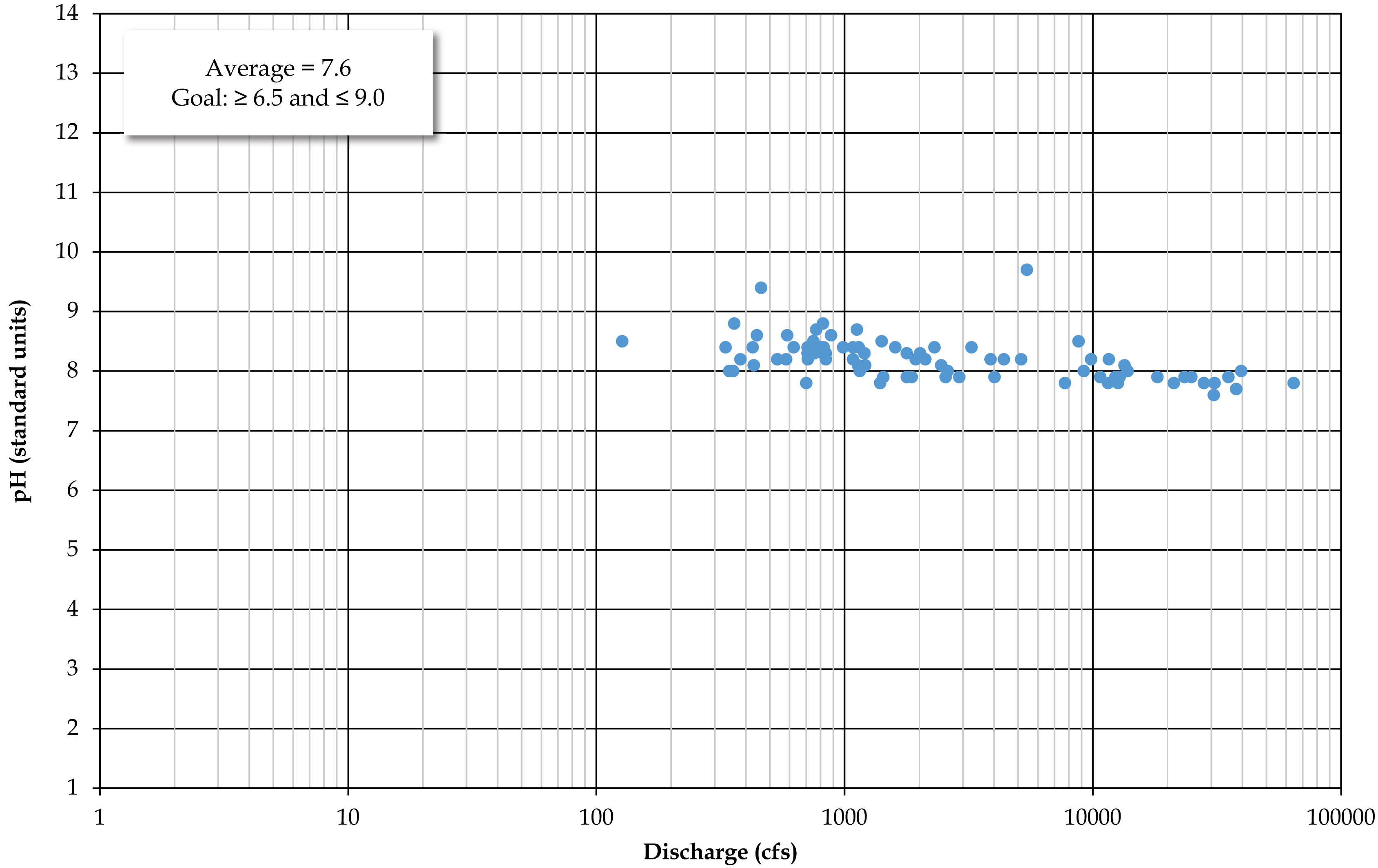


Figure G - 61. pH for surface water quality monitoring Station 11850 near Hempstead.

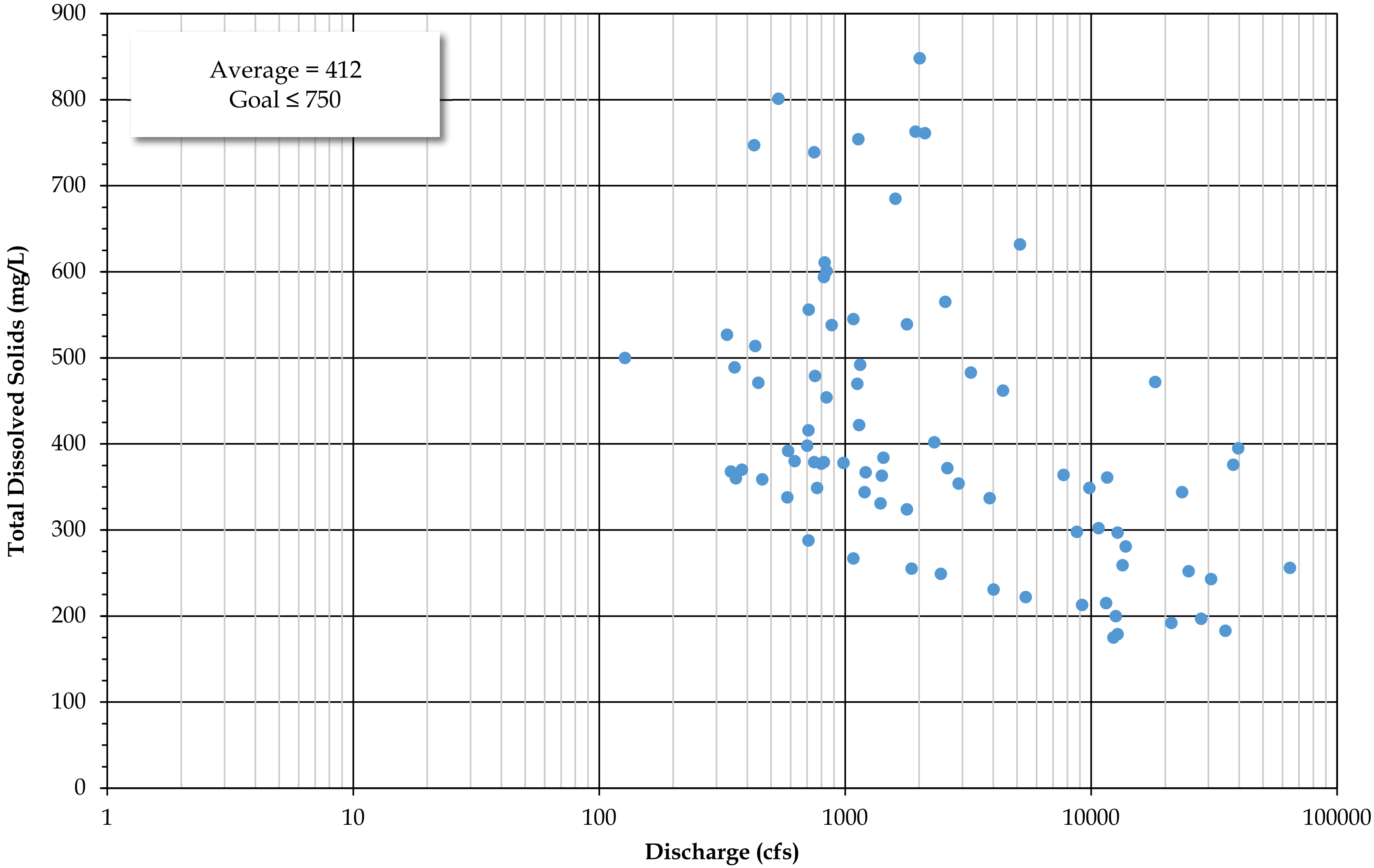


Figure G - 62. Total dissolved solids for surface water quality monitoring Station 11850 near Hempstead.

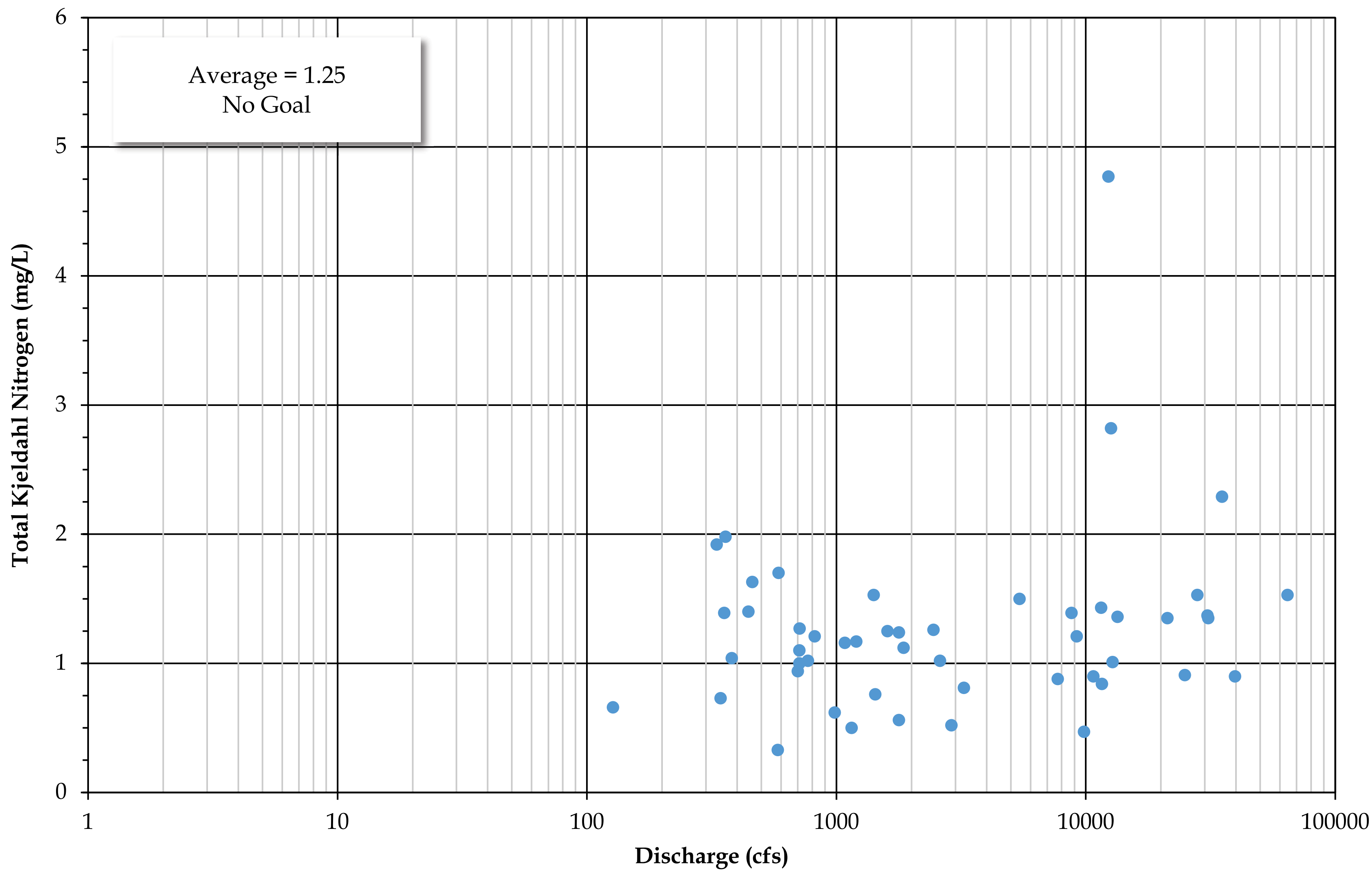


Figure G - 63. Total kjeldahl nitrogen for surface water quality monitoring Station 11850 near Hempstead.

Water Quality Sonde Graphs

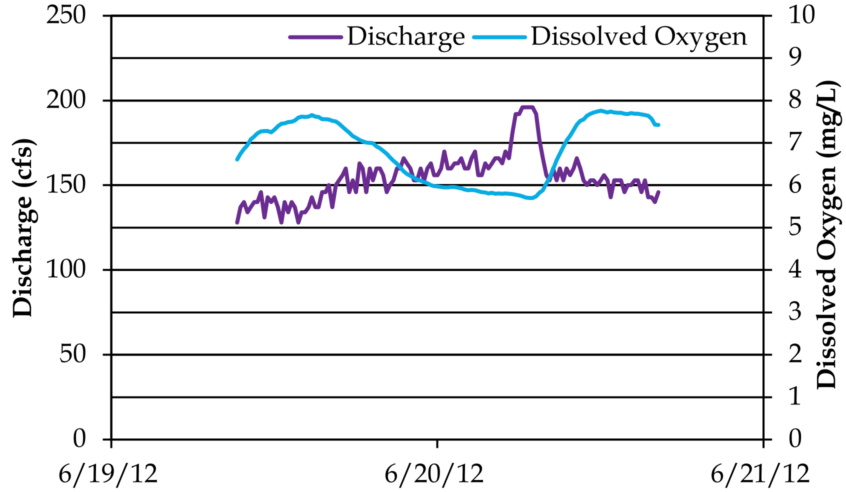


Figure G - 64. Marlin study site dissolved oxygen data for 6/20/12 through 6/21/12.

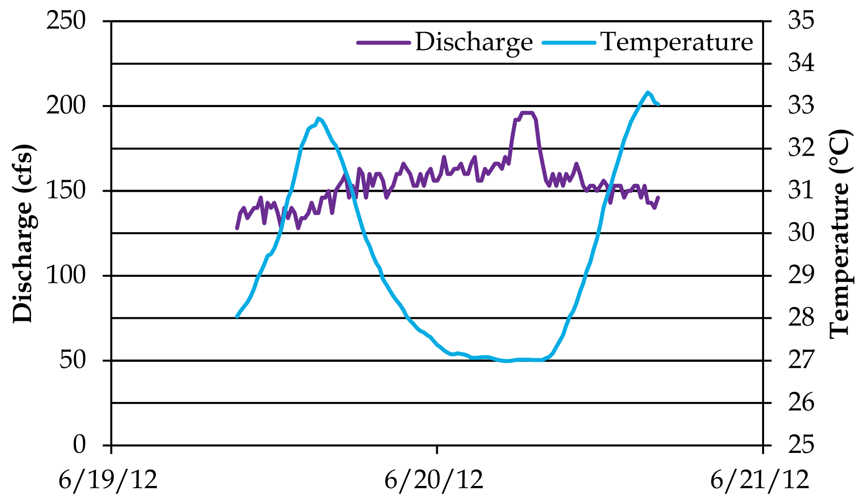


Figure G - 65. Marlin study site temperature data for 6/20/12 through 6/21/12.

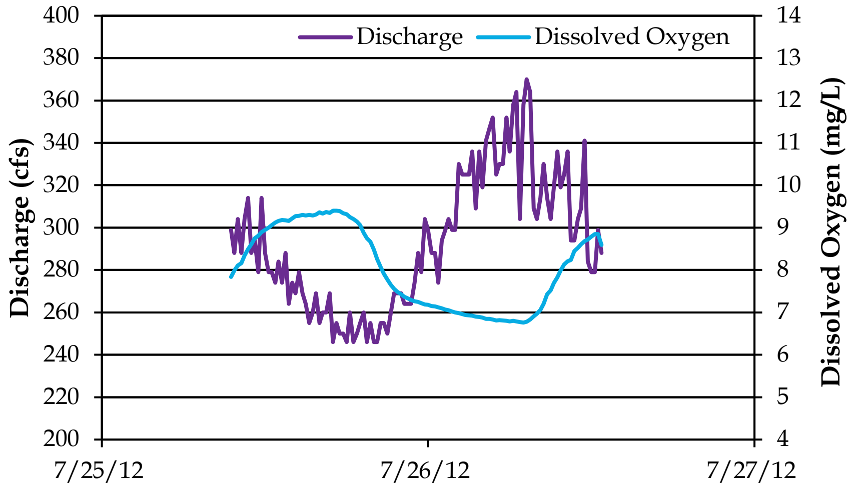


Figure G - 66. Marlin study site dissolved oxygen data for 7/25/12 through 7/26/12.

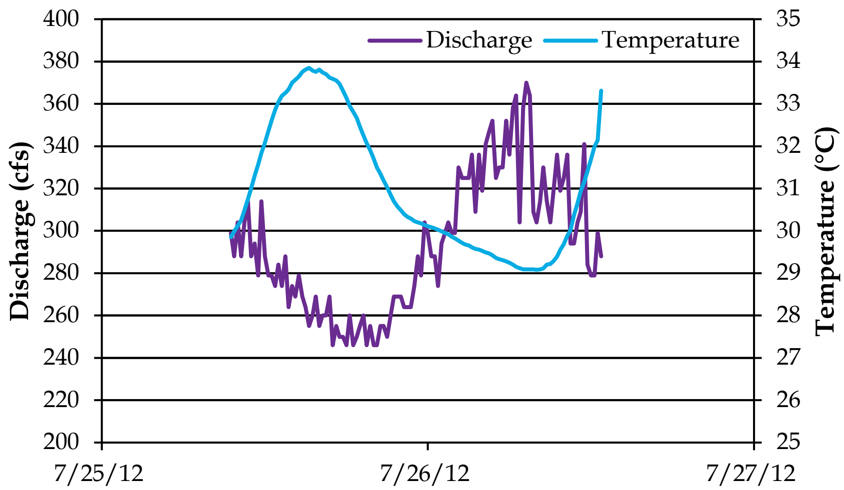
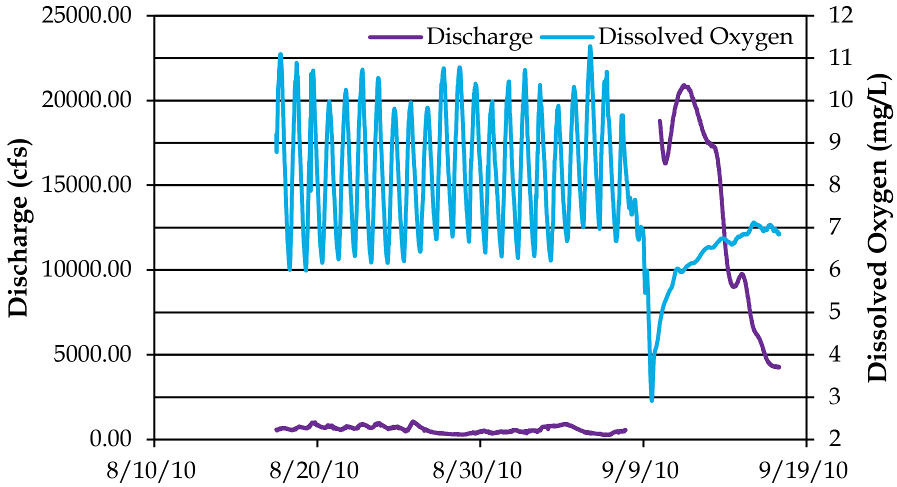
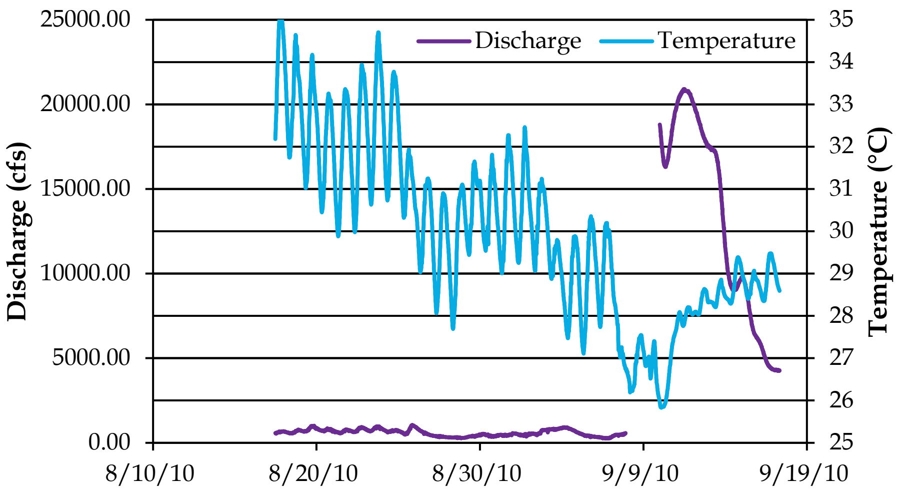


Figure G - 67. Marlin study site temperature data for 7/25/12 through 7/26/12.



* USGS gage data unavailable on 9/9/10

Figure G - 68. Marlin study site dissolved oxygen data for 8/17/10 through 9/17/10.



* USGS gage data unavailable on 9/9/10

Figure G - 69. Marlin study site temperature data for 8/17/10 through 9/17/10.

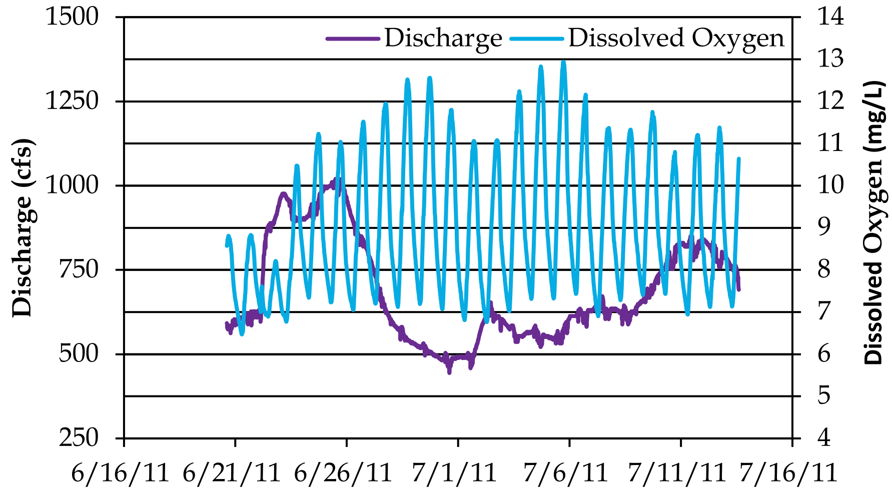


Figure G - 70. Mussel Shoals study site dissolved oxygen data for 6/20/11 through 7/13/11.

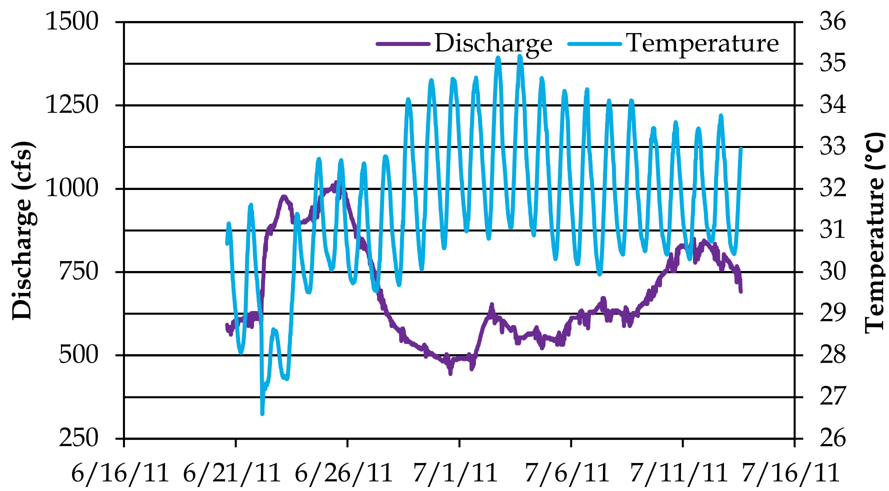


Figure G - 71. Mussel Shoals study site temperature data for 6/20/11 through 7/13/11.

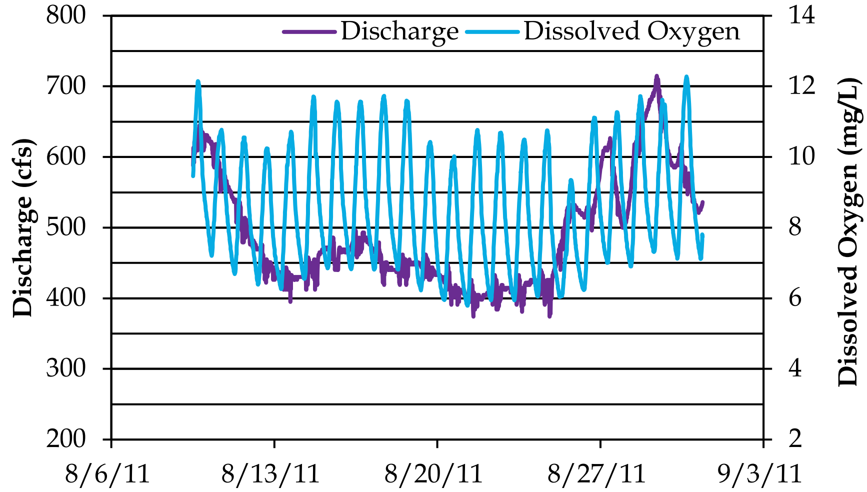


Figure G - 72. Mussel Shoals study site dissolved oxygen data for 8/10/11 through 8/31/11.

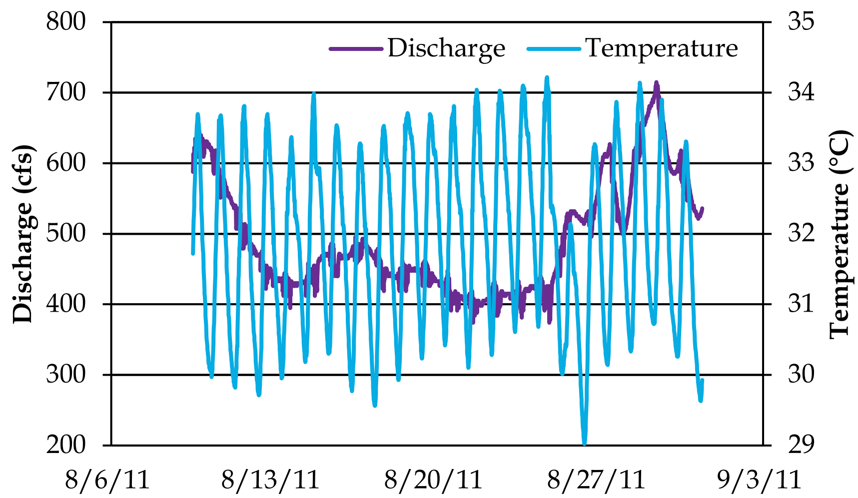


Figure G - 73. Mussel Shoals study site temperature data for 8/10/11 through 8/31/11.

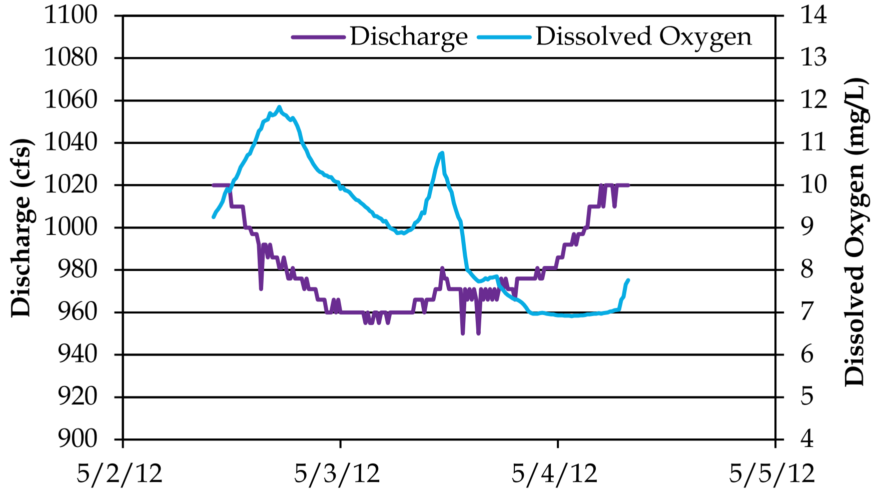


Figure G - 74. Navasota study site dissolved oxygen data for 5/2/12 through 5/4/12.

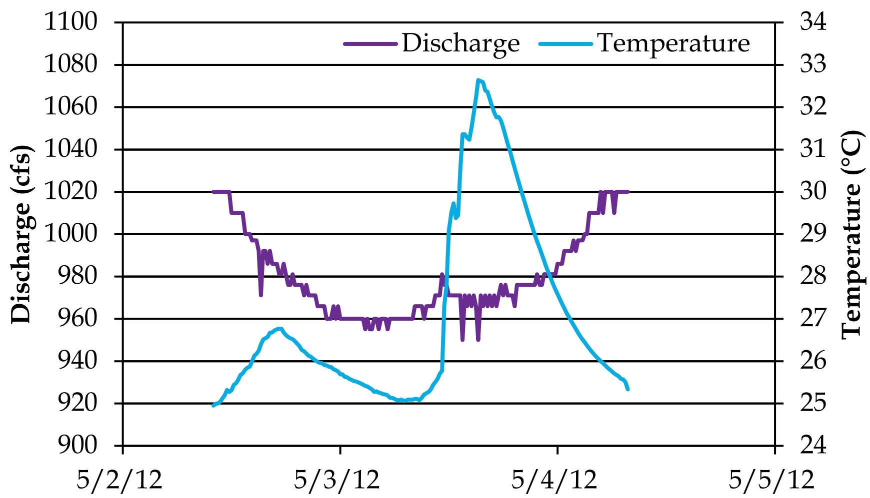


Figure G - 75. Navasota study site temperature data for 5/2/12 through 5/4/12.

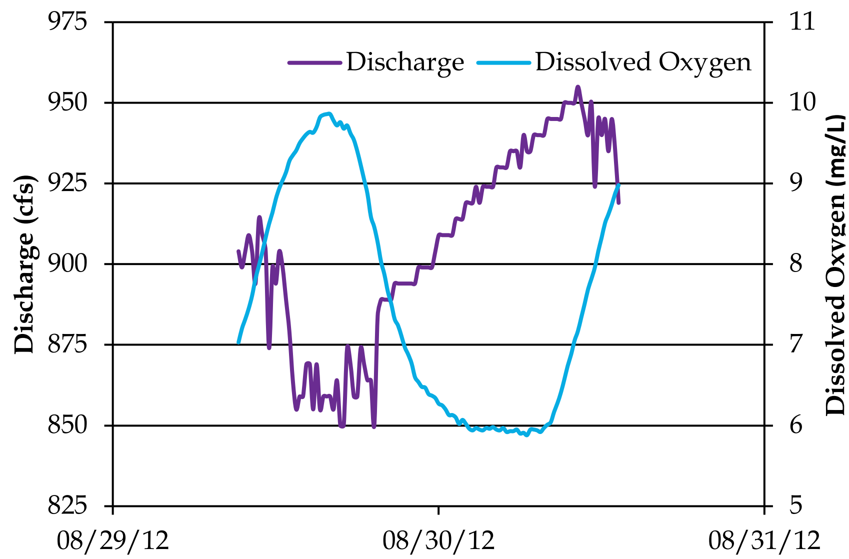


Figure G - 76. Navasota study site dissolved oxygen data for 8/29/12 through 8/30/12.

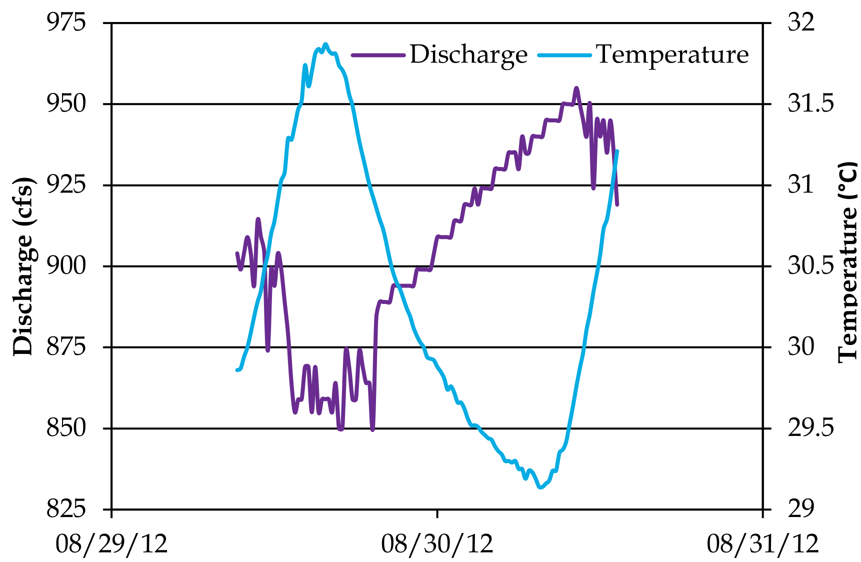


Figure G - 77. Navasota study site temperature data for 8/29/12 through 8/30/12.

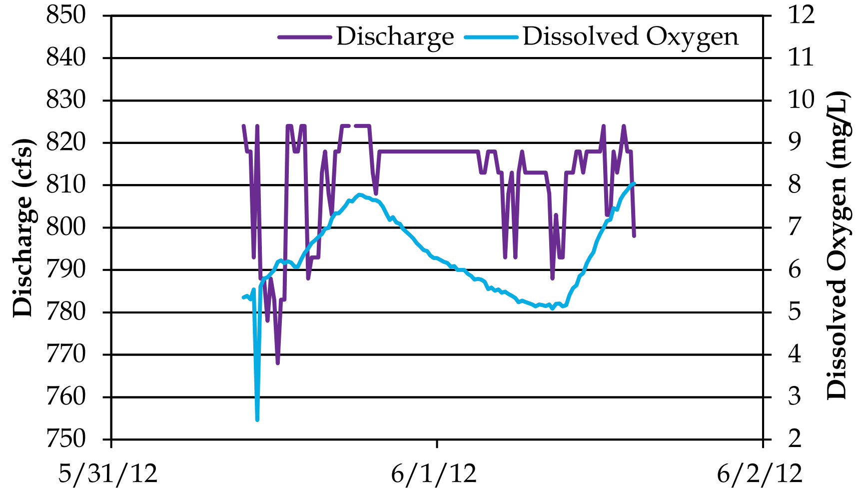


Figure G - 78. Wildcat Bend study site dissolved oxygen data for 5/31/12 through 6/1/12.

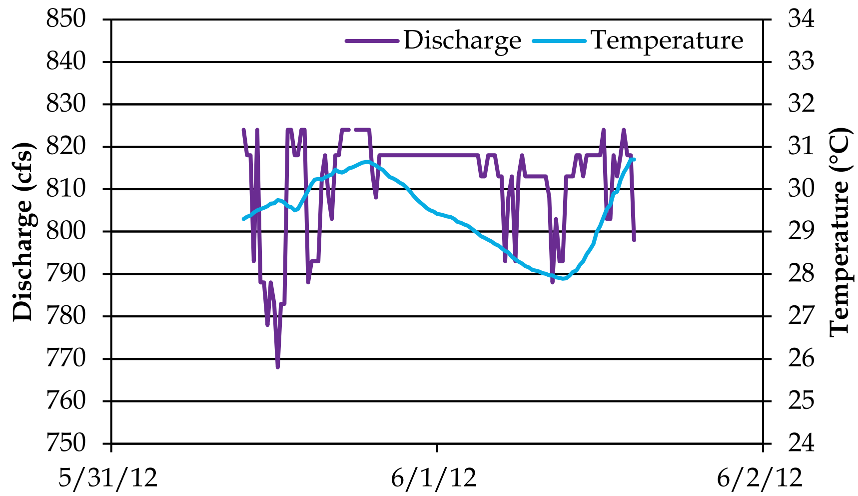


Figure G - 79. Wildcat Bend study site temperature data for 5/31/12 through 6/1/12.

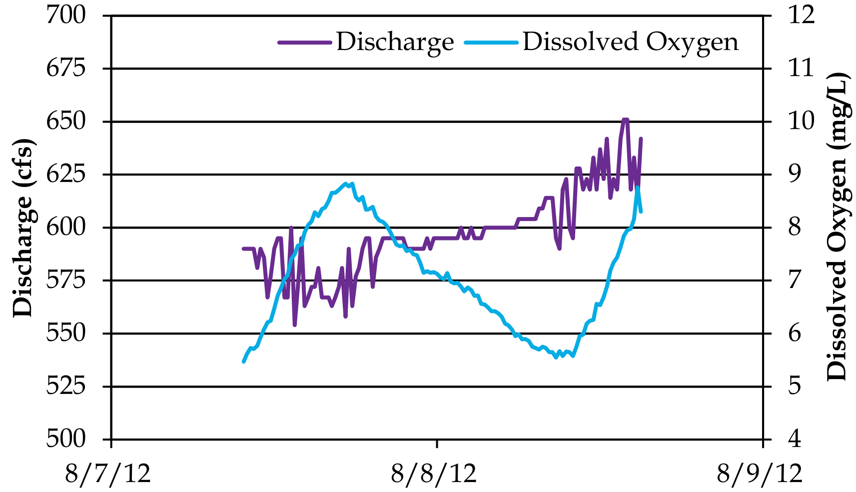


Figure G - 80. Wildcat Bend study site dissolved oxygen data for 8/7/12 through 8/8/12.

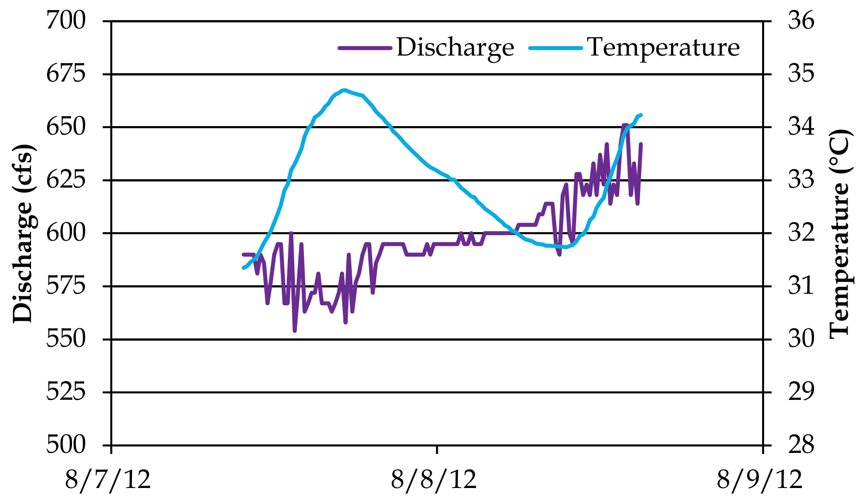


Figure G - 81. Wildcat Bend study site temperature data for 8/7/12 through 8/8/12.

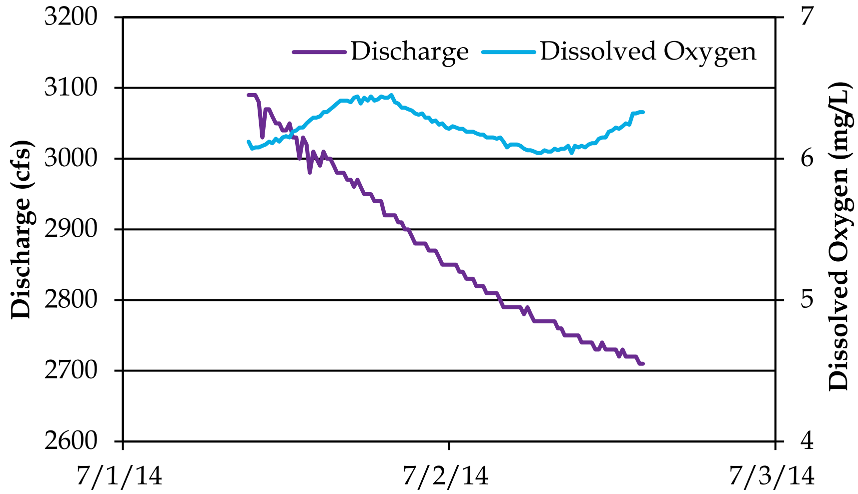


Figure G - 82. Wildcat Bend study site dissolved oxygen data 7/1/14 through 7/2/14.

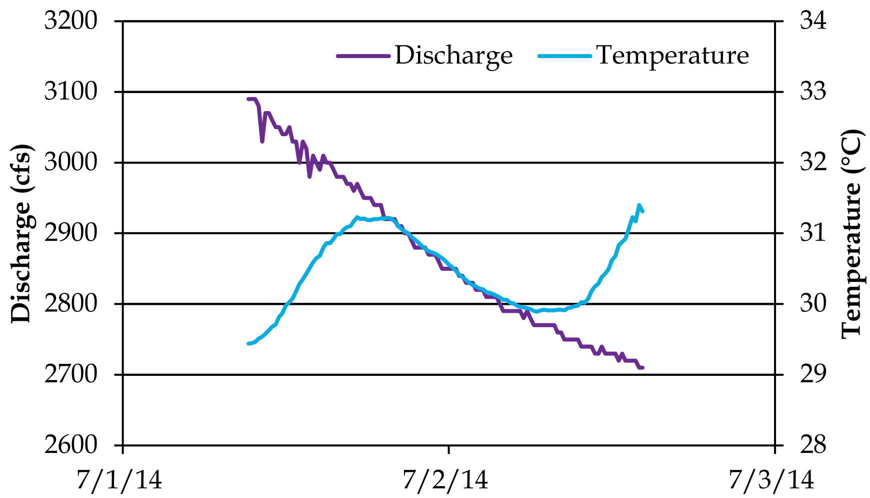


Figure G - 83. Wildcat Bend study site temperature data 7/1/14 through 7/2/14.

APPENDIX H
TIFP RESPONSES TO BRAZOS RIVER AUTHORITY COMMENTS

- The Brazos River Authority (BRA) commented that the goal for this work, as crafted by the stakeholders, was to recommend a flow regime that supported sustainable environmental, economic, and social uses and that the end result only focuses on the environment.

  Response: The focus of Texas Instream Flow Program studies is the environmental aspect of flow, specifically to identify instream flow recommendations for a sound ecological environment. Although it is recognized that stakeholders may have additional aspects to their goal for a river ecosystem, those additional aspects are not the focus of Texas Instream Flow Program studies. The TIFP acknowledges these comments. No changes were made in response to this comment.

- BRA commented that they do not feel the recommended flow regimes are supported by science nor do they accomplish the stakeholders' stated goals and desires.

  Response: The report was revised to address comments received from the BRA. TIFP appreciates the input of BRA staff throughout the study and continues to appreciate the comments of BRA and other stakeholders regarding the instream flow recommendations for the middle and lower Brazos River. The agencies are confident that the flow recommendations were developed based on a valid and rigorous scientific approach and are supportive of a sound ecological environment.

- BRA commented that there are numerous items in the draft report that cause them concern, are not scientifically supported, are not feasible, or fail to present the limitations of the assumptions and data used. Brazos River Authority requested that their name be removed from the title page as a preparer.

  Response: The report was revised to address comments received from the BRA. The agencies appreciate BRA's participation in the study and will comply with their wishes regarding the title page.

- BRA commented that they are concerned that the tone of the draft report implies that flood storage is bad and recommends overbank flows. While BRA concedes that flood storage alters the hydrologic function of the river, BRA noted that flood storage has been in place for over eighty years and the current ecosystem and biota has adapted to this change. BRA also notes that in a state where water supply is limited relative to population growth, and destructive, life-threatening flooding occurs in spite of existing flood control structures, this seems like an irresponsible view to espouse.

  Response: The agencies recognize that flood control reservoirs provide important benefits to society and appreciate that BRA recognizes that their operation does alter hydrologic aspects of the river. Section 2.2.1 was revised to add clarifying language.

- BRA commented that they were left with the impression that the TIFP agreed that overbank flows were not going to be included in the recommendation. Given the potential for overbank flows to threaten human health, safety and property, BRA commented that they cannot support the recommendation for overbank flows and that the U.S. Corps of Engineers, who owns and operates many of the basin's reservoirs, has established downstream flow targets to prevent flooding and the resultant threats to human health, safety and property that make these recommendations infeasible to implement, which is not noted anywhere in the report.

Response: Section 2.2.1 was revised to include additional information on downstream flow targets related to US Army Corp of Engineers flood operations. The agencies regret any miscommunication that may have led the BRA to believe that overbank flows would not be included in the instream flow recommendations.

- BRA commented that the draft report is not clear about the number of actual sampling events that occurred and the time frame over which they occurred. BRA noted that all the samples were collected in one to four sampling events per site over a period of a few years; however, in the context of documenting ecological needs, BRA does not consider this a statistically-supportable number or duration of events. BRA also commented that all data collected was during severe, prolonged drought which has the potential for the results to be biased towards that extreme and that limitations in sampling and the conditions during which the sampling occurred need to be clearly articulated and their potential impacts on the reliability of the data beyond representing drought conditions need to be clearly acknowledged.

  Response: Section 2.3.4 was revised in response to this comment. The TIFP recognizes that much of the data collection occurred during drought conditions. However, fish-habitat suitability sampling was not designed to assess population or assemblage level responses to streamflow. Table 11 in the report provides a breakdown of fish-habitat sampling efforts across all study sites and base flow conditions.

- BRA commented that several of the key indicator species identified during the Stakeholder Process, for example alligator gar (*Atractosteus spatula*) and shoal chub (*Macrhybopsis hyostoma*), are naturally elusive or naturally rare in abundance. Therefore, their absence or low numbers in catches, given the limited number of sampling events, does not necessarily indicate an ecological concern.

  Response: Section 2.3.10 was revised to include additional information related to Alligator Gar. Table 12 provides the numbers of small and large Shoal Chub and other abundant fishes collected during habitat suitability data collection.

- BRA noted that they understand that periodic oxbow connectivity is critical to the diversity of the fish community, and that over time, as the river meanders and ages toward a state of equilibrium, some oxbows will lose connectivity and be abandoned by the river while others will be created. BRA commented that nowhere in the discussion or supporting figures (Figure 39 or Table 16) is the distance between the main channel and each identified oxbow discussed, nor is the unique elevation required to inundate each oxbow discussed. They noted that this does not allow the reader any means to determine whether some oxbows, for example those needing the largest flows for connectivity, are reaching the point where it is no longer reasonable to expect ongoing, routine connectivity. BRA commented that while they can support the need for occasional connectivity, and can even support the need for annual connectivity for those oxbows closest to the river, they question the scientific justification for the monthly oxbow connectivity recommended in Table 32, as this frequency is certainly not supported by the historical hydrograph.

Response: Section 3.3.2 was revised to address this comment. Additional text has been added to the report to clarify that Tables 30, 31 and 32 provide descriptions of the environmental benefit of high pulse and overbank flows when they occur.

- BRA commented that much discussion is given to the presence or absence of box elder (*Acer negundo*) and black willow (*Salix nigra*) as indicators of healthy riparian vegetation. They noted that this can be misleading as both are successional species that colonize after environmental disturbances, and in parts of the country, black willow is considered an unwanted, invasive and that the absence of either in and of itself, does not indicate a damaged riparian corridor. BRA commented that while both species can quickly establish on newly available habitat and are important to bank stability after a disturbance, the river should not be managed to maintain successional species as we would be managing for continuous disturbance. They also noted that while disturbances are an essential part of the riverine ecosystems, healthy riparian communities should include established hardwood species such as hickories, ash, oaks, walnuts, cottonwoods, etc.

  Response: Section 3.3.1 was revised to clarify that recommendations are based on maintaining current/recent riparian area, not restoring historical conditions.

- BRA noted that to determine mussel temperature tolerance and dissolved oxygen demands, data from research performed on similar but different species in other, more northern states was relied upon by the TIFP. BRA also commented that they understand that there is a current absence of published data specific to Texas species, although there are ongoing studies to identify the temperature tolerances and oxygen demands of Brazos basin mussel species. BRA commented that that initial results for the smooth pimpleback (*Quadrula houstonensis*) indicate the species is hardier than the *Quadrula* spp. in the studies from other states, and lethality has not occurred up to 36°C. BRA also commented that these preliminary results do not support the thermal tolerance limit of 30°C stated in Section 3.2.2 and that adopting criteria based on research from other states and on other species, will only generate recommendations that will not be effective in supporting Texas' endemic species. They commented that given that research into mussel tolerances on Brazos basin species is currently underway, they feel it would be wise to wait until those studies can be completed and published before adopting flow criteria specific to mussels.

  Response: Section 2.3.11 and Section 3.2.2 were revised to include clarifying information regarding mussel thermal tolerance.

- BRA noted that much importance in the report is placed on the thermal maxima for several fish species and that at times, during the summer, water temperatures may exceed these maxima. BRA commented that no discussion is made of the duration at or above these thermal maxima that will result in lethality. They note that given that there have been no routinely documented fish kills of these species tied to the occasional, brief exceedance of water temperature maxima, indicates that this is not the dire problem implied in the draft report. BRA commented that more discussion to help the reader reconcile the statements regarding water temperature and the lack of historical evidence supporting these statements would be helpful.

  Response: Section 4 was revised to clarify the discussion regarding thermal maxima for fish.

- BRA commented that the discussions of sediment transport and flows required to maintain channel stability are somewhat confusing. They note that both sections 2.4.2 and part of 3.3.3 discuss that the channel is not stable, is degrading, is a threat to current flow ecology relationships, and needs to be restored to stable conditions and in contrast, Section 4, states that neither the recommended high flow pulses nor the recommended overbank flows will be sufficient for maintaining sediment transport and will cause the channel to aggrade. They also note that this is in direct conflict with Phillips' findings that the threshold for sediment mobility in the Brazos are regularly exceeded (Phillips, J.D. 2013. *Flow Modifications and Geomorphic Thresholds in the Lower Brazos River*. Austin, Texas: Texas Water Development Board). BRA commented that if the primary concern was degradation or aggradation and that if high flow pulses and overbank flows are not sufficient to move sediment and prevent aggradation, how large would these flows need to be.

  Response: A description of findings of Phillips (2013) was added to Section 2.4.1. Clarification of the relationship between those findings and the sediment transport modeling effort described in the report was added to Section 2.4.3.

- BRA commented that base flow recommendations for some sites appear to be based on the presence of what is deemed to be high quality riffle habitat at the site. These substrates at these sites are noted to consist of sand, silt, clay and gravel, all easily eroded, suspended and moved by high flows. While providing valuable habitat when they exist, these riffle features are transient by nature. BRA commented that it does not seem practical to make site-specific flow recommendations solely on the existence of a transient structure.

  Response: Section 2.1 was revised to include additional explanation and clarification of how the size of study sites (a length of channel that includes at least one meander wave length) mitigates for changing habitat conditions.

- BRA commented that determination of hydrologic condition differs from that adopted in the environmental flow standards. They noted that it appears that a wet or dry condition in the study analysis is strictly based on streamflow, and specifically streamflow conditions in recent past decades; however, streamflow in a post-reservoir world is influenced by reservoir operations, diversions by water right holders and return flows. BRA commented on how these impacts considered in determining a wet or dry condition if streamflow is the only indicator of a hydrologic condition and that clear methodology explaining how the hydrologic condition was calculated for each site needs to be included in the report.

Response: Section 4 was revised to include language clarifying that wet, average, and dry base flows are expected to be in place 25%, 50%, and 25% of the time, respectively, has been added to the report. Implementation issues are not addressed by Senate Bill 2 studies.

- BRA commented that it is unclear how streamflow is translated from USGS gage locations to other locations and that the drainage areas used for these locations is not documented anywhere in the report. They commented that a table identifying drainage ratios and other relationships used to translate the flows to ungaged locations and that identifies periods of missing data in data set used would be helpful.

  Response: Table 27 shows the relationship of study sites and USGS gaging sites. Periods of record for USGS gages in the sub-basin are provided in Table 2 of the Study Design (TIFP/BRA 2010).

- BRA commented that updated subsistence flows indicate that extended hydrology was considered in calculating these flow recommendations; however, it is not clear if the extended hydrology was considered in the selection of the range of base flows recommendations or the sources of the base flow statistics. They commented that if the extended hydrology was not used in base flow calculations, consideration should be given to reanalyzing using this data set and that more detail about the data used to calculate base flows and the actual calculation of base flows should be provided. BRA commented that Table 28 shows flow ranges based on habitat but it is not clear what the period of record is for this analysis.

  Response: Section 3.2 was revised to include additional explanation and clarification. Additional text and Figure 60 provide an example of how base flow ranges shown in Table 28 were selected from habitat versus flow curves.

- BRA noted that it appears that the monthly base recommendations are indirectly based on pre-reservoir conditions. They commented if there is a reason that the subsistence flows should not also use a consistent period of record to truly capture the full extremes of natural streamflow conditions.

  Response: TIFP acknowledges the comment and notes that subsistence flow recommendations relied on water quality data that is only available in the more recent period.

- BRA commented that the subsistence flows for the periods used for base flow recommendations should also be presented.

Response: As described in Section 3.2, base flow recommendations were based on flow-ecology relationships, not flow data for a period of record. Extreme low flow statistics for several time periods are included in Figure 9 and Table 9 of the report and Tables A-1 through A-3 of Appendix A.

- BRA noted that it is not clear how the base flow recommendations compare to historical streamflow and that it appears that the range of base flows are selected on a habitat analysis that may use river conditions from recent decades but the range of base flows appear to be distributed monthly based on a pre-reservoir analysis. They commented that a comparison between the recommended flow values and the historical streamflow in both pre-reservoir and post-reservoir periods would be helpful.

  Response: Appendix A, Figures A-16 through A-21 show how base flow recommendations compare to recent hydrologic data (1996-2015). Flow recommendations can also be compared to flow exceedance statistics for several time periods as shown in Tables A-1 through A-3.

- BRA commented that a table that provides the values, Q25 and Q75 flows in the earlier period discussed in the section on Establishing Intra-annual Variability, for each of the sites would be helpful.

  Response: The TIFP acknowledges this comment. No changes were made in response to this comment. In Appendix A, daily Q25 and Q75 flows for 1996-2015 are shown in Figures A-16 through A-21. Values of Q25 and Q75 can be interpolated for several time periods from Tables A-1 through A-3.

- BRA noted that many of the recommended high flow pulse frequencies and durations are not supported by the historical hydrographs, pre- or post- dam. They commented on whether the recommended flow regimes could be the critical flows needed to support a sound ecological environment if the recommended flows have not been documented to occur at similar frequencies and durations in historic hydrology records. BRA commented that it would be helpful to provide a table documenting the validation of the recommended flow regimes, using historical hydrology data sets.

  Response: Figures A-16 through A-21 of Appendix A, demonstrate that flows in excess of most of the recommended high flow events have occurred in the recently gaged record (1996-2015). The two exceptions are the two highest pulse flow recommendations at the Marlin study site (Figure A-16).

- BRA noted that how habitat and species needs determinations were translated into the flow regime recommendations is not plainly and clearly stated for each location. They commented that the reasoning and analyses for each recommendation need to be clearly documented, otherwise the reader is unable to determine the value and veracity of the recommendations in the draft report.

Response: Section 3.2 was revised to include additional explanation and clarification. Additional text and Figure 60 provide an example of how base flow ranges shown in Table 28 were selected from habitat versus flow curves.