Environmental Flows Recommendations Report
Final Submission to the Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission, Copano, Aransas, and San Antonio Bays Basin and Bay Area Stakeholder Committee, Environmental Flows Advisory Group, and Texas Commission on Environmental Quality

Guadalupe, San Antonio, Mission, and Aransas Rivers and
Mission, Copano, Aransas, and San Antonio Bays
Basin and Bay Expert Science Team

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1. Preamble

1.1 Senate Bill 3 Environmental Flows Process

Senate Bill 3 (SB3) of the 80^{th} Texas Legislature established a process for the development and implementation of environmental flow standards applicable to major river basins and estuarine systems across the State of Texas. As summarized in Figure 1.1-1, this process began with selection of the Environmental Flows Advisory Group (EFAG) and reaches an interim conclusion for each river basin and associated estuarine system upon Texas Commission on Environmental Quality (TCEQ) adoption of rules implementing environmental flow standards. This Environmental Flows Recommendations Report is the primary deliverable of the Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission, Copano, Aransas, and San Antonio Bays Basin and Bay Expert Science Team (GSA BBEST) and is timely submitted in the midst of the SB3 environmental flows process to serve as a useful technical resource.

1.1.1 Environmental Flows Advisory Group (EFAG)

The EFAG is comprised of nine members including three Texas state senators, three state representatives, and three commissioners or board members respectively representing the TCEQ, Texas Parks and Wildlife Department (TPWD), and the Texas Water Development Board (TWDB). Key responsibilities of the EFAG include appointment of the Science Advisory Committee (SAC) and Basin and Bay Area Stakeholder Committees (BBASC).

1.1.2 Science Advisory Committee (SAC)

The SAC is comprised of nine technical experts in diverse areas relevant to evaluation of environmental flows, and has since 2009 diligently provided documented guidance to both BBESTs and BBASCs. Guidance provided by the SAC regarding environmental flows has addressed geographic scope, use of hydrologic data, fluvial sediment transport (geomorphology), methodologies for establishing freshwater inflow regimes for estuaries, biological overlays, nutrient and water quality overlays, moving from flow regimes to flow standards, lessons learned from early BBESTs, work plans for adaptive management, methods for evaluating inter-relationships between environmental flow regimes and water supply projects, and consideration of attainment frequencies and hydrologic conditions. This guidance has been relied upon by the GSA BBEST in execution of its charge and creates the general structure of this recommendations report.

1.1.3 Basin and Bay Area Stakeholder Committee (BBASC)

BBASCs must reflect a fair and equitable balance of interest groups concerned with particular river basins and bay systems. Interest groups represented on BBASCs include: agriculture, recreation, municipalities, soil and water conservation districts, refining industry, chemical manufacturing, electricity generation, commercial fishing, public interests, regional water planning, groundwater conservation districts, river authorities, and environmental groups. BBASCs, in turn, appoint BBESTs comprised of technical experts with knowledge of particular river basin and bay systems and/or development of environmental flow regimes. The GSA

BBASC is comprised of 24 members and, on March 1, 2010, acted to appoint 12 scientists as members of the GSA BBEST, with two of these members classified as non-voting. Information regarding the GSA BBEST is summarized in Section 1.2.

Once a BBEST issues its recommendations report, the appointing BBASC will consider the BBEST recommendations in conjunction with other factors—including the present and future needs for water for other uses related to water supply planning—and prepare recommendations on environmental flow standards and strategies within six months. Subsequently, BBASCs are charged with development of a work plan that addresses periodic review of environmental flow standards, prescribes necessary monitoring and studies, and establishes a schedule for continuing validation or refinement of environmental flow regime recommendations.

1.1.4 Texas Commission on Environmental Quality (TCEQ)

With due consideration and balancing of all relevant information available, including BBEST and BBASC recommendations, the TCEQ will adopt environmental flow standards for each river basin and bay system through an established, public rule-making process.

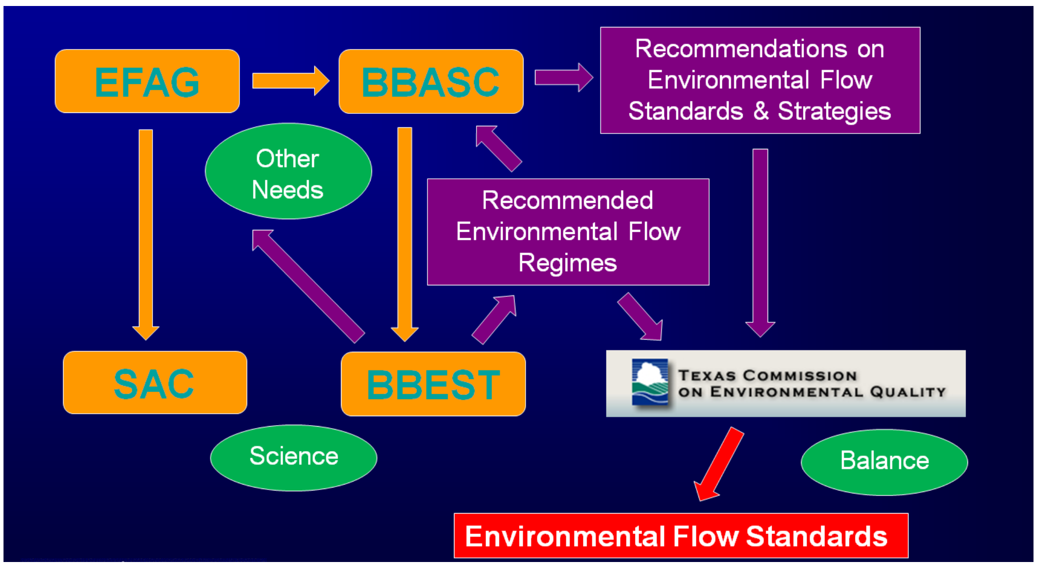


Figure 1.1-1. SB3 Environmental Flows Process

1.2 Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission, Copano, Aransas, and San Antonio Bays Basin and Bay Expert Science Team (GSA BBEST)

1.2.1 Membership

The GSA BBEST was initially comprised of 12 members appointed by the GSA BBASC. Due to scheduling conflicts and other commitments, one member chose to withdraw prior to participating in a meeting of the GSA BBEST. Active membership of the GSA BBEST is summarized below along with administrative and subcommittee assignments.

Sam Vaugh – Chair, Hydrology Subcommittee Lead
Norman Johns – Vice-Chair, Estuary and Hydrology Subcommittees
Thom Hardy – Instream Subcommittee Lead, Hydrology Subcommittee
Warren Pulich – Estuary Subcommittee Lead, Hydrology Subcommittee
Tim Bonner – Instream and Hydrology Subcommittees
Ed Buskey – Estuary Subcommittee
Mike Gonzales – Instream and Estuary Subcommittees
Scott Holt – Estuary and Hydrology Subcommittees
Elizabeth Smith – Instream and Hydrology Subcommittees
Gregg Eckhardt – Instream and Hydrology Subcommittees, Non-Voting
Debbie Magin – Instream, Estuary, and Hydrology Subcommittees, Non-Voting

1.2.2 GSA BBEST Charge

Pursuant to Section §11.02362(m) of the Texas Water Code, the initial charge of a BBEST is summarized as follows (emphasis added):

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

SB3 of the 80th Texas Legislature offers the following definitions pertinent to the BBEST initial charge (emphasis added):

> *"<u>Environmental flow analysis</u>" means the application of a scientifically derived process for predicting the response of an ecosystem to changes in instream flows or freshwater inflows.*
> *"<u>Environmental flow regime</u>" means a schedule of flow quantities that reflects seasonal and yearly fluctuations that typically would vary geographically, by specific location in a watershed, and that are shown to be adequate to support a sound ecological*

environment[1] *and to maintain the productivity, extent, and persistence of key aquatic habitats in and along the affected water bodies.*

Since its first meeting on April 7, 2010, the GSA BBEST has worked with diligence and determination to accomplish the tasks with which it is charged. As a result of monthly meetings of the full GSA BBEST, focused subcommittee meetings, and the individual and collective efforts of BBEST members, we believe that we have met our initial charge. It is acknowledged with great appreciation that our efforts were very ably supported and significantly enhanced by dedicated personnel from the TWDB, TPWD, TCEQ, San Antonio River Authority (SARA), Guadalupe-Blanco River Authority (GBRA), San Antonio Water System (SAWS), Texas River Systems Institute (TRSI), and a number of other organizations.

[1] Opinions of the GSA BBEST regarding sound ecological environment are summarized in Section 1.3.

1.3 Sound Ecological Environment

One of the primary charges to the BBEST emanating from SB3 is to develop both instream flow and estuarine inflow regimes "adequate to support a sound ecological environment and to maintain the productivity, extent, and persistence of key aquatic habitats in and along the affected water bodies." Because the conceptualization of what does, or does not, constitute a "sound ecological environment" obviously has great bearing on our tasks, the GSA BBEST feels that some discussion of this topic is warranted.

As the current SAC for Environmental Flows points out (SAC 2009a), SB3 did not explicitly define sound ecological environment; thus the current SAC refers to the definition put forth by a previous SAC in 2006 (SAC 2006), which states:

> **A sound ecological environment is one that:**
> **• sustains the full complement of native species in perpetuity,**
> **• sustains key habitat features required by these species,**
> **• retains key features of the natural flow regime required by these species to complete their life cycles, and**
> **• sustains key ecosystem processes and services, such as elemental cycling and the productivity of important plant and animal populations.**

We note that these points refer broadly to measures of the attributes or status of an environment (e.g. species composition and habitats) as well as those related to functions and processes. The 2006 SAC, in subsequent discussion, also hit upon a point which we feel is key; namely, that the adjective "sound" may be interpreted differently when viewing different aquatic systems, and when viewing through the lens of various stakeholders or others. In the view of this science team, "sound" does not equate to "natural" or "pristine."[2] In other words, evidence of some level of alteration still allows for a determination of "soundness."

We believe, given the 2006 SAC definitional concepts and the recognition of the scope of the word "sound," that a comprehensive definition can be offered.

> A sound ecological environment maintains, to some reasonable level, the physical, chemical, and biological attributes and processes of the natural system.

Given the broadness of this definition, there is no single measure that can be employed to test or determine "soundness." However, there are many individual measures that are commonly used to assess components of a sound environment. These measures include water quality standards, habitat suitability and availability, indices of biologic integrity, estuarine salinity patterns, sediment transport, nutrient delivery, and species occurrence, abundance, and diversity.

The GSA BBEST feels that river and stream, riparian, wetland, and estuarine ecosystems of our assigned area are, broadly speaking, "sound" today with few exceptions. Further, we

[2] In fact, some ecological researchers feel that the obvious widespread influence of human activity at modifying all ecosystems has led to an undue focus on ever rarer "natural" systems (Marris 2010).

acknowledge that such ecosystems have exhibited characteristics of a sound ecological environment throughout the past century as many ecosystems have transitioned from a natural condition to the modified conditions typical of the present. By sound we mean that the measures of the status of native communities and habitats have been generally good and that no obvious long-term losses of function or undue impairment of important biologic, physical, or chemical processes are evident. Exceptions include communities and habitats directly affected by anthropogenic modifications in localized areas (i.e., within and immediately downstream of reservoirs or highly urbanized areas). In separate sections, we briefly describe the evidence for this determination, and note special conditions or circumstances that warrant particular attention in the development of work plans for continued monitoring and re-evaluation.

1.3.1 Sound Ecological Environments – Riverine

Support for a sound ecological environment in riverine systems includes relatively intact fish communities in most reaches of the San Antonio River (Runyan 2007), Guadalupe River, San Marcos River (Perkin and Bonner, In press), and the Blanco River (Bean et al 2007). The fish community in the Lower San Antonio River (LSAR) is considered relatively intact (i.e., high biotic integrity), although increases in the number and abundances of exotic species, increases in abundance of generalist species, and declines in abundance of two slackwater species were observed between an early period of fish collection records (1950-1969) and a later period of record (1970-2006) (Runyan 2007). Fish communities in the upper and lower Guadalupe River and San Marcos River are considered relatively intact, although declines in abundance of some moving-water specialists, increases in abundance of generalist species, changes in trophic structure, and occurrences and abundances of exotic species were observed between an early period of fish collection records (1938-1963) and a later period of record (1965-2000) (Perkin and Bonner, In press). The fish community in the Blanco River is considered relatively intact, although declines in abundance of two moving-water specialists and increases in abundances of two exotic species were observed between one early period fish collection (1957) and a later collection (2003-2005) (Bean et al. 2007).

Aquatic macrophytes, macroinvertebrates, mussels, and various ecosystem processes were not used as indicators of a sound ecological environment by the GSA BBEST. This is due to the paucity of quantitative information available for these plant and animal groups, and certain processes, and their respective relationships to streamflow within the Guadalupe and other river basins. We acknowledge that our evidence of sound ecological environments doesn’t necessarily represent the ecological soundness of all aquatic organisms and river-based processes.

1.3.2 Sound Ecological Environments – Estuarine

Several lines of evidence support our determination that the Guadalupe Estuary and Mission-Aransas Estuary are, and have been, of a “sound” status.

The Coastal Bend Bays and Estuary Program (CBBEP) was originally part of the National Estuaries Program established by the Clean Water Act of 1987 and administered by the Environmental Protection Agency (EPA). It is now a not-for-profit organization “dedicated to protecting and restoring bays and estuaries … in the Texas Coastal Bend.” The area of coverage includes the Mission/Aransas Estuary as well as the Nueces and Upper Laguna Madre, but does not include the Guadalupe/San Antonio Estuary. The general assessments by the CBBEP of the status and trends in the health and condition of the local estuarine environment are nevertheless informative. In the first years of the program, the CBBEP did an assessment of more than 30 components of the biotic and abiotic environment in the estuaries, and compared the current (as of the mid 1990s) conditions with those of the past 50 to 100 years (depending on data availability). A summary assessment called "The State of the Bay: A Report for the Future" (Holt 1998) concluded that the estuaries of the Coastal Bend were "moderately healthy." Furthermore, the report states that "Unlike many other estuaries across the nation, our scientific findings do not show major problems."

As part of a regular update on estuarine conditions in the Coastal Bend, the CBBEP recently produced a report titled "Environmental Indicators Report 2010" (CBBEP 2010) which it describes as an "environmental report card." This report shows that the condition of the estuaries in question is still "generally good." The report points out that the most recreationally and ecologically important fish populations are increasing and that seagrass and saltwater marsh habitat is increasing. The report also points out, however, that blue crab populations continue to decline and that the incidences of harmful algal blooms have been increasing over the past two decades.

Additionally, the Final Programmatic Environmental Impact Statement for federal approval of the Mission-Aransas National Estuarine Research Reserve (NERR) includes a thorough review of the environmental condition of the Mission-Aransas Estuary, with the overall conclusion that the estuary is ecologically sound and has suffered only limited human impact and habitat loss (NOAA 2006). A more recent site profile of the NERR (Evans et al, in review) reviews the hydrography, geology, water quality, habitats, endangered species, and human dimension of the Mission Aransas estuary, and again concludes that the estuarine environment is fundamentally sound.

The long-term recovery of the population of the endangered Whooping Crane, from a low of 16 individuals in 1941 (ICF 2010) would appear to only be possible within the context of a generally sound estuarine environment. As noted below, this general observation must be qualified, given periodic setbacks.

Vegetative wetlands in the Guadalupe Estuary (Guadalupe, San Antonio, Espiritu Santo, and Mesquite Bays) have been assessed in recent status and trends studies, and these reflect fairly stable amounts of estuarine wetlands. Pulich (1991) inventoried submerged vegetation and determined that seagrasses had decreased about 13% between 1972 and 1988. However, this change was considered to be within the range of normal seasonal variation, and also did not account for increases in freshwater submerged vegetation in the Guadalupe Delta over the same period. Moulton et al. (1997) compared US Fish and Wildlife Service (FWS) National Wetlands Inventory data for emergent marshlands between the mid-1950s and 1992. Their study determined that estuarine marsh had declined less than 1% for the San Antonio Bay system, much less than the average 9.5% loss for the upper Texas coast. While freshwater marsh (palustrine wetlands) decreased the most across the Texas coast (an average of 29%), the

Calhoun and Refugio County areas around the San Antonio Bay area showed very minor change in this wetlands category.

Additionally, at the request of the GSA BBEST, Norman Boyd of the Port O'Connor Regional Office of TPWD compiled a status and trends assessment based upon the twenty eight years of sample data collected by the TPWD Coastal Fisheries Resource Monitoring Program. This sampling program monitors the dominant fishery species (16 trawl-caught species; 21 seine-caught species) in Texas estuaries. For the Guadalupe Estuary, the results of this analysis covering 95% of the samples caught over the 1982-2009 period show routine fluctuations in catch rates, except for the blue crab and southern flounder noted below (see TPWD Resource Monitoring data in Appendix 1.3-1).

While the GSA BBEST feels that the lines of evidence presented above support our determination that a sound ecological environment has existed and currently exists in the Guadalupe and Mission-Aransas Estuaries, we do note the following issues that may warrant special attention in the future.

- There has been a great decline in the numbers of Tarpon, a large game fish. However, there is no compelling evidence that these alterations are related to modifications in inflow regimes.
- There has been a well-documented decline in blue crab abundance. However, this is a broad-scale phenomenon, encompassing the entire Gulf coast and Atlantic seaboard, and there is no apparent relationship to inflow alterations.
- There has been an extended decline in the southern flounder population. As with blue crab, this trend is seen all along the Texas coast, and there is no apparent relationship to freshwater inflow trends.
- There have been occasional short-term declines in Whooping Crane population which may be correlated with re-occurring drought conditions.

1.4 Introduction to Environmental Flows Recommendations Report

The Environmental Flows Recommendations Report of the GSA BBEST is comprised of eight major sections, plus supporting appendices. These eight major sections may be categorized into four broad subject areas described as follows. Sections 1 and 2 provide general overviews of the SB3 environmental flows process and the characteristics of the Guadalupe – San Antonio River Basin, the San Antonio – Nueces Coastal Basin, and the associated bay systems. Environmental flow analyses performed by the GSA BBEST in general accordance with SAC guidance are summarized in Sections 3, 4, and 5, focusing successively on instream habitats, estuarine habitats, and the integration of these analyses. Environmental flow regime recommendations of the GSA BBEST are provided in Section 6. Finally, research, data collection, and monitoring activities identified as priorities by the GSA BBEST are summarized in Section 7.

Readers simply seeking the environmental flow regime recommendations of the GSA BBEST may proceed directly to Section 6. Readers seeking a deeper understanding of the scientific bases for the environmental flow regime recommendations, however, are encouraged to consider summary information in Sections 2, 3, 4, and 5, alphabetically listed references in Section 8, and comprehensive appendices. All appendices are available in electronic format on a compact disc included with this report.

2. Overview of Watersheds and Bays

2.1 Guadalupe River Basin

The Guadalupe River Basin is located in south central Texas, with the headwaters in southwestern Kerr County. The river is 432 miles long and flows southeastward through a drainage area of 6,061 square miles (sq. mi.). The land mass that makes up the basin is divided into two distinct regions by the Balcones Escarpment. The northern region consists of the Edwards Plateau of the Great Plains Province. This is a rough area with rolling hills divided by limestone-walled valleys. The southern region is referred to as the Gulf Coastal Plains area and consists of gently sloping prairie. The basin's principle tributaries are the North and South Fork of the Guadalupe River, Johnson Creek, the Comal River, the Blanco River, the San Marcos River, Geronimo Creek, Plum Creek, Peach Creek, Sandies Creek and Coleto Creek.

The Blanco River's 440 square-mile watershed begins in Kendall County. The Blanco River flows through Blanco and Hays Counties and the cities of Blanco and Wimberley, and confluences with the San Marcos River near the city of San Marcos. The upper portions of the river have been known to go dry during prolonged periods of drought, and the banks and substrate of the river exhibit significant scouring during extended wet periods. The San Marcos River watershed is 522 sq. mi.. Its headwater springs are found in Spring Lake in the city of San Marcos, and the river confluences with the Guadalupe River near the city of Gonzales. The Comal River, the shortest river in Texas, has its headwater springs in Landa Lake. The Comal River's watershed and confluence with the Guadalupe River lie completely within the city of New Braunfels.

The springs that feed the Comal and San Marcos Rivers have an average monthly discharge of 308 and 164 cubic feet per second (cfs) respectively. The Comal Springs are more subject to drought conditions and ceased to flow during the severe drought of the 1950s. During that historical drought, the San Marcos River continued to flow, but dropped to 46 cfs.

The geology of the area consists primarily of sedimentary material that was deposited during the later Mesozoic and Cenozoic Eras. The principle geologic structures in the basin are the Balcones and Luling fault zones. The Balcones Fault Zone consists of a series of semi-parallel faults, about 15 miles long, extending from Hays County southwestward to Bexar County. The Luling Fault Zone extends from Caldwell County to Medina County and is 9.9 to 19.8 miles southeast of the Balcones Fault Zone. The displacement varies from less than three feet to a combined displacement of over 1,500 feet. Edwards limestone covers the Edwards Plateau.

The Guadalupe River Basin and Lavaca-Guadalupe Coastal Basin are located within four ecoregions. The delineation of ecoregions is based on geographic conditions that cause or reflect differences in ecosystem patterns. These conditions include geology, physiography, vegetation, climate, soils, land use, wildlife and hydrology. The basin lies within the Edwards Plateau (Ecoregion 30), the Texas Blackland Prairie (Ecoregion 32), the East Central Texas Plains (Ecoregion 33), and the Western Gulf Coastal Plain (Ecoregion 34). The Edwards Plateau is characterized by spring-fed, perennial streams, and is predominantly rangeland. The Texas Blackland Prairie has bottomland forest along many of the streams, including oaks, pecan, cedar elm, and mesquite. In its native state, it was largely a grassy plain, but most of the area has been cultivated and only small areas of meadowland remain. The East Central Texas Plains is characterized by subtropical dryland vegetation made up of small trees, shrubs, cacti, weeds and grasses. Principal plants include mesquite, live oak, post oak, blackbrush acacia, and huisache. Long-continued grazing has contributed to the dense cover of brush. According to the South Central Texas Regional Water Plan, the Gulf Prairies and Marshes of the Western Gulf Coastal Plain are divided into two subunits: 1) marsh and salt grasses at the tidewater, and 2) bluestems and tall grasses further inland. Oaks, elm and other hardwoods grow along the streams. The area is abundant with fertile farmland.

The climate of the region is mild and normal temperatures seldom fall below 32 degrees Fahrenheit in the winter. The upper basin averages 24 inches of rainfall per year, while the average rainfall along the coast is 37 inches. The overall basin average is 32 inches of rainfall per year, with the minimum occurring in the winter and maximum in the late spring and early fall. The cool season begins in November and extends through March. According to USGS Water Resources Data from Water Year 2006, the annual average runoff is 166,200 acre-feet (ac-ft) per year in the northern part of the river basin; 1,535,000 ac-ft per year in the middle portion; and 1,433,000 ac-ft per year in the lower basin. These discharge volumes represent the average amount of water reaching the stream annually in the form of runoff at the cities of Comfort, Gonzales, and Victoria, respectively. The region is subject to wide swings in weather and rainfall patterns. The northern part of the basin is known for flash floods, with the lower portion under the threat of tropical storms and hurricanes from mid-June through the end of October. The region has experienced several prolonged droughts, one of the worst being recorded from October 2008 through September 2009. In comparison to the 2006 data, the annual runoff during that period at the three locations described above was 33,220; 350,600; and 365,900 ac-ft respectively.

Mainstream impoundments in the basin include UGRA Lake, Flat Rock Lake, Canyon Reservoir, Lake Dunlap, Lake McQueeney, Lake Placid, Meadow Lake, Lake Gonzales, Lake Wood, and Coleto Creek Reservoir. Canyon Reservoir, built in the 1960s, is the largest impoundment in the river basin and inundates 8,230 surface acres at full conservation storage capacity. It is a multipurpose reservoir designed to serve flood control and water supply functions. It is also used for recreation. UGRA Lake, Flat Rock Lake, and Lakes Dunlap, McQueeney, Placid, Meadow, Gonzales, and Wood are run-of-river impoundments, used for water supply and hydroelectric power generation.

The population of the basin was estimated to be 474,828 in 2000, with the heaviest concentrations in Victoria, Comal, Hays, and Guadalupe Counties. The fastest growing counties in the region are located in the Guadalupe River Basin: Hays, Guadalupe, Kendall, and Caldwell Counties. These counties are experiencing explosive growth, as the populations of the cities of San Antonio and Austin spill over into these communities. Population projections in the lower end of the basin may prove to be low. The area may experience more growth than expected due to increased interest by residential developers in Refugio and Calhoun Counties.

Agriculture, in the form of crop and livestock production, is the primary industry in the basin, with the manufacture of steel, gravel, plastics and chemicals contributing to the economy of the basin as well. Oil and gas production can be found in all counties except Comal and Hays Counties.

2.1.1 Summary of Water Quality Characteristics

The water quality of the Guadalupe River is highly influenced by the ground water that makes up its base flow. The largest contribution to the base flow is the Edwards Aquifer, with additional volume from the Cow Creek, Trinity, Leona, Carrizo, and Gulf Coast Aquifers. Each aquifer is unique in its water quality, discharge points and volume. The headwaters of the Guadalupe are located in Kerr County, and originate from springs in the North and South Forks. The discharge of the Edwards Aquifer at the Comal Springs and San Marcos Springs forms two small, crystal clear lakes that support aquatic vegetation and wildlife, including the fountain darter and Texas Wild Rice, two endangered species. Springs that come from the Leona formation, which is high in nitrate-nitrogen, are thought to be, in part, the source of the nutrient concern and dissolved solids in Plum and Geronimo Creek.

The Guadalupe River flows through Kerr and Kendall Counties and into Canyon Reservoir, the largest reservoir in the basin, located in Comal County. Water exits the reservoir through a bottom penstock and is used for hydroelectric generation. In most years, the lake stratifies in the late summer months. After the first strong cold front of the winter, usually in October, the lake will experience a lake "turnover." During times of lake stratification, the bottom release from the reservoir is low in temperature and dissolved oxygen (DO), though the water is aerated as it leaves either the hydroelectric plant or penstock. The cold water conditions of Canyon Reservoir's bottom release system have been used by TPWD and Trout Unlimited for a "put and take" trout sport fishery.

Downstream of Canyon Reservoir, the Guadalupe River flows over bedrock substrate and through swift water runs. The river is shallow, with few pools until it nears the city of New Braunfels, where it confluences with the Comal River and enters the first of six hydroelectric impoundments. The flow through the impoundments is diverted through turbines to generate hydroelectric power. The river at this point is nutrient-rich, with nitrogen and phosphorus contributions from wastewater discharges, non-point source contributions and organic sediments. The impoundments exhibit the water quality conditions of a flowing stream in years of high flow. In years of medium to high flows, the impoundments have low chlorophyll concentrations and no stratification. In years of low flow conditions, the impoundments provide the residence time needed for the assimilation of nutrients that promote higher chlorophyll production. Also, during periods of low flow, the impoundments exhibit weak temporal stratification. Historically, these impoundments have been subject to infestations of non-native aquatic vegetation and algal blooms.

From Kerr County to Refugio County, the Guadalupe River receives treated wastewater discharges. The cities of Kerrville, Boerne, Buda, New Braunfels, Kyle, San Marcos, Lockhart, Luling, Seguin, Gonzales, Cuero, and Victoria, along with other small wastewater treatment plants, discharge treated wastewater, most of which receives up to secondary treatment.

At the extreme lower end of the basin, the Guadalupe River confluences with the San Antonio River. The Guadalupe River Diversion Canal and Fabridam (also called the Salt Water Barrier) are located below the confluence with the San Antonio River. The fabridam is made up of two large inflatable bags that are used to prevent salt water intrusion from the bay during times of low river flows. The canal system diverts fresh water for irrigation, industrial, and municipal water supply.

Segments in the Guadalupe River Basin that are listed on the 2010 Texas Water Quality Inventory and 303d list because they do not meet the applicable water quality criteria for dissolved oxygen include the Guadalupe River Tidal; Elm Creek, Sandies Creek, and Peach Creek; the Guadalupe River above Canyon Reservoir; Camp Meeting Creek; the upper Blanco River; and the North Fork. Segments that have been listed due to bacterial impairment include Sandies Creek, Peach Creek, Geronimo Creek, and Plum Creek; the Guadalupe River above Canyon Reservoir; Quinlan and Town Creeks in Kerr County; and the Dry Comal. Stream segments that are listed with concerns for nutrient concentrations are the Guadalupe River Tidal; the Guadalupe River below the San Antonio River; Geronimo Creek; and Plum Creek. Canyon Reservoir has been listed on the 303d list due to elevated concentrations of mercury found in the fish tissue of striped bass and long-nosed gar.

2.1.2 Electric Cooling Water

In several locations, the Guadalupe River or one of its tributaries is used for cooling water. In the upper part of the watershed, a power plant diverts flow from the Guadalupe River to mix with treated wastewater and use as cooling water. This power plant in western Guadalupe County is a zero discharge facility; no water is returned to the stream. In the lower basin, two electric-generation plants, one near Nursery and the other near the city of Victoria, divert a portion of the flow in the Guadalupe River to serve as once-through cooling water; the water is returned to the stream. The Coleto Creek Reservoir also provides cooling water for the power plant located in Goliad County. In these last three locations, the returned water is warmer than the receiving stream. Coleto Creek Reservoir was designed to hold water long enough to dissipate the heat. The warm water conditions are conducive for the growth of aquatic vegetation. The volume and temperature of the release from the power plant near Victoria are regulated by a discharge permit that is protective of the receiving stream.

2.1.3 Canyon Reservoir and the Guadalupe Hydroelectric System

Canyon Reservoir is located west of the city of New Braunfels in Comal County. The multipurpose reservoir, built by the US Army Corps of Engineers (USACE) and GBRA and impounded in the mid-1960s, is designed to serve flood control and water supply functions. It is also used for recreation. Canyon Reservoir has 8,230 surface acres, over 80 miles of shoreline, seven public parks, two military recreational areas, and two marinas. The lake has designated uses of contact recreation, exceptional aquatic life use, domestic water supply and aquifer protection.

The reservoir is monomictic, stratifying into layers in the summer and having one mixing "turnover" per year, usually with the first strong cold front in the fall. The reservoir can be divided into three zones, moving down the reservoir, toward the dam. Those zones include the riverine zone, the transitional zone and the lacustrine zone. The riverine zone does not routinely stratify because it is flow-dominated, keeping the waters in this zone mixed. The conditions are often turbid because it is in this zone that sediments carried by runoff from upstream enter the reservoir. The transitional zone is the zone where the river reacts with the reservoir. As the flow from the river slows and spreads, the sediment carried by the stream begins to drop out and settle to the bottom. Studies have found that in years of high runoff and sediment loading, the reservoir's anoxic zone can develop in this transitional zone where the decay of organic deposition depletes the oxygen. The lacustrine zone is located near the dam. The lacustrine zone is clear and deep. It is in this area that thermal stratification occurs, as well as the development of an anoxic layer.

In years of low incoming flow, the lake will stratify, with layers called the epilimnion at the surface and the hypolimnion at the bottom, separated by a thermocline (area of rapid thermal change). In years with heavy spring rains and incoming flows, the lake will be more weakly stratified because of the volume coming into the reservoir and the release of water from the bottom, used to evacuate the flood pool. In times when the reservoir is strongly stratified, the thermocline is strong enough to keep the waters of the epilimnion and hypolimnion from mixing. This creates distinct density and oxygen differences through the water column. During these periods of stratification, the dissolved oxygen concentration in the lower stratum will approach 0 milligrams per liter.

The reservoir operates as two parts. The lower portion from elevation 800 to 909 mean sea level (msl) is operated by GBRA for conservation storage. GBRA was granted water rights for 90,000 ac-ft of water per year to be made available to customers through water purchase contracts. GBRA releases water from the conservation pool as it is called for by downstream customers. The upper portion of Canyon Reservoir is referred to as the "flood pool" and is controlled by the USACE. This part of the reservoir captures floodwaters, which are usually released at rates sufficient to empty the flood pool while attempting to minimize downstream flooding (up to 5,000 cfs).

Releases out of Canyon Reservoir are governed by several regulatory and contractual requirements. First, the Federal Regulatory Energy Commission stipulated as part of their license agreement with GBRA for hydropower generation at Canyon Dam that GBRA release a minimum of 120 cfs during the months of February through May, and 100 cfs during other months of the year, except under drought conditions. Second, the TCEQ, as part of the Canyon Amendment process, added a flow regime that is protective of the instream flow requirements downstream. Third, GBRA has signed a temporary agreement with Trout Unlimited for higher releases during the period of the year that is most critical in maintaining the desired thermal regime for stocked rainbow trout downstream of the reservoir (May through September). Each May, the Trout Unlimited agreement provides for minimum flows that range from 140 to 170 cfs; in June, the flows range from 210 to 240 cfs. For the months of July, August and September the minimum flow is 200 cfs. This agreement expires in 2018. Lastly, in recent years, a "seasonal pool" program has been implemented. The base flow of the Guadalupe River coming into the reservoir, which would be the amount released from the reservoir under normal flow conditions, can be augmented with additional water that is stored under an annual agreement with the

USACE and used to enhance flow conditions downstream for recreational use, such as tubing and rafting. The agreement is renewed annually and is most likely not available in years of drought. Efforts are underway to make this USACE agreement permanent.

As the water moves downstream from Canyon Reservoir through the city of New Braunfels, it is impounded by a series of six dams, which are operated by GBRA to generate hydroelectric power. The river must initially pass through the Dunlap Dam, which impounds Lake Dunlap; followed by the McQueeney Dam, which impounds Lake McQueeney; the TP4 Dam, which impounds Lake Placid; the Nolte Dam, which impounds Meadow Lake; the H-4 Dam, which impounds Lake Gonzales; and the H-5 Dam, which impounds Lake Wood. The water impounded in these series of hydroelectric lakes does not take on many of the properties of a reservoir and maintains the attributes of a flowing stream segment, due to the shallow depths and small retention time of the water in these structures. The river must support approximately 528 cfs discharge at the Lake Dunlap power plant in order for the power plants to generate power. When a discharge of this level cannot be supported, the water is allowed to pond in the upper four hydroelectric impoundments for several hours and then is released through the turbines at a rate of 528 cfs. At two facilities, the flow from the Guadalupe River is diverted through water canals above the Dunlap Dam and Nolte Dam to the hydroelectric turbines.

2.2 San Antonio River Basin

The San Antonio River Basin is located in portions of 14 counties in south central Texas, but the majority of the watershed is in Medina, Bexar, Wilson, Karnes and Goliad Counties. The San Antonio River supports a diverse ecological community that relies on the quality, quantity, and timing of water moving through the system. The San Antonio River Basin (particularly Bexar County) has undergone rapid transformation over the past several decades due to development. Historically, the majority of the San Antonio River base flow was from area springs, but the river has experienced an evolution from a system driven predominantly by spring flow to a system highly influenced by year-round wastewater treatment plant discharges, intermittent diversions, and a mix of various urban and rural land uses. There are only three reservoirs in the San Antonio basin; Braunig Lake, Calaveras Lake and Medina Lake. Braunig and Calaveras Lakes are off-channel reservoirs developed to provide cooling water for municipal power plants. Lake levels are maintained through diversions from the San Antonio River. Medina Lake, located on the upper reach of the Medina River between Bandera and Medina Counties, is the largest reservoir in the basin (approximately 254,000 ac-ft), and was developed to provide irrigation water to farmers in Bexar, Medina, and Atascosa Counties.

The LSAR's hydrology continues to vary with the seasons, driven by precipitation patterns, supported by spring flow, and augmented by treated municipal effluent that originates primarily as groundwater from the Edwards Aquifer. The increased use of groundwater to sustain development has resulted in increasing return flows to the San Antonio River over this rapid development period. This trend may continue if population growth is supported by additional groundwater usage or other water development strategies. However, population growth often corresponds with heavier demand on water resources within the basin; one strategy currently applied to relieve demand and support the Bexar County economy is the reuse of treated effluent. The current capacity to reuse treated effluent in Bexar County is limited to a maximum of approximately 33 million gallons per day. Reuse water development and usage downstream in Wilson, Karnes and Goliad Counties is relatively insignificant. However, there is concern that reuse water development strategies will increase and be implemented in the future, potentially reducing river flows and impacting the riverine, estuarine and bay ecosystems (TIFP 2009).

Another issue that the rapid land development in the San Antonio River Basin has generated is increasing impervious cover and resulting storm water runoff. Storm water runoff has intensified and has influenced the natural flow regimes in the San Antonio River. The timing, intensity and duration of peak flows during and immediately after storm events seem to cause stream bed and bank scour, erosion, and channel migration that could be affecting the aquatic and riparian habitats and associated biota. There is also a concern that the increased scour, erosion, and channel migration are causing an increase in the rate at which trees and woody vegetation fall into the river. This causes log jams that obstruct flow and potentially increase the risk of flood damage to developed areas in the lower basin.

2.2.1 Hydrology

The U.S. Geological Survey (USGS) has maintained a network of streamflow gages in the LSAR sub-basin since the 1920s. Currently, 12 gages are operational in the sub-basin, including five on the main stem of the San Antonio River and five on Cibolo Creek. Some historical data is available from an additional five stream gages that are no longer being maintained in the sub-basin.

The median flow of Cibolo Creek near Falls City (approximately 10 miles upstream of its confluence with the mainstem of the San Antonio River) during the period from 1930 to 2007 is approximately 29 cfs. In comparison, the median flow in the San Antonio River near Falls City (approximately 20 miles upstream of its confluence with Cibolo Creek) over the period from 1925 to 2007 is 262 cfs. It appears that at their confluence, the flow of Cibolo Creek is approximately 10% of the flow of the mainstem of the San Antonio River. No other tributary of the LSAR appears to make as significant a contribution to its flow. Review of the available gage data indicates that flow conditions in the LSAR sub-basin have been changing over time, and it seems that flows in the lower sub-basin have increased dramatically (TIFP 2009). Changes in flows in the lower sub-basin are likely due to a number of factors, including changes in precipitation, urban growth, and groundwater pumping and return flows. Since 1970, average monthly precipitation for San Antonio, Texas has been greater relative to the three decades before this period. Urbanization in the upper basin may also have played a role in changes in flow in the LSAR. According to U.S. Census data, the population of the city has increased from about 250,000 in 1940 to more than 650,000 in 1970, and more than 1.3 million in 2007. Growth and expansion of the city of San Antonio has resulted in changes in water withdrawals and return flows, as well as patterns of runoff from the land surface. Much of the water demand in the city of San Antonio and surrounding areas is met by groundwater pumping from the Edwards Aquifer. Pumping from this aquifer increased from about 120,000 ac-ft per year in 1940 to a yearly maximum value of 542,000 ac-ft in 1989 (EAA 2008). Since that maximum, annual pumping has averaged 401,300 ac-ft per year (1990-2007). The median estimated well production for the 10-year period of 1998-2007 is 379,900 ac-ft (EAA 2008). The relationship between levels of groundwater in aquifers and flows in the LSAR sub-basin is complicated. Increased groundwater pumping can increase flows in some portions by increasing return flows to the river, while lowered groundwater tables can reduce spring flows in other areas.

Conditions in upper portions of the river basin have a significant influence on flows in the LSAR. A USGS study (Ockerman and McNamara, 2002) evaluated the linkage between the upper and lower portions of the San Antonio River Basin. Watershed models (Hydrologic Simulation Program-FORTRAN) were developed for the San Antonio River watershed area upstream of USGS gage 08181800 (San Antonio River near Elmendorf). Models were calibrated and then used to simulate daily flow conditions (water quantity and quality) for the years 1997 to 2001. During this period, the four largest contributors to flow at the Elmendorf gage were found to be storm water runoff in Bexar County (33 %), the Medina River upstream of Bexar County (22 %), wastewater discharge (20 %), and groundwater inflow (18 %). The Elmendorf gage is located at the upper boundary of this study of the LSAR sub-basin.

The LSAR is an important source of freshwater inflow to the Guadalupe Estuary (San Antonio Bay). According to Longley (1994), the contribution of the San Antonio River (as measured at USGS gage 08188500 at Goliad) to freshwater inflow to the estuary is approximately 23% of the total amount (TIFP 2009).

2.2.2 Biology

The San Antonio River Basin is host to over 70 species of fish (SARA 1996a), many of which are introduced or exotic. All fish of the San Antonio River Basin are used by SARA as biotic indicators of aquatic ecosystem health (SARA 1988, 1996a, 2000b). Sixty fish species have been reported from the mainstem of the San Antonio River from collections dating back to 1950. Life history and population information for these species is based upon scientific studies (Balon 1975, Balon 1981, Bonner and Runyan 2007, Hildebrand and Cable 1938, Hubbs et al. 1991, Linam and Kleinsasser 1998, Simon 1999, Warren et al. 2000, Williams et al. 1989). *Cyprinidae* was the most abundant family, followed by families *Poeciliidae*, *Ictaluridae*, *Centrarchidae*, and *Cichlidae*. Three native fish species—central stoneroller (*Campostoma anomalum*), green sunfish (*Lepomis cyanellus*), and longear sunfish (*Lepomis megalotis*)—have increased in abundance since the earliest collection records, whereas pugnose minnow (*Opsopoeodus emiliae*) and western mosquitofish (*Gambusia affinis*) have significantly declined (Bonner and Runyan 2007). Seventeen species showed stable populations, while the rest had indeterminable changes. Only five non-native species were reported in the earliest records, whereas now there are 17.

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 hardy species such as gar, mosquitofish, and mollies as well as a number of species intolerant of degraded water quality such as Texas logperch (*Percina carbonaria*), Guadalupe bass (*Micropterus treculii*), and mimic shiner (*Notropis volucellus*) (Linam and Kleinsasser 1998). A rich variety of reproductive strategies are also represented within the fish assemblage, including three species with marine spawning requirements. These species are the striped mullet (*Mugil cephalus*), which spawn offshore; the hogchoker (*Trinectes maculatus*), which reproduce in estuaries; and the American eel (*Anguilla rostrata*), which spawn in the Sargasso Sea. In addition, the big claw river shrimp (*Macrobrachium carcinus*) is another catadromous species known to occur in the San Antonio River.

Four live mussel species were collected during baseline sampling efforts in 2006 and 2007 (Karatayev and Burlakova 2008). These mussels included threeridge (*Ablema plicata*), Tampico pearlymussel (*Cyrtonaias tampicoensis*), yellow sandshell (*Lampsilis teres*), and golden orb (*Quadrula aurea*). Mussels represent one of the most rapidly declining faunal groups in North America. A variety of life history traits related to their vulnerability include sensitivity to toxic contaminants in the water, low selectivity of feeding, long life span, size and mobility limitations, low fertilization rates, high juvenile mortality, irregular recruitment, and unique life cycle, including an obligate parasitic larval stage (Fuller 1974; Downing et al. 1993; McMahon and Bogan 2001). Large quantities of dead shells of the Texas endemic golden orb were found in the upper reaches of the LSAR during the aforementioned baseline mussel sampling. At some sites it was apparently the dominant species; however, live individuals were only found at two sites located in the middle and lower reaches. Golden orb was selected as a potential target species, since statewide sampling by TPWD suggests this mussel species may be declining (Howells et al. 1996), and because the American Fisheries Society considers this species one of special concern (Williams et al. 1993).

2.2.3 Physical Processes

The geomorphology of the LSAR sub-basin is influenced by the unique climatic and physiographic setting of central Texas. Weather conditions in central Texas include convective thunderstorms and tropical disturbances that produce intense precipitation. In addition, many physical features of the Edwards Plateau (steep slopes, sparse vegetative cover, thin soils, and underlying geology) contribute to high runoff rates. As a result, peak flow rates for watersheds in this region generally exceed those for similar sized watersheds in other parts of the world (Baker 1977). Central Texas streams are "flashy," tending to carry a large percentage of their annual flow volume in large, infrequent events. Baker (1977) suggests that flashiness causes central Texas streams to behave differently in terms of their geomorphic processes and characteristics. General principles of geomorphology assume that relatively frequent, modest sized flow events transport the greatest amount of sediment over time and are therefore responsible for the characteristic shape of a stream channel. After the disturbance caused by a large flood event, modest sized flow events rework the channel and allow a relatively rapid recovery of the characteristic shape of the channel. This assumption of the relationship of the geomorphic significance of large flood and modest flow events appears to be valid in many parts of the world. However, for flashy streams, extremely large scale sediment transport and channel modification may occur during large flood events. Under these conditions, modest sized flow events may not occur often enough to rework the channel significantly before the next large flood. In these systems, the channel shape remains in a state of recovery from the disturbance caused by the last large flood event and may not recover a shape characteristic of channels in other parts of the world (TIFP 2009).

The characteristics, distribution and stability of log jams were investigated by Cawthon (2007), who presents an overview of log jam characterization methods and a series of metrics that are used to quantify location, degree and configuration of log jams observed in the San Antonio River. Field observations are reported for the period November 2006 through February 2007, and are related to log jams evident on December 7, 2003, as interpreted from high-resolution aerial imagery. Log jams are found to be mobile; only 10% of those identified in 2003 still existed in 2007. None of the full-channel jams identified in 2003 still existed in 2007. Six high-flow events (between 5,000 and 20,000 cfs) occurred between December 2003 and January 2005. The high mobility of log jams is attributed to these events, considering the high stream power caused by narrow incised banks. Based on field efforts (2006-2007), spacing between log jams decreased moving downstream, with a notable lack of jams within six miles downstream of the County Road 117 low-water crossing where debris removal typically occurred (In 2008, this low-water crossing was removed and replaced with a clear span bridge.). The number of "in-channel obstruction" jams increases in the lower half of the study reach, but percent of lateral coverage of log jams (percent of the channel width obstructed by a log jam) is relatively uniform throughout the reach.

A geomorphic classification of the LSAR was completed by Engel and Curran (2008). This classification provides a useful tool to understand differences in physical processes and habitats along the river. The river was segmented into 25 reaches based on channel and valley characteristics. A description of each reach was provided, including characteristic channel and floodplain features such as point bars, large woody debris dams, cobble riffles, oxbow lakes, and backwater swamps.

Cawthon and Curran (2008) examined channel change on the LSAR and found that the river has widened over a 68-year period, primarily due to floods. The study examined channel migration, widening, erosion, and deposition by analyzing aerial photos of the river from Wilson to Victoria counties taken from 1938 to 2004. The 1946 flood had the greatest impact on the channel in the upper portion of the river (above central Karnes County), while the 1967 flood caused the greatest amount of change in the lower portion. Conditions prior to the 1946 flood (over-steepened banks saturated by an extended period of rainfall) probably contributed to the severity of changes due to this event. The effectiveness of large floods is reduced in the lower portion of the study area, where the valley becomes wider and the channel is less confined.

2.2.4 Water Quality

TCEQ, in cooperation with SARA through the Clean Rivers Program (CRP), produces the San Antonio River Basin Summary Report every five years. The Basin Summary Report provides an overview of monitoring and assessment activities in the San Antonio River Basin. The 2008 report was prepared by SARA staff in coordination with the TCEQ and in accordance with the State's guidelines. The report presents a 10-year history of the levels of bacteria, nutrients, aquatic life use, and other water quality parameters at over 40 sites throughout six watersheds in the basin, covering the period January 1997 through August 2007.

Portions of the San Antonio River and Cibolo Creek do not meet the contact recreation standard due to E. coli bacteria. Generally, there is a relationship between high flows and increased levels of bacteria, indicating a non-point source of bacterial pollution. The actual source of the pollution (whether of wildlife, livestock or human origin) is difficult to determine. TCEQ, SARA, the City of San Antonio, SAWS, and Bexar County are working together to abate the bacterial pollution by implementing the Watershed Protection Plan for the urban portion of the upper San Antonio River watershed. An implementation plan for the entire upper San Antonio River watershed (including Bexar, Wilson and northern Karnes Counties) has begun.

Nutrients are a concern in portions of the San Antonio River and Cibolo Creek. Currently, there are no numerical standards for nutrients, only screening criteria. High nutrient levels may cause algal blooms and, consequently, low dissolved oxygen levels. At this time, no segments on the San Antonio River or Cibolo Creek are identified as impaired for low dissolved oxygen levels by the TCEQ. The sources of nutrients are varied and depend on the sampling location. Elevated nutrient levels are typically found downstream of wastewater discharge points, but nutrients can also enter the stream system from storm water runoff, discharge of groundwater polluted with nutrients, through natural and manmade sources, and even through the atmosphere.

Water quality data in the LSAR sub-basin is also collected and analyzed through several other programs and agencies (TIFP 2009).

2.3 San Antonio Bay

Bays and estuaries are transitional systems, intermediate between freshwater and marine. As transitional systems, their hydrography and chemical qualities are governed by both terrestrial and marine controls, as well as factors that are unique to the estuary environment. The predominance and interplay of these qualities depend upon relative position in the estuary and result in pronounced environmental gradients.

Among the terrestrial controls are freshwater influxes; flooding and inundation; runoff and inflow loads (sediment, nutrients, and pollutants); and atmospheric deposition. Among the marine controls are tides, waves, non-astronomical sea-level variations, marine storms, salinity, and littoral sediment influx. Among the factors unique to the estuary and coastal environment are density currents (arising from gradients of salinity), bathymetric controls on circulation, tidal modifications (dissipation, amplification, and harmonic interaction), and sea-breeze circulations. The considerable time variation in these controls and their relative importance creates extreme time variability in the estuary (Smith and Ward 2004).

The range of chemical concentrations, most notably salinity, turbidity and nutrients, coupled with the ranges in bathymetry and vegetation, creates a wide range in habitats spanning the estuarine zone. Of the estuarine macrofauna, only a relative minority are permanent residents of the estuary. The majority of the macrofauna are in the system only temporarily for specific biological purposes, such as breeding, maturing, or feeding. The abundance and health of specific organisms in the estuary are dependent upon 1) the population capable of entering the system, which includes both the abundance and health of the source population, and its capability to negotiate entrance into the system, and 2) the availability of suitable combinations of physical and chemical conditions and/or food sources during the time that the organisms are within the estuary. Food webs in the bay are complex and shifting, with frequent overlap between the free-floating (planktonic), free-swimming (pelagic), and bottom-dwelling (benthic) communities. Many estuarine animals are opportunistic, which complicates the food web even more by introducing a behavioral element to the mixture.

Freshwater inflow can affect the estuarine environment in many ways, including:

- providing a source of renewal water that flows through the estuary,
- diluting seawater,
- delivering a complex of nutrients, trace constituents, and sediment of terrestrial origin,
- contributing to the establishment of a gradient of water properties across the estuary, due to entering the estuary preferentially in upland zones,
- producing inundation and flushing of important zones of the estuary, due to short-term flooding, and
- providing variability over time, creating fluctuation in estuarine properties that can be important to ecosystem function.

These influences are exerted on the hydrography and waterborne constituents (i.e., the "water quality") of the estuary. These, in turn, affect the biological populations, so chains of cause and effect can be traced from freshwater inflow to the abundance and health of organisms. San

Antonio Bay exhibits greater sensitivity to freshwater inflows compared to the other Texas bays because of its relative isolation from the Gulf of Mexico; the geography and location of the watersheds contributing inflow to the estuary; and the shallow character of the system. These factors have important implications for the mix and abundance of species within this system (Smith and Ward 2004).

The San Antonio Bay system (Guadalupe Estuary) lies on the central Gulf coast and is sheltered from the Gulf of Mexico by Matagorda Island. San Antonio Bay is composed of several interconnected bodies of water, with Hynes Bay, Mission Lake, and Guadalupe Bay in the northwest, Ayres and Mesquite Bays to the southwest, and Espiritu Santo Bay to the east. San Antonio Bay supports a wide range of economically important fish and shellfish, as well as an active sport fishery. The southwestern shoreline of the bay forms the northeastern boundary of the Aransas National Wildlife Refuge. The physical and chemical characteristics of the San Antonio Bay system are a result of the mixing of freshwater from the San Antonio and Guadalupe rivers with salt water from the Gulf of Mexico. Water in San Antonio Bay is exchanged with Matagorda Bay (the Lavaca-Colorado estuary) to the northeast and with Aransas-Copano Bay (the Mission-Aransas Estuary) to the southwest. The only direct connection with the Gulf of Mexico is through a small tidal pass, Cedar Bayou, which historically has often been closed. Thus, only a small exchange of volume has occurred intermittently through this connection over time. When it is open, the exchange is limited.

The San Antonio Bay system’s hydrogeomorphology is unusual among the Texas bays due to its isolation from the Gulf of Mexico and extreme shallow bathymetry. The average depth of the unmodified estuary (i.e., outside the dredged channels) is approximately four feet; the maximum natural depth is approximately seven feet. There has been little peripheral development of this area historically, as there has never been a major port within San Antonio Bay. The San Antonio Bay system was channelized for shallow-draft navigation with the completion of the Victoria Barge Canal in the late 1960s. The Gulf Intracoastal Water Way (GIWW) bisects San Antonio Bay northeast to southwest.

The two principal sources of freshwater inflow into the San Antonio Bay system are the San Antonio River and the Guadalupe River, which converge just upstream from the estuary and flow into the northern end of the bay system. The total contributing drainage area covers approximately 10,000 sq. mi., including the San Antonio and Guadalupe River Basins, as well as portions of two smaller coastal basins, the Lavaca-Guadalupe and San Antonio Coastal Basins.

The annual inflow pattern into San Antonio Bay is bimodal, with the high flow seasons in late spring to early summer and late winter, and the low flow season in late summer to early fall (Smith and Ward 2004).

2.4 San Antonio – Nueces Coastal Basin

The San Antonio – Nueces Coastal Basin is approximately 3,100 sq. mi., covering all or part of seven counties. The basin is bordered by the San Antonio River Basin to the north; the Lavaca-Guadalupe Coastal Basin to the northeast; bays, estuaries, and the Gulf of Mexico to the east; the Nueces-Rio Grande Coastal Basin to the south; and the Nueces River Basin to the northwest (NRA 2008). The San Antonio-Nueces Coastal Basin lies in the South Texas Coastal Plain. The region is a flat, low-lying coastal plain bordered by miles of coastal shoreline. The predominant streams in the basin are the Mission River and the Aransas River. The Aransas River drains 536 sq. mi. of the coastal prairie of south Texas, and the Mission River drains 488 sq. mi. of the coastal prairie of south Texas. The rivers are gentle sloping streams with pools and few riffles. Only a few tributaries to these rivers are perennial streams; most are intermittent and seasonal (TNRCC 1994). Significant creeks include the Medio Creek, Poesta Creek, West Aransas Creek, Blanco Creek, Copano Creek and Artesian Creek. The creeks and rivers are all relatively short streams that flow slowly through shallow river beds, riparian wetlands, and salt marshes to eventually empty into the Hynes Bay, St. Charles Bay, Mission Bay, Aransas Bay and Redfish Bay, all portions of the Mission-Aransas Estuary.

The San Antonio – Nueces Coastal Basin is in a sub-humid climate, with mild winters and hot summers. The average winter temperature is 55.4 degrees Fahrenheit and the average summer temperature is 82.4 degrees Fahrenheit. Annual rainfall varies across the region from 27.4 inches to 30 inches. The region is hot and dry during the summer months, and can experience long periods of drought and low stream flow conditions. Tropical storms strike intermittently and cause widespread flooding. The area is distinctly characterized by natural resource extremes. For instance, salinity levels fluctuate widely due to the variable amount of freshwater supplied to the estuaries by episodic tropical storms and intervening dry periods. In addition, extensive shorelines and narrow inlets of the estuaries form quasi-autonomous estuarine systems and reduce water circulation and exchange with adjacent water bodies, so that freshwater inflows are generally not easily mixed with the Gulf of Mexico, and may be retained for long periods, depressing estuarine salinity levels (TNRCC 1994). Despite these wide ranges of salinity levels, the bays and estuaries adjacent to the San Antonio – Nueces Coastal Basin support healthy recreational and commercial marine fisheries. These fisheries contribute towards an estimated $364 million annual income in the central Texas coastal economy.

Many inland areas of the San Antonio – Nueces Coastal Basin are rural and entirely dependent on agriculture and ranching for income. The predominant land use within the basin is agriculture, consisting mostly of pasture, range land and some cultivated cropland. Riparian lands adjacent to rivers are generally wooded, while uplands are covered with brush and mesquite/granejo rangelands. Linear barrier island complexes covered in dunes and grasses lie to the east of the estuaries. The urban portion of the watershed—the cities of Beeville, Skidmore, Rockport/Fulton, Aransas Pass, and Tynan—account for less than 5% of the land area. Other land uses include sand, gravel, and caliche mining; and oil and gas exploration. Against this setting of extensive ranching operations, coastal marshes and wetlands provide habitat for many animals and migratory avian species. Being a coastal area, the basin is naturally host to several recreational areas. These include Goose Island State Park near Rockport; Copano Bay State Fishing Pier along State Highway 35 north of Fulton; Fulton Mansion Sate Historical Park in

Fulton; and the Aransas National Wildlife Refuge in Aransas County (NRA 2008, 2003). Unique ecological and physiographic features add to the scenic beauty of the area. Federal and state wildlife agencies list over 35 rare and endangered species in the area, such as the Whooping crane, Snowy plover, ocelot, and Kemp's Ridley sea turtle (TNRCC 1994).

2.4.1 Water Quality

Regional Assessments of Water Quality in the San Antonio – Nueces Coastal Basin (TNRCC 1994, NRA 2003, NRA 2008) contain an analysis of surface water quality data dating back to 1982. The data were collected by the sampling networks of the Nueces River Authority (NRA), Texas Natural Resource Conservation Commission (TNRCC) and USGS. The analysis compares, or screens, the data against the State of Texas Surface Water Quality Standards (TSWQS) or other appropriate screening levels. The screening analysis identifies water quality problems and shows where and how often pollutants appear at elevated levels (NRA 2008, 2003). The screening analysis shows water quality in the Nueces Coastal Basins to be generally good; aquatic life, contact recreation, and general uses are fully supported. However, nutrient concentrations exceed screening levels throughout the basin. Nutrient concentrations above screening levels are not a violation of water quality standards since there are no standards for nutrients. None of the segments in this basin have any impairment. There are concerns for bacteria, DO, and orthophosphorus. There are increasing trends for DO deficit, total organic carbon, and volatile suspended solids (NRA 2008, 2003).

2.4.2 Hydrology

The major mechanism driving any estuarine salinity regime is the volume of freshwater inflow. However, only 15% of this system's annual freshwater volume is gaged (measured). Of this gaged inflow to the estuary, the Mission River contributes 49%, the Aransas River 15%, Chiltipin Creek 18%, and Copano Creek 18% (USGS, 1990). Ungaged inflows account for 39% of freshwater inflows, and direct precipitation accounts for the other 46% of the freshwater added to the system (TDWR, 1981). Thus, any relationships between inflow and salinity in this system must consider impacts of other factors such as wind and evaporation.

The same hydraulic and physiographic characteristics of Copano and Mission Bays that reduce water exchange rates also reduce flushing rates and lengthen retention periods. This reduced flushing or "cleansing" ability makes the estuary more likely to trap pollutants and concentrate dissolved substances delivered in freshwater runoff and rainfall. This concentration potential provides the basis for estimates of nutrient loadings for both nitrogen and phosphorus. The water quality screening analysis in Section 3.4 confirms the presence of these nutrients (TNRCC 1994).

2.5 Mission, Copano, and Aransas Bays

The Copano and Aransas Bay system is located along the central Texas coast, separated from the Gulf of Mexico by San Jose Island. Aransas Bay is centrally located in the system and is hydrologically connected to the Gulf via Aransas Pass (artificially maintained) and Cedar Bayou (currently closed); to the San Antonio Bay system via Carlos, Mesquite, and Ayres Bays; and to the Corpus Christi Bay system via Redfish Bay. Freshwater from Mission River flows through Mission Bay, mixing with freshwater from Aransas River in Copano Bay, prior to entering Aransas Bay. Coastal bays are described as either being formed by seawater flooding drowned river valleys (e.g., Copano Bay) or by creation of lagoons from the formation of an offshore barrier (e.g., Aransas and Redfish Bays protected by San Jose Island) (Behrens 1963). In addition, the geographic position of the bays can be organized as having a primary (Aransas and Redfish Bays), secondary (Copano, St. Charles, and Port Bays), or tertiary (Mission Bay) connection with the open ocean (Gulf of Mexico) (Diener 1975). The average depth of these bays ranges from two feet in Mission Bay to nine feet in Aransas Bay, with the exception of the GIWW, which is maintained at approximately 16 feet in depth (Chandler et al. 1981).

Tidal exchange in Copano and Aransas Bays is driven by astronomical tides, meteorological conditions, and density stratification (Armstrong, 1987). Due to the shallow bay depths (1-4 meters at mid-tide) and a relatively small tidal prism, wind exerts a much greater influence on bay circulation than astronomical tides (Morton and McGowen, 1980; Armstrong, 1987). Wind-generated tides also result in substantial exchange of water between the Gulf of Mexico and Aransas Bay (Ward and Armstrong, 1997). Astronomical tides are predominately diurnal, but also have a semi-diurnal component. The greatest influence of astronomical tides is at the tidal inlet. Seasonal high tides occur during the spring and fall, while seasonal low tides occur during the winter and summer months.

The total contributing drainage area is 690 sq. mi. from the Mission River Basin; and 247.1 sq. mi. from the Aransas river basin (Mooney 2009), as well as from several smaller coastal basins, including St. Charles, Copano Creek, Mullens Bayou, and Port Bay. Freshwater inflow is delivered from the watershed as a result of precipitation events, which are highly variable in South Texas. As a result of these episodic events, the typical flow regime in south Texas bays and estuaries is characterized by relatively small base flows punctuated by large inflow events from frontal systems and tropical storm activity (Russell et al. 2006). For example, from 2007 to 2008, the Aransas River discharge ranged from 2.83 to 8,020.04 cfs, with a mean flow of 52.97 cfs. During the same time period the Mission River discharge was slightly higher and ranged from 0.35 to 12,600.39 cfs, with a mean flow of 151.85 cfs (Mooney 2009).

3. Instream Flow Analyses

Environmental flow analyses focusing on instream or fluvial locations at which flow regime recommendations are provided by the GSA BBEST are summarized in the following sub-sections of Section 3. These sub-sections follow a logical progression established in SAC guidance through which:

a) Regime recommendation locations are selected with due consideration of geographic scope (Section 3.1);
b) Hydrology-based tools are applied to extract statistics descriptive of flows and flow regime components at the selected locations (Section 3.2); and
c) Biological (Section 3.3), water quality (Section 3.4), geomorphology (Section 3.5), and riparian vegetation (Section 3.6) overlays are applied to refine or confirm the hydrology-based statistics.

The conclusion of this logical progression and integration of instream with estuarine environmental flow analyses is the set of flow regime recommendations provided in Section 6.

3.1 Geographic Scope

The first step in performing instream environmental flow analyses is consideration of the geographic scope to be encompassed by flow regime recommendations. The GSA BBEST has considered geographic scope in general accordance with SAC guidance issued April 3, 2009 and entitled: "Geographic Scope of Instream Flow Recommendations." In recognition of the fact that ecological functions associated with rivers and streams are generally supported by daily variations in instream flows, the GSA BBEST considers streamflow gaging stations maintained by the USGS as the best available sources of basic data to support environmental flow analyses. Streamflow gaging stations selected by the GSA BBEST to serve as flow regime recommendation locations are identified in Section 3.1.1 and the bases for selection of these gages is described in Section 3.1.2.

3.1.1 Streamflow Gaging Stations

Over 75 streamflow gaging stations have been maintained by the USGS in the Guadalupe – San Antonio River Basin and the San Antonio – Nueces Coastal Basin at various times during the past 90 years. Many of these stations, however, are no longer in service or have only been placed into service in the last few decades. The sixteen (16) streamflow gaging station locations selected by the GSA BBEST for performance of environmental flow analyses and issuance of flow regime recommendations are shown in Figure 3.1-1. Fourteen (14) of these 16 gages were selected on recommendation of the Hydrology Subcommittee and consensus of the GSA BBEST on June 11, 2010. As a result of subsequent discussions regarding potential base flow trends and adequacy of geographic coverage, two (2) additional locations (i.e., Guadalupe River at Comfort, USGS# 08167000, and Guadalupe River at Gonzales, USGS# 08173900) were selected by consensus of the GSA BBEST on July 8, 2010. Discussion of the bases for selection of these gage locations is found in Section 3.1.2.

3.1.2 Selection of Flow Regime Recommendation Locations

A summary of reference data regarding each of the 16 streamflow gaging stations selected for development of flow regime recommendations is included in Table 3.1-1. As is apparent upon review of Table 3.1-1 and Figure 3.1-1, hydrology, biology, water quality, geomorphology, water availability and supply planning, and other factors are relevant to the selection of flow regime recommendation locations. Information of importance to the GSA BBEST in consideration of these factors is discussed in the following subsections.

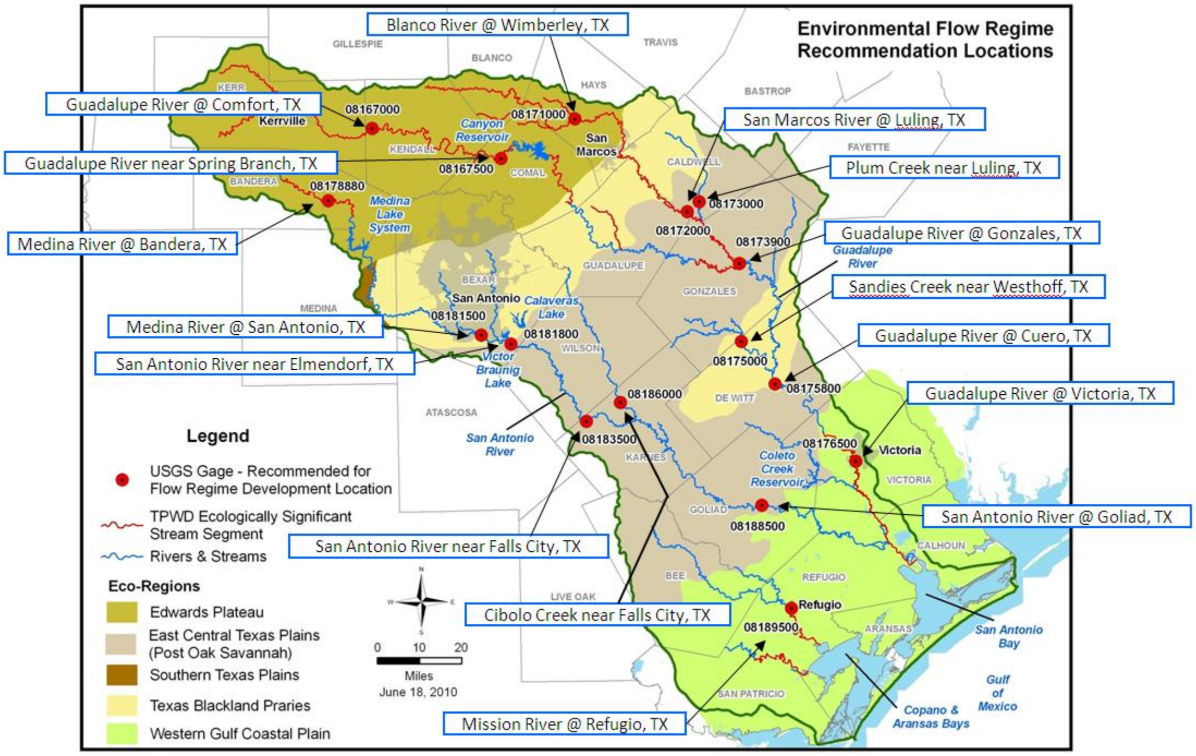


Figure 3.1-1. Environmental Flow Regime Recommendation Locations

3.1.2.1 Hydrology

Key considerations for gage selection with respect to hydrology include period of record, the degree to which gage records may have been affected by anthropogenic influences, and utility of the most downstream gages for evaluations of freshwater inflows to bays and estuaries. The average number of full years of streamflow record among the 16 gages shown in Table 3.1-1 is 66 years. If record extensions by regression for three of the 16 sites are included, then the average number of full years of streamflow record increases to 73 years. Figure 3.1-2 provides a graphical illustration of the periods of measured streamflow record for each of the 16 gages as well as indication by shading of the first year during which deliberate impoundment in a large upstream reservoir began to affect such records. As shown in Table 3.1-1, more than half of the drainage area contributing to any one of the 16 gages is unaffected by impoundment in a large upstream reservoir. Selected gages on the Guadalupe River at Victoria (USGS# 08176500), the San Antonio River at Goliad (USGS# 08188500), and the Mission River at Refugio (USGS# 08189500) are the closest full service stations to San Antonio, Copano, and Aransas Bays. These are, in fact, the longest period of record gaging stations used by the TWDB for estimating historical freshwater inflows to these estuarine systems (TWDB 2010 and TWDB 2011).

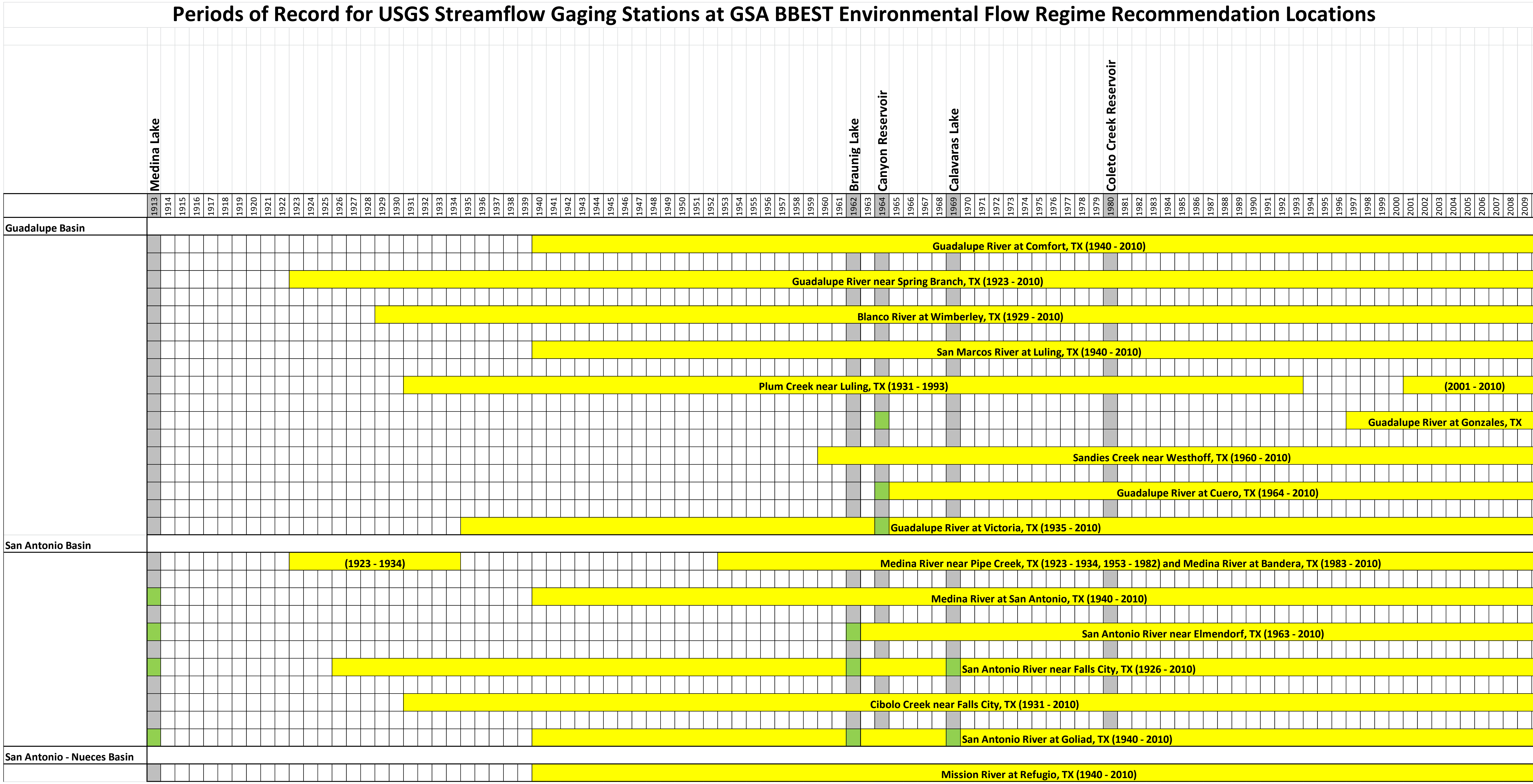
Table 3.1-1. GSA BBEST Environmental Flow Regime Recommendation Location Reference Data Summary

GSA BBEST Environmental Flow Regime Recommendation Location Reference Data Summary

Pilot	River Basin	USGS Streamflow Gage Name	USGS#	USGS Core Gage	First Full Year of Record	Full Years of Record	Drainage Area (sq mi)	Uncontrolled Drainage Area (sq mi)	Approximate Percentage of Drainage Area Uncontrolled	WAM Primary Control Point	WAM Unappr. Water Availability (% time)	Potential Reservoir Site	Regional Water Plan Reference	TPWD Ecologically Significant Segment	TCEQ Stream Segment	TCEQ 2010 DRAFT 303(d) List***	TCEQ Aquatic Life Uses
☐	Guadalupe	Guadalupe River at Comfort, TX	08167000	Yes	1940	70	839	839	100%	Yes	0 - 25	No	No	Yes	1806		Exceptional
✓	Guadalupe	Guadalupe River near Spring Branch, TX	08167500	Yes	1923	87	1,315	1315	100%	Yes	0 - 25	Yes	No	Yes	1806		Exceptional
☐	Guadalupe	Blanco River at Wimberley, TX	08171000	Yes	1929	81	355	355	100%	Yes	25 - 50	Yes	No	Yes	1813		Exceptional
✓	Guadalupe	San Marcos River at Luling, TX	08172000	Yes	1940	70	838	838	100%	Yes	25 - 50	Yes	Yes	Yes	1808		High
☐	Guadalupe	Plum Creek near Luling, TX	08173000	No	1931	73	309	309	100%	Yes	50 - 75	Yes	No	No	1810		High
☐	Guadalupe	Guadalupe River at Gonzales, TX*	08173900	No	1997	13	3,490	2058	59%	No	50 - 75	Yes	No	Yes	1803		High
☐	Guadalupe	Sandies Creek near Westhoff, TX	08175000	Yes	1960	50	549	549	100%	Yes	50 - 75	Yes	No	No	1803B	B,DO,IFC, IMC	
☐	Guadalupe	Guadalupe River at Cuero, TX*	08175800	No	1964	46	4,934	3502	71%	Yes	50 - 75	Yes	No	No	1803		High
✓	Guadalupe	Guadalupe River at Victoria, TX	08176500	Yes	1935	75	5,198	3766	72%	Yes	50 - 75	No	Yes	Yes	1803		High
☐	San Antonio	Medina River at Bandera, TX**	08178880	Yes	1983	70	427	427	100%	No	0 - 25	No	No	Yes	1905		Exceptional
☐	San Antonio	Medina River at San Antonio, TX	08181500	Yes	1940	70	1,317	668	51%	Yes	0 - 25	Yes	No	No	1903		High
☐	San Antonio	San Antonio River near Elmendorf, TX*	08181800	No	1963	48	1,743	1087	62%	Yes	0 - 25	No	No	No	1911	IFC	High
✓	San Antonio	San Antonio River near Falls City, TX	08183500	Yes	1926	84	2,113	1392	66%	Yes	25 - 50	No	Yes	No	1911	IFC	High
☐	San Antonio	Cibolo Creek near Falls City, TX	08186000	Yes	1931	79	827	827	100%	Yes	25 - 50	Yes	No	No	1902	B,IFC	High
☐	San Antonio	San Antonio River at Goliad, TX	08188500	Yes	1940	70	3,921	3200	82%	Yes	50 - 75	Yes	Yes	No	1901		High
✓	San Antonio - Nueces	Mission River at Refugio, TX	08189500	Yes	1940	70	690	690	100%	Yes	75 - 100	No	No	Yes	2002		High

* USGS streamflow records for this location have been supplemented by regression techniques.
** USGS streamflow records for this location have been supplemented by records for the Medina River near Pipe Creek, TX (USGS# 08179000) available from 1923 through 1934 and 1953 through 1982 adjusted by drainage area ratio.
*** Key to Abbreviations: B = Bacteria; DO = Dissolved Oxygen; IFC = Impaired Fish Community; IMC = Impaired Macrobenthic Community

Table 3.1-2. Periods of Record for USGS Streamflow Gaging Stations at GSA BBEST Environmental Flow Regime Recommendation Locations



Daily streamflow records were extended at three of the 16 locations (Guadalupe River at Gonzales, USGS# 08173900, Guadalupe River at Cuero, USGS# 08175800, and San Antonio River near Elmendorf, USGS# 08181800) by application of simple monthly regression and daily disaggregation techniques relying on records for proximate gaging stations. Monthly regression equations used for the Cuero and Elmendorf gage locations are identical to those used in development of the Guadalupe – San Antonio River Basin Water Availability Model (GSA WAM) (HDR 1999) and have associated coefficients of determination (r^2) of 0.99 and 0.97, respectively. Disaggregation of estimated monthly flows to daily values was accomplished using daily records (as a percentage of monthly totals) at the same gages used in the monthly regression equations.

Monthly regression equations and daily disaggregation techniques used to estimate flows for the Guadalupe River at Gonzales for the 1940 through 1996 historical are based on the sum of concurrent records for three or four upstream gages, depending on availability. These upstream gages are identified in the primary and secondary equations below:

Primary Equation: $Q_G = 1.0949 * (Q_{GAC} + Q_C + Q_{SM} + Q_P)$

Secondary Equation: $Q_G = 1.1513 * (Q_{GAC} + Q_C + Q_{SM})$

Where:

Q_G = Estimated Flow, Guadalupe River at Gonzales (USGS# 08173900)

Q_{GAC} = Measured Flow, Guadalupe River above Comal River at New Braunfels (USGS# 08168500);

Q_C = Measured Flow, Comal River at New Braunfels (USGS# 08169000);

Q_{SM} = Measured Flow, San Marcos River at Luling (USGS# 08172000); and

Q_P = Measured Flow, Plum Creek near Luling (USGS# 08173000).

The primary regression equation based on four upstream gages was used for all but three years and has an associated coefficient of determination of 0.96 while the secondary equation, based on three upstream gages, has an associated coefficient of determination of 0.93.

3.1.2.2 Biology

Key considerations for gage selection with respect to biology include representation of eco-regions and ecologically significant stream segments as well as making use of best available science from the Texas Instream Flow Program (TIFP) and other research. As shown in Figure 3.1-1, flow regime recommendation locations have been selected in each of the four major eco-regions occurring in the Guadalupe – San Antonio River Basin and San Antonio – Nueces Coastal Basin. From the headwaters to the coast, four (4) locations are in the Edwards Plateau eco-region, four (4) are in the Texas Blackland Prairies, six (6) are in the East Central Texas Plains (Post Oak Savannah), and two (2) are in the Western Gulf Coastal Plain.

Stream segments identified as ecologically significant by the TPWD are shown in red in Figure 3.1-1. Additional information regarding each of these segments is available on the TPWD website (http://www.tpwd.state.tx.us/landwater/water/environconcerns/water_quality/sigsegs/) under planning data for Regions L (South Central) and J (Plateau). Criteria for identification of these stream segments as ecologically significant includes biological function, hydrologic function, riparian conservation area(s), high water quality/exceptional aquatic life/high aesthetic value, and/or threatened or endangered species/unique communities. With the exceptions of two river segments (Guadalupe River immediately below Canyon Dam and Aransas River from

Copano Bay upstream to a point 3.3 miles upstream of the Chiltipin Creek confluence), short river segments immediately below Comal and San Marcos Springs, and several relatively small tributary streams, flow regime recommendation locations have been selected within or very near each stream segment identified as ecologically significant. Reasons that the GSA BBEST chose not to select flow regime recommendation locations within the segments listed above as exceptions include: a) Limited long-term daily streamflow records and gaged drainage area for the Aransas River and several relatively small tributary streams; b) Gage records immediately below Canyon Dam reflect an highly modified flow regime since 1965 when deliberate impoundment began in Canyon Reservoir; and c) Recognition that discharges necessary to maintain sound ecological environments below Comal and San Marcos Springs are being addressed in the Edwards Aquifer Recovery Implementation Program (EARIP) pursuant to SB3 of the 80th Texas Legislature.

Three locations on the LSAR (Elmendorf, Falls City, and Goliad) and one on lower Cibolo Creek (near Falls City) were selected, in part, to make full use of draft information from the TIFP developed pursuant to Senate Bill 2 (SB2) of the 77th Texas Legislature. A December 2010 draft memorandum summarizing this information is attached to this report as Appendix 3.1-1. Two of these San Antonio River locations (Falls City and Goliad) are also considered in research conducted by Bonner and Runyan (Bonner 2007).

Two locations on the Guadalupe River (Gonzales and Victoria) were selected, in part, to make full use of draft work from the TPWD initiated prior to, and continued subsequent to, the passage of SB2. In addition, research conducted by Perkin and Bonner (Perkin 2010) focused on locations on the Guadalupe River at Spring Branch and Victoria and on the San Marcos River at Luling thereby suggesting inclusion of these locations for GSA BBEST development of flow regime recommendations.

3.1.2.3 Water Quality

Key considerations for gage selection with respect to water quality focus primarily on adequate coverage among TCEQ Water Quality Segments including segments with exceptional or high water quality and aquatic life uses and segments with identified impairments pursuant to the current draft Clean Water Act Section 303(d) list (http://www.tceq.texas.gov/compliance/monitoring/water/quality/data/wqm/305_303.html#fy2010). As listed in Table 3.1-1, most selected gages are located in stream segments exhibiting high aquatic life uses and four (4), located in the Edwards Plateau eco-region, exhibit exceptional aquatic life uses. Table 3.1-1 also shows that only four (4) gages are located in stream segments appearing on the current draft Section 303(d) list. Specific impaired parameters for these segments are listed in Table 3.1-1 although it is recognized that such impaired parameters may or may not be related to streamflow magnitude, duration, or frequency of occurrence. For most of these sites and parameters, a review of the water quality standards for the associated water body will be conducted or additional data and information will be collected before a Total Maximum Daily Load (TMDL) assessment is scheduled. The GSA BBEST recognizes that there are other stream segments with exceptional aquatic life uses or potential water quality concerns and has assumed that its selection of gage locations will provide sufficiently broad coverage so as to be protective of water quality to the extent that flow regime recommendations and environmental flow standards can accomplish this objective.

3.1.2.4 Geomorphology

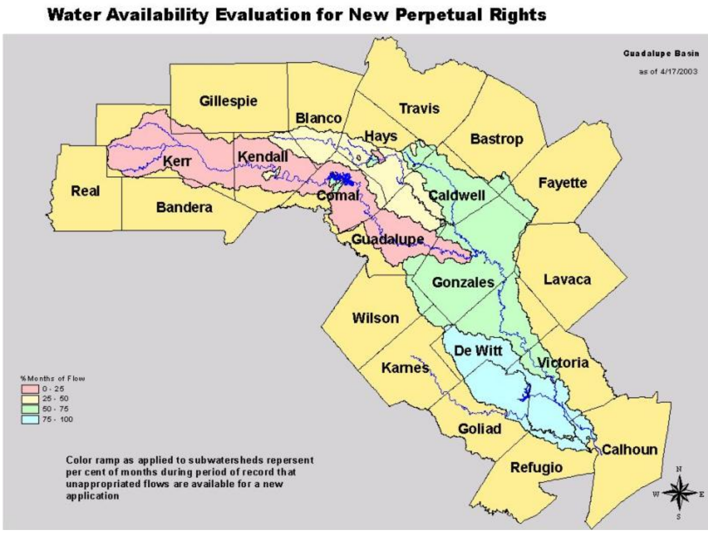
The primary consideration for gage selection with respect to geomorphology or sediment transport processes is to ensure that headwater, transfer, and deposition zones are represented. Referring to Figure 3.1-1, these zones might be assumed to roughly coincide with the Edwards Plateau, the Blackland Prairies and Post Oak Savannah, and the Western Gulf Coastal Plain, respectively, in the Guadalupe – San Antonio River Basin. As is apparent in Figure 3.1-1, the GSA BBEST has selected gages for development of flow regime recommendations located in the headwater, transfer, and deposition geomorphic zones.

3.1.2.5 Water Availability and Supply Planning

GSA BBEST performance of environmental flow analyses and development of environmental flow regime recommendations are essentially independent of water availability and supply planning. Nevertheless, it is important that the GSA BBEST ensure that streamflow gages selected are appropriately located so as to be useful in TCEQ consideration of future water rights applications and amendments and in the regional water planning process. Using Water Availability Models (WAMs), the TCEQ has quantified the approximate percentages of time that unappropriated streamflow might be available for diversion or impoundment under perpetual water rights. These percentages of time are presented spatially in Figures 3.1-3, 3.1-4, and 3.1-5 and shown for selected gage locations in Table 3.1-1. Recognizing that future water rights applications and amendments are most likely to occur in areas showing reasonably frequent water availability, the GSA BBEST has selected only five (5) gage locations where water is available less than 25% of the time. Similarly, Table 3.1-1 indicates that the GSA BBEST has selected 10 gage locations in stream segments potentially affected by new reservoir development at a site considered at some time in the past (Kretzschmar 2008). No new on-channel reservoirs are recommended in the Guadalupe – San Antonio River Basin or the San Antonio – Nueces Coastal Basin in the approved 2011 regional water plans.

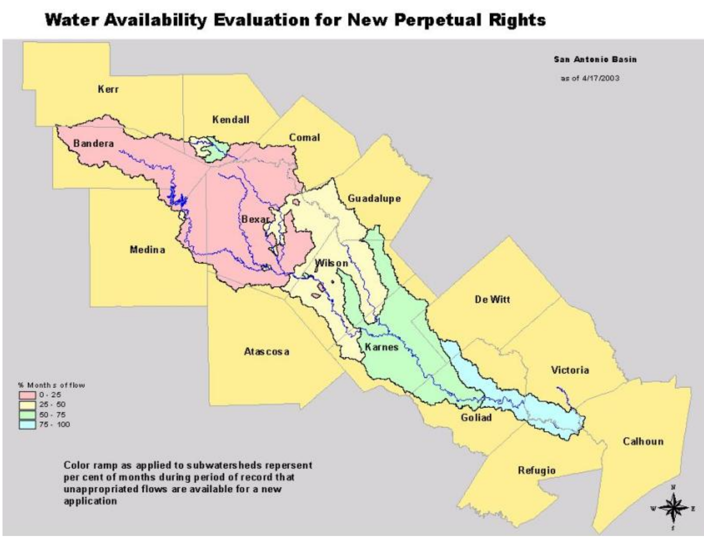
3.1.2.6 Geographic Interpolation

The GSA BBEST has provided flow regime recommendations at streamflow gaging stations located throughout the Guadalupe – San Antonio River Basin and the San Antonio – Nueces Coastal Basin. These reference locations are, among other things, representative of major streams above and below existing reservoirs as well as some tributary streams in the middle portions of each river basin. The GSA BBEST recommends that the TCEQ develop appropriate methods for interpolation of flow conditions applicable to future inter-adjacent permits and amendments from reference locations for which flow regimes supporting a sound ecological environment are established. Such methods should include, at a minimum, drainage area adjustments, but may also include consideration of springflow contributions, channel losses, aquifer recharge zones, soil cover complex, and other factors as necessary and appropriate.



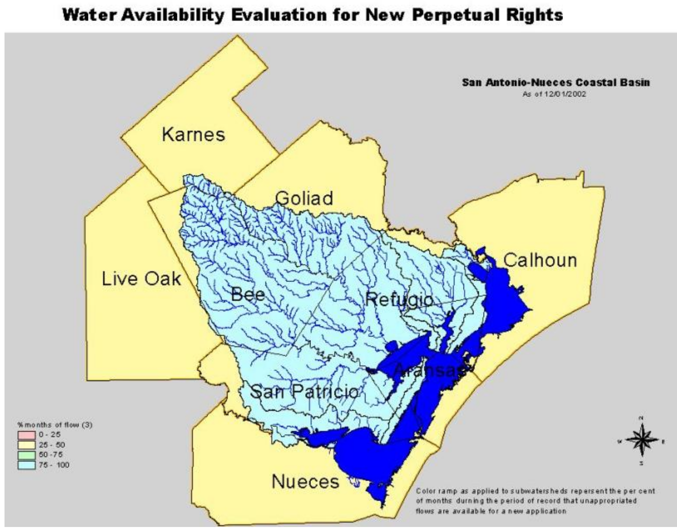
http://www.tceq.texas.gov/assets/public/permitting/watersupply/water_rights/maps/guadalupe/guad3.jpg downloaded 2/11/2011.

Figure 3.1-2. Water Availability in the Guadalupe River Basin



http://www.tceq.texas.gov/assets/public/permitting/watersupply/water_rights/maps/san_antonio/san3s.jpg downloaded 2/11/2011.

Figure 3.1-3. Water Availability in the San Antonio River Basin



http://www.tceq.texas.gov/assets/public/permitting/watersupply/water_rights/maps/san_antonio/run3.jpg downloaded 2/11/2011.

Figure 3.1-4. Water Availability in the San Antonio – Nueces Coastal Basin

3.2 Hydrology-Based Environmental Flow Regimes

Once locations for development of environmental flow regime recommendations were selected by the GSA BBEST, performance of environmental flow analyses began with compilation and consideration of USGS gaged streamflow records as they are the best hydrologic data available. The GSA BBEST has used hydrologic data in general accordance with SAC guidance issued April 20, 2009 and entitled: "Use of Hydrologic Data in the Development of Instream Flow Recommendations for the Environmental Flows Allocation Process and the Hydrology-Based Environmental Flow Regime (HEFR) Methodology." In addition, the GSA BBEST has used certain elements of a December 2010 working draft update of this guidance document. Recognizing early that the HEFR methodology provides a meaningful statistical depiction of the occurrence of instream flows and, when integrated with appropriate biology, water quality, geomorphology, and riparian vegetation overlays, provides a foundation for environmental flow regime recommendations, the GSA BBEST made a consensus decision at its June 11, 2010 meeting to use the HEFR methodology.

Within this recommendations report, the term "HEFR" may be used in reference to either a methodology or a computational tool developed on a Microsoft Excel platform for efficient statistical analysis and summary of daily streamflow records. The HEFR methodology or approach is conveniently summarized in flowchart format in Figure 3.2-1 which generally identifies the information considered and decisions made in using gaged streamflow records to formulate initial hydrology-based flow regimes for potential refinement through the application of ecological overlays. In keeping with the general progression of the HEFR methodology illustrated in Figure 3.2-1, the following sub-sections address major decision points, decisions made by the GSA BBEST, and the technical bases for these decisions.

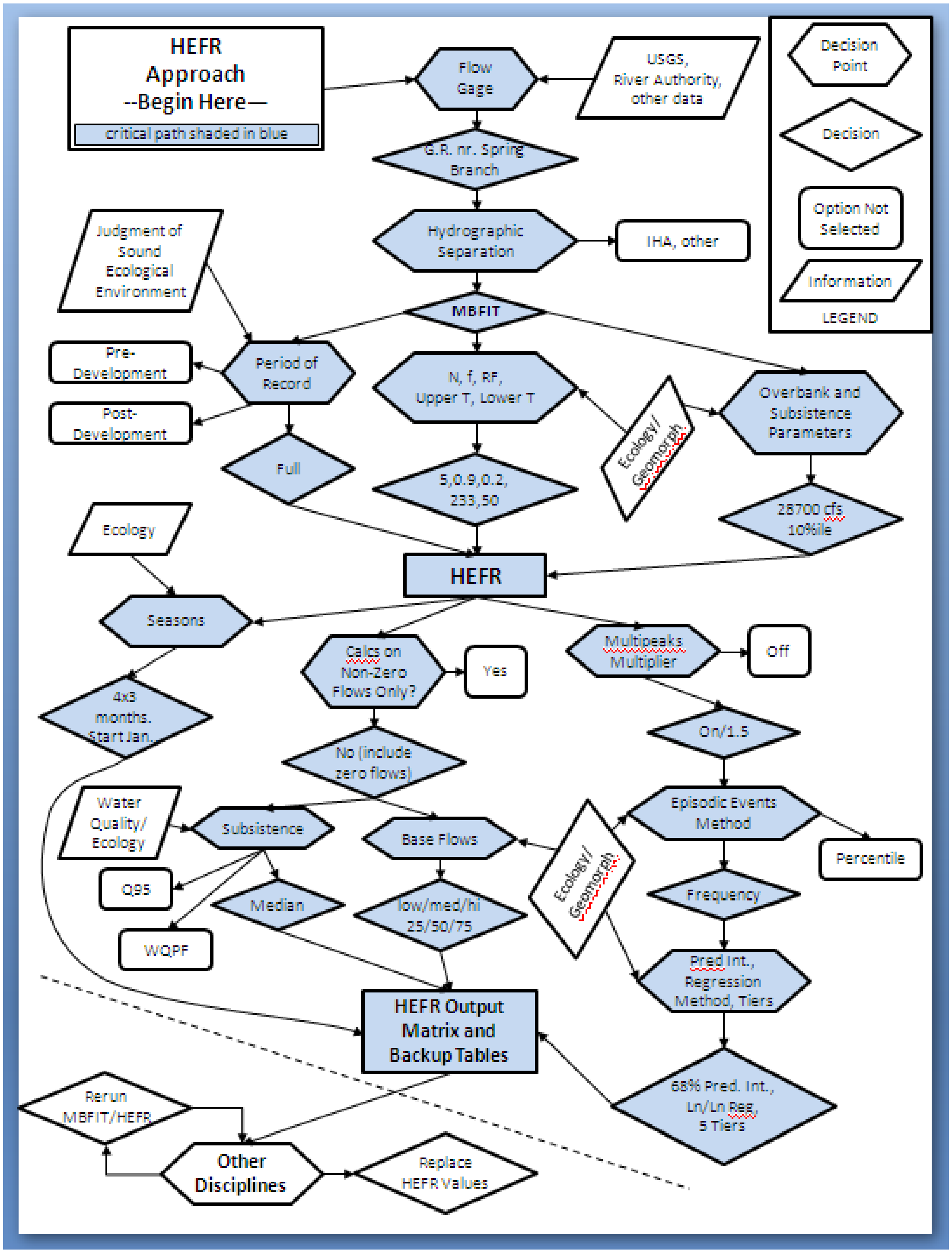


Figure 3.2-1 Hydrology-Based Environmental Flow Regime (HEFR) Approach

3.2.1 Hydrographic Separation

The first major decision in application of the HEFR methodology is the selection of an appropriate method for hydrographic separation. Methods considered by the GSA BBEST and its Hydrology Subcommittee included Modified Base Flow Index with Threshold (MBFIT) and Indicators of Hydrologic Alteration (IHA), both of which are described in referenced SAC guidance. The GSA BBEST decided by majority vote during its August 12, 2010 meeting to use the MBFIT method with modifications to address inordinately high base flows, ensure recognition of small pulses, and separate extended high flow periods with multiple peaks into multiple events. Selection of MBFIT was based primarily on perceived better performance in identification of small pulses, particularly those occurring during dry periods.

MBFIT has seven parameters which can be set by the user, of which the most important are usually N, the lower high flow pulse (HFP) threshold, and the upper HFP threshold. Based on a visual inspection of the results, selected N values ranged from five for somewhat smaller watersheds to nine for the most downstream locations. This scaling of N with watershed size or recession length is not uncommon (Wahl and Wahl, 1995).

The BBEST reached a consensus decision (September 14, 2010) that flows below the 25th percentile of all flows do not primarily provide the ecological functions associated with HFPs, thus the lower HFP threshold was set to the 25th percentile. Similarly, the BBEST reached a consensus decision (September 14, 2010) that flows above the 75th percentile of all flows do not primarily provide the ecological functions associated with base flows, thus the upper HFP threshold was set to the 75th percentile. Because the early period of record was deemed more representative of natural conditions than the full period of record (due to the lesser degree of anthropogenic influences such as impoundments, diversions, return flows, and use of the Edwards Aquifer, etc.), these percentiles were calculated using the early period of record and the corresponding flow magnitudes were set as the thresholds in the full period of record, and late period of record, simulations.

Flow thresholds to distinguish (in-bank) HFPs from overbank events in the MBFIT hydrographic separation step were determined primarily from the National Weather Service website (www.weather.gov) with additional information obtained from GBRA and SARA. This website includes action stages and various flood stages for each USGS streamflow gaging station. Unfortunately, flows corresponding to these stages cannot always be precisely visually estimated using their charts, the scaling on the charts (and accordingly the ability to read them) changes as flows change, and the rating curves themselves may change over time.

Table 3.2-1 shows the visually estimated action and flood stages from weather.gov as of February 18, 2011. Table 3.2-1 also shows the values used in MBFIT. These values are sometimes different, possibly because of different visual estimations and/or changes to rating curves. Some values used in MBFIT are reported more precisely than others because of the ready availability of flow records on 15-minute intervals immediately after a flood event allowing for more precise selection of the flow rate associated with the stage at which overbank flow occurs. Fortunately, because the frequency approach used in HEFR treats HFPs and overbank events identically (they are pooled in the statistics), the distinction between these two flow components is largely immaterial for the construction of the HEFR matrix. The distinction may be of greater importance to the GSA BBASC, which is charged with considering human impacts and water demands.

MBFIT uses changes in flows to distinguish base flows from runoff (and hence HFPs). MBFIT is generally very sensitive to changes in flows (i.e., a modest flow change triggers the identification of runoff), although this can be managed somewhat through careful parameter selection. At locations downstream of hydroelectric facilities (Guadalupe River at Gonzales, Cuero, and Victoria), day-to-day variations in flows during dry periods caused largely by store and release hydropower operations were being identified by MBFIT as numerous small HFPs. Changes to MBFIT parameters provided little relief from this problem. Hence, at each location, a new time series of hydrology was constructed using a three-day centered moving average (referred to as a 3 day low pass filter, or LP3). This calculation smoothed three-day (or shorter duration) variations in flow and allowed for a more reasonable hydrographic separation. Note that the original flows were used in HEFR and all subsequent analyses; the LP3 values were only used in the hydrographic separation step.

Table 3.2-1 Estimated Action and Flood Stages

	Action Stage		Flood Stage		Used in MBFIT
Location	ft	cfs	ft	cfs	cfs
Guadalupe River at Comfort	10	1,406	21	40,000	4,650*
Guadalupe River near Spring Branch	25	30,000	30	42,946	28,700*
Blanco River at Wimberley	10	6,261	13	13,000	12,290*
San Marcos River at Luling	11	2,002	20	6,000	3,780*
Plum Creek near Luling	20	4,500	23	10,685	4,598*
Guadalupe River at Gonzales	17	4,154	31	14,000	14,100*
Sandies Creek near Westhoff	12	850	21	3,748	3,171*
Guadalupe River at Cuero	19	9,500	24	14,000	11,900*
Guadalupe River at Victoria	12	3,200	21	9,100	8,426*
Medina River at Bandera	10	2,990	13	5,000	2,990
Medina River at San Antonio	16	3,500	20	6,000	3,900
San Antonio River near Elmendorf	33	7,000	35	8,500	6,426
San Antonio River near Falls City	6	3,600	12	9,194	3,603
Cibolo Creek near Falls City	6	1,202	17	7,000	959
San Antonio River at Goliad	15	4,000	25	9,000	3,938
Mission River at Refugio	20	3,500	23	5,000	3,600

Because of the construction of the NWS charts, shaded values are only roughly estimated.
* Values provided by GBRA, 9/3/2010 and 9/30/2010

At four locations, a satisfactory period of record of measured data was not available from the USGS. For these sites, daily streamflow estimates were calculated using measured data at nearby

USGS streamflow gaging stations. Estimation techniques used for extension of daily streamflow records for the Guadalupe River at Gonzales and Cuero and the San Antonio River near Elmendorf are described in Section 3.1.2.1. Measured data are available for the Medina River at Bandera from October 1982 to the present. Estimated daily streamflows for the Medina River at Bandera were developed from December 1922 through June 1935 and from October 1952 through September 1982 by multiplying Medina River near Pipe Creek daily measured data by the ratio of drainage areas (328/474).

HEFR requires continuous periods of record. Two gages selected for analyses by the GSA BBEST do not have continuous periods of record and continuous periods had to be synthesized. The Medina River at Bandera gage has data from October 1982 to the present. Data from the Medina River near Pipe Creek gage was used to synthesize older data (see discussion above). However, the Medina River near Pipe Creek gage has a gap in its period of record; data are available for December 1922 through June 1935 and from October 1952 to October 19, 1982. In order to use all available data and provide a continuous period of record for HEFR, data from the early period was simply shifted or placed in sequence immediately before the later period, thereby providing a "continuous" period of record approaching 70 years in duration. The discontinuity in the hydrologic data between the two days at which the two periods were joined may have led to the early termination of one HFP, or the initiation of a HFP, in the hydrographic separation step. However, one potentially spurious event in such a long period of record is of little consequence. Due to a break in the records for Plum Creek near Luling extending from October 1993 into July 2001, a similar shift was applied in order to use all available data, resulting in a "continuous" period of record of about 73 years in duration.

3.2.2 Period of Record

The second major decision in application of the HEFR methodology is the selection of an appropriate period of record for development of initial hydrology-based flow regimes. As mentioned in Section 1.3, members of the GSA BBEST have generally acknowledged that riverine ecosystems in the Guadalupe – San Antonio River Basin and adjacent coastal basins have exhibited characteristics of a sound ecological environment throughout the past century as many ecosystems have transitioned from a natural condition to the modified conditions typical of the present. This general acknowledgement was confirmed by consensus of the GSA BBEST on February 3, 2011.

In order to explore potential trends in streamflow, the GSA BBEST selected five representative gage locations for consideration: Guadalupe River near Spring Branch, Guadalupe River at Victoria, San Marcos River at Luling, San Antonio River near Falls City, and Mission River at Refugio. Figure 3.2-2 illustrates a time series of annual flow volumes for the entire period of record for the Guadalupe River near Spring Branch USGS gage (blue line with diamonds). The red line (with squares) illustrates a 10 year lagged moving average of the same data. Due to the initiation of deliberate impoundment in Canyon Reservoir in 1964, flow statistics are presented for the periods from January 1923 through December 1964 and from January 1965 through December 2009 for Spring Branch and other representative gage locations in the Guadalupe River Basin. In addition, flow statistics for the entire period of record are shown. The results suggest that flows have increased with time, as the flow statistics for the latter period of record are generally about two times the same statistics for the early period of record. This increase is consistent with other analyses that document increased precipitation and runoff per unit rainfall in the watershed over comparable time periods (HDR 2000). Figure 3.2-3 provides flow frequency curves derived from daily streamflow data for the Guadalupe River near Spring Branch site with one for the early period of record (blue) and another for the later period of record (orange). These curves also illustrate the increase in flows over time at this gage.

Figures 3.2-4 through 3.2-11 provide similar depictions for the four additional gages selected by the GSA BBEST. Records for all gages show apparent increases in flow in the latter portion of the period of record. For the gages in the San Antonio and Mission River basins, the early and late periods of record were separated at January 1, 1970, as both a reasonable approximation of when return flows started to significantly increase below the City of San Antonio and a reasonable approximation of when precipitation appears to have increased. Appendix 3.2-2 includes time series and simple statistical analyses of measured annual precipitation from long-term gages in or near the Guadalupe – San Antonio River Basin.

Upon consideration of these significant increases in streamflow, the GSA BBEST decided to apply HEFR for early (pre-development) and late (post-development) sub-periods as well as the full period of record at each selected streamflow gaging station with the exception of Sandies Creek near Westhoff. Available daily streamflow records at this site began in 1959 and it was determined that these records could not be extended with sufficient accuracy to reasonably support hydrographic separation and HEFR application for an early period. Early and late sub-periods were separated between 1964 and 1965 for all sites in the Guadalupe River Basin and between 1969 and 1970 for all sites in the San Antonio River Basin and San Antonio – Nueces Coastal Basin. Results of HEFR applications for all three periods are included as Appendix 3.2-1. On October 14, 2010, the GSA BBEST chose by consensus to use HEFR results based on the full period of record as initial hydrology-based flow regimes with which to begin the ecological overlay process.

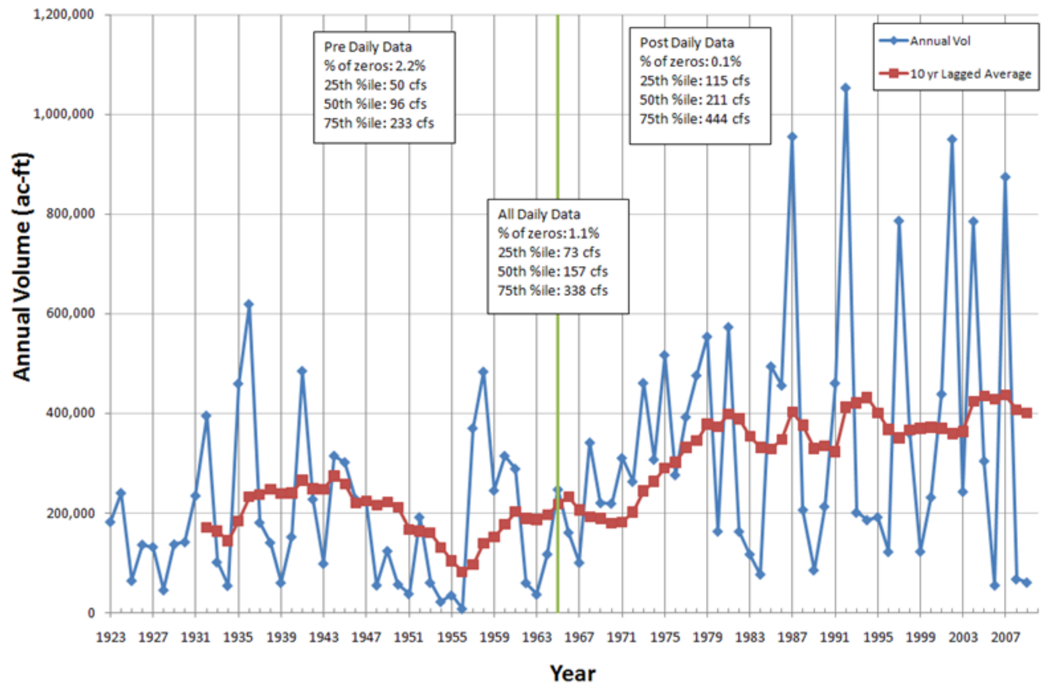


Figure 3.2-2. Historical Streamflow, Guadalupe River near Spring Branch

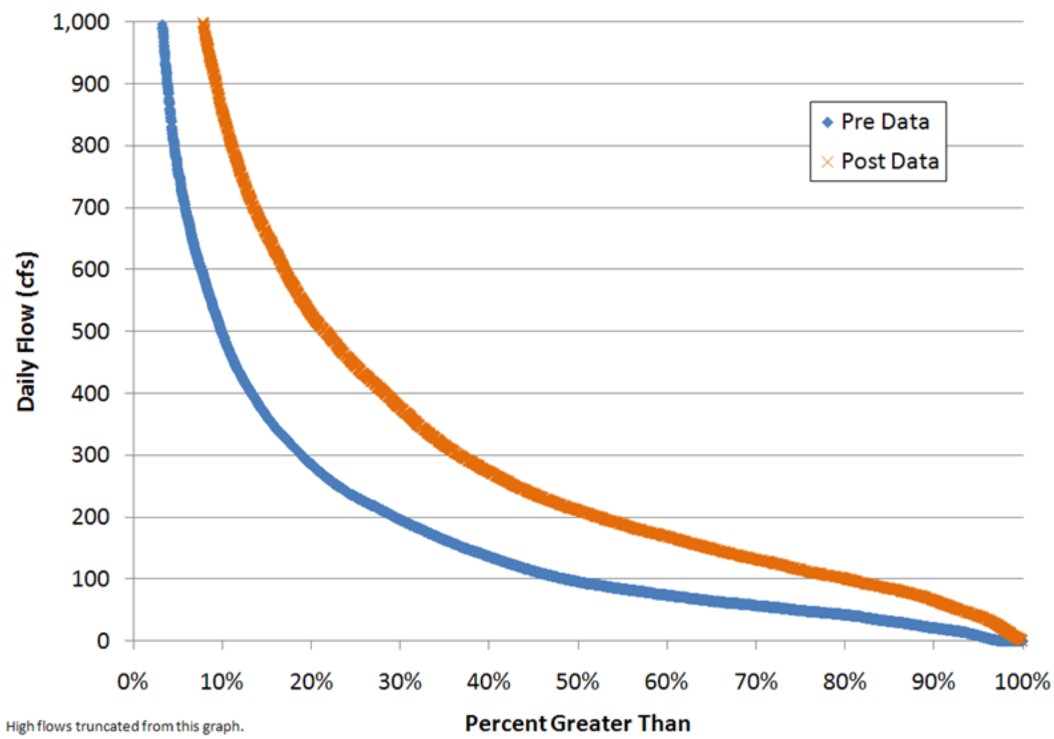


Figure 3.2-3. Historical Streamflow Frequency, Guadalupe River near Spring Branch

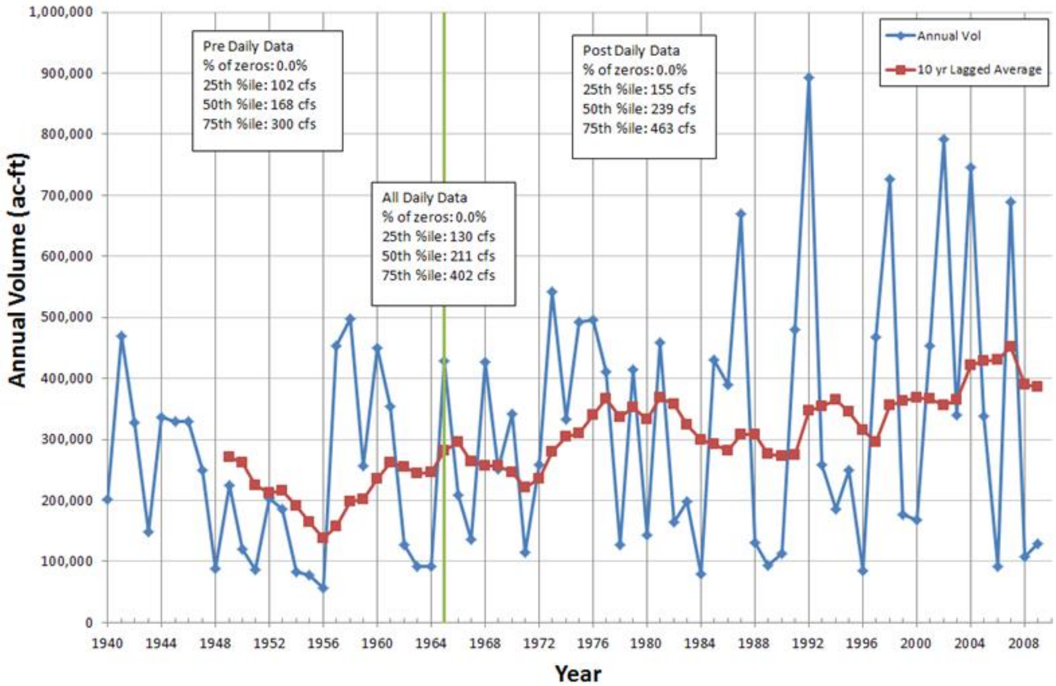


Figure 3.2-4. Historical Streamflow, San Marcos River at Luling

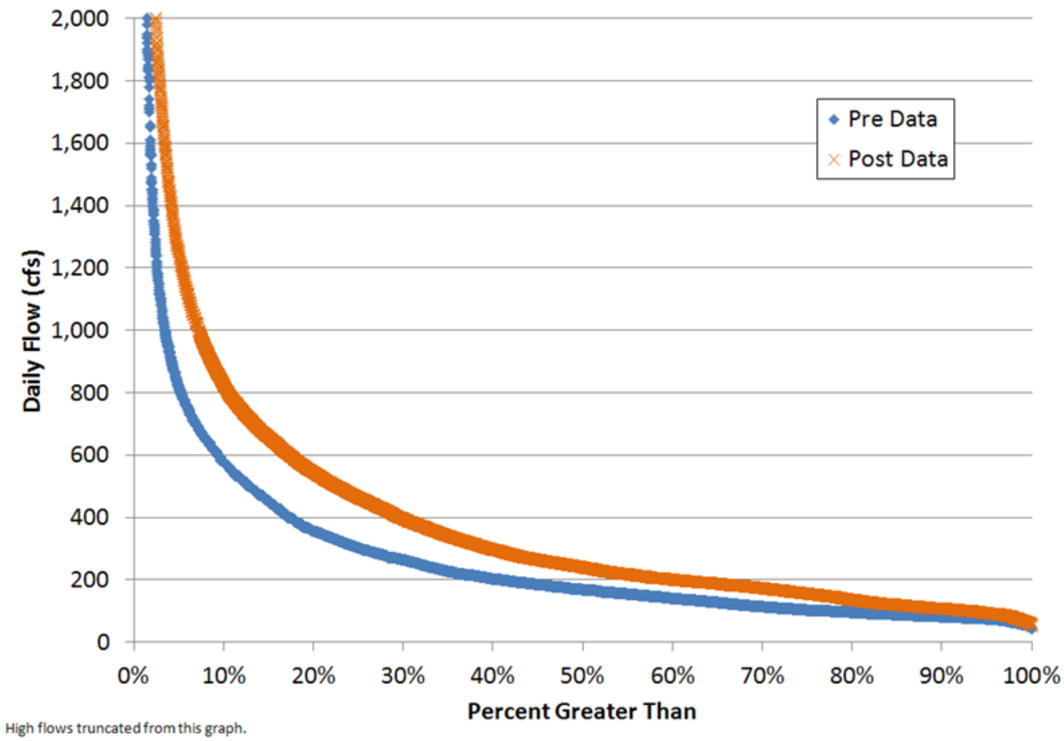


Figure 3.2-5. Historical Streamflow Frequency, San Marcos River at Luling

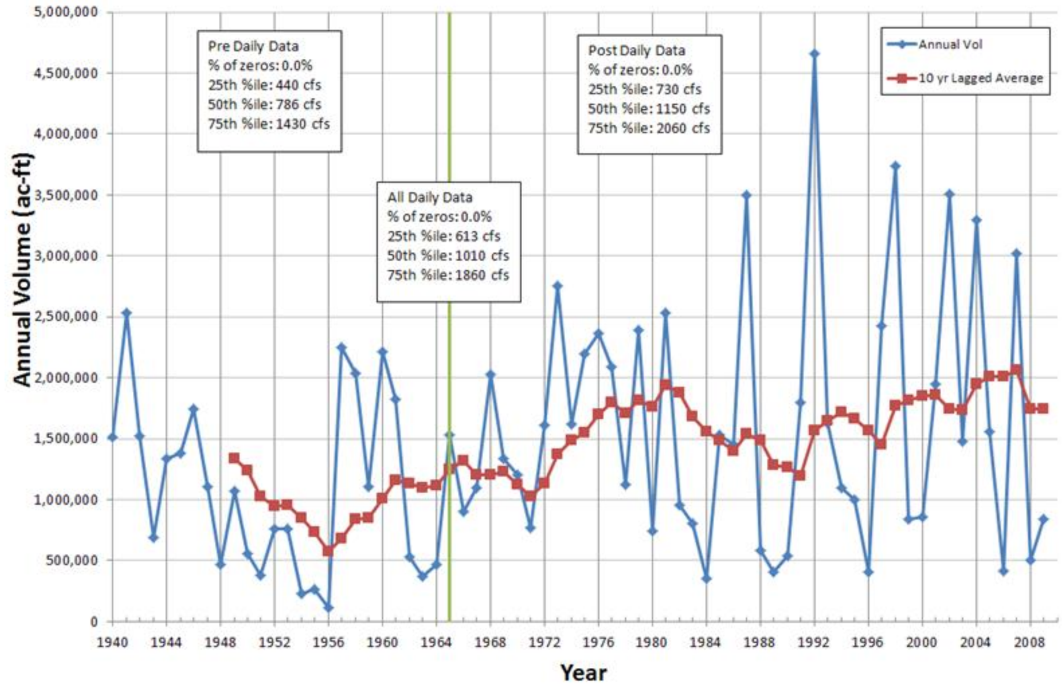


Figure 3.2-6. Historical Streamflow, Guadalupe River at Victoria

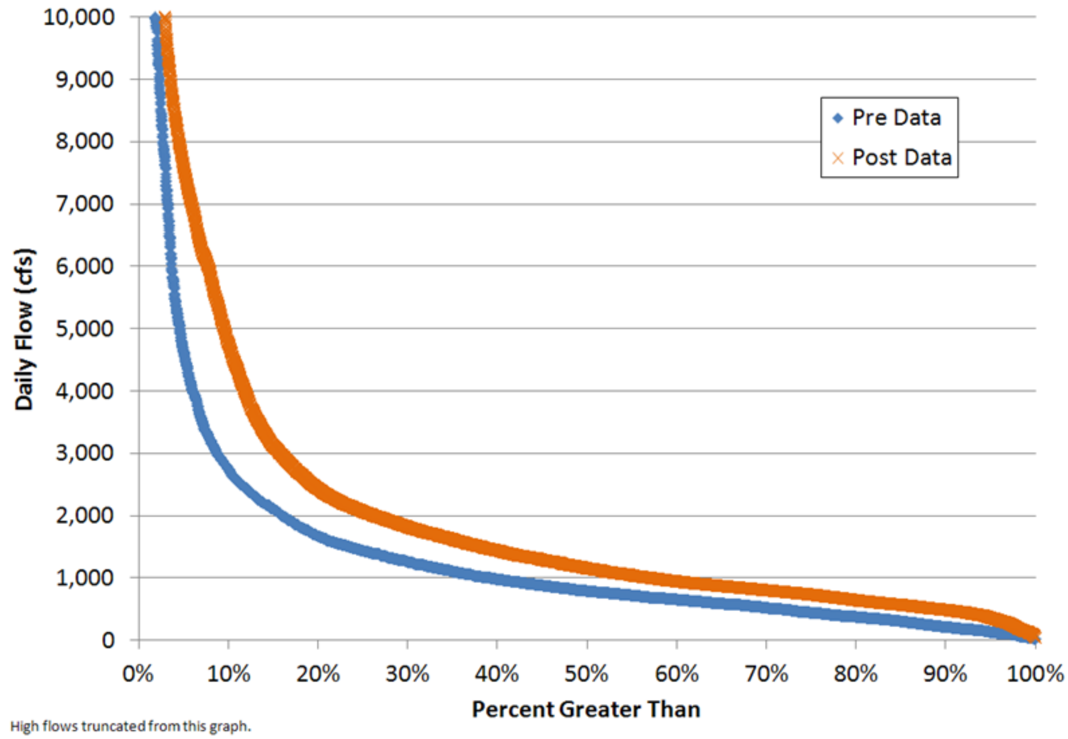


Figure 3.2-7. Historical Streamflow Frequency, Guadalupe River at Victoria

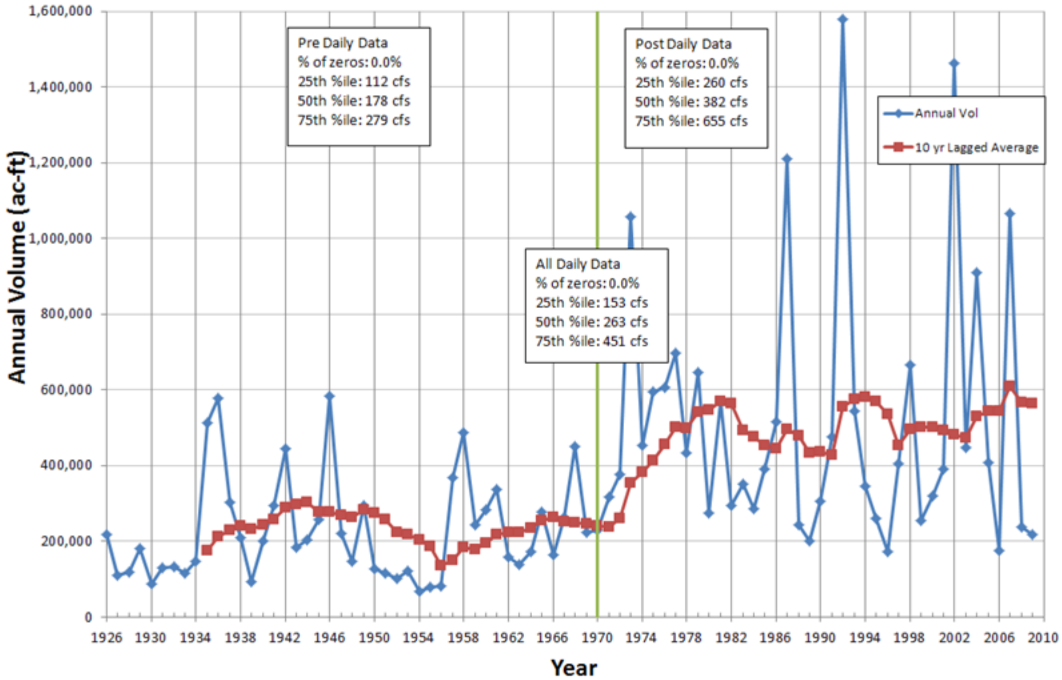


Figure 3.2-8. Historical Streamflow, San Antonio River near Falls City

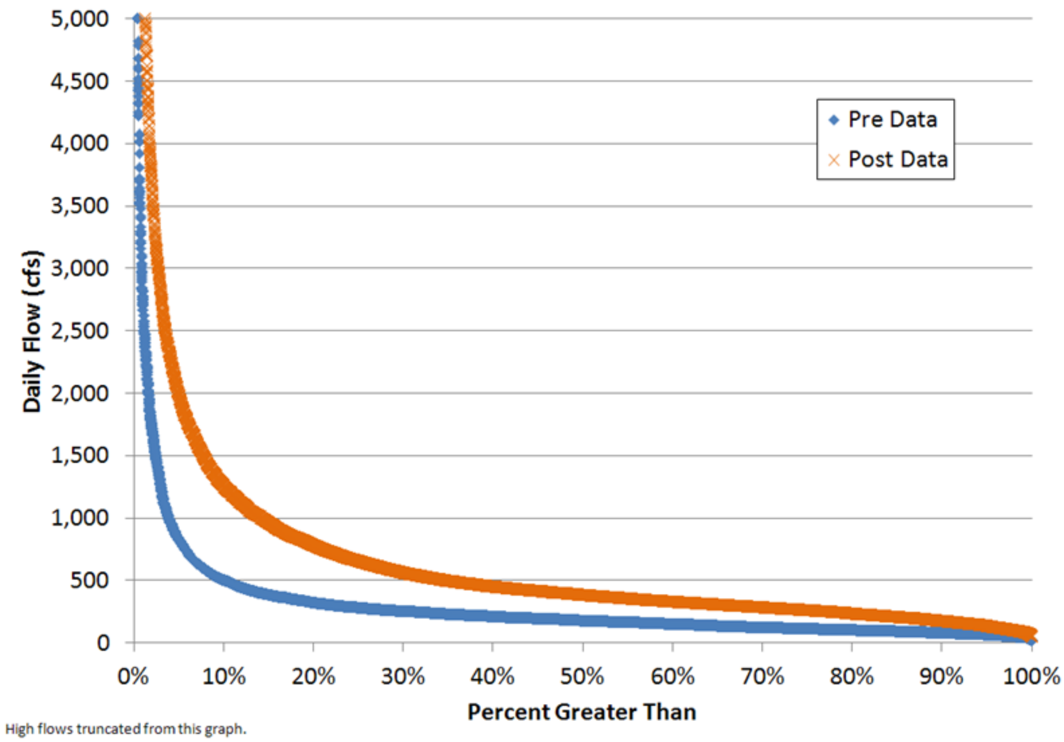


Figure 3.2-9. Historical Streamflow Frequency, San Antonio River near Falls City

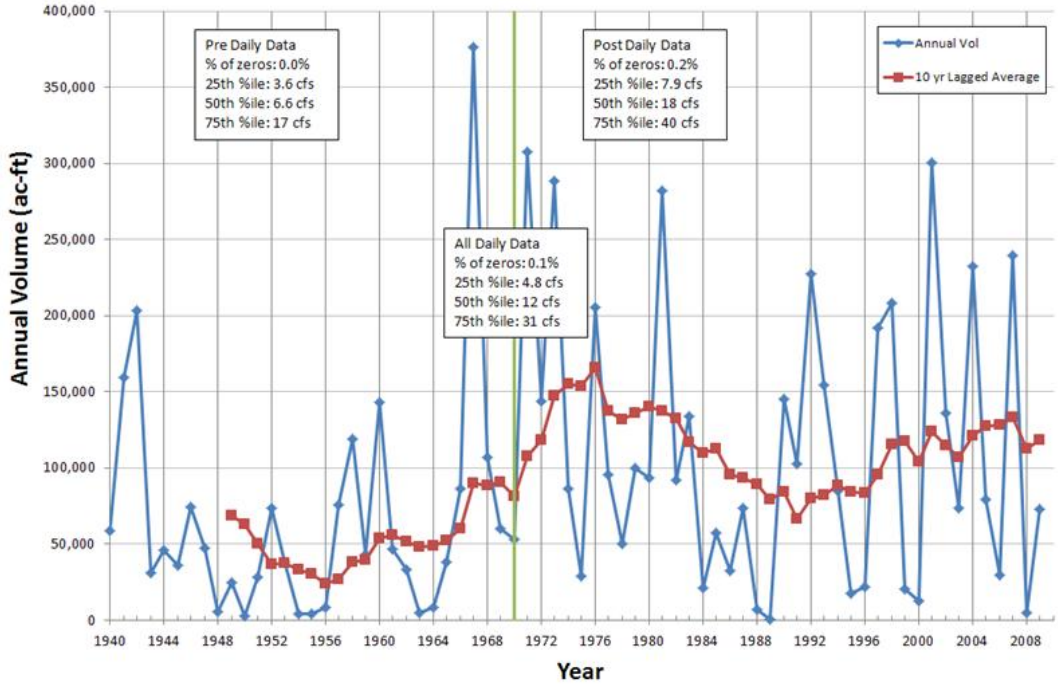


Figure 3.2-10. Historical Streamflow, Mission River at Refugio

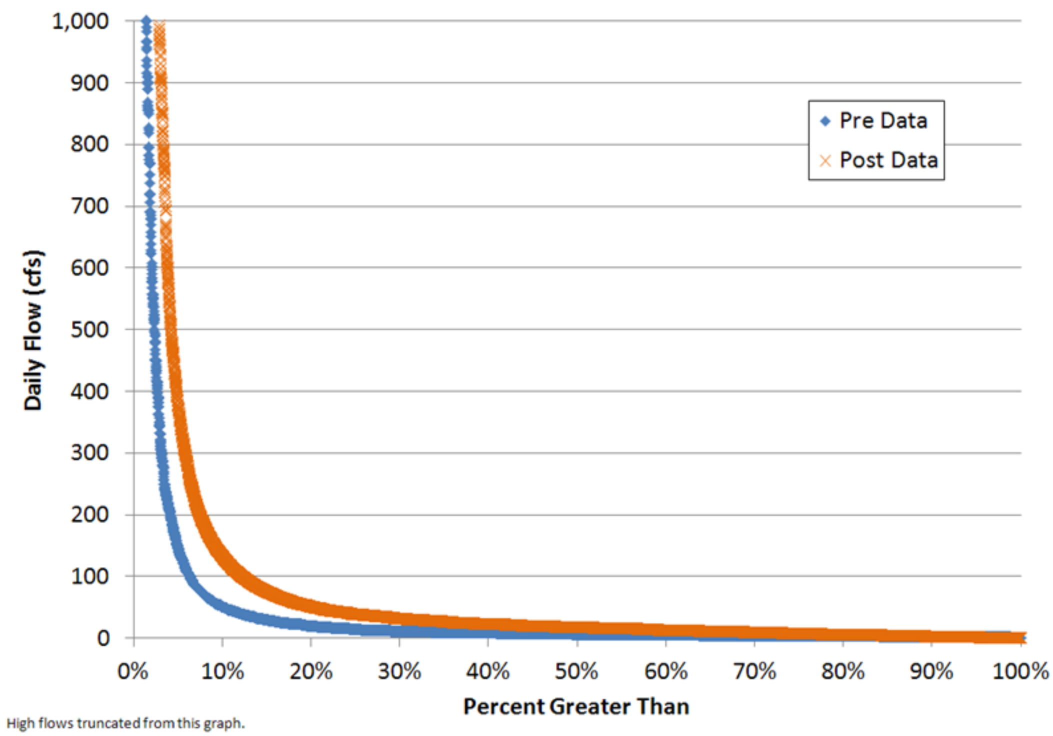


Figure 3.2-11. Historical Streamflow Frequency, Mission River at Refugio

3.2.3 Season Selection

A third major decision in application of the HEFR methodology is the selection of seasons for aggregation and analyses of daily streamflows in hydrologically and ecologically appropriate groups of months. In order to formulate its recommendation regarding season selection to the GSA BBEST, the Hydrology Subcommittee reviewed natural monthly median and 25th percentile flow variations at 11 locations in the Guadalupe – San Antonio River Basin (HDR 1998). From an ecological perspective, temperature variations were not expected to be significant in season selection and April was grouped with May and June to better consolidate months with significant spawning activity. Discussions of season selection by the Hydrology Subcommittee on July 1, 2010 lead to a recommendation approved by consensus of the GSA BBEST on July 8, 2010. The GSA BBEST selected four three-month seasons as follows: a) Winter (January through March); b) Spring (April through June); c) Summer (July through September); and d) Fall (October through December).

3.2.4 Flow Regime Components

The remainder of the major decisions in application of the HEFR methodology relate to the four flow regime components defined for the Texas Instream Flows Program (TIFP) established by SB2 of the 77th Texas Legislature. These four components include subsistence, base, pulse, and overbank flows (TCEQ 2008). The ecological functions of each of these flow components are briefly identified in the context of application of the HEFR methodology and computational tool by the GSA BBEST in the following sub-sections.

3.2.4.1 <u>Subsistence Flows</u>

Ecological functions of subsistence flows include provision for aquatic habitat, longitudinal connectivity, dissolved oxygen, and temperature sufficient to ensure survival of aquatic species for transient periods. HEFR is designed to calculate a single tier of seasonal subsistence flows which may be verified and/or refined upon consideration of biology and water quality overlays. The GSA BBEST chose to use the HEFR default calculation of seasonal subsistence flow as the median of the lowest 10% of base flows with very infrequent zero flows included in the calculations. This was deemed a reasonable choice pending biology and water quality overlays.

3.2.4.2 <u>Base Flows</u>

Base flows provide variable flow conditions, suitable and diverse aquatic habitat, longitudinal connectivity, soil moisture, and water quality sufficient to sustain aquatic species and proximate riparian vegetation for extended periods. As simply stated in SAC guidance, “base flows provide instream habitat conditions needed to maintain the diversity of biological communities in streams and rivers (SAC, August 31, 2009).” The GSA BBEST chose to use the default HEFR calculation of seasonal base flows in three tiers as the 25th, 50th, and 75th percentile values with association of these percentile values with dry, average, and wet hydrologic conditions, respectively, pending biology overlays. Procedures for determination of hydrologic conditions are described in Section 6.3.

3.2.4.3 High Flow Pulses and Overbank Flows

HFPs provide elevated in-channel flows of short duration, recruitment events for organisms, lateral connectivity, channel and substrate maintenance, limitation of riparian vegetation encroachment, and in-channel water quality restoration after prolonged low flow periods as necessary for long-term support of a sound ecological environment. Overbank flows, a sub-set of HFPs, provide significantly elevated flows exceeding channel capacity, life phase cues for organisms, riparian vegetation diversity maintenance, conditions conducive to seedling development, floodplain connectivity, lateral channel movement, floodplain maintenance, recharge of floodplain water table, flushing of organic material into the channel, nutrient deposition in the floodplain, and restoration of water quality in isolated floodplain water bodies as necessary for long-term support of a sound ecological environment. The GSA BBEST chose to use the frequency, rather than percentile, episodic events method to enhance understanding and potential utility of resulting pulse peak flows, cumulative volumes, and durations. HFPs having frequencies of 2/season, 1/season, 1/year, 1/2-years, and 1/5-years have been calculated and are summarized in the tables in Appendix 3.2-1. The GSA BBEST has chosen not to associate HFP frequencies or tiers with hydrologic conditions. Geomorphology (sediment transport) and riparian vegetation overlays provide additional information regarding the ecological significance of multiple tiers of HFPs.

To quantify recommended episodic event (i.e., HFP and overbank event) volumes and durations, HEFR generates regression equations relating: (1) episodic event volume and peak flow; and (2) episodic event duration and peak flow. Two regression forms are available in HEFR: (1) ln/ln; and (2) quadratic. Because of natural variability and the imprecision of dissecting flow patterns into flow components (and associated ecological functions), there is scatter in the data in these regressions. Past experience has shown that the ln/ln regression often provides a reasonable fit and rarely provides an unacceptable fit, whereas the quadratic equation often provides a reasonable fit, but also can generate results that are far removed from the data in the vicinity of a particular peak flow recommendation. Accordingly, HEFR was run using the ln/ln regression form for both volume and duration. Collectively, Dan Opdyke and Sam Vaugh briefly examined each regression (16 gages × 2 periods of record × 11 events × 2 regressions (volume and duration) = 704 regressions) with the intent of identifying any regressions where the best-fit line is outside of the range of the data in the vicinity of each peak flow recommendation. Only two unacceptable regressions were identified: (1) for the Guadalupe River at Comfort full period of record results, the overbank (1 per 5 year event) volume was biased high and a volume of 100,000 ac-ft is recommended; (2) for the Medina River at Bandera full period of record results, the overbank (1 per 5 year event) volume was biased high and a volume of 50,000 ac-ft is recommended. These adjustments are reflected in the flow regime recommendations summarized in Section 6.1.

As parameterized by the GSA BBEST, the MBFIT hydrographic separation method does not distinguish multiple episodic events when flows are consistently above the 75th percentile of all flows. Such a distinction can be achieved in HEFR using the multipeaks multiplier option. For all runs, the multipeaks multiplier option was set to 1.5. This means that once the daily flow in an episodic event drops off of an initial peak, any subsequent day during that event when the flow increases by 50% from one day to the next causes the termination of the current episodic event and a new episodic event is initiated immediately. In this way, extended wet periods characterized by multiple storm events can be reasonably split into discrete events for HEFR statistical computations.

3.2.5 Initial Hydrology-Based Flow Regimes

Pursuant to an October 14, 2010 consensus decision of the GSA BBEST, initial hydrology-based flow regimes with which we began the ecological overlay process were based on the full period of record. These flow regimes are included, along with those for the early and late sub-periods of record, in Appendix 3.2-1. Comprehensive HEFR and hydrographic separation analyses are included in Appendix 3.2-3.

3.3 Biology Overlay

3.3.1 Description of Methodologies and Assumptions

3.3.1.1 Natural Flow Paradigm

The guiding principle applied to the Guadalupe-San Antonio BBEST's instream flow analyses and associated methodologies is the concept of the 'Natural Flow Regime,' which is founded on the theory that the integrity of flowing water systems depends largely on their natural dynamic character (Poff et al. 1997). The Instream Flow Council, an organization that represents the interests of state and provincial fish and wildlife management agencies in the United States and Canada dedicated to improving the effectiveness of their instream flow programs, has adopted this principle as a cornerstone of riverine resource stewardship (Annear et al., 2004; Locke et al., 2009). The natural flow regime was also a central principle for the scientific basis of the Texas Instream Flow Program (TIFP) as well as the associated technical approaches for quantification of instream flows (TIFP 2008). Both the conceptual foundation and technical approaches proposed by the TIFP were critically reviewed by the National Academy of Science National Research Council's *Committee on Review of Methods for Establishing Instream Flows for Texas Rivers* (NRC 2005). The committee soundly supported the underpinnings of the natural flow regime as the scientific basis of the program as well as concurring with the breadth of technical approaches identified for addressing instream flow needs within Texas and at a national level.

The paradigm of the natural flow regime relates five critical components of flow characteristics that are known to regulate ecological processes in river ecosystems: the magnitude, frequency, duration, timing, and rate of change in flow (Poff and Ward 1989, Richter et al. 1996, Walker et al. 1995, Annear et al. 2004, NRC 2005, Locke et al. 2009). The five components represent attributes of the entire range of flows, such as floods or low flows. The flow regime is the master variable of central importance in sustaining the ecological integrity of flowing water systems (Poff and Ward 1989). Ecological integrity is defined as *"The ability to support and maintain a balanced, integrated adaptive assemblage of organisms having species composition, diversity, and functional organization comparable to that of natural habitat of the region"* (Karr and Dudley 1981, Karr et al. 1986). The five components of the flow regime influence ecological integrity both directly and indirectly, through their effects on other primary regulators of ecosystem integrity (Figure 3.3-1). Therefore, modification of any of the components of the flow regime can have cascading effects on the ecological integrity of rivers.

Aquatic biota have life history strategies that have been adapted to these flow regime characteristics that include such things as initiation of migration or spawning that is cued to changes in the seasonal flow regime, and they generally respond differentially to low, base, and high flow components of the flow regime. The annual (and inter-annual) variations of the flow regime are directly and indirectly linked as key determinants of aquatic community structure and stability (Poff and Ward 1989, Poff et al. 1997, Richter et al. 1996, Dilts et al. 2005). Alteration of the natural flow regime has been documented to modify the ecological function and overall characteristic of the ecosystem in riverine habitats throughout the world (Bunn and Arthington 2002, Postel and Richter 2003, Poff and Zimmerman 2009, Robinson et al. 1998, Tyus et al. 2000).

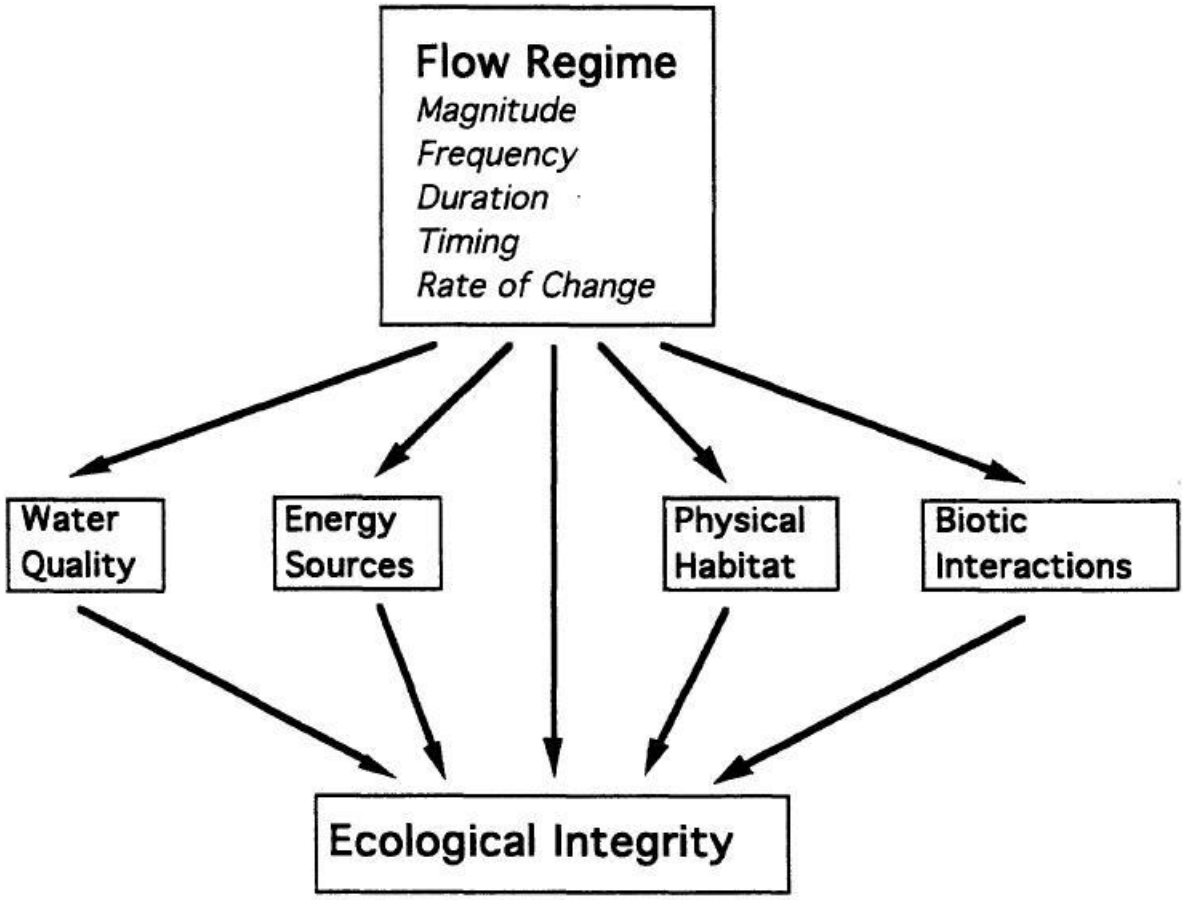


Figure 3.3-1. The five components of the natural flow regime that directly and indirectly affect the ecological integrity of river ecosystems (adapted from Poff et al. 1997).

3.3.1.2 Quantification of Flow Regime Components

Excellent reviews of instream flow approaches in the United States can be found in Reiser et al. (1989), EPRI (1986), Gore (1989), and Hardy (1998). Annear et al. (2004) and NRC (2005) synthesize additional work over the past decade and elucidate the multidisciplinary philosophies and application level challenges associated with the assessment of instream flows. A broader view of the status and future directions of instream flow science at the international level can be found in Harby et al. (2004). This later effort reviews the existing status of instream flow science used throughout the European Union and is comprehensive in its coverage of sampling, hydrology, hydraulic, water quality, temperature, and aquatic habitat modeling approaches. Methods developed for assessing habitat availability vary in data requirements, cost, predictive ability, legal defensibility, and biological realism (Annear et. al. 2004). While some methods require rigorous, site-specific data collection and computer modeling, others rely more heavily on simplified approaches such as application of summary hydrologic-based statistics. Although the application of rigorous site-specific methodologies typically occurs for high-intensity instream flow studies, many management objectives can be achieved with less intensive efforts, especially for early project screening or broad level watershed planning (Stalnaker et al. 1995, NRC 2005).

Several widely applied screening methods allow practitioners to estimate flow requirements with no, or a minimum of, field-data collection efforts such as the Tennant Method and the New England Aquatic Base Flow method (Annear et al. 2004). Many of these approaches, however, vary in their ability to integrate or relate site-specific data with biological criteria in the assessment process. Some recent efforts to develop alternative methodologies for habitat assessment can be found in Jowett (1990, 1992, 1998), Lamouroux, Capra, and Pouilly (1996), and Annear et al. (2004).

While physical habitat modeling has a long track record of application to impact assessments in riverine systems, it is not without limitations. Intense data collection and analysis requirements have typically limited its application to those studies where legal, institutional, or political sensitivities are high (Annear et al. 2004). Some have criticized physical habitat modeling approaches for lacking biological realism (Orth 1986) and for not properly representing the pertinent biological mechanisms important in river ecosystems (Mathur et al. 1985). Despite criticisms, the analytical approach and the resultant flow recommendations have proven defensible (Beecher et al. 1993, Cavendish and Duncan 1986, Gore and Nestler 1988, Jowett 1992) and a critical element of state-of-the-art instream flow programs (NRC 2005).

Based on the recommendation of the NRC (2005), and consistent with Maidment et al. (2005), the SAC (2009) led the development of the HEFR Methodology. HEFR relies on a framework that quantifies key attributes of four components of the flow regime intended to support a sound ecological environment. These instream flow regime components are: subsistence flows, base flows, HFPs, and overbank flows (SAC 2009). For each of these flow regime components, HEFR was designed to assist in characterizing their attributes in terms of magnitude, volume, duration, timing, frequency, and in conjunction with IHA or MBFIT, the rate of change. HEFR results are then integrated with overlays of biology that include fisheries (i.e., physical habitat) and riparian components as well as overlays of water quality and geomorphology. A description of the ecological function of these flow components can be found in Richter et al. (2006), Richter and Thomas (2007), TIFP (2008) and SAC (2009).

Flow regimes vary over time from between specific seasons to even decadal periods (or longer) in response to larger scale spatial and temporal patterns of climatic variability (i.e., precipitation and temperature). This variation is in response to such factors as the shorter term El Nino and La Nina conditions that comprise the El Nino/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), which is an ENSO-like pattern of climate variability affecting both the tropics and the north pacific and North American regions but which varies on a much longer time scale than ENSO. These variations lead to flow regimes that are often characterized as drought, normal and wet hydrologic conditions. This is important ecologically in terms of overall aquatic community dynamics that naturally exhibit variability in response to these very different hydrologic conditions. For example, a low base-flow regime might provide favorable conditions for species that inhabit slow shallow habitats at the expense of deep fast water species while conversely at a high base-flow regime the opposite would occur. At the extreme, a single base-flow regime could result in the complete loss of a specific component of the aquatic community because there is no longer the necessary variability within the flow regime that provides favorable conditions for its life history requirements. This range in variability is accommodated for within the HEFR-based analyses, which can partition the base flow component of the flow regime into low, medium, and high states.

3.3.1.3 Linking the Hydrologic Regime to Riverine Habitat

Physical heterogeneity of riverine systems influences species richness and abundance (Thienemann 1954, Hynes 1970, Vannote et al. 1980, Elwood et al. 1983, Ward 1989). Furthermore, in riverine systems, the physical habitat structure (microhabitat and mesohabitat scales) is one of the critical factors that determine the distribution and abundance of aquatic organisms. In general, as spatial heterogeneity increases at the scale of aquatic organisms, there is greater microhabitat and hydraulic diversity that leads to greater biotic diversity. This variability in physical habitat from the microhabitat to mesohabitat scales is primarily derived from the physical processes of flow and sediment both within the channel as well as the lateral connectivity of floodplain habitats. The diversity and availability of these habitats are in turn maintained by variability in the flow regime and is a key process in the evolutionary response of aquatic species life history traits that allow them to exploit this variable and dynamic habitat mosaic. In many instances, the successful completion of various life history requirements requires use of different habitat types. For example, spawning and egg incubation may occur in riffles (turbulent velocities in conjunction with appropriate substrate sizes); upon hatching, the fry move to the slow side margins of the stream, while non-spawning adults may primarily inhabit deep pools. This variability in space and time of the habitat mosaic directly (or indirectly) influences the distribution and abundance of riverine species as well as overall ecosystem function (Poff and Allan 1995, Schlosser 1990, Sparks 1992, Stanford et al. 1996).

Several investigators have quantified the range of conditions and resources that various riverine fishes inhabit, particularly with respect to depth and velocity, throughout North America (Lobb and Orth 1991, Aadland 1993, Bain et al. 1988, Bowen et al. 1998) and in Texas (Bean et al. 2007; Leavy and Bonner 2009; Kollaus and Bonner, Accepted pending revision). They have identified species and life-stage habitat guilds that use the gradients of depth and velocity in a similar manner. Guilds typically use a set of environmental conditions or resources similarly, but typically differ in the temporal or spatial use of these resources or differ along other niche dimensions to coexist (i.e., food utilization). Because stream flow is one of the key factors that controls the temporal and spatial availability of stream hydraulics (interaction of depth and velocity), substrate, cover, food, and, to a lesser extent, temperature (e.g., Statzner 1986), stream flow within a given river system controls the abundance and diversity of physical habitat and ultimately the diversity of species that can exist. Ecological flow regimes are aimed at maintaining the natural diversity of habitats (i.e., riffles may only represent 7% of available habitat types) rather than the often false assumption that flow regimes should optimize diversity. Optimizing habitat diversity is not the same as maintaining habitat diversity, which is required to maintain ecological integrity of aquatic ecosystems. One method of quantifying the effects of stream flow on riverine biota is to quantify the quantity and quality of habitat types (types inhabited by typical riverine fish guilds) versus flow (e.g., Aadland 1993, Bowen et al. 1998, BIO-WEST 2008a). These relationships, particularly for key bottleneck habitats that may affect, for example, recruitment of fishes at various times of the year (e.g., nursery habitat), can be used to identify stream flows that maintain habitats for a diversity of species and life stages (Bain et al. 1988, Scheidegger and Bain 1995, Nehring and Anderson 1993).

In addition, fish use different microhabitats (depth, velocity) in different mesohabitats (pools, riffles, eddies) (Jackson 1992, Moody and Hardy 1992) and use different microhabitats at different flows (e.g., Shrivell 1994). They also use different habitats depending on localized predation threats (e.g., Powers 1985; Schlosser 1982), during different seasons (e.g., Baltz et al. 1991), during different parts of a day (night vs. day) and life stages (Williams 2011). Fish swimming capabilities change with temperature (Brett and Glass 1973, Smith and Li 1983, Addley 1993) and the velocities that they use is dependent on temperature. Temperature in rivers varies dramatically between seasons, within seasons, and daily; therefore, habitat use varies on these same time scales. What these studies underscore is the importance of maintaining the range of flow variability inherent in the natural flow regime to ensure the full complement of habitat diversity is available over spatial and temporal scales necessary to support a sound ecological environment.

3.3.2 Development of Habitat Guilds and Selection of Focal Species

As a first step in defining the linkage between the aquatic resources and the physical habitat mosaic at each quantification site, the Instream Flow Workgroup developed a framework for evaluating potential target focal species and defining preliminary habitat guilds within the basin. The framework is based on classification of the physical habitat across a gradient of depth and velocity to derive five primary riverine habitat types or guilds as a starting point as described below:

- Riffle
- Deep Run
- Shallow Run
- Deep Pool
- Shallow Pool

Published literature on fish distribution and status within the basins were reviewed as a starting point for selection of draft focal species and associated draft habitat guilds (Leavy and Bonner 2009). The team also considered other target aquatic organisms such as mussels, macroinvertebrates, etc., but concluded that protection of the habitats related to fish use would implicitly protect these other organisms. The team also discussed other factors such as causative mechanisms for observed trends and their relative significance. Other considerations included distribution, status, trophic position, reproductive strategies, sensitivity to flow regime changes and/or water quality, etc. Selection of the draft focal species also considered their suitability for use in monitoring responses at the fish community level under an adaptive environmental monitoring and management program.

3.3.3 Habitat Guild Suitability in terms of Physical Habitat Attributes

3.3.3.1 Habitat Suitability Criteria (HSC)

Habitat suitability criteria (HSC) generated from fish observations in a river system are typically used to quantify the range of suitable depth, velocity, and substrate for target species and life stages. However, generation of suitability criteria is fraught with many difficulties. Some of the most serious of these are logistics constraints affecting the size, timing, and quality of the sample data. This includes biases in habitat availability, predation/competition, low abundance, sampling gear bias, etc. As a result, even though it is generally known that fish habitat use changes with fish size, season, temperature, activity, habitat availability, presence and abundance of competitors and predators, discharge, and changes between years (Orth 1987, Shrivell 1989, Heggenes 1990, Shrivell 1994, Smith and Li 1983, Bozek and Rahel 1992, Everest and Chapman 1972, Moore and Gregory 1988, Modde and Hardy 1992) practical data collection constraints dictate that suitability criteria are generated from a finite number of fish observations over a small range of conditions. Typically, data are collected for a discrete range of fish sizes (e.g., fry), during one or two seasons, in a range of different habitat types and at the flows, fish densities, predator and competitor densities, and temperatures available in the river at the time of sampling. These data are then lumped together to create, for example, fry suitability criteria. These data are only an approximation of the gradient of suitable depths, velocities, and substrates useable by fry. Some investigators who have dealt with the problems outlined above have suggested that "envelope curves" are a practical solution. An "enveloping" suitability curve (envelope curve) is created around the HSC of the representative species for use in modeling to represent the entire habitat guild. Bozek and Rahel (1992) found differences in the suitability and preference criteria (corrected for habitat biases) of young cutthroat trout between years and between rivers. They found that composite envelope curves (combining data from rivers and years) provided a practical solution for representing the gradient of usable depth and velocity. Jowett (1991) found that using enveloped suitability criteria from four rivers preformed almost as well as stream-specific criteria, and very much better than functions developed at one river and applied to another. Based on Jowett's data, he advocated the use of generalized envelope criteria. Now, properly defined envelope curves appear to be one of the most practical approaches for describing the gradients of depth, velocity, and substrate of species/life stages where robust, high quality (properly developed) site-specific data are not available.

To protect the integrity of the aquatic system, the needs of the entire aquatic community should be considered. In diverse, warm-water systems such as the Guadalupe and San Antonio river basins, flow-habitat relationships would need to be developed for many species and potentially different life stages of species, complicating the analysis and interpretation of a multitude of flow-habitat curves. To simplify interpretation of these relationships (e.g., reducing the number of response variables), habitat guilds—group of species using similar habitats—are used to represent the diversity of mesohabitat types found in the streams and rivers in a basin. Habitat guilds also allow for the representation of rare species or species for which no habitat suitability data is available. Because of these reasons, many recent instream flow assessments have used habitat guild-based criteria as input to physical habitat-based assessments of instream flows (Leonard and Orth 1988, Vadas and Orth 2001, Lamouroux and Souchon 2002, BIO-WEST 2008, Persinger et al. 2010; and others). HSC for each guild were developed using an envelope curve approach based on individual relationships of depth, velocity, and substrate of species-specific curves.

3.3.3.2 Selection of Final Focal Species and Habitat Guilds

To begin the process, the Instream Subcommittee of the GSA BBEST a priori assigned selected fish species to represent habitat guilds based on available historical fish assemblage lists as noted above, known life-history information, and expert opinion (Table 3.3-1). In subsequent discussions with the BBEST, it was decided that the habitat guilds by basin would be collapsed, where all the fishes representing a habitat guild for each basin would be combined into one habitat guild to simplify interpretation. Not enough data in the compiled database were available to develop HSC for greenthroat darter and roundnose minnow and were excluded from further analysis. Given that Guadalupe darter *Percina apristis* had until recently been considered synonymous with dusky darter *Percina sciera*, dusky darter habitat data were used to supplement Guadalupe darter habitat data. Similarly, all available data for *Macrhybopsis* species were used to develop HSC for burrhead chub *Macrhybopsis marconis*.

Table 3.3-1. Guadalupe-San Antonio BBEST initial focal species list and guilds.

Habitat Guild	Upper Guadalupe River	Lower Guadalupe River	San Antonio River	San Marcos River	Blanco River
Pool	bluegill largemouth bass river carpsucker	white crappie blackstripe topminnow largemouth bass smallmouth buffalo river carpsucker	white crappie pugnose minnow largemouth bass smallmouth buffalo river carpsucker	bluegill largemouth bass river carpsucker	bluegill largemouth bass river carpsucker
Shallow Run	roundnose minnow Texas shiner mimic shiner	ghost shiner mimic shiner	burrhead chub central stoneroller mimic shiner	roundnose minnow Texas shiner mimic shiner	Texas shiner mimic shiner
Shallow Riffle	greenthroat darter Texas logperch	Guadalupe darter Texas logperch	Texas logperch central stoneroller	Guadalupe darter Texas logperch	orangethroat darter central stoneroller
Deep Run	burrhead chub gray redhorse channel catfish Guadalupe bass	burrhead chub gray redhorse channel catfish	burrhead chub gray redhorse channel catfish	burrhead chub gray redhorse channel catfish	burrhead chub gray redhorse channel catfish Guadalupe bass

3.3.3.3 Habitat Suitability Curve Development

Once the initial focal species were partitioned into habitat guilds, available data and published literature on habitat use were utilized to develop guild specific HSC which are used to evaluate the effect of stream flow changes on the available habitat to a species or group of species with the use of flow-habitat models. To protect the biological integrity of the aquatic system, the needs of the entire aquatic community have to be considered, though HSCs may not be available for many species. One solution to this problem is the use of habitat guilds (Persinger et al. 2010), where the HSC for multiple species are used to represent a mesohabitat type (e.g. shallow run

guild), which allows for the inclusion of rare species or species for which no data are available. Once habitat guilds and species are defined, an envelope curve is then created around the HSC of the representative species for use in modeling to represent the entire habitat guild.
Draft habitat suitability curves developed for the LSAR SB2 studies were provided and used for all analyses at the LSAR study sites where habitat versus flow relationships were generated. As noted below, the underlying data for these curves in conjunction with a broader database of available fisheries collection data were used to generate GSA Habitat Guild envelope suitability curves for application at all other sites where habitat versus discharge relationships were generated. Transfer of site-specific suitability curves (i.e., LSAR guild curves) are not advised without transferability tests to each new site, which was beyond the scope and time available for the GSA BBEST.

TPWD and BIO-WEST, Inc. staff compiled existing fish abundance-habitat association data from a number of studies conducted in Texas rivers and streams to develop species-specific HSCs. Although individual study goals may have differed, collections were targeted that sampled fishes in relatively homogeneous patches of habitat and measured velocity, depth, substrate and other habitat conditions. Sources included Texas Instream Flow Program (TIFP) baseline fish sampling from the middle and lower Brazos, lower San Antonio, and lower Sabine rivers conducted between 2006-2008, unpublished TIFP fish habitat suitability samples from the LSAR and lower Cibolo Creek conducted during 2009-2010, Blanco River data from a recent Master's thesis (Littrell 2006), and data from studies in the upper (BIO-WEST 2009) and lower Colorado River (BIO-WEST 2008a) as well as studies on the LSAR (BIO-WEST 2008b) and its tributaries (BIO-WEST 2008c). In addition to providing a robust dataset, compiling collections from these river systems increased the data available for rare/under-sampled species supporting development of HSC for those species. In total, 1,338 fish abundance-habitat data points covering a broad range of systems, habitats, and flow conditions were used to develop species-specific HSC.

Habitat data for each species were combined to generate frequency histograms for the continuous variables depth and velocity and divided into equal increments for depth and velocity. HSC were then created using nonparametric tolerance limits (NPTL) based on the central 50%, 75%, 90%, and 95% of the data (Bovee 1986) at the 0.95 confidence level. Tolerance limits for the central 50% of the data were used as cutoffs for the most selected habitat and the range of data between these two points was given a suitability of one. Data between the 50% tolerance limits and the 75% tolerance limits was given a suitability of 0.5. Data between the 75% tolerance limits and the 90% tolerance limits was given a suitability of 0.2, and the data between the 90% tolerance limits and the 95% tolerance limits received a suitability of 0.1. The data beyond the 95% tolerance limits was considered unsuitable and given a suitability of zero. 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 to the most utilized substrate.

With the species-specific HSCs developed, the next step in the process was to plot the depth, velocity, and substrate HSCs for each species in each habitat guild. Plotting was facilitated by the use of the HSC Development Tool (HSC Tool) software package authored by Dr. Thom Hardy (River Systems Institute, Texas State University – Appendix 3.1). The HSC Tool was utilized to visually represent HSCs for each species in each habitat guild allowing determination of the species fit in the habitat guild (similar depth/velocity preferences) or if some species needed to be moved to another guild (dissimilar depth/velocity preferences). Changes to the habitat guilds are summarized below and are reflected in the final habitat guilds (Table 3.3-2) used for envelope curve development. It should be noted that inclusion, removal, or movement of specific species between guilds adhered to known life history requirements, field based observations throughout the basin and the desire to provide the most quantitative assessment of the underlying guild envelope suitabilities. In reviewing the final envelope curves it should also be noted that in some instances, the depth suitabilities were extended over an indefinite upper depth limit. This is common practice in suitability curve development that recognizes gear bias, sampling limitations, and known biological traits that indicate there are no physiological or behavioral limits to depth use. The suitability value associated with the extended depth ranges is a combination of the available component or underlying suitability curves used to develop the envelope curves and professional judgment. A case in point, is that the GSA BBEST and LSAR habitat guilds for deep pools were both extended, where the GSA BBEST set the suitability at 0.5 and LSAR set it at 0.1) (see Section 3.3.5.2 for an example). We believe the more generic basin wide basis of the GSA BBEST curves clearly support the chosen value while the LSAR curves are more site-specific and therefore are reflective of such site specific factors as existing habitat availability.

Pool - the pool guild was split into shallow pool and deep pool based on species depth suitability criteria. Shallow and deep pool guilds are consistent with recent assessments on the lower Colorado (BIO-WEST 2008a) and LSAR (see 20 December 2010 memo from TIFP and SARA).

Shallow Run - Burrhead chub was removed from this guild based on its depth and velocity suitability. Guadalupe bass was added to this guild based on its depth and velocity suitability.

Shallow Riffle - Central stoneroller was removed from this guild based on its velocity suitability. Burrhead chub was added to this guild based on its depth and velocity suitability.

Deep Run - Burrhead chub was removed from this guild based on its depth and velocity suitability. Guadalupe bass was removed from this guild based on its depth suitability. Smallmouth buffalo was added to this guild based on its depth and velocity suitability.

Table 3.3-2. Final GSA BBEST habitat guilds

Habitat Guild	Guild Focal Species
Deep Pool	largemouth bass smallmouth buffalo white crappie
Shallow Pool	blackstripe topminnow bluegill pugnose minnow river carpsucker
Shallow Run	central stoneroller ghost shiner Guadalupe bass mimic shiner Texas shiner
Riffle	burrhead chub Guadalupe darter orangethroat darter Texas logperch
Deep Run	channel catfish gray redhorse smallmouth buffalo

3.3.3.4 Key Life History Characteristics of Guild Species

For each of the defined habitat guilds, the following species were used to develop species-specific HSC. As noted below, these species-specific HSC were used as the basis to define the overall habitat guild envelope curves. It should be noted that these are not the same as the focal species described in Table 3.3-1, which were selected based on a broad range of criteria that included the consideration of future monitoring under the adaptive management program. The use of the species below was based on the need to estimate the overall hydraulic suitability of the specific habitat guilds based on available quantitative data from fisheries collections. The species were selected based on species' historic and current abundance and having sufficient information available to be considered in the quantitative habitat-based analysis. Species were combined into groups to form five habitat guilds. Species-specific life history information is derived from the Texas Freshwater Fishes website (http://www.bio.txstate.edu/~tbonner/txfishes/index.htm).

Deep Pool Guild

Largemouth bass *Micropterus salmoides*

Occurs throughout central and eastern North America and statewide in Texas. Populations are stable and managed as a recreational fishery. Inhabits shallow to deep pools and run habitats, often associated with cover. Life span is up to 10 years, females become sexually mature at > 250 mm Total Length (TL), and reproductive season is from late winter through early spring. Diets consist of aquatic insects, crustaceans, and fish.

Smallmouth buffalo *Ictiobus bubalus*

Occurs statewide except in the panhandle region of Texas. Populations are stable. Inhabits deep to moderately deep runs and pools with sluggish to moderate current velocities. Life span is up to 18 years, females become sexually mature >450 mm TL (up to age 6), and reproductive season is from March through September. Generally considered benthic invertivore and herbivore.

White crappie *Pomoxis annularis*

Occurs in central North America and statewide in Texas. Populations are stable and managed for recreational fishery. Inhabits deep pools with sluggish current velocities. Life span is up to 10 years, females become sexually mature at age 1, and reproductive season is from March through May. Diets consist of aquatic insects, crustaceans, and fish.

<u>Shallow Pool Guild</u>

Blackstripe topminnow *Fundulus notatus*

Occurs in central North America and from Red River drainage to the Guadalupe River basin in Texas. Populations are stable. Inhabits pools, backwaters, and stream margins with sluggish current velocities. Life span is up to 3 years, females likely become sexually mature at age 1, and reproductive season is from late Spring through Summer. Diets consist of terrestrial insects, gastropods, aquatic insects, and crustaceans.

Bluegill *Lepomis macrochirus*

Occurs in central and eastern North America and statewide in Texas. Populations are stable and managed as a recreational fishery. Inhabits relatively shallow pools with sluggish current velocities. Life span up to 5 years; females become sexually mature at age 1 and reproductive season is from March through September. Diets consist of aquatic insects, crustaceans, and fish.

Pugnose minnow *Opsopoeodus emiliae*

Occurs in central North America and in low gradient streams and tributaries of Texas. Populations are stable, but potentially declining in the San Antonio River (Runyan 2007). Inhabits pools, backwaters, and stream margins with sluggish current velocities. Life span is likely 3 years and reproductive season is from late winter through summer. Diets consist of filamentous algae, crustaceans, aquatic insects, and larval fish.

River carpsucker *Carpiodes carpio*

Occurs in central North America and statewide in Texas. Populations are stable. Inhabits pools with sluggish current velocities and silt to sand substrates. Life span is up 11 years, females become sexually mature by age 3, and reproductive season is spring through summer. Diets consist of benthic organic detritus and associated faunal community (crustaceans, aquatic insects).

Shallow Run Guild

Central stoneroller *Campostoma anomalum*

Occurs throughout central and eastern North America and in most drainages in Texas. Populations are stable. Associated with riffle habitats and cobble substrates in the Blanco River (Bean et al. 2007), but also found in shallow runs with gravel and cobble substrates elsewhere. Life span is up to 4 years, females become sexually mature by age 1 or 2, and reproductive season is from February thought July. Diet consists primarily of algae but also includes aquatic insects and crustaceans.

Ghost shiner *Notropis buchanani*

Occurs throughout central North America and in most drainages of Texas. Populations are stable. Inhabits shallow runs with sluggish to moderate currents over silt substrates. Associated with slackwater habitats in large rivers. Life span is up to 2 years, females become sexually mature at 31 mm TL (age 1), and reproductive season is from May through September (Williams 2011). Diet consists of detritus and aquatic insects in the Brazos River (Williams 2011).

Guadalupe bass *Micropterus treculii*

Occurs naturally in the Edwards Plateau of central Texas, from the Brazos River drainage to the Guadalupe River drainage. Populations are imperiled. Inhabits swift flowing runs and pools over silt to bedrock substrates (Perkin et al. 2010). Often associated with cover-type habitats, including ledges and large woody debris, and avoids open water. Life span is up to 6 years, females become sexually mature by > 125 mm TL (age 1), and reproductive season is from March through June and possibly again in autumn. As with most predatory fishes, diet consists of aquatic insects and crustaceans when young and shifts to piscine prey when older.

Mimic shiner *Notropis volucellus*

Occurs in Texas from the Nueces River to the Sabine River. Populations are stable. Inhabits shallow runs with slit and sand substrates in the Blanco River (Bean et al 2007). Life span is up to 3 years, females become sexually mature at age 1, and reproductive season is from April through August. Diet consists of aquatic insects and crustaceans.

Texas shiner *Notropis amabilis*

Occurs in the Edwards Plateau region of central Texas, from the Colorado River drainage to the Rio Grande drainage. Populations are stable. Inhabits run and flowing pool habitats with sluggish to moderate current velocities. Life span is up to 2 years, females become sexually mature at age 1, and reproductive season is from February through September (Littrell 2006). Diet consists of drifting aquatic insects.

Riffle Guild

Burrhead chub *Macrhybopsis marconis*

Occurs in the Guadalupe River and Colorado basins of Texas. Populations are imperiled (Hubbs et al. 2008) with declining abundances in the upper Guadalupe River, San Marcos River (Perkin and Bonner, In press) and elsewhere. Inhabits riffle habitats with gravel to cobble substrates (Eisenhour 2004). Life span likely is up to two years, and reproductive season is during the summer (April through October in congener *M. hyostoma* in the lower Brazos River; Williams 2011). Diet primarily consists of aquatic insects in congener *M. hyostoma*.

Guadalupe darter *Percina apristis*

Occurs in the Guadalupe River basin of Texas. Populations are imperiled (Hubbs et al. 2008) with declining abundance in the lower Guadalupe River and possible extirpation from the upper Guadalupe River (Perkin 2009; Perkin and Bonner, In press). Inhabits stenothermal run habitats with gravel substrates (Hubbs and Hubbs 1954; Robins and Page 2007). Life span is up to two or three years, females become sexually mature at 53 mm TL (age 1), and reproductive season is from October through June (9 months) in the San Marcos River (Folb 2010). Diet consists of aquatic insects, fish eggs, and plant material (Folb 2010).

Orangethroat darter *Etheostoma spectabile*

Occurs throughout the central North America. Populations are stable. Inhabits riffle habitats with gravel substrates but habitat associations are variable throughout its distribution. Life span is up to two years, females become sexually mature at age-1, and reproductive season is from October through July in Texas.

Texas logperch *Percina carbonaria*

Occurs in the Brazos, Colorado, Guadalupe, and San Antonio rivers of Texas. Populations are stable. Inhabits riffle habitats with gravel to cobble substrates, moderate current velocities, and shallow to moderate depths in Edwards Plateau streams (Shattuck 2010). Life span is up to three years, females become sexually mature at 74 mm TL (age 1), and reproductive season is from December through April (6 months) in the Pedernales River (Folb 2010). Diet consists of aquatic insects, detritus, nematodes, leeches, and fish eggs (Folb 2010).

Deep Run Guild

Channel catfish *Ictalurus punctatus*

Occurs statewide and with stable populations. Most sought after game fish in Texas. Populations are stable. Inhabits sluggish to swift currents with silt through bedrock substrates. Life span is up to 10+ years, females become sexually mature at > 300 mm TL (age 2 to 3), and reproductive season is from late spring to early summer. Generally considered benthic invertivore and carnivore.

Gray redhorse *Moxostoma congestum*

Occurs in the Brazos, Colorado, Guadalupe, San Antonio, Nueces Rivers and Rio Grande of Texas. Populations are stable. Inhabits run to pool habitats with moderate depths and sand to silt substrates in the Blanco River (Bean et al. 2007). Life span is up to five years and likely much longer, females become sexually mature at 260 mm TL (age 1), and reproductive season is from late February through early May with adults likely spawning during a few day period and at least two distinct clutches are produced (Bean and Bonner 2008). Diet consists of benthic invertebrates, including aquatic insects and mollusks (Bean and Bonner 2008).

Smallmouth buffalo *Ictiobus bubalus*

Occurs statewide except in the panhandle region of Texas. Populations are stable. Inhabits deep to moderately deep runs and pools with sluggish to moderate current velocities. Life span is up to 18 years, females become sexually mature >450 mm TL (up to age 6), and reproductive season is from March through September. Generally considered benthic invertivore and herbivore.

3.3.3.5 Development of Guild Specific Habitat Suitability Curves

Envelope curves for each habitat guild are presented in Figures 3.3-2 through 3.3-6 and the corresponding tabular values are provided in Table 3.3-3. Depth, velocity, and substrate suitability curves were plotted for the individual species representing each guild. Using the HSC Tool, envelope curves were drawn to reflect the range of depth and velocity used by all species included in the guild. An envelope curve did not necessarily encompass or enclose the full range of each parameter. Based on Instream Flow Workgroup guidance, the minimum depth for each habitat guild was constrained by at least 1.5 times the body depth of the deepest-bodied species to support fish passage and current velocity was checked against a potential maximum swimming velocity (i.e., 4-6 times the TL of the smallest fish in the guild); no adjustments in velocity criteria were needed. Further, the depth envelope curves for deep pool, shallow pool, and deep run guilds were extended beyond the available data, given the characteristics of these habitats, the known life history information available for deep-habitat species (e.g. 20 ft depths should be suitable for deep pool species although the available data only covered depths to around 15 ft) and sampling bias in deep pools (i.e., difficulty in quantitatively sampling deep water habitats). Specifically, for deep-water habitats, the tail of the depth criteria was extended at 0.5 suitability, and for the tail of the shallow pool depth criteria a suitability of 0.2 was used.

Suitability values for substrate classes were also assigned for each guild. A constraint in application of the HSC in the Comparative Cross section Method (CCM described below) required standardization of codes between existing fisheries collection data and substrate classifications within the CCM reference database (Table 3.3-3). To accomplish this standardization, clay and silt HSCs were combined into one class (clay/silt); the greatest value of the two was chosen for each species. Six substrate classes were used in this analysis: clay/silt, sand, gravel, cobble, boulder, and bedrock. The substrate class with the greatest suitability across all species in a guild was set to 1.0 and the remaining substrate types were normalized. However, a minimum value of 0.1 was used for substrates with any defined suitability greater than 0.0.

To validate guild membership and to look for potential problems or outliers in the range of depth and velocity criteria, final envelope curves were compared to species data collected to date (January 3, 2011) from the online survey of fish experts being conducted by TPWD and Texas State University (http://rsi-db.its.txstate.edu/fishhabitatsurvey/). No adjustments were necessary based on this information.

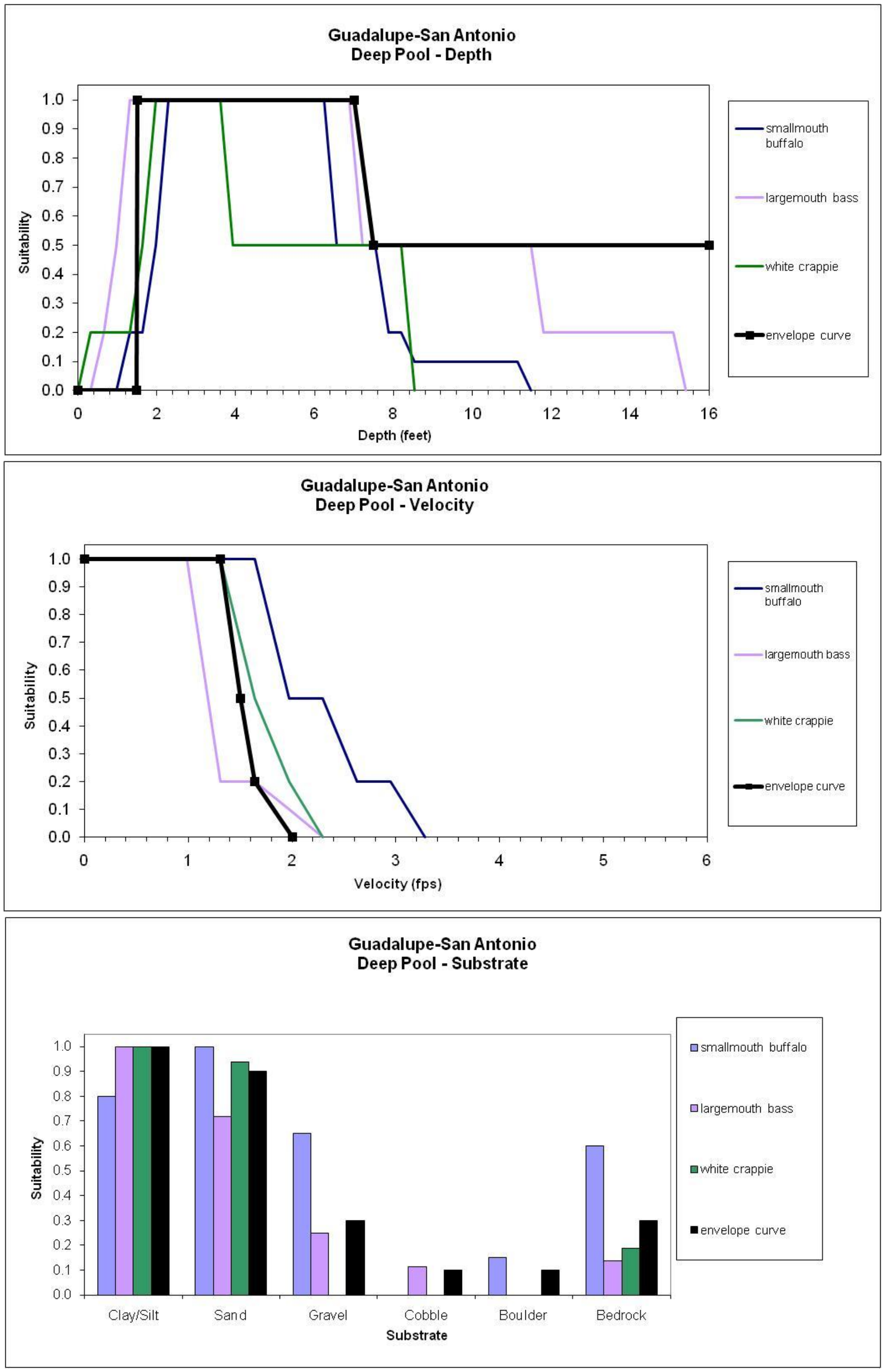


Figure 3.3-2. Envelope and species-specific habitat suitability curves for Guadalupe-San Antonio fish in the Deep Pool habitat guild.

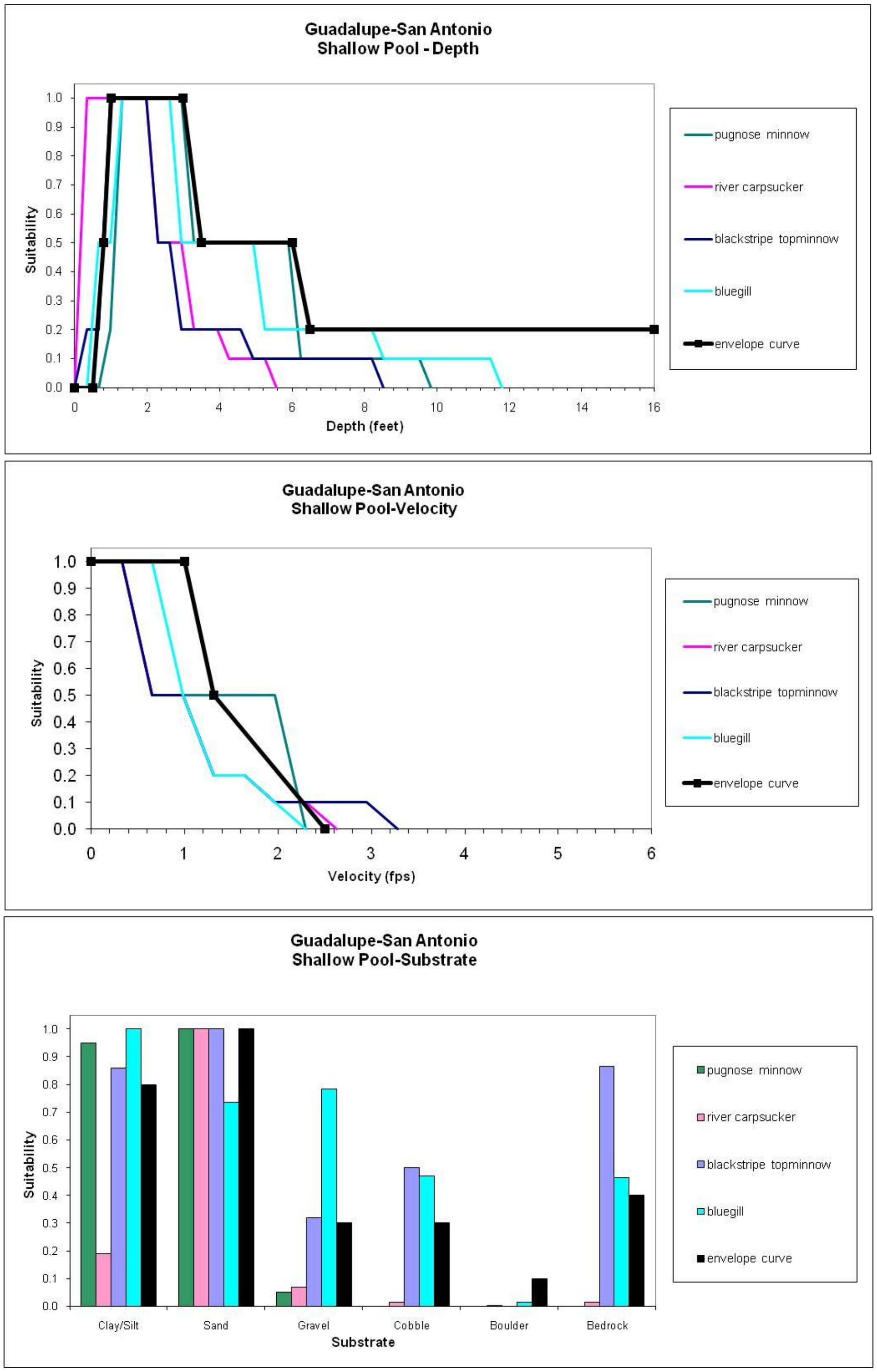


Figure 3.3-3. Envelope and species-specific habitat suitability curves for Guadalupe-San Antonio fish in the Shallow Pool habitat guild.

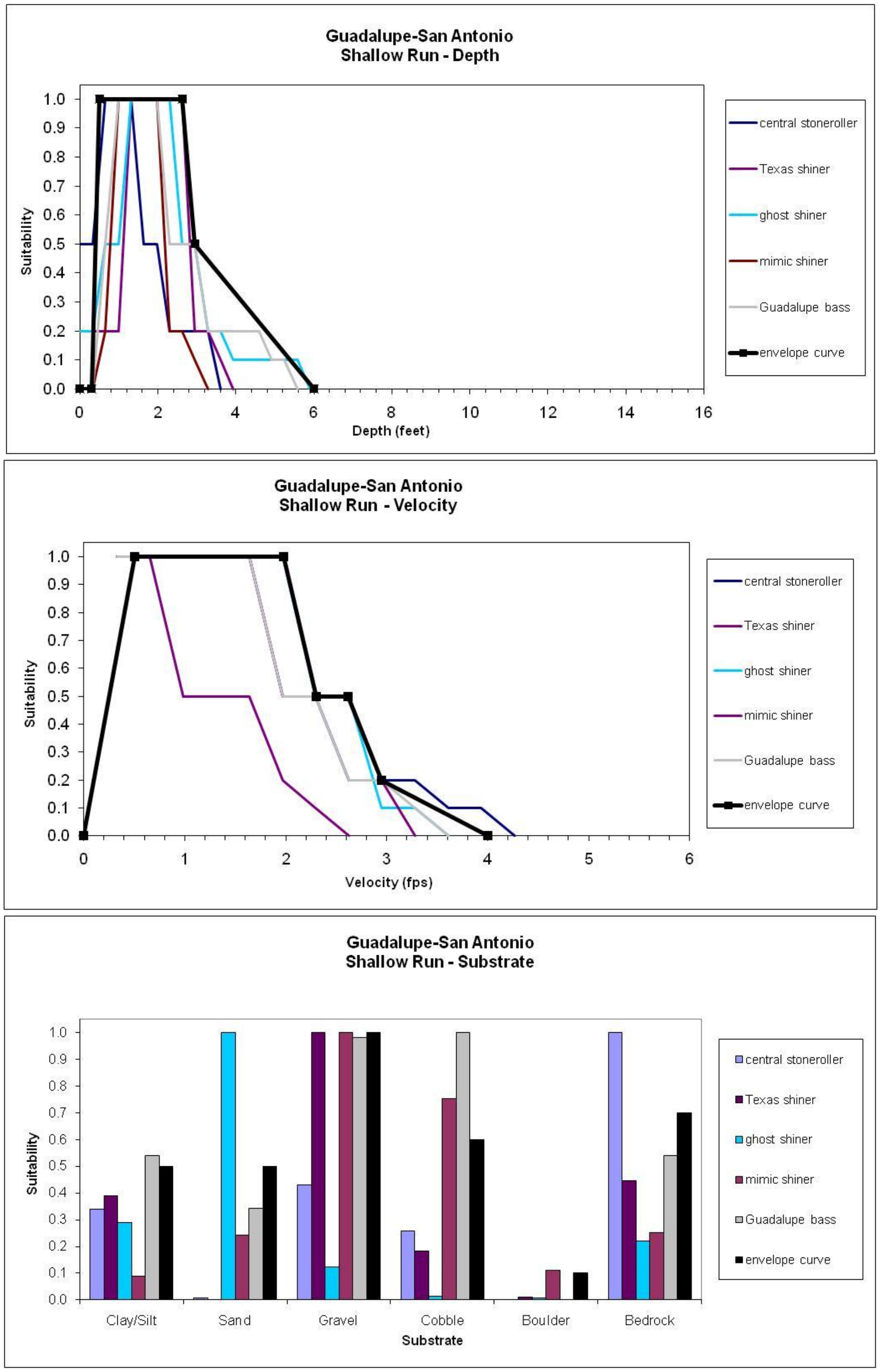


Figure 3.3-4. Envelope and species-specific habitat suitability curves for Guadalupe-San Antonio fish in the Shallow Run habitat guild.

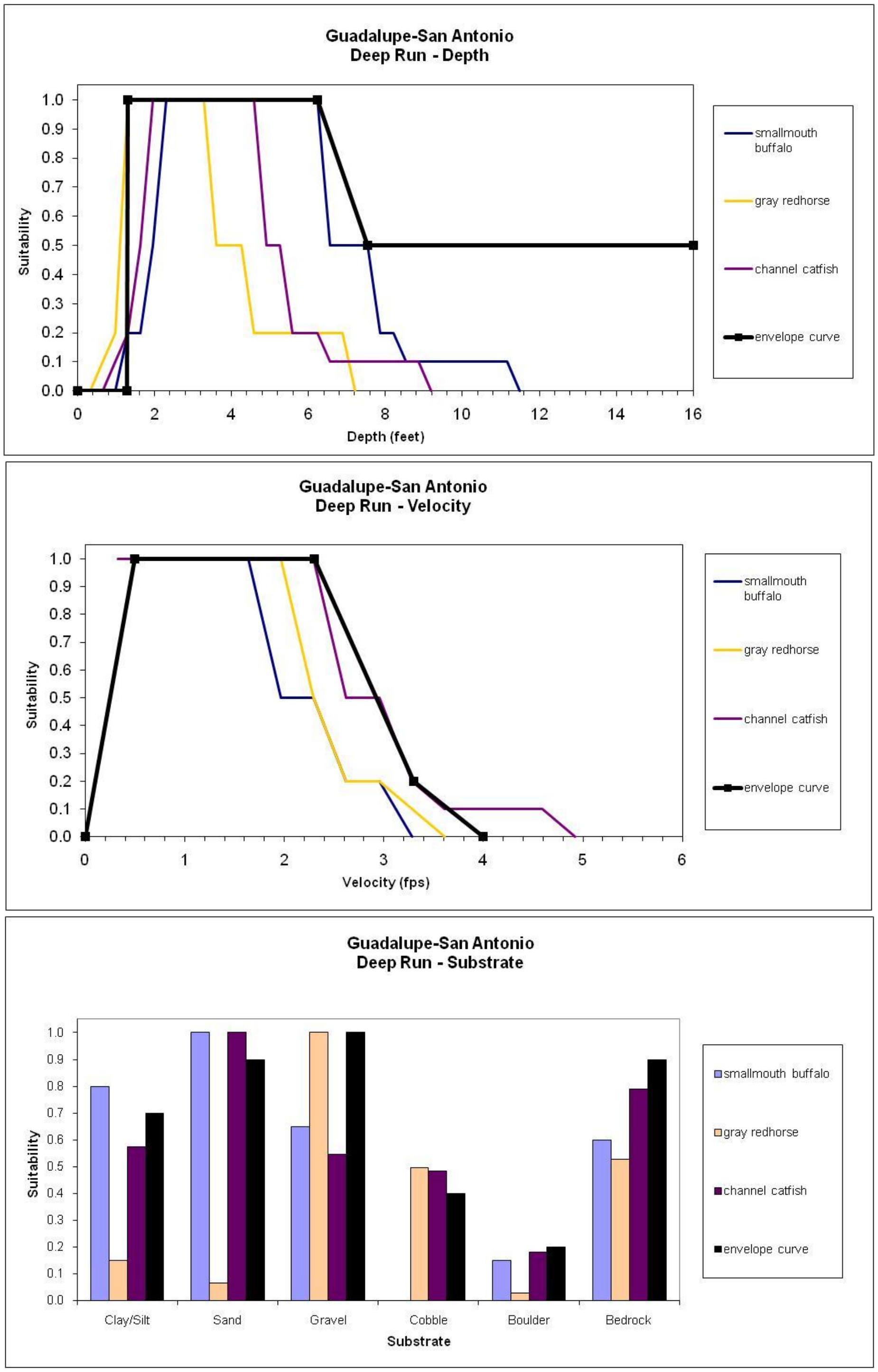


Figure 3.3-5. Envelope and species-specific habitat suitability curves for Guadalupe-San Antonio fish in the Deep Run habitat guild.

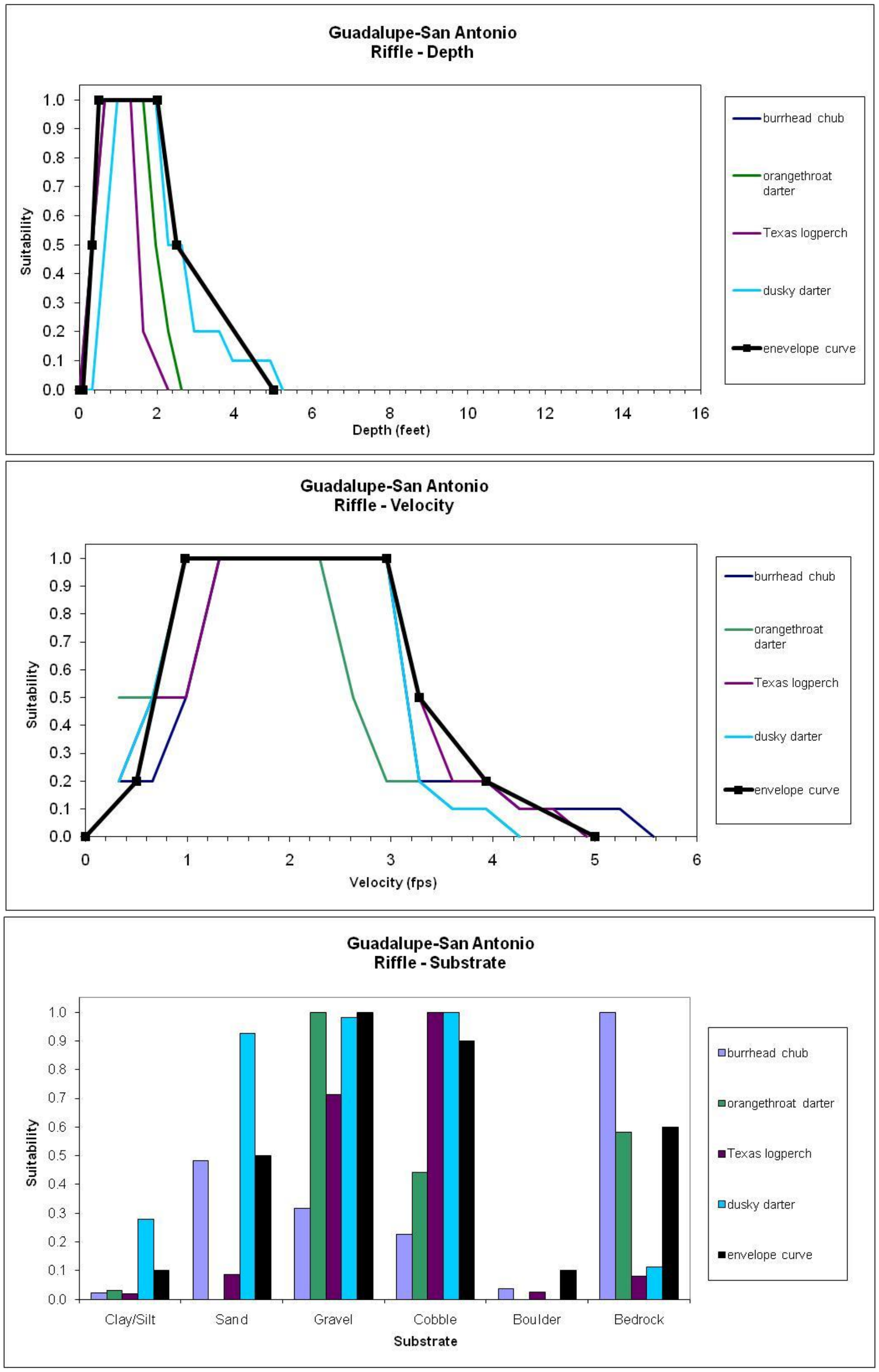


Figure 3.3-6. Envelope and species-specific habitat suitability curves for Guadalupe-San Antonio fish in the Riffle habitat guild.

Table 3.3-3. Guadalupe-San Antonio habitat suitability envelope curve values for depth (feet), velocity (f/s) and substrate. See Table 3.3-4 for substrate code definitions. Substrate codes 1, 5 and 9 are not used for this application and set to zero.

Deep Pool		Shallow Pool		Shallow Run		Deep Run		Riffle	
Velocity (f/s)	Suitability	Velocity (f/s)	Suitability	Velocity (f/s)	Suitability	Velocity (f/s)	Suitability	Velocity (f/s)	Suitability
0.00	1.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
0.10	1.00	1.00	1.00	0.50	1.00	0.50	1.00	0.50	0.20
1.31	1.00	1.30	0.50	2.10	1.00	2.30	1.00	1.00	1.00
1.50	0.50	1.50	0.20	2.60	0.50	3.00	0.50	3.00	1.00
1.64	0.20	2.50	0.00	3.00	0.20	3.30	0.20	3.30	0.50
2.00	0.00			4.00	0.00	4.00	0.00	4.00	0.20
								5.00	0.00
Depth (feet)	Suitability	Depth (feet)	Suitability	Depth (feet)	Suitability	Depth (feet)	Suitability	Depth (feet)	Suitability
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.49	0.00	0.50	0.00	0.30	0.00	1.00	0.00	0.09	0.00
1.50	1.00	0.51	1.00	0.50	1.00	1.10	0.20	0.33	0.50
7.00	1.00	3.00	1.00	2.50	1.00	1.50	0.50	0.50	1.00
7.50	0.50	3.50	0.50	3.00	0.50	1.60	1.00	2.00	1.00
25.00	0.50	6.00	0.50	6.00	0.00	6.40	1.00	2.50	0.50
		6.50	0.20	20.00	0.00	7.50	0.50	5.00	0.00
		20.00	0.20			20.00	0.50		
Substrate	Suitability	Substrate	Suitability	Substrate	Suitability	Substrate	Suitability	Substrate	Suitability
1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00
2.00	1.00	2.00	0.80	2.00	0.50	2.00	0.70	2.00	0.10
3.00	0.90	3.00	1.00	3.00	0.50	3.00	0.90	3.00	0.50
4.00	0.50	4.00	0.30	4.00	1.00	4.00	1.00	4.00	1.00
5.00	0.00	5.00	0.00	5.00	0.00	5.00	0.00	5.00	0.00
6.00	0.10	6.00	0.30	6.00	0.60	6.00	0.40	6.00	0.80
7.00	0.10	7.00	0.10	7.00	0.10	7.00	0.20	7.00	0.10
8.00	0.30	8.00	0.40	8.00	0.70	8.00	0.90	8.00	0.60
9.00	0.00	9.00	0.00	9.00	0.00	9.00	0.00	9.00	0.00

Table 3.3-4. Guadalupe-San Antonio habitat suitability envelope curve substrate code definitions. Note that substrate codes 1, 5 and 9 are not used for this application and set to zero.

Substrate	Code
Organics/Grass	1
Silt	2
Sand	3
Fine Gravel	4
Coarse Gravel	5
Cobble/Rubble	6
Boulder	7
Bedrock	8
Aquatic Vegetation	9

3.3.4 Other Important Species

Although the development of the habitat guilds and corresponding habitat suitability relationships were derived from fisheries data, these relationships are expected to provide protection for other components of the aquatic resources such as macroinvertebrates, mussels, turtles, etc. The GSA BBEST members believe this is justified based on the breadth of the habitat guilds that reflect the primary physical habitat features within river systems and the basic assumption that other aquatic resources partition within the defined gradients of depth, velocity, and substrates (Williams et al. 2005, Pendergrass 2006, Shattuck 2010).

3.3.5 Estimating Habitat Guild Availability as a Function of Discharge Ranges

An important component of establishing environmental flow regimes to ensure a sound ecological environment is the integration or overlay of biological information with the HEFR-based flow regimes (SAC 2009a; SAC 2009b). Fundamentally, this step in the process evaluates the flow magnitudes on a monthly basis within the low, medium, and high base flow tiers in terms of providing adequate habitat availability across all habitat guilds. That is not to imply, for example, that at a specific flow magnitude associated with a low base flow regime that the specific flow will necessarily provide optimal habitat conditions for all guilds simultaneously but it does imply that over the range of base flow conditions (low, medium and high tiers) that adequate habitat availability for all guilds are achieved. As noted previously, it is the variability of flow conditions seasonally (e.g., monthly) and the inter-annual variation in the overall flow regime (dry, normal and wet conditions) that are important to ensure that habitat is available for all habitat guilds, thus all aquatic species, at one time or another within the river.

3.3.5.1 Physical Habitat Modeling

Use of physical habitat modeling is perhaps the most commonly applied approach in instream flow assessments at the national and international levels (COST 626 2005, Locke et al. 2008; Annear et al. 2004). The general theory behind physical habitat modeling is based on the assumption that aquatic species will react to changes in the hydraulic environment (i.e., changes in depth and velocity as a function of flow rate). Estimation of available depths and velocities over a range of discharges is typically achieved through the calibration and simulation of 1-dimensional or 2-dimensional hydrodynamic models based on field measured topographies and hydraulic properties. In essence the stream reach at a particular flow is represented by a series of computational cells (each with a specific area) having different combinations of hydraulic parameters (i.e., depth, velocity, and substrate) as illustrated in Figure 3.3-7.

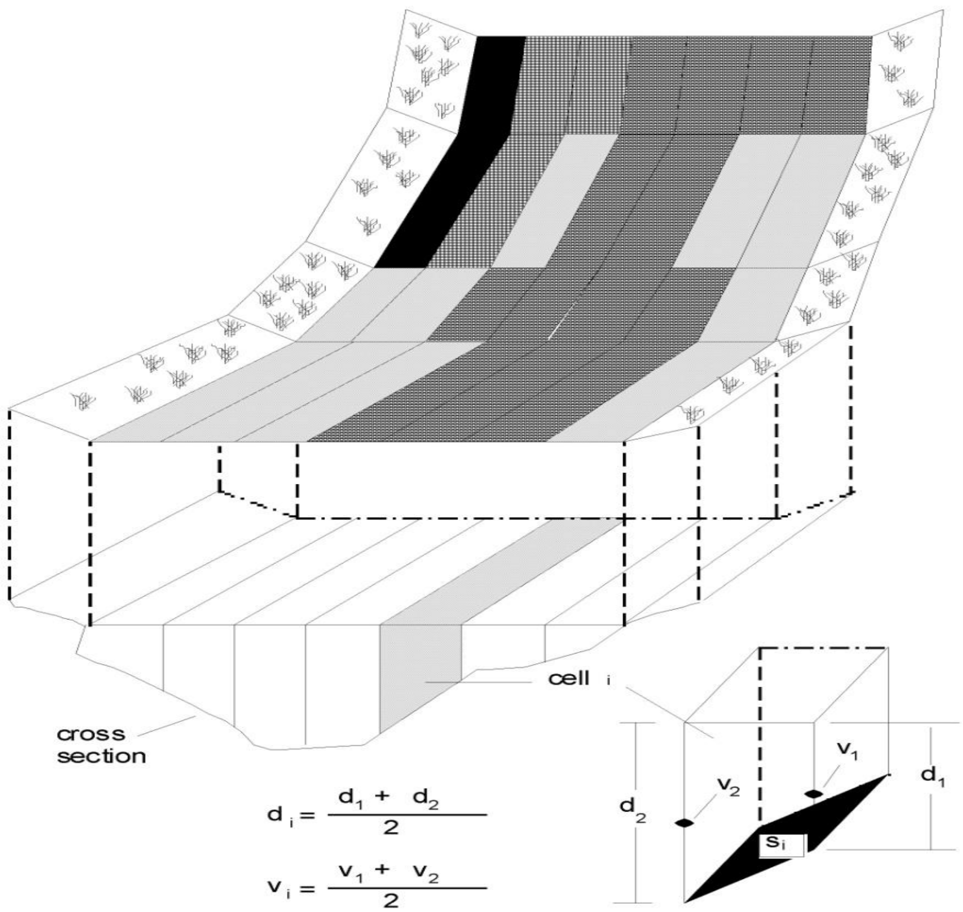


Figure 3.3-7. Conceptual example of a stream used in physical habitat modeling.

Depth and velocity attributes vary on a computational cell-by-cell basis with simulated changes in discharge resulting in changes in the amount and quality of available habitat. Physical habitat modeling uses the habitat suitability curves for depth, velocity, and substrate to estimate the cell-by-cell suitability given the various combinations of depth, velocity, and substrate to produce an estimate of the quantity and or quality of habitat. This measure of available physical habitat is referred to as weighted usable area (WUA). Analytically, WUA is computed at a specific discharge from the sum of all cell habitat areas that are suitable as:

$$WUA = \sum_{i=1}^{n} A_i * C_i$$

where:

WUA	=	Total Weighted Usable Area in the stream at specified discharge.
C_i	=	Composite suitability for cell $_i$.
A_i	=	Area of cell $_i$.

And the composite suitability for a cell is derived from the component suitability for depth, velocity and substrate based on the HSC:

$$C_i = (V_i * D_i * S_i)^{1/3}$$

This process is then repeated for all simulated discharges, which produces the functional relationship between available physical habitat (i.e., WUA) and discharge. In many applications (as here) the habitat versus flow relationships are presented as a percent of maximum available habitat as illustrated in Figure 3.3-8.

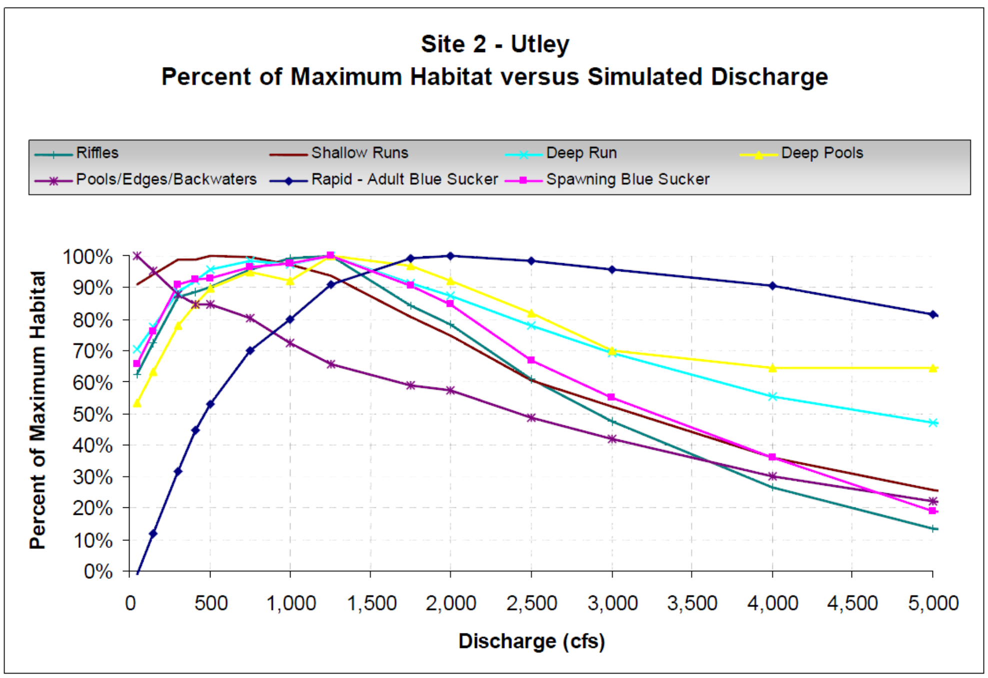


Figure 3.3-8. Example of the functional relationship between the percent of maximum habitat versus discharge (adapted from BIO-WEST, Inc. 2008a).

These relationships are then used in conjunction with the HEFR hydrologic results to provide one aspect of the biological overlay process to define the environmental flow regime at quantification sites. Specifically, we determined which discharge period of record (pre-, full, post) best represented the historical hydrograph. In most cases, full period of record was accepted as the best representation because longer periods of record likely capture the natural variation in precipitation and discharge. However, we retained the option to select a different period of record, depending on available information on anthropogenic modifications to stream discharges. For example, pre-period of record was selected for San Antonio River sites (Elmendorf, Falls City, and Goliad) to eliminate what we perceived as higher base flows in the full period attributed to waste-water return to the stream upstream from the sites. Next, we assessed the relative intactness or biological integrity of the fish community. In most cases, fish communities were considered relatively intact despite some species changes in the San Antonio River (Runyan 2007), Guadalupe and San Marcos rivers (all sites; Perkin and Bonner, In press), and Blanco River (Bean et al. 2007). Fish community information was obtained from SARA for the Medina River and Cibolo Creek. The information contained only 40 years of collection information and, therefore, not enough temporal data to statistically assess community shifts. Nevertheless, fish communities were tentatively considered relatively intact, despite some notable changes in a few species. Fish community information was not sufficiently available for Plum Creek, Sandies Creek, or the Mission River. Collectively, level of fish community intactness and the best representation of the natural hydrograph were used to adjust or justify the baseflow recommendations at each site. Adjustments to pre- (San Antonio River) or full period of record baseflows were not deemed necessary at any of the sites because the level of fish community intactness was considered fairly high or unknown.

3.3.5.2. <u>Use of Existing Site-specific Habitat Modeling Results</u>

Draft TIFP site-specific habitat versus flow relationships were available for three LSAR study sites (TIFP and SARA 2009):

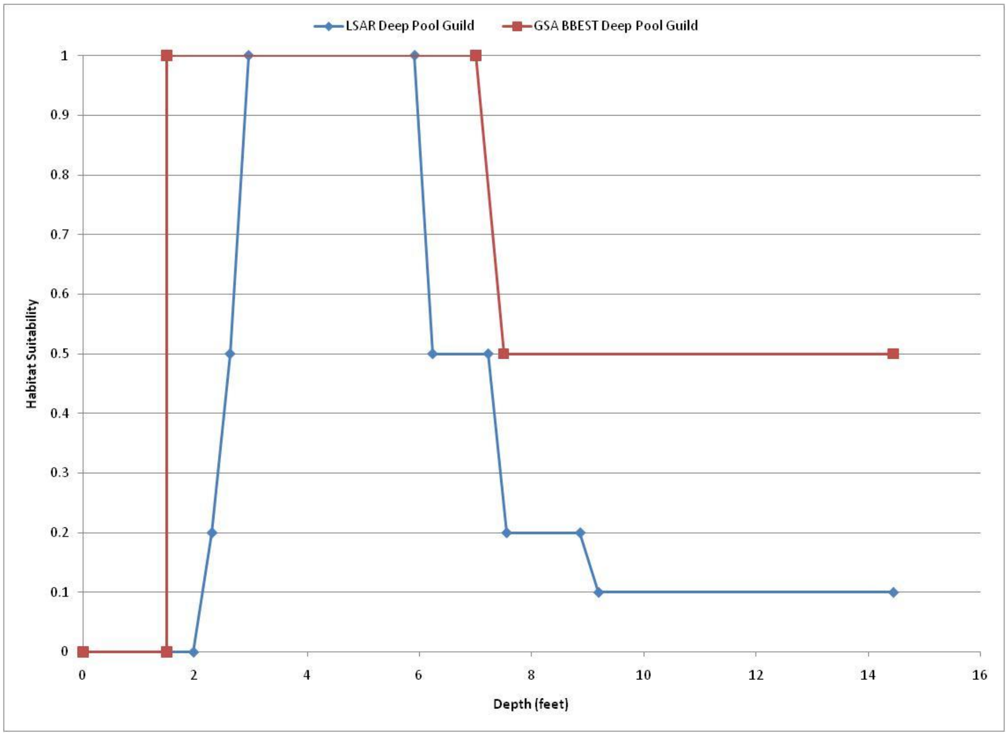
- San Antonio River near Goliad State Park RM 87
- San Antonio River near Calaveras Creek RM 252
- Cibolo Creek near Stockdale RM 30

These results were generated using two-dimensional hydrodynamic models for the hydraulic simulations and the LSAR site-specific habitat guild curves developed as part of those ongoing studies. The LSAR habitat guild definitions are similar to the guild categories adopted by the GSA BBEST as illustrated in Table 3.3-5.

Table 3.3-5. Comparison between LSAR and GSA BBEST habitat guild definitions.

LSAR	GSA BBEST
Deep Pool	Deep Pool
Mod Pool	Shallow Pool
Back Water	n/a
Deep Run	Deep Run
Shallow Run	Shallow Run
Riffle	Shallow Riffle

In addition to the differences in the guild definitions, the underlying HSC relationships are also slightly different as illustrated in Figures 3.3-9 and 3.3-10 for riffle and deep pool guilds.



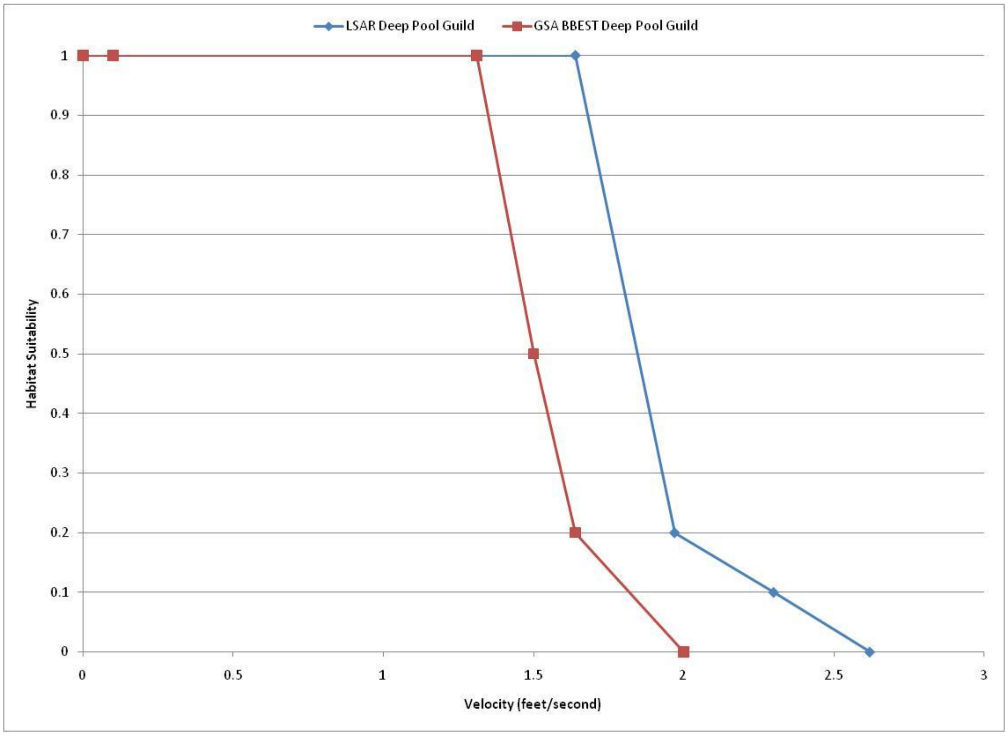


Figure 3.3-9. Comparison between LSAR and GSA BBEST depth and velocity habitat suitability curves for the Deep Pool habitat guild.

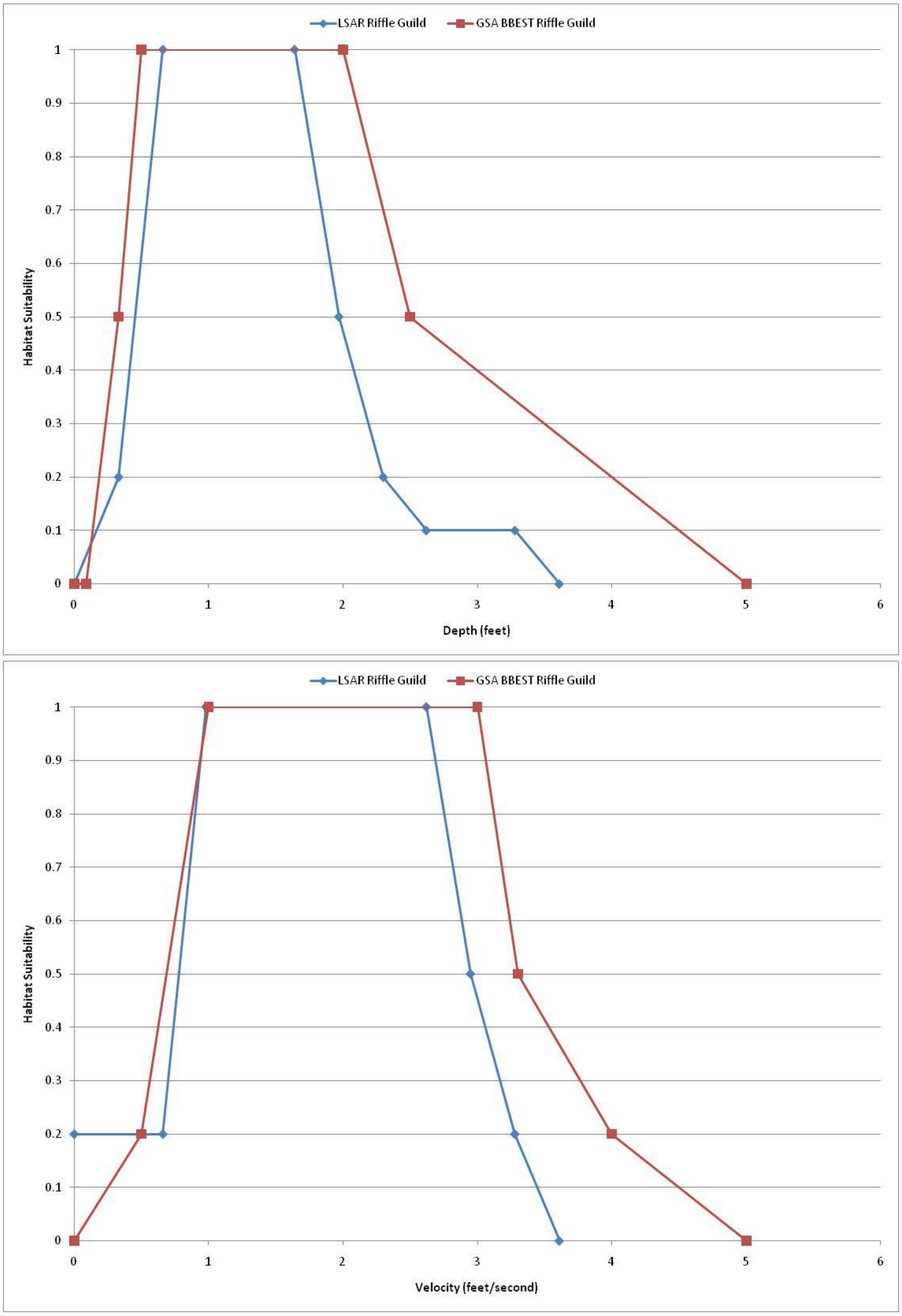


Figure 3.3-10. Comparison between LSAR and GSA BBEST depth and velocity habitat suitability curves for the Riffle habitat guild.

The LSAR HSC curves reflect the application of site-specific fisheries observation data in conjunction with published literature, while the GSA BBEST curves rely on a broader set of fish collection data and published literature and therefore tend to be broader and reflect not only the choice of underlying focal species but also the need to support analyses throughout the entire basin rather than just the LSAR study sites. The GSA BBEST also recognized that the existing LSAR guilds are continuing to be refined (Ed Oborny, personal communication GSA BBEST meeting February 24, 2011). The sensitivity of resulting habitat versus discharge relationships dependent on the choice of habitat guild HSC is discussed below.

The BBEST recognized that the TIFP studies at these locations are also incorporating detailed sediment transport modeling, riparian inundation modeling, as well as detailed water quality and temperature modeling (TIFP and SARA 2009). These studies are being conducted consistent with the goals and objectives of the TIFP. The BBEST reached a consensus that these integrated study results when completed should be evaluated for potential modification of our flow recommendations during the adaptive management process. In the interim, the BBEST elected to use the draft habitat versus flow relationships as part of our biological overlay process. The habitat versus flow relationships for the three LSAR sites are provided in Figures 3.3-11 to 3.3-13 with the supporting tabular data in Tables 3.3-6 to 3.3-8.

3.3.6 Use of Historical Cross Section Data to Develop Habitat Relationships

Existing cross section data collected by TCEQ, TPWD, TWDB and GBRA as part of pre-TIFP instream flow study efforts were available at the Guadalupe River at Gonzales (14 cross sections) and the Guadalupe River at Victoria (16 cross sections) quantification sites. These data were collected consistent with the data collection strategies for 1-dimensional cross section approaches recognized by the TIFP. These cross sections had multiple calibration stage-discharge data sets as well as a calibration velocity data set. These data were used in the Physical Habitat Simulation System (PHABSIM) to calibrate and simulate the hydraulic properties and habitat versus flow relationships (Appendix 3.2). Model calibration and simulation followed standard practice as outlined in Waddle et al. (1998) and Hardy (2002). These analyses utilized the GSA BBEST guild habitat HSC for all simulations to derive the relationships between habitat availability and discharge for the range of discharges that encompasses the HEFR base flow ranges at these sites as illustrated in Figures 3.3-14 and 3.3-15. The corresponding tabular data is provided in Tables 3.3-9 and 3.3-10.

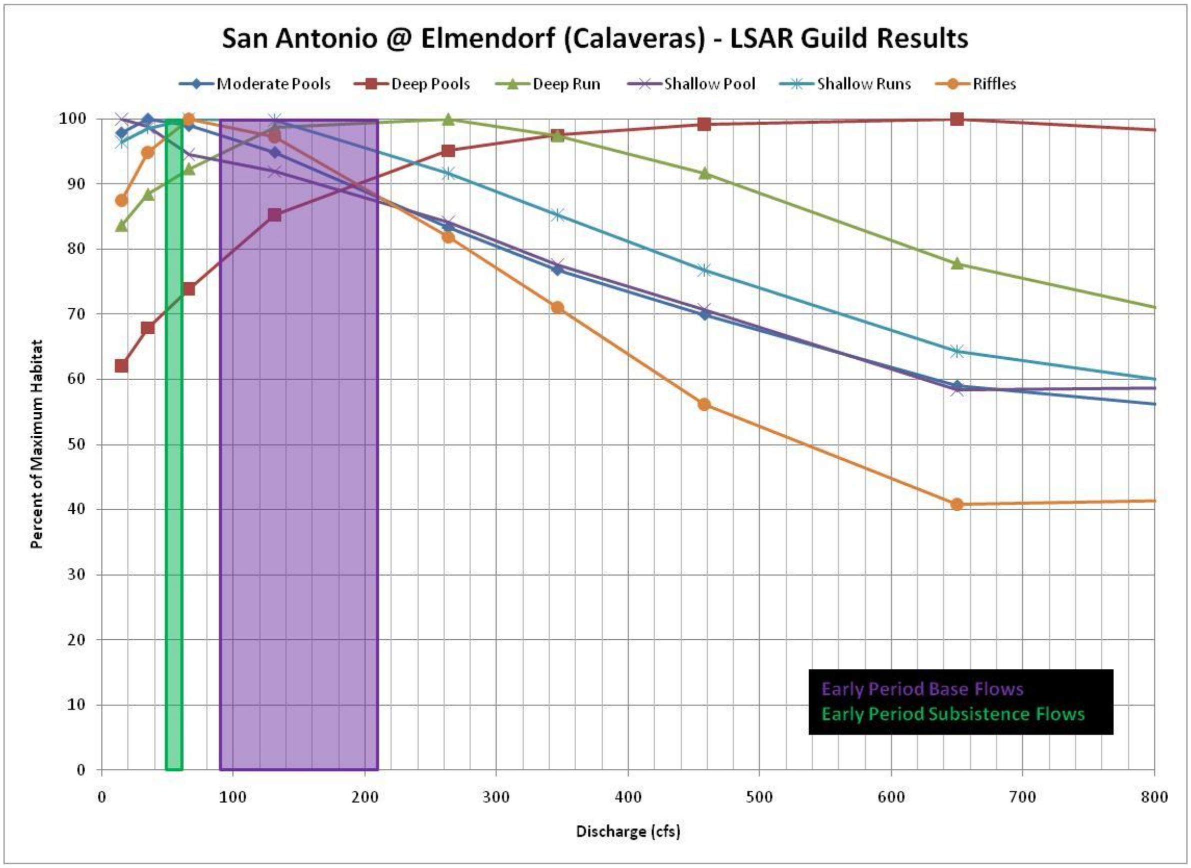


Figure 3.3-11. Percent of maximum habitat versus discharge for habitat guilds at San Antonio River at Elmendorf (Calaveras) (results provided by BIO-WEST, Inc.).

Table 3.3-6. Percent of maximum habitat versus discharge for habitat guilds at San Antonio River at Elmendorf (Calaveras) (results provided by BIO-WEST, Inc.).

Discharge (cfs)	Moderate Pools	Deep Pools	Deep Run	Shallow Pool	Shallow Runs	Riffles
15	97.87	62.02	83.64	100.00	96.41	87.47
35	100.00	67.90	88.41	98.80	98.59	94.87
66	98.98	73.96	92.36	94.52	100.00	100.00
131	94.87	85.22	98.72	91.90	99.79	97.21
263	83.32	95.09	100.00	84.11	91.64	81.82
346	76.86	97.49	97.44	77.61	85.24	71.02
458	69.98	99.15	91.69	70.78	76.80	56.14
650	59.01	100.00	77.81	58.39	64.36	40.77
1000	52.49	96.10	62.17	59.08	54.37	42.04

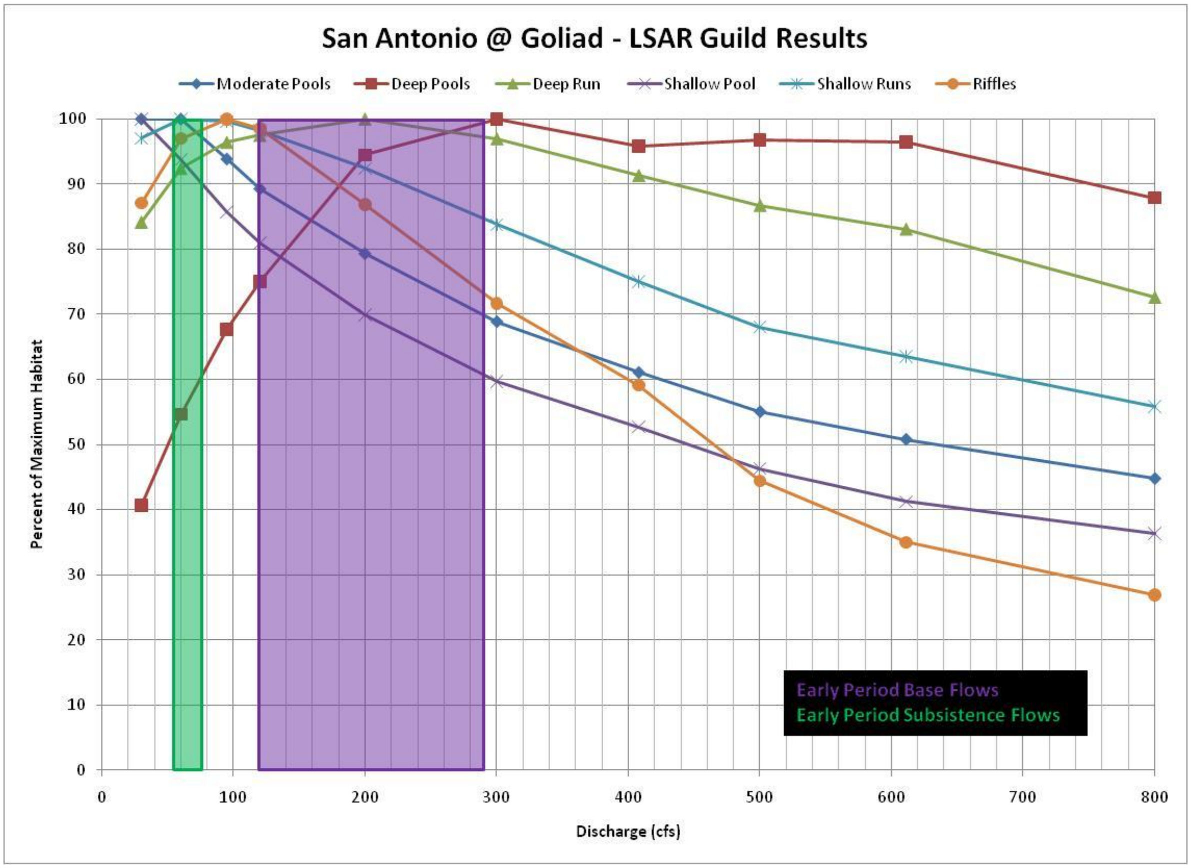


Figure 3.3-12. Percent of maximum habitat versus discharge for habitat guilds at San Antonio River at Goliad (results provided by BIO-WEST, Inc.).

Table 3.3-7. Percent of maximum habitat versus discharge for habitat guilds at San Antonio River at Goliad (results provided by BIO-WEST, Inc.).

Discharge (cfs)	Moderate Pools	Deep Pools	Deep Run	Shallow Pool	Shallow Runs
30	100.00	40.70	84.14	100.00	97.02
60	99.99	54.64	92.39	93.72	100.00
95	93.85	67.72	96.40	85.74	99.57
120	89.28	75.05	97.50	80.95	98.20
200	79.30	94.47	100.00	69.88	92.38
300	68.86	100.00	96.96	59.64	83.76
408	61.05	95.78	91.33	52.70	75.04
500	55.03	96.73	86.72	46.33	68.06
611	50.79	96.46	83.09	41.22	63.51
800	44.75	87.88	72.59	36.34	55.89
1015	40.08	79.36	63.57	32.88	48.73
1250	35.78	75.49	56.39	30.01	41.55
1500	33.02	71.57	51.73	28.67	37.69

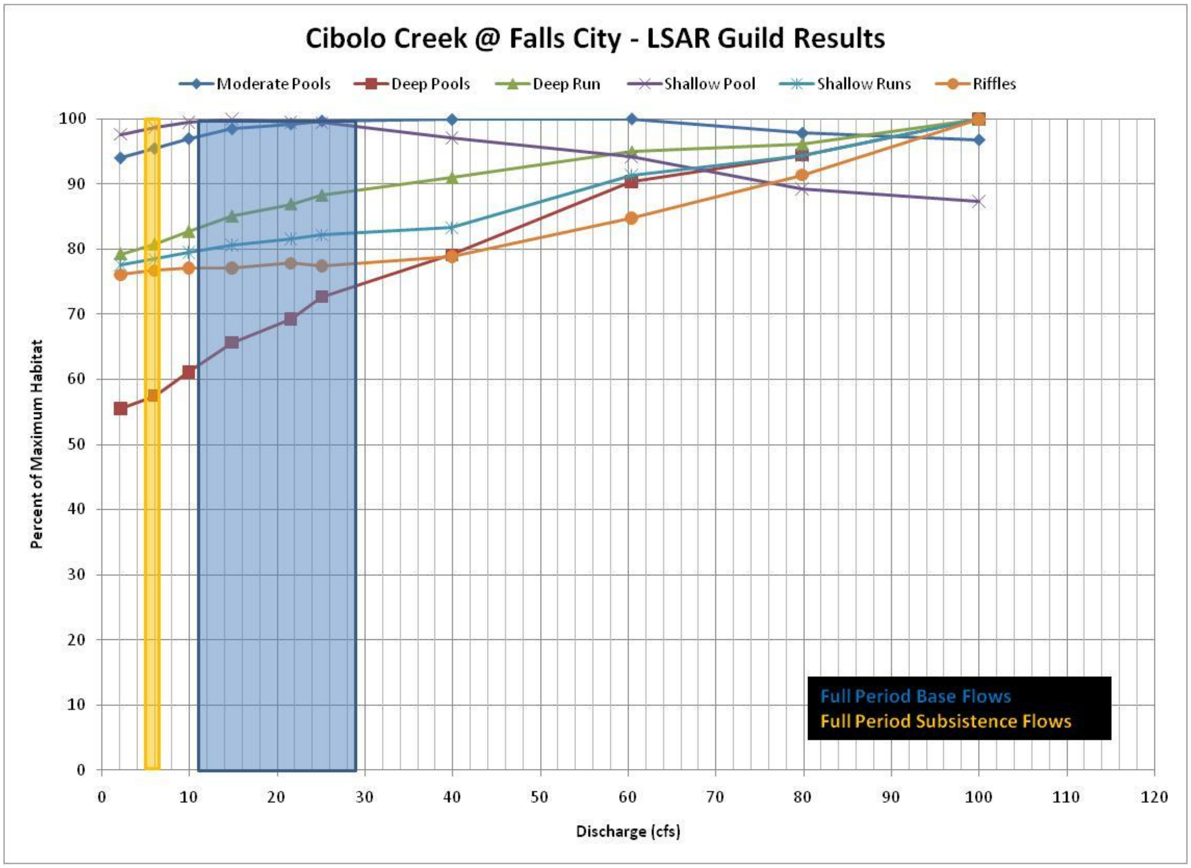


Figure 3.3-13. Percent of maximum habitat versus discharge for habitat guilds at Cibolo Creek (results provided by BIO-WEST).

Table 3.3-8. Percent of maximum habitat versus discharge for habitat guilds at Cibolo Creek (results provided by BIO-WEST).

Discharge (cfs)	Moderate Pools	Deep Pools	Deep Run	Shallow Pool	Shallow Runs	Riffles
2	93.98	55.48	79.25	97.64	77.62	76.07
6	95.45	57.52	80.75	98.68	78.48	76.71
10	96.97	61.17	82.69	99.49	79.50	77.05
15	98.46	65.67	85.05	100.00	80.65	77.12
22	99.23	69.32	86.92	99.50	81.56	77.84
25	99.69	72.70	88.26	99.41	82.16	77.45
40	99.91	79.11	90.97	97.06	83.28	78.86
60	100.00	90.38	94.95	94.13	91.30	84.82
80	97.81	94.44	96.15	89.24	94.32	91.40
100	96.77	100.00	100.00	87.31	100.00	100.00

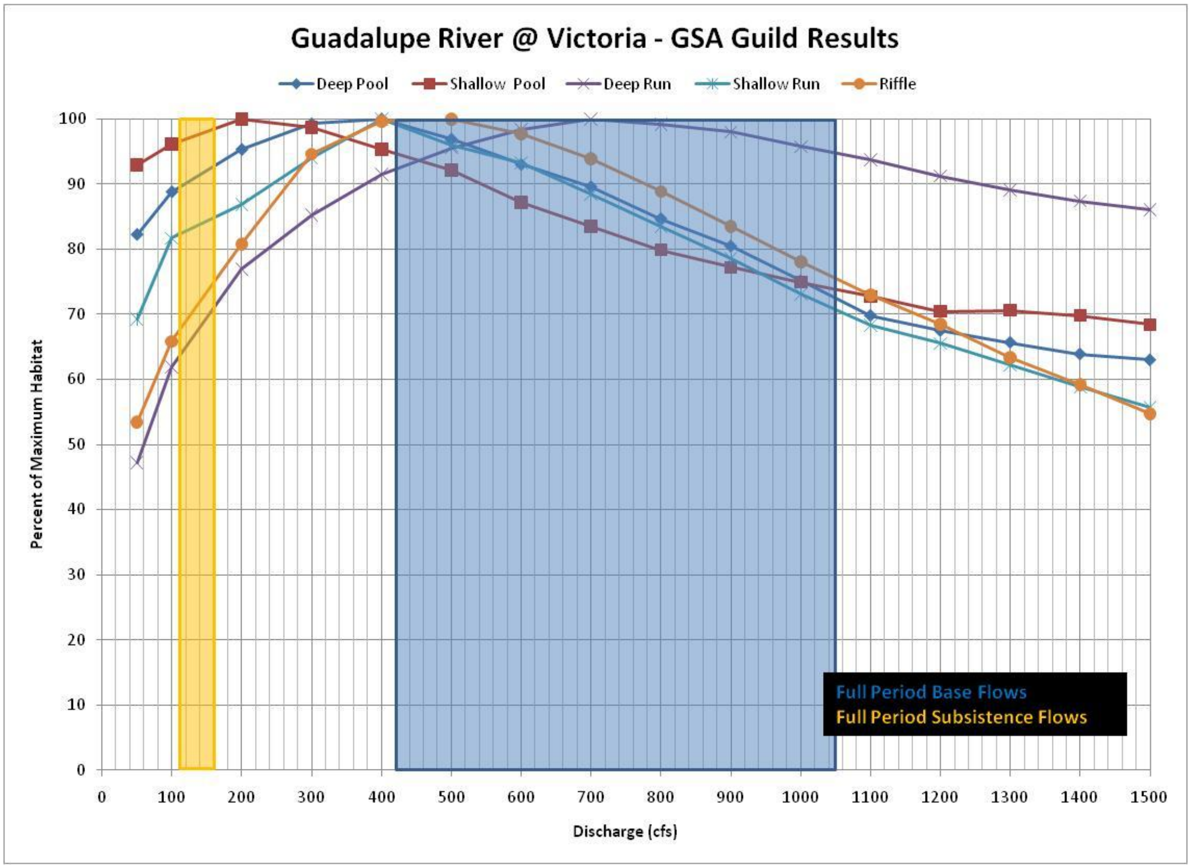


Figure 3.3-14. Percent of maximum habitat versus discharge for habitat guilds at Guadalupe River at Victoria.

Table 3.3-9. Percent of maximum habitat versus discharge for habitat guilds at Guadalupe River at Victoria.

Discharge (cfs)	Deep Pool	Shallow Pool	Deep Run	Shallow Run	Riffle
50	82.25	92.89	47.23	69.30	53.49
100	88.81	96.08	61.89	81.67	65.83
200	95.33	100.00	76.89	86.87	80.80
300	99.26	98.64	85.30	94.03	94.63
400	100.00	95.28	91.46	100.00	99.63
500	96.90	92.16	95.55	95.90	100.00
600	93.01	87.22	98.40	93.26	97.75
700	89.59	83.51	100.00	88.38	93.88
800	84.67	79.88	99.15	83.54	88.88
900	80.46	77.19	97.99	78.51	83.46
1000	75.12	74.94	95.74	73.11	78.02
1100	69.79	72.72	93.73	68.32	72.93
1200	67.47	70.45	91.25	65.52	68.48
1300	65.66	70.60	89.04	62.18	63.30
1400	63.87	69.82	87.41	58.86	59.17

1500	62.96	68.41	86.03	55.71	54.70
1600	62.21	66.40	84.08	52.71	50.43
1700	61.40	64.95	82.43	50.07	46.83
1800	61.76	64.52	80.26	47.60	43.89
1900	61.04	63.47	78.04	45.10	41.52
2000	63.19	63.91	76.26	43.53	39.17
2100	63.40	64.06	74.54	42.39	37.10
2200	62.80	63.10	72.40	41.33	35.54
2300	63.15	62.50	70.55	40.55	34.16
2400	63.61	62.20	69.12	39.77	32.80
2500	63.59	61.89	67.53	39.29	31.67
2600	63.05	62.48	65.22	38.85	30.62
2700	62.74	62.00	64.17	38.26	29.72
2800	62.49	61.31	63.22	37.69	29.06
2900	61.75	62.13	62.24	37.00	28.40

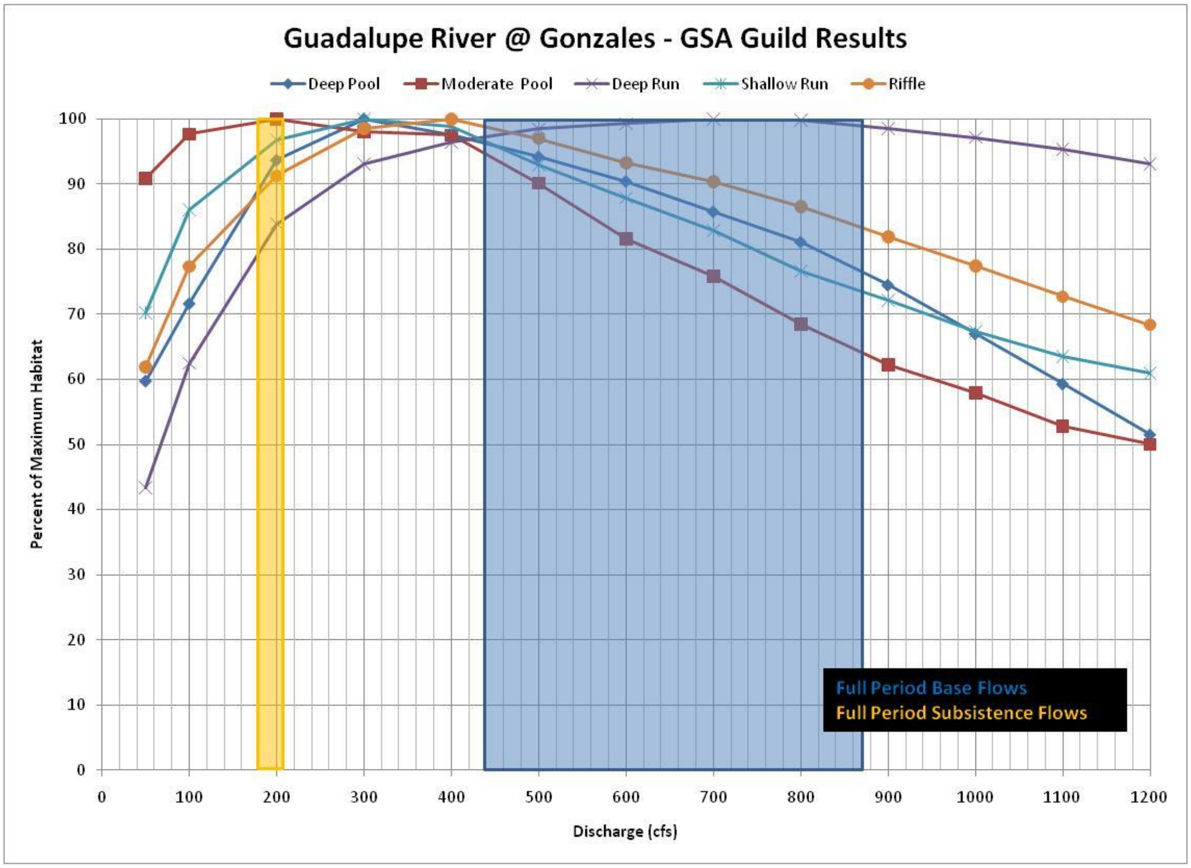


Figure 3.3-15. Percent of maximum habitat versus discharge for habitat guilds at Guadalupe River at Gonzales.

Table 3.3-10. Percent of maximum habitat versus discharge for habitat guilds at Guadalupe River at Gonzales.

Discharge (cfs)	Deep Pool	Moderate Pool	Deep Run	Shallow Run	Riffle
50	59.75	90.86	43.36	70.23	61.94
100	71.63	97.67	62.47	86.07	77.36
200	93.67	100.00	83.89	96.72	91.26
300	100.00	98.03	93.09	100.00	98.57
400	97.58	97.51	96.37	98.82	100.00
500	94.18	90.13	98.45	92.96	96.98
600	90.41	81.58	99.25	87.89	93.24
700	85.75	75.78	100.00	82.85	90.35
800	81.10	68.49	99.83	76.61	86.50
900	74.49	62.22	98.57	72.10	81.93
1000	67.01	57.90	97.15	67.30	77.39
1100	59.30	52.76	95.30	63.54	72.72
1200	51.51	50.02	93.10	60.95	68.38
1300	45.74	45.50	90.98	58.49	64.01
1400	39.41	44.87	88.62	55.33	60.40
1500	32.06	43.38	85.78	51.71	56.30
1600	26.29	40.53	82.68	49.09	52.51
1700	23.17	39.70	80.65	46.69	49.14
1800	19.94	40.52	77.77	43.95	45.30
1900	18.96	37.97	75.29	41.76	42.54
2000	17.91	35.45	73.88	39.69	40.21
2100	16.66	33.32	71.31	37.37	37.75
2200	15.38	31.15	68.91	35.18	35.74
2300	15.89	29.67	66.65	33.53	33.88
2400	15.57	28.22	64.91	32.57	32.70
2500	16.54	27.53	62.62	30.98	31.12
2600	16.86	27.51	60.45	29.66	30.39
2700	17.20	26.78	58.35	28.64	29.78
2800	16.63	26.97	56.06	27.55	28.80
2900	16.09	26.31	53.12	26.71	28.31

3.3.7 Comparative Cross Section Methodology

Site specific instream flow assessments or historical data were not available at several quantification sites. In these cases, a Comparative Cross-section Method (CCM) was used to estimate the habitat versus flow relationships for the habitat guilds (Kennard 2000). The CCM relies on previously collected instream flow hydraulic model results as the basis for predicting the distribution of depths and velocities given a target river’s channel cross section morphology, flow estimate, habitat type, wetted width, substrate and slope. The underlying assumption to this methodology is based on physics of open channel flow where two cross sections having the same basic channel shape, slope, discharge, wetted width, and substrates will have the same basic hydraulic properties over simulated ranges of discharge.

The current analysis used two reference databases developed at the Utah Water Research Laboratory representing study results from the western United States (US) and the United Kingdom (UK). The US reference database contains 629 cross sections from 139 river locations with modeled flows between 25,000 and 0.1 cfs and includes rivers and streams with wetted widths that range from 440 feet to 0.1 feet. The UK reference database contains 460 cross sections from 54 river locations across the UK including data from Scotland, Northern Ireland, England, and Wales. Flows range from 3,128 cfs to 0.4 cfs, and wetted widths vary between 188 feet and 0.3 feet. Inclusion of cross section data in the reference databases required, at a minimum, three sets of calibration discharge and water surface elevation pairs and at least one set of calibration velocities. The calibration and simulation of the hydraulic properties at each cross section followed established guidelines, and only simulation results over valid ranges of discharges for each cross section were included (Hardy 2002).

The limitations of this approach is primarily based on finding a representative cross section within the reference database and having adequate cross section samples of the target streams' variability in mesohabitat features. In cases where no suitable reference cross section is found in the reference database, Manning's equation is calibrated to the field measured hydraulic properties and used to simulate hydraulic properties over the required range of discharges. In some instances, field measured channel topographies were extended based on professional judgment, including Google Earth imagery and field notes.

The TWDB and TPWD provided cross section geometry, slope, substrates, wetted width, velocities, and discharge estimates at a single flow rate for representative mesohabitats at nine sites indicated in Table 3.3-11. The number of mesohabitat types sampled varied between sites due to site access and logistical constraints. Appendix 3.3 provides the CCM related datasets and documentation.

Table 3.3-11. Comparative cross section study sites.

Guadalupe River at Cuero
Sandies Creek at Westhoff
Guadalupe River at Spring Branch
Plum Creek at Luling
Blanco River at Wimberley
Guadalupe River at Comfort
Medina River at Bandera
Medina River at San Antonio
Mission River at Refugio

3.3.7.1 Habitat versus Flow Relationships for Habitat Guilds

The field derived cross section data were used in conjunction with the habitat guild suitability criteria to estimate the relationship between the amounts of habitat for various discharge ranges at each of the quantification sites listed in Table 3.3-11. The ranges of discharge were simulated to encompass the low, medium, and high base flow discharge ranges estimated by the HEFR analysis at each site. Figures 3.3-16 to 3.3-24 provide the relationships between the percent of maximum habitat versus discharge at each quantification site used in the fisheries component of the biological overlays to the HEFR matrices. The corresponding tabular data are provided in Tables 3.3-12 through 3.3-20.

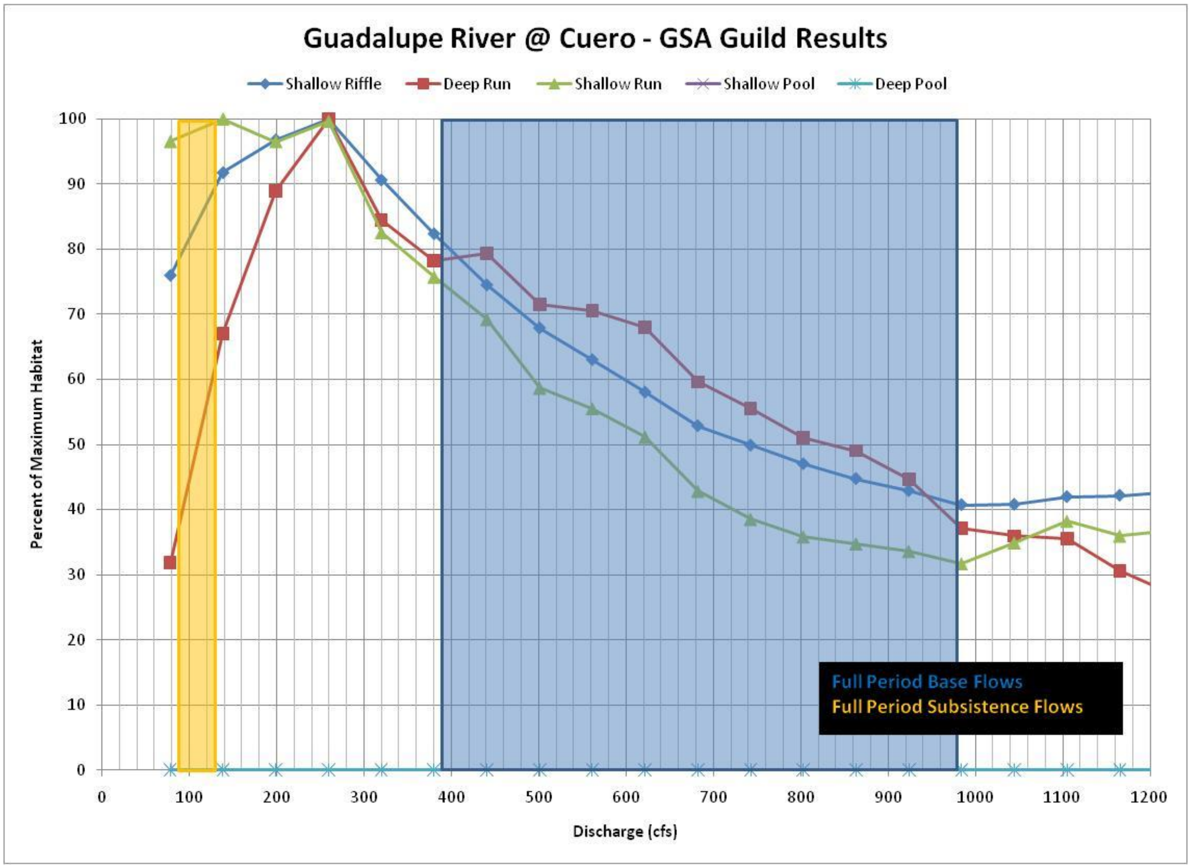


Figure 3.3-16. Percent of maximum habitat versus discharge for habitat guilds at Guadalupe River at Cuero.

Table 3.3-12. Percent of maximum habitat versus discharge for habitat guilds at Guadalupe River at Cuero.

Discharge (cfs)	Shallow Riffle	Deep Run	Shallow Run	Shallow Pool	Deep Pool
78	75.97	31.89	96.55	0.00	0.00
139	91.76	67.01	100.00	0.00	0.00
199	96.82	88.89	96.52	0.00	0.00
259	100.00	100.00	99.65	0.00	0.00
320	90.63	84.46	82.53	0.00	0.00
380	82.36	78.20	75.74	0.00	0.00
441	74.49	79.34	69.22	0.00	0.00
501	67.89	71.53	58.68	0.00	0.00
561	63.01	70.52	55.56	0.00	0.00

622	58.01	68.03	51.16	0.00	0.00
682	52.85	59.61	42.85	0.00	0.00
743	49.86	55.51	38.54	0.00	0.00
803	47.00	51.01	35.85	0.00	0.00
863	44.72	49.04	34.79	0.00	0.00
924	42.87	44.70	33.62	0.00	0.00
984	40.72	37.10	31.73	0.00	0.00
1045	40.76	35.94	34.96	0.00	0.00
1105	41.94	35.56	38.25	0.00	0.00
1165	42.16	30.59	35.99	0.00	0.00
1226	42.70	27.12	36.84	0.00	0.00
1286	42.94	26.05	41.55	0.00	0.00
1347	43.19	29.78	43.70	0.00	0.00
1407	41.80	30.03	42.41	0.00	0.00
1467	42.42	29.17	42.19	0.00	0.00
1528	44.82	29.41	45.13	0.00	0.00
1588	46.68	29.00	50.88	0.00	0.00
1649	45.41	29.90	52.29	0.00	0.00
1709	43.45	34.83	49.14	0.00	0.00
1770	42.99	40.53	47.83	0.00	0.00
1830	41.45	39.56	44.93	0.00	0.00

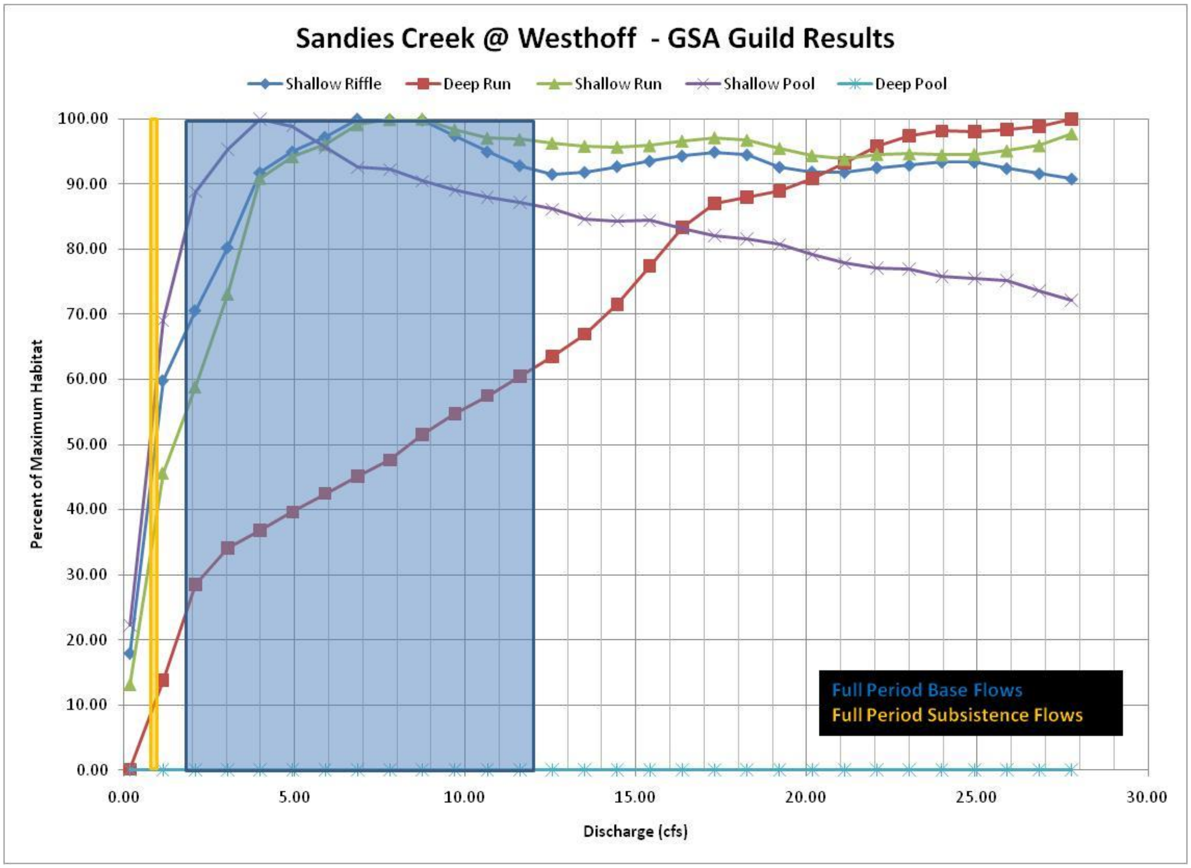


Figure 3.3-17. Percent of maximum habitat versus discharge for habitat guilds at Sandies Creek at Westhoff.

Table 3.3-13. Percent of maximum habitat versus discharge for habitat guilds at Sandies Creek at Westhoff.

Discharge (cfs)	Shallow Riffle	Deep Run	Shallow Run	Shallow Pool	Deep Pool
0.19	17.98	0.15	13.10	22.28	0.00
1.14	59.84	13.79	45.61	69.03	0.00
2.09	70.60	28.54	58.84	88.83	0.00
3.04	80.26	34.13	73.11	95.31	0.00
3.99	91.74	36.80	90.88	100.00	0.00
4.94	94.95	39.62	94.19	98.91	0.00
5.90	97.20	42.49	96.10	95.68	0.00
6.85	100.00	45.11	99.13	92.53	0.00
7.80	99.90	47.61	99.93	92.24	0.00
8.75	99.84	51.52	100.00	90.45	0.00
9.70	97.43	54.76	98.33	89.09	0.00
10.65	94.94	57.49	97.04	87.94	0.00
11.60	92.83	60.43	96.85	87.20	0.00
12.55	91.50	63.47	96.30	86.15	0.00
13.50	91.81	66.95	95.82	84.66	0.00

14.45	92.69	71.50	95.68	84.36	0.00
15.41	93.52	77.39	95.89	84.38	0.00
16.36	94.31	83.37	96.61	83.18	0.00
17.31	94.91	87.00	97.13	82.01	0.00
18.26	94.49	87.98	96.74	81.58	0.00
19.21	92.59	88.89	95.49	80.72	0.00
20.16	91.88	90.88	94.35	79.19	0.00
21.11	91.79	93.23	93.82	77.84	0.00
22.06	92.51	95.85	94.58	77.06	0.00
23.01	92.89	97.41	94.63	76.96	0.00
23.96	93.39	98.14	94.46	75.85	0.00
24.92	93.34	98.05	94.59	75.52	0.00
25.87	92.38	98.38	95.10	75.19	0.00
26.82	91.60	98.86	95.89	73.61	0.00
27.77	90.79	100.00	97.72	72.16	0.00

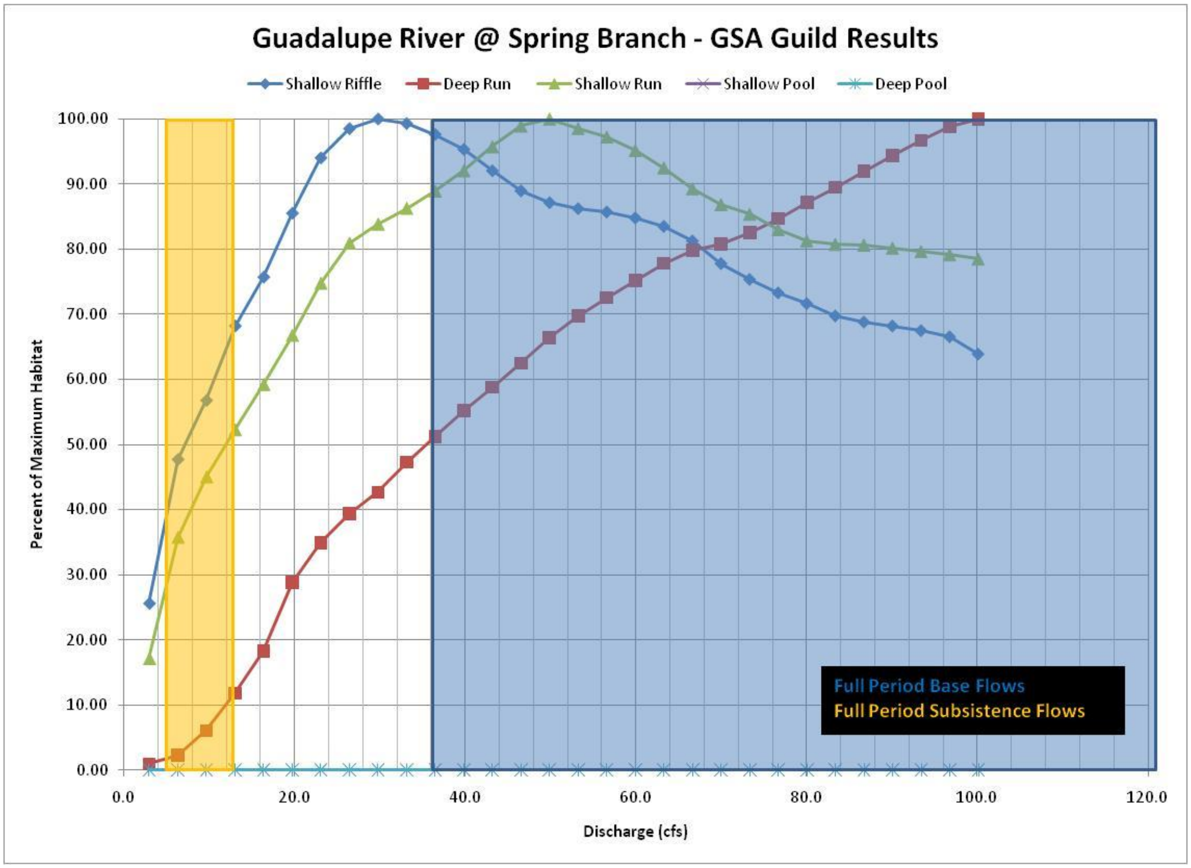


Figure 3.3-18. Percent of maximum habitat versus discharge for habitat guilds at Guadalupe River at Spring Branch.

Table 3.3-14. Percent of maximum habitat versus discharge for habitat guilds at Guadalupe River at Spring Branch.

Discharge (cfs)	Shallow Riffle	Deep Run	Shallow Run	Shallow Pool	Deep Pool
3.0	25.59	0.95	17.11	0.00	0.00
6.3	47.72	2.30	35.75	0.00	0.00
9.7	56.78	6.07	45.04	0.00	0.00
13.0	68.22	11.82	52.26	0.00	0.00
16.4	75.73	18.27	59.23	0.00	0.00
19.7	85.53	28.78	66.77	0.00	0.00
23.1	94.04	34.92	74.77	0.00	0.00
26.4	98.52	39.37	80.94	0.00	0.00
29.8	100.00	42.65	83.86	0.00	0.00
33.1	99.31	47.26	86.29	0.00	0.00
36.5	97.63	51.17	88.93	0.00	0.00
39.8	95.33	55.17	92.06	0.00	0.00
43.2	92.05	58.80	95.74	0.00	0.00
46.5	88.96	62.48	98.94	0.00	0.00
49.9	87.16	66.42	100.00	0.00	0.00
53.2	86.23	69.72	98.56	0.00	0.00
56.6	85.72	72.54	97.24	0.00	0.00
59.9	84.81	75.13	95.18	0.00	0.00
63.3	83.50	77.80	92.50	0.00	0.00
66.6	81.27	79.87	89.28	0.00	0.00
70.0	77.81	80.75	86.85	0.00	0.00
73.3	75.38	82.54	85.36	0.00	0.00
76.7	73.30	84.69	83.00	0.00	0.00
80.0	71.66	87.22	81.30	0.00	0.00
83.4	69.76	89.48	80.74	0.00	0.00
86.7	68.82	91.94	80.63	0.00	0.00
90.1	68.21	94.34	80.17	0.00	0.00
93.4	67.50	96.69	79.64	0.00	0.00
96.8	66.56	98.87	79.15	0.00	0.00
100.1	63.90	100.00	78.50	0.00	0.00

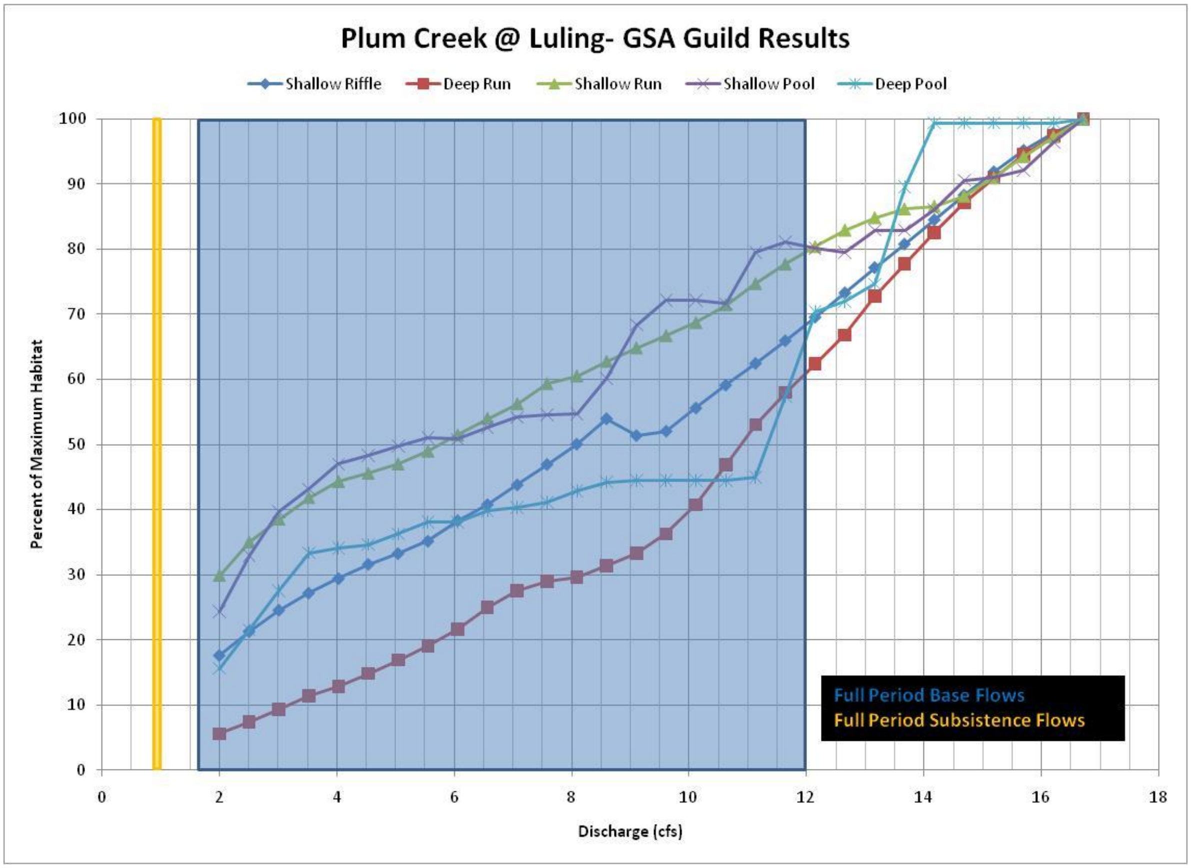


Figure 3.3-19. Percent of maximum habitat versus discharge for habitat guilds at Plum Creek at Luling.

Table 3.3-15. Percent of maximum habitat versus discharge for habitat guilds at Plum Creek at Luling.

Discharge (cfs)	Shallow Riffle	Deep Run	Shallow Run	Shallow Pool	Deep Pool
2.0	17.59	5.58	29.85	24.38	15.63
2.5	21.29	7.37	34.98	32.98	21.56
3.0	24.55	9.32	38.49	39.70	27.52
3.5	27.17	11.40	41.82	43.15	33.37
4.0	29.39	12.85	44.27	46.98	34.07
4.5	31.59	14.83	45.54	48.31	34.63
5.0	33.25	16.90	46.98	49.81	36.28
5.6	35.15	19.12	48.95	50.99	38.08
6.1	38.32	21.68	51.45	50.81	38.11
6.6	40.76	25.01	53.99	52.67	39.86
7.1	43.80	27.50	56.23	54.18	40.38
7.6	46.94	28.99	59.34	54.55	41.16
8.1	50.06	29.67	60.51	54.67	42.87
8.6	53.96	31.42	62.74	60.16	44.23
9.1	51.37	33.28	64.82	68.37	44.46
9.6	52.04	36.27	66.71	72.16	44.46
10.1	55.61	40.76	68.71	72.11	44.46

10.6	59.12	46.88	71.43	71.59	44.46
11.1	62.45	53.02	74.71	79.51	44.94
11.6	65.95	57.99	77.70	81.13	57.42
12.1	69.57	62.40	80.39	80.10	70.35
12.7	73.30	66.81	82.93	79.49	72.00
13.2	77.18	72.77	84.83	82.93	74.63
13.7	80.79	77.71	86.18	82.92	89.59
14.2	84.53	82.49	86.61	86.02	99.39
14.7	88.32	87.11	88.16	90.60	99.39
15.2	91.89	90.91	90.98	91.00	99.39
15.7	95.21	94.49	94.25	92.17	99.39
16.2	97.84	97.42	97.29	96.47	99.39
16.7	100.00	100.00	100.00	100.00	100.00

Figure 3.3-20. Percent of maximum habitat versus discharge for habitat guilds at Blanco River at Wimberley.

Table 3.3-16. Percent of maximum habitat versus discharge for habitat guilds at Blanco River at Wimberley.

Discharge (cfs)	Shallow Riffle	Deep Run	Shallow Run	Shallow Pool	Deep Pool
5.0	26.55	6.55	25.53	0.00	0.00
8.9	30.52	8.35	31.31	0.00	0.00
12.8	38.25	10.66	36.76	0.00	0.00
16.6	49.92	15.04	46.55	0.00	0.00
20.5	60.71	18.03	58.23	0.00	0.00
24.4	68.29	21.49	66.35	0.00	0.00
28.2	73.80	24.39	71.90	0.00	0.00
32.1	77.30	28.08	76.04	0.00	0.00
36.0	80.70	32.12	79.94	0.00	0.00
39.8	83.66	35.94	83.36	0.00	0.00
43.7	85.93	39.20	85.81	0.00	0.00
47.6	88.38	42.80	88.03	0.00	0.00
51.5	90.81	46.74	89.63	0.00	0.00
55.3	93.04	50.14	90.84	0.00	0.00
59.2	94.03	53.28	91.91	0.00	0.00
63.1	94.48	56.40	92.75	0.00	0.00
66.9	94.99	59.25	93.72	0.00	0.00
70.8	95.18	61.90	95.28	0.00	0.00
74.7	95.66	64.40	97.30	0.00	0.00
78.6	96.45	66.98	98.91	0.00	0.00
82.4	97.04	70.09	99.65	0.00	0.00
86.3	97.59	74.02	100.00	0.00	0.00
90.2	98.31	78.38	99.94	0.00	0.00
94.0	98.97	82.39	99.54	0.00	0.00
97.9	99.22	86.59	98.92	0.00	0.00
101.8	99.75	91.37	98.51	0.00	0.00
105.7	100.00	95.16	97.82	0.00	0.00
109.5	99.25	96.84	96.22	0.00	0.00
113.4	99.23	98.34	95.81	0.00	0.00
117.3	99.66	100.00	95.97	0.00	0.00

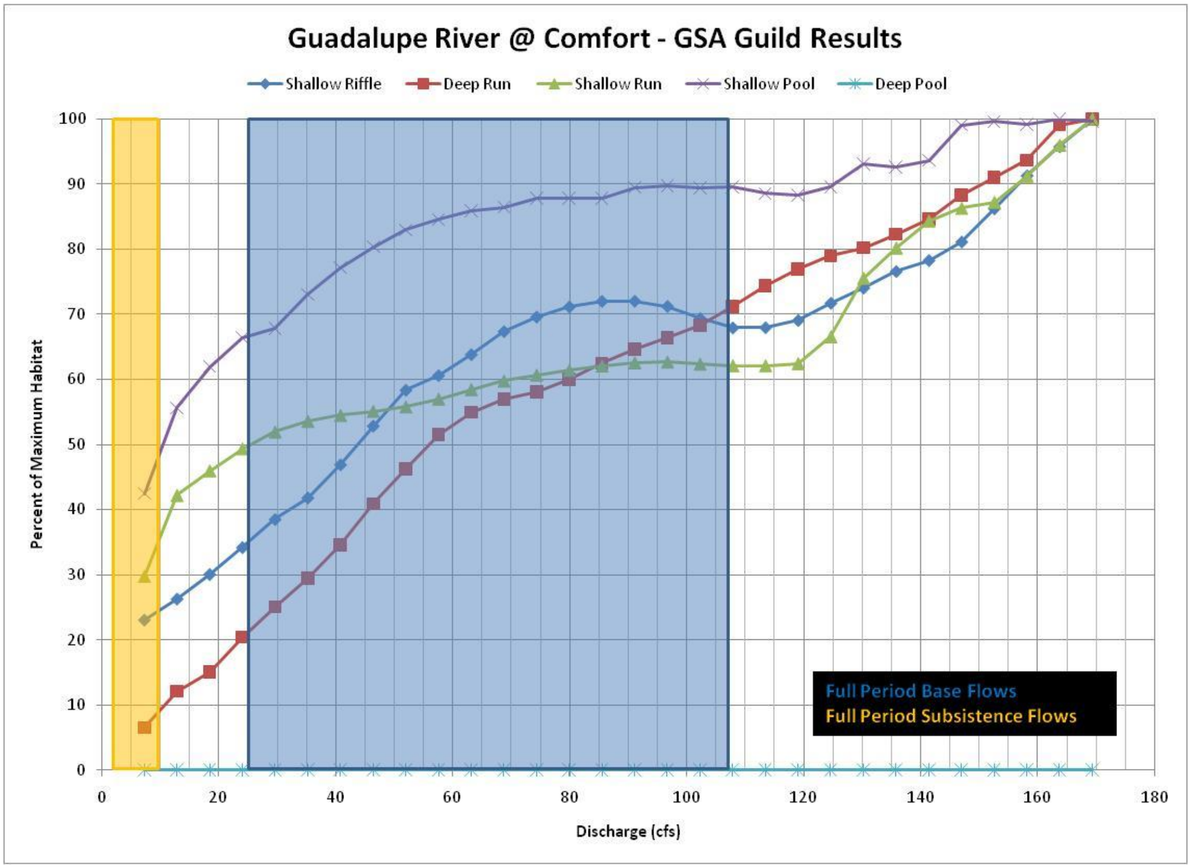


Figure 3.3-21. Percent of maximum habitat versus discharge for habitat guilds at Guadalupe River at Comfort.

Table 3.3-17. Percent of maximum habitat versus discharge for habitat guilds at Guadalupe River at Comfort.

Discharge (cfs)	Shallow Riffle	Deep Run	Shallow Run	Shallow Pool	Deep Pool
7	23.09	6.54	29.78	42.47	0.00
13	26.32	12.10	42.20	55.62	0.00
18	30.09	15.10	45.99	61.99	0.00
24	34.22	20.40	49.36	66.36	0.00
30	38.53	25.07	51.93	67.81	0.00
35	41.83	29.47	53.58	73.05	0.00
41	46.92	34.61	54.50	77.16	0.00
46	52.86	40.91	55.12	80.36	0.00
52	58.36	46.26	55.80	82.96	0.00
58	60.61	51.48	56.99	84.54	0.00
63	63.83	54.94	58.46	85.94	0.00
69	67.37	56.94	59.77	86.44	0.00
74	69.60	58.07	60.68	87.79	0.00
80	71.15	60.02	61.42	87.86	0.00
85	72.01	62.49	62.08	87.86	0.00

91	72.03	64.60	62.57	89.48	0.00
97	71.24	66.35	62.69	89.76	0.00
102	69.39	68.26	62.36	89.44	0.00
108	67.93	71.17	62.12	89.58	0.00
113	67.97	74.38	62.11	88.53	0.00
119	69.07	76.94	62.45	88.29	0.00
125	71.72	78.95	66.57	89.52	0.00
130	74.05	80.20	75.54	93.06	0.00
136	76.59	82.28	80.20	92.57	0.00
141	78.28	84.62	84.34	93.64	0.00
147	81.12	88.32	86.30	99.07	0.00
153	86.22	90.96	87.21	99.59	0.00
158	91.29	93.65	91.23	99.21	0.00
164	95.75	99.06	95.97	100.00	0.00
169	100.00	100.00	100.00	99.66	0.00

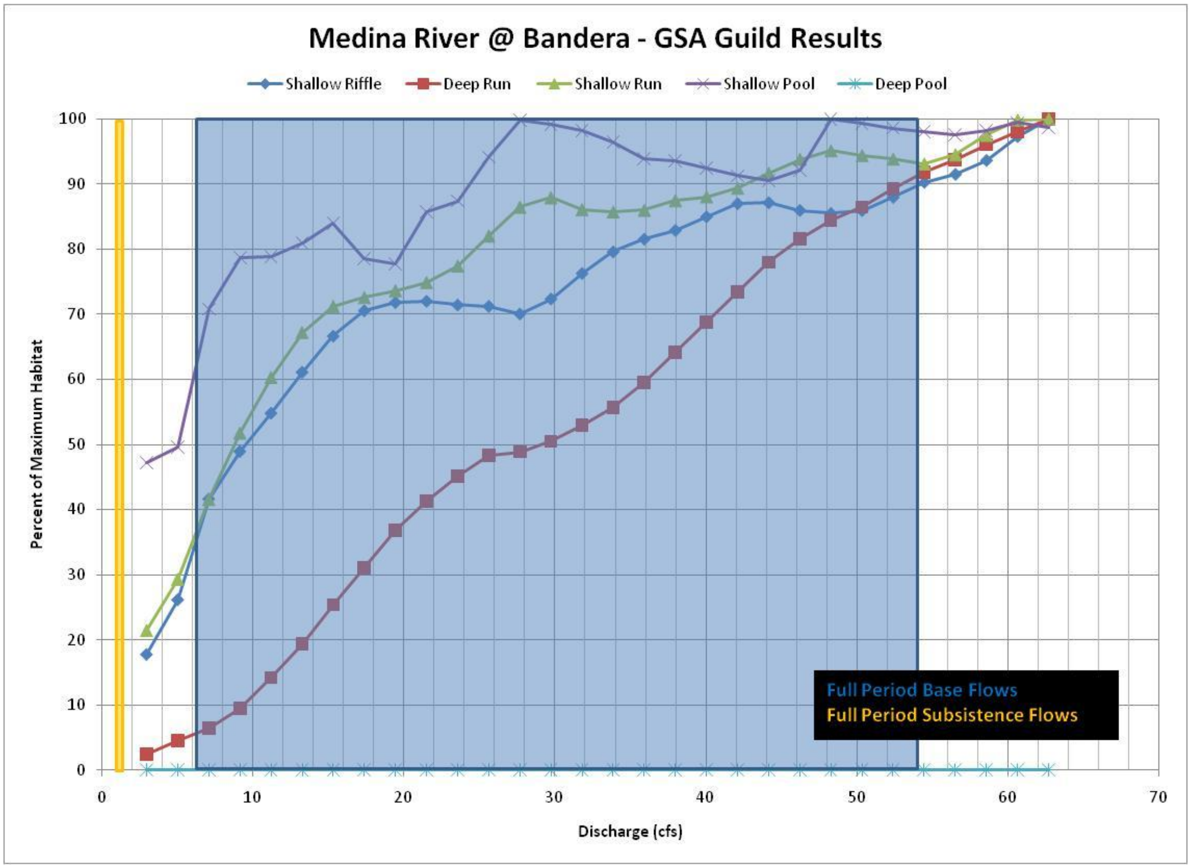


Figure 3.3-22. Percent of maximum habitat versus discharge for habitat guilds at Medina River at Bandera.

Table 3.3-18. Percent of maximum habitat versus discharge for habitat guilds at Medina River at Bandera.

Discharge (cfs)	Shallow Riffle	Deep Run	Shallow Run	Shallow Pool	Deep Pool
3.0	17.79	2.46	21.45	47.19	0.00
5.0	26.18	4.48	29.31	49.57	0.00
7.1	41.65	6.46	41.59	70.81	0.00
9.1	48.95	9.49	51.78	78.68	0.00
11.2	54.82	14.22	60.32	78.88	0.00
13.3	61.12	19.42	67.21	80.96	0.00
15.3	66.66	25.38	71.24	83.95	0.00
17.4	70.55	31.11	72.57	78.52	0.00
19.4	71.82	36.77	73.63	77.79	0.00
21.5	72.02	41.27	74.89	85.75	0.00
23.6	71.44	45.10	77.42	87.41	0.00
25.6	71.24	48.32	82.03	94.15	0.00
27.7	70.07	48.87	86.47	99.80	0.00
29.7	72.37	50.49	87.91	99.12	0.00
31.8	76.29	52.91	86.08	98.19	0.00
33.9	79.59	55.65	85.73	96.47	0.00
35.9	81.55	59.46	85.99	93.92	0.00
38.0	82.89	64.19	87.47	93.60	0.00
40.0	84.98	68.80	88.05	92.43	0.00
42.1	87.00	73.41	89.37	91.26	0.00
44.2	87.14	77.99	91.67	90.53	0.00
46.2	85.97	81.63	93.80	92.16	0.00
48.3	85.50	84.48	95.13	100.00	0.00
50.3	85.95	86.47	94.40	99.29	0.00
52.4	87.97	89.24	93.83	98.59	0.00
54.4	90.28	91.85	93.09	98.08	0.00
56.5	91.51	93.70	94.50	97.55	0.00
58.6	93.64	96.04	97.50	98.24	0.00
60.6	97.30	98.03	99.83	99.41	0.00
62.7	100.00	100.00	100.00	98.68	0.00

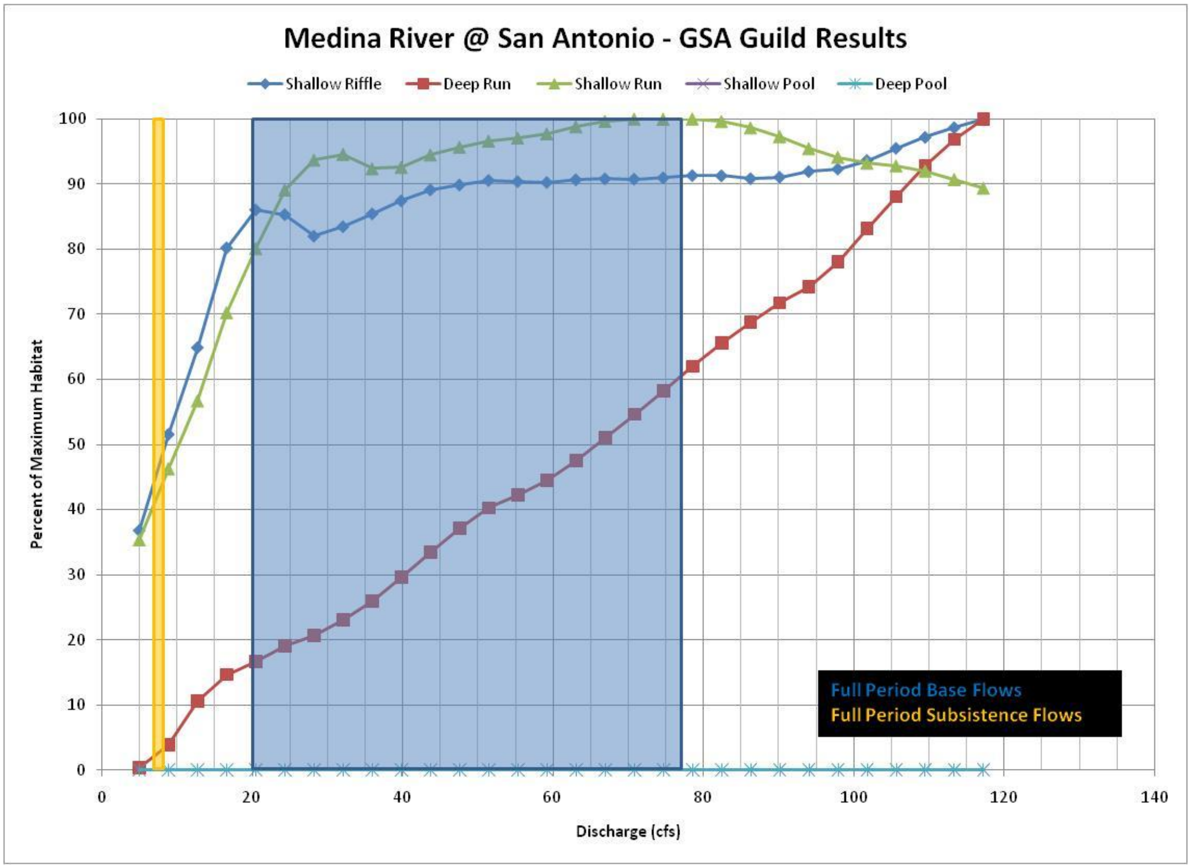


Figure 3.3-23. Percent of maximum habitat versus discharge for habitat guilds at Medina River at San Antonio.

Table 3.3-19. Percent of maximum habitat versus discharge for habitat guilds at Medina River at San Antonio.

Discharge (cfs)	Shallow Riffle	Deep Run	Shallow Run	Shallow Pool	Deep Pool
5.0	36.74	0.35	35.40	0.00	0.00
8.9	51.52	3.87	46.32	0.00	0.00
12.8	64.86	10.60	56.75	0.00	0.00
16.6	80.19	14.67	70.28	0.00	0.00
20.5	86.04	16.62	80.11	0.00	0.00
24.4	85.30	19.08	89.10	0.00	0.00
28.2	81.99	20.67	93.69	0.00	0.00
32.1	83.45	23.05	94.59	0.00	0.00
36.0	85.43	25.98	92.38	0.00	0.00
39.8	87.41	29.60	92.59	0.00	0.00
43.7	89.11	33.50	94.48	0.00	0.00
47.6	89.86	37.19	95.68	0.00	0.00
51.5	90.55	40.27	96.61	0.00	0.00
55.3	90.38	42.29	97.08	0.00	0.00
59.2	90.25	44.48	97.75	0.00	0.00

63.1	90.67	47.55	98.81	0.00	0.00
66.9	90.79	51.08	99.65	0.00	0.00
70.8	90.75	54.62	99.99	0.00	0.00
74.7	90.96	58.19	99.97	0.00	0.00
78.5	91.31	62.02	100.00	0.00	0.00
82.4	91.26	65.56	99.62	0.00	0.00
86.3	90.83	68.78	98.65	0.00	0.00
90.2	91.06	71.77	97.30	0.00	0.00
94.0	91.93	74.25	95.47	0.00	0.00
97.9	92.30	78.04	94.12	0.00	0.00
101.8	93.63	83.19	93.22	0.00	0.00
105.6	95.50	88.08	92.80	0.00	0.00
109.5	97.18	92.73	92.02	0.00	0.00
113.4	98.65	96.82	90.71	0.00	0.00
117.2	100.00	100.00	89.40	0.00	0.00

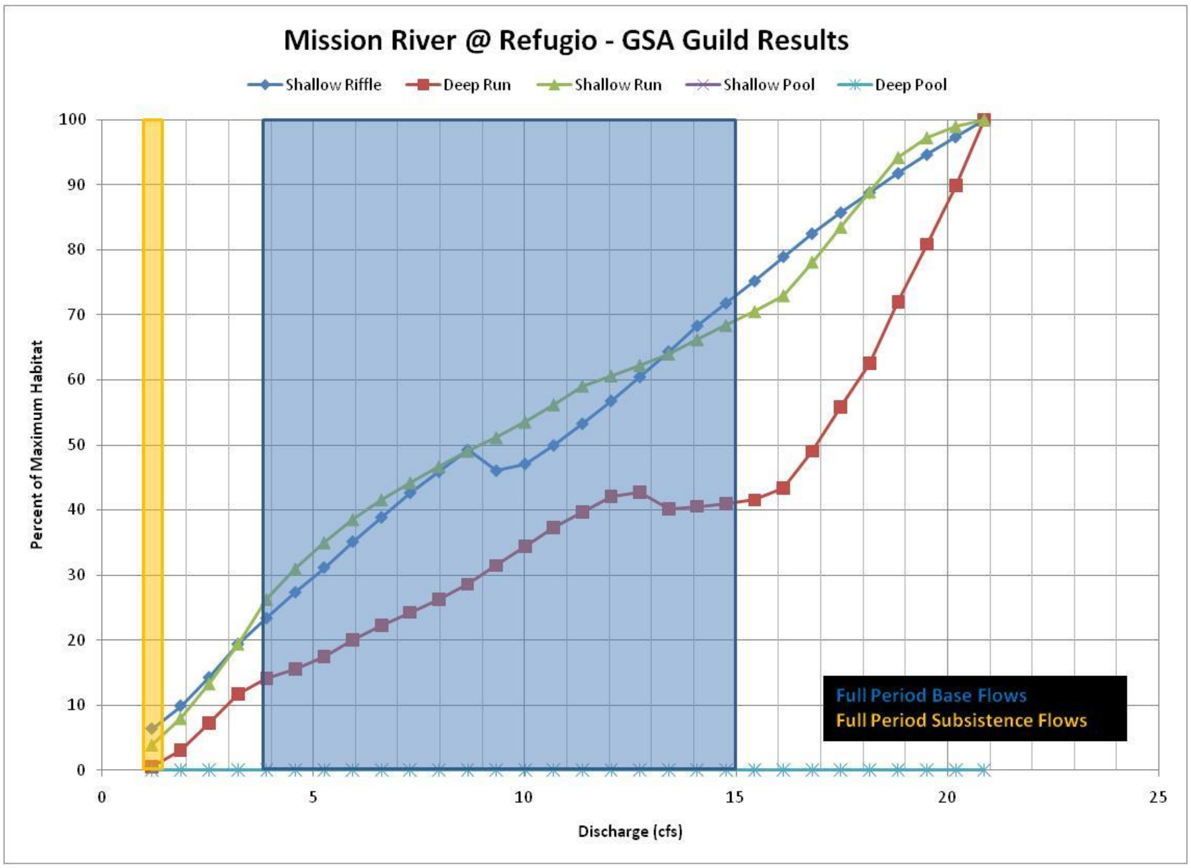


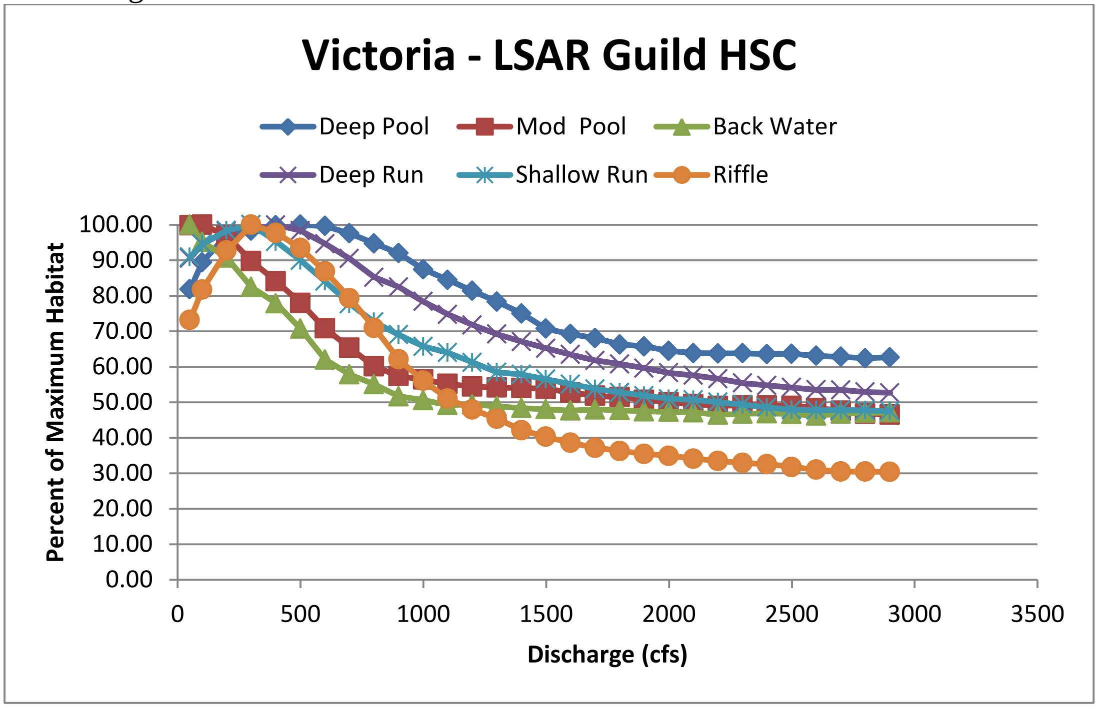
Figure 3.3-24. Percent of maximum habitat versus discharge for habitat guilds at Mission River at Refugio.

Table 3.3-20. Percent of maximum habitat versus discharge for habitat guilds at Mission River at Refugio.

Discharge (cfs)	Shallow Riffle	Deep Run	Shallow Run	Shallow Pool	Deep Pool
1.2	6.35	0.53	3.91	0.00	0.00
1.9	9.87	3.10	8.02	0.00	0.00
2.5	14.21	7.24	13.30	0.00	0.00
3.2	19.34	11.75	19.45	0.00	0.00
3.9	23.33	14.07	26.29	0.00	0.00
4.6	27.32	15.53	30.99	0.00	0.00
5.3	31.13	17.42	35.03	0.00	0.00
5.9	35.11	20.01	38.56	0.00	0.00
6.6	38.84	22.25	41.59	0.00	0.00
7.3	42.62	24.25	44.21	0.00	0.00
8.0	45.89	26.25	46.68	0.00	0.00
8.6	49.21	28.59	49.06	0.00	0.00
9.3	46.01	31.48	51.17	0.00	0.00
10.0	47.06	34.44	53.56	0.00	0.00
10.7	49.91	37.34	56.22	0.00	0.00
11.4	53.24	39.71	59.11	0.00	0.00
12.0	56.77	42.06	60.65	0.00	0.00
12.7	60.45	42.72	62.25	0.00	0.00
13.4	64.35	40.16	64.02	0.00	0.00
14.1	68.29	40.57	66.22	0.00	0.00
14.8	71.78	40.98	68.41	0.00	0.00
15.4	75.19	41.54	70.51	0.00	0.00
16.1	78.94	43.36	72.99	0.00	0.00
16.8	82.49	49.06	78.14	0.00	0.00
17.5	85.73	55.83	83.49	0.00	0.00
18.2	88.81	62.54	88.92	0.00	0.00
18.8	91.77	72.01	94.21	0.00	0.00
19.5	94.63	80.84	97.25	0.00	0.00
20.2	97.35	89.85	98.96	0.00	0.00
20.9	100.00	100.00	100.00	0.00	0.00

3.3.7.2 Sensitivity of Habitat versus Discharge Curves to Habitat Guild HSC

To examine the implications of the differences between the LSAR and GSA BBEST habitat guild specific HSC, the data at Victoria and Gonzales were used to simulate the habitat relationships using both HSC. The results presented in Figures 3.3-25 and 3.3-26 clearly indicate that although the overall pattern in the functional relationships between available habitat and discharge remain fairly consistent there are shifts in the discharge that maximizes the habitat for comparable guild types. This variability or sensitivity in the habitat versus discharge relationships are within expected ranges of variation observed over a large number of instream flow studies conducted in a wide array of river types (Dr. Thomas Hardy, personal observations from over 1000 river sites modeled). This source and degree of uncertainty should was considered when the GSA BBEST formulated their instream flow recommendations and should be considered by the BBASC when evaluating the environmental implications of their water allocation strategies.



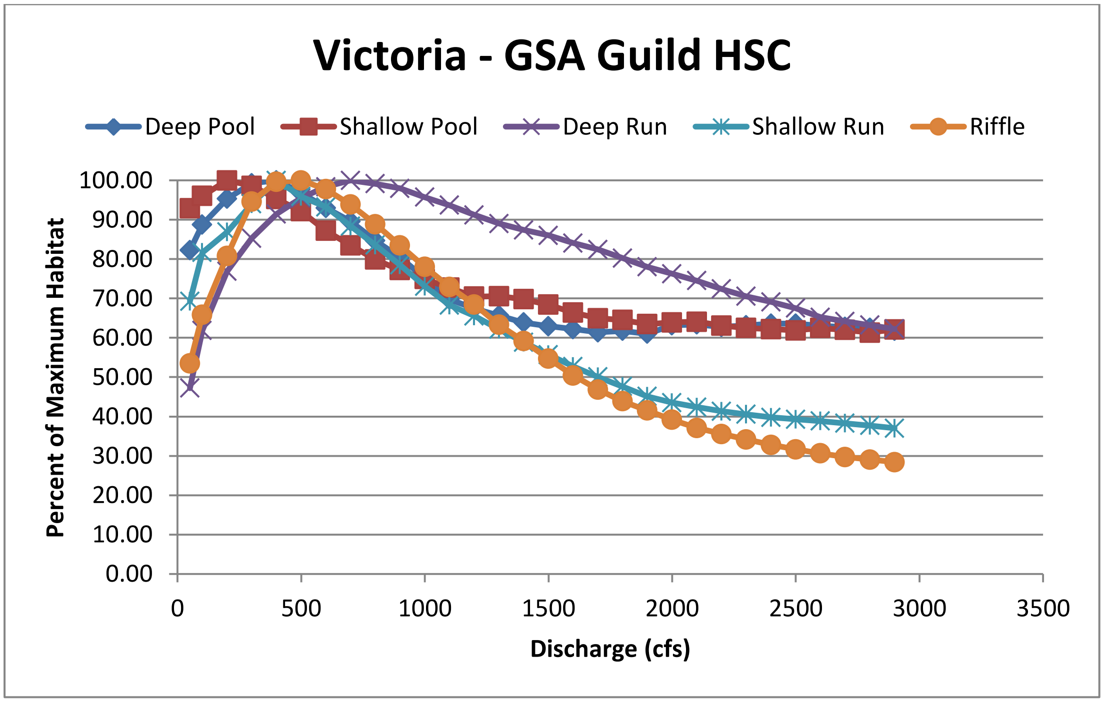
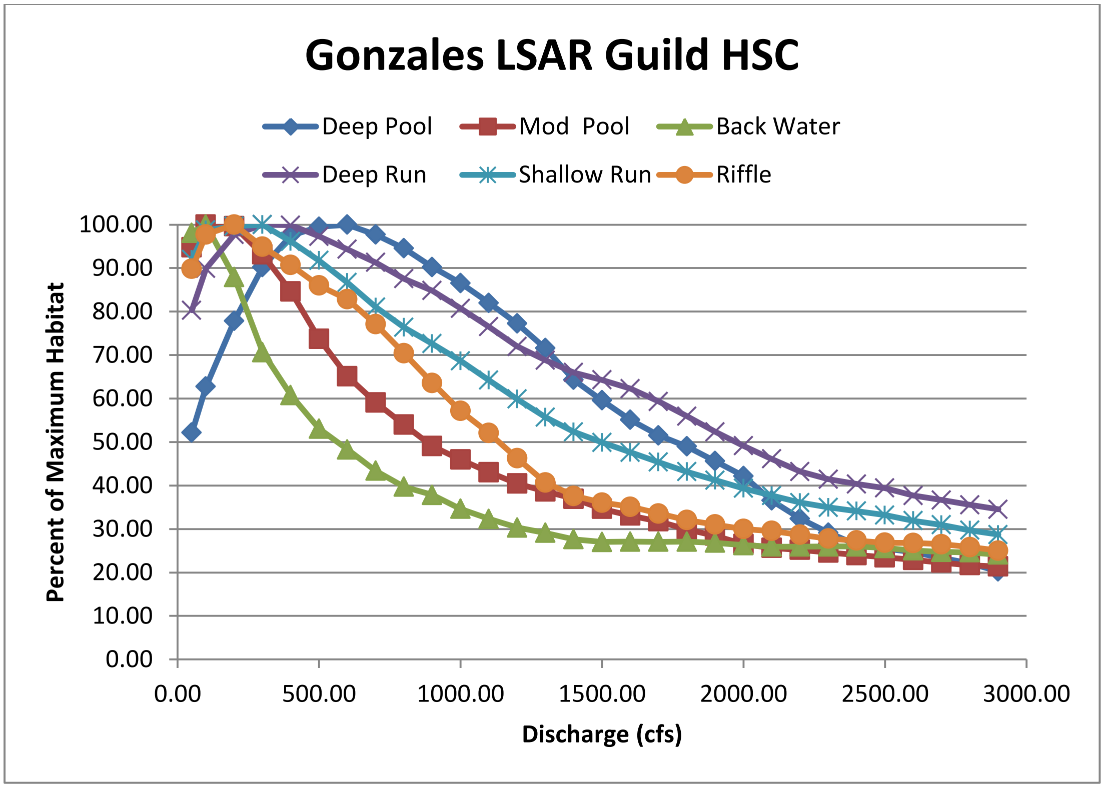


Figure 3.3-25. Simulated relationships between available habitat and discharge for LSAR and GSA BBEST based habitat guild suitability curves at Guadalupe River at Victoria.



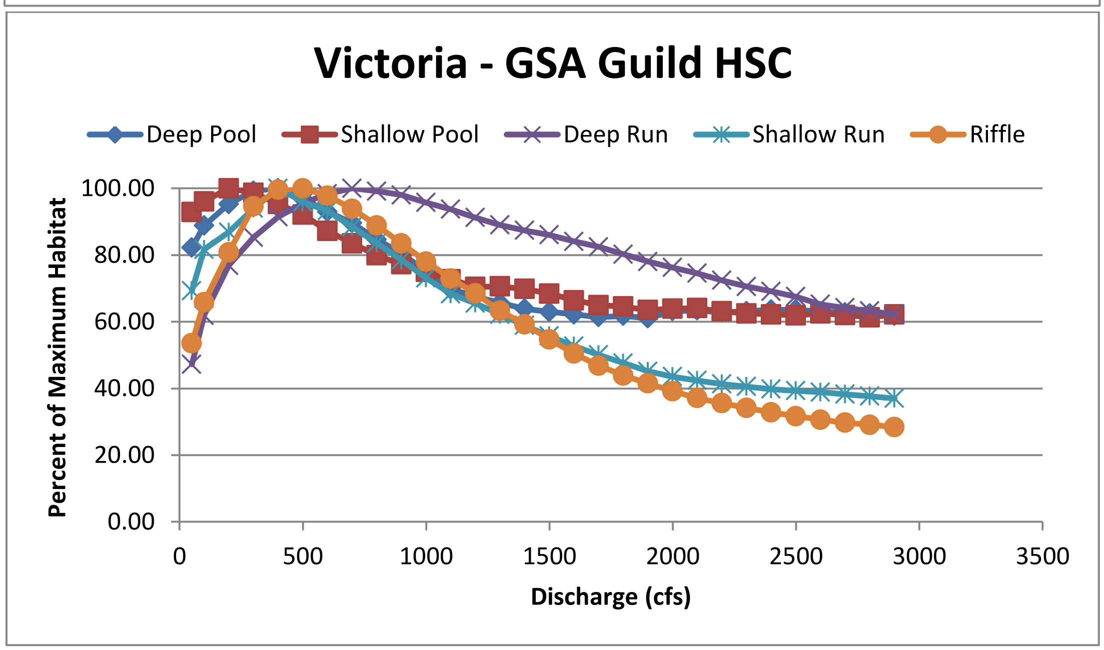


Figure 3.3-26. Simulated relationships between available habitat and discharge for LSAR and GSA BBEST based habitat guild suitability curves at Guadalupe River at Gonzales.

3.4 Water Quality Overlay

Data collected on water quality at or near the 16 selected streamflow gaging stations was assessed to determine how water quality may be used as an overlay for making appropriate instream flow recommendations. There are several water quality parameters that are important to a sound ecology that may also be flow related. For example, if a strong relationship between flow and dissolved oxygen is observed, this may help inform BBEST members regarding subsistence or base flow rates necessary to maintain a sound ecological environment.

For this analysis, TCEQ staff was asked to provide selected historical data for 30 sites from the agency's Surface Water Quality Monitoring Information System (SWQMIS). BBEST members from SARA and GBRA identified these 30 sites as being relevant to a water quality analysis because of their proximity to one of the 16 USGS gages for which the BBEST will recommend a flow regime, or because the data may generally inform BBEST members regarding the historical and current ecological health of streams in the Guadalupe/San Antonio basin. Table 3.4-1 provides a list of SWQMIS sites and the nearest USGS gage, and Figure 3.4-1 shows these locations on a map. Eleven of the SWQMIS sites are at a USGS gage location; of these, 10 are among the 16 selected for recommendation of a flow regime. Site maps showing sampling site locations and their proximity to a USGS gage are provided in Appendix 3.4.

The water quality parameters identified as being of interest were dissolved oxygen, pH, conductivity, temperature, ammonia-nitrogen, total phosphorus, and total kjeldahl nitrogen. Records from SWQMIS that were marked as "Qualified", meaning the data is of questionable quality, were not included in the analyzed data set. Likewise, quality control samples such as equipment blanks were not included in the analysis. The analysis included 4,217 sampling events between October of 1973 and August of 2010.

For each of the 30 sites and seven parameters, regression analysis was used to investigate the relationship between flow and constituent level. Regression analysis estimates the conditional expectation of a dependent variable when an independent variable is held fixed, and the technique is widely used for prediction and forecasting. In this case, the objective was to determine if regression could be used to infer causal relationships between instream flow (the independent variable) and parameter level (the dependent variable). If so, then the tool could be used to help determine appropriate flow levels.

A period-of-record analysis suggested that for these parameters, water quality is generally acceptable and not flow-related. Regarding dissolved oxygen, which is one of the most important water quality parameters from an instream ecological perspective, the highest coefficient of correlation observed was 0.346 at a site on the San Antonio River near Elmendorf. This coefficient indicates that only about 35% of the variation in dissolved oxygen levels can be explained in terms of flow. At this location there were no dissolved oxygen levels below the stream standard of 5.0 mg/l. At all sites, observation of dissolved oxygen levels below stream standards was generally infrequent, especially in recent years. In the 1970s and up until 1987, poor quality wastewater discharges in San Antonio resulted in DO levels in the San Antonio and Medina Rivers frequently falling below acceptable levels; however in the last two decades these events have become rare.

Regarding conductivity, the relationships observed were largely expected and were not a cause for flow-related water quality concerns. Electrical conductivity is used to approximate Total Dissolved Solids (TDS); for the Guadalupe and San Antonio basins, a factor of about 0.7 is applied to conductivity measurements in umhos/cm to get TDS in mg/L. In general, conductivity was observed to decrease with increasing flow; and this is as expected, since waters from storm water runoff contains lower dissolved solids than waters originating from karstic limestone systems.

Regarding pH, there were almost no observations made at any flow rate of a value outside the acceptable range of 6-9 standard units (su). Out of 3,106 observations, six were above 9.0 su, the highest being 9.6 su. The correlation coefficients of the regression analyses indicated that pH is not dependent on increasing or decreasing flow.

Temperature was included as a parameter of concern because temperature is directly related to the capacity of water to solubilize oxygen, and water temperature also affects the amount of oxygen actually needed by aquatic organisms. Observed values were largely unrelated to flow. As expected, temperatures are mostly related to season and only related to flow in that flow rates can also be seasonal. Since 1988, 43% of all low-DO events occurred in the warmer months of June to August.

The remaining analyzed parameters, total phosphorus, ammonia nitrogen, and kjeldahl nitrogen, were included because they can contribute significantly to oxygen demand, eutrophication, and algal blooms in lentic systems. High levels of ammonia nitrogen can be toxic to aquatic organisms, especially when pH and temperature are low. Phosphorus concentrations in wastewater discharges have decreased in recent decades as alternative agents have replaced them in most detergents. Nitrogen levels in wastewater discharges have also decreased due to better treatment and more stringent permit limits. The analysis revealed an interesting set of circumstances in that levels of nutrients may increase or decrease with flow depending on the sampling location’s proximity to a major wastewater discharge. At sites below major discharges, concentrations decrease with increasing flow from runoff events. At other sites, nutrients may increase during runoff events, possibly due to land use practices and use of nitrogen and phosphorus in fertilizers. Even so, correlation coefficients were generally low for all nutrients at all sites. As long as wastewater treatment practices remain effective, nutrient levels at any flow rate do not appear to be of a magnitude that will adversely impact instream ecosystems by demanding oxygen or creating toxicity.

In addition to the period-of-record analysis, a similar analysis was conducted for the summertime June-August period, and for the lowest 10% of flow values at each site. For the summertime analysis, two sites on the Guadalupe and one on Sandies Creek exhibited significantly higher correlations between flow and dissolved oxygen, in the range of 40-50%; however, the number of actual observations was very low, so it is difficult to conclude if the observed relationship is representative of instream behavior and conditions. In general, correlations remained low for both the summertime and lowest 10% analysis at all sites; when they are high, it can be explained in terms of a very small number of sampling observations.

In summary, the water quality analysis did not identify flow rates at which water quality would be unable to support a sound ecological environment.

A summary of SWQMIS dissolved oxygen data is provided in Table 3.4-2. Similar tabular reports for each of the analysis periods for each parameter are provided in Appendix 3.4. These reports provide the number and range of sampling dates at each site, the minimum, maximum, and average values observed, and the coefficient of determination with flow. Because many different distributions of data can provide the same statistical correlation, it is essential to examine the scatterplots, so these are also provided in Appendix 3.4.

Table 3.4-1
SWQMIS sites for GSA BBEST Water Quality Overlay and Nearby USGS Gages

SWQMIS Site	Location	Nearest USGS Gage	Gage is BBEST Site	Site is at BBEST gage
12578	Guadalupe River at Lower Diversion Dam	08188800 Guadalupe River near Tivoli	no	no
12590	Guadalupe River at FM 477	08176500 Guadalupe River at Victoria	yes	no
12592	Guadalupe River at FM 766	08175800 Guadalupe River at Cuero	yes	no
12605	Guadalupe River at Hermann Sons Rd.	08167000 Guadalupe River at Comfort	no	no
12608	Guadalupe River at Center Point Lake	08167000 Guadalupe River at Comfort	no	no
12626	San Marcos River at SH 80	08172000 San Marcos River at Luling	yes	yes
12640	Plum Creek at CR 135	08173000 Plum Creek near Luling	yes	no
12647	Plum Creek at CR 202	08172400 Plum Creek at Lockhart	no	no
12661	Blanco River at SH 12	08171000 Blanco River at Wimberley	yes	yes
12673	Cypress Creek at Blanco River	08171000 Blanco River at Wimberley	yes	no
12790	San Antonio River at FM 2506	08188500 San Antonio River at Goliad	yes	no
12791	San Antonio River at US 77-A	08188500 San Antonio River at Goliad	yes	yes
12793	San Antonio River at SH 239	08188500 San Antonio River at Goliad	yes	no
12798	Cib olo Creek at SH 123	08186000 Cibolo Creek near Falls City	yes	yes
12812	Medina River at US 281 South	08181500 Medina River at San Antonio	yes	no
12813	Medina River at Cassin Crossing	08181500 Medina River at San Antonio	yes	yes
12830	Medina River at Old English Crossing	08178800 Medina River at Bandera	no	no
12879	San Antonio River at FM 791	08183500 San Antonio River near Falls City	yes	yes
12883	San Antonio River at Dietzfield Rd.	08181800 San Antonio River near Elmendorf	yes	no
12886	San Antonio River at Loop 1604	08181800 San Antonio River near Elmendorf	yes	yes
12944	Mission River at US 77	08189500 Mission River at Refugio	yes	yes
13657	Sandies Creek near Westhoff	08175000 Sandies Creek near Westhoff	yes	yes
13700	Guadalupe River near Spring Branch	08167500 Guadalupe River near Spring Branch	yes	yes
14211	Cibolo Creek at CR 389	08186000 Cibolo Creek near Falls City	yes	no
15113	Guadalupe River at Split Rock Rd.	08167000 Guadalupe River at Comfort	no	no
15998	Sandies Creek at FM 1116	08175000 Sandies Creek near Westhoff	yes	no
16580	San Antonio River at Conquista	08183500 San Antonio River near Falls City	yes	no
17404	Guadalupe River at FM 474	08167500 Guadalupe River near Spring Branch	yes	no
17406	Plum Creek at Plum Creek Rd.	08173000 Plum Creek near Luling	yes	no
20470	Guadalupe River at US 183	08173900 Guadalupe River at Gonzales	no	no

Table 3.4-1. SWQMIS Sites for GSA BBEST Water Quality Overlay and Nearby USGA Gages

Figure 3.4-1

GSA BBEST

Water Quality Overlay

SWQMIS Sampling Locations

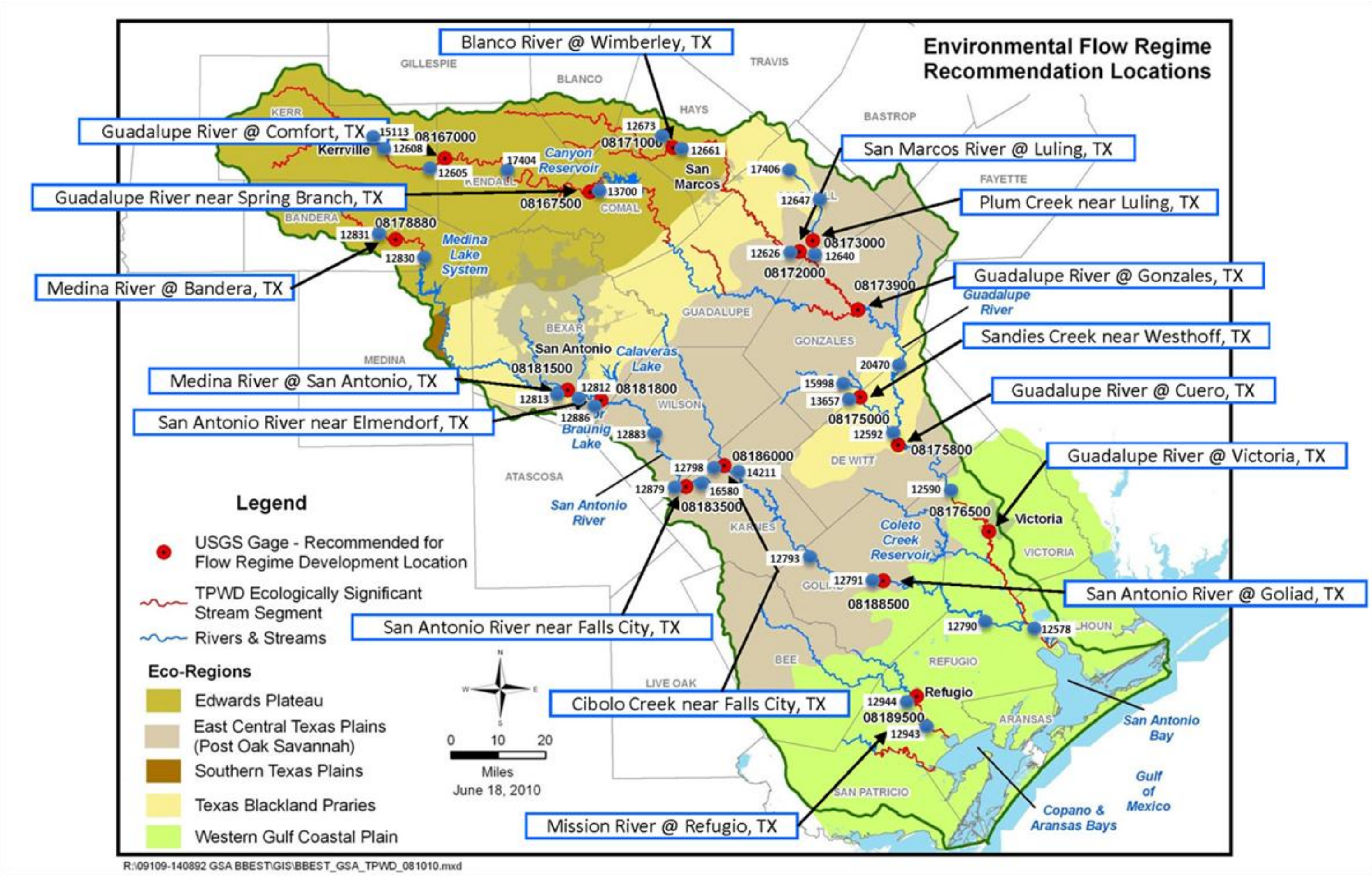


Figure 3.4-1. GSA BBEST Water Quality Overlay SWQMIS Sampling Locations

Table 3.4-2 Summary of Dissolved Oxygen Data

File: GSA_BBEST_SWQMIS_DATA.ACCDB
Report: FULL PERIOD - DO

Summary of SWQMIS Dissolved Oxygen Data
For Full Period of Record

1/16/11 5:33:10 PM
Page 1 of 1

SWQMIS Site Number	Nearest USGS Gage	USGS Gage Name	Earliest Sampling Date	Latest Sampling Date	Count	Min (mg/l)	Max (mg/l)	Avg (mg/l)	R^2 Coefficient of Determination (with flow)
12590	08176500	Guadalupe River at Victoria	10/16/01	4/20/10	34	5.90	11.90	8.82	0.06753
12592	08175800	Guadalupe River at Cuero	10/16/73	2/23/79	33	5.60	11.40	8.48	0.26894
12605	08167000	Guadalupe River at Comfort	8/8/85	2/17/10	25	6.04	13.90	8.92	0.00004
12608	08167000	Guadalupe River at Comfort	7/22/03	11/12/09	14	5.90	12.50	8.72	0.00469
12626	08172000	San Marcos River at Luling	10/15/73	8/18/05	60	5.50	11.10	8.50	0.02115
12640	08173000	Plum Creek near Luling	3/30/83	8/3/10	164	2.50	14.60	7.55	0.03532
12647	08172400	Plum Creek at Lockhart	9/23/02	8/3/10	30	4.40	13.60	8.31	0.00686
12661	08171000	Blanco River at Wimberley	10/17/73	8/25/10	166	3.90	12.80	9.04	0.00001
12673	08171000	Blanco River at Wimberley	8/8/02	8/25/10	30	3.10	10.90	7.35	0.05616
12790	08188500	San Antonio River at Goliad (FM-2506 downstream)	5/7/03	4/28/04	59	5.90	10.90	8.22	0.13148
12791	08188500	San Antonio River at Goliad	3/30/74	5/12/10	304	3.40	13.60	8.09	0.07466
12793	08188500	San Antonio River at Goliad (SH-239 upstream)	7/25/00	8/10/05	86	5.50	14.20	8.60	0.13157
12798	08186000	Cibolo Creek near Falls City	11/5/73	12/19/06	123	5.00	15.00	8.96	0.00214
12812	08181500	Medina River at San Antonio (US-281 downstream)	12/3/74	8/16/05	161	1.00	12.40	6.89	0.01094
12813	08181500	Medina River at San Antonio	10/18/05	5/20/10	30	5.80	10.10	8.20	0.03671
12830	08178880	Medina River at Bandera	10/25/73	3/1/10	106	6.10	13.20	9.18	0.00717
12879	08183500	San Antonio River near Falls City	10/16/73	8/10/10	429	0.30	17.80	6.77	0.00410
12883	08181800	San Antonio River near Elmendorf (Dietzfield Road downstream)	6/3/93	4/19/07	41	5.40	10.00	7.51	0.34620
12886	08181800	San Antonio River near Elmendorf	11/5/73	8/10/10	405	0.70	13.10	7.23	0.00652
12944	08189500	Mission River at Refugio	3/28/74	3/29/10	159	1.80	12.60	7.49	0.00177
13657	08175000	Sandies Creek near Westhoff	8/25/83	8/4/10	152	0.80	13.00	6.78	0.04755
13700	08167500	Guadalupe River near Spring Branch	10/14/81	8/2/10	169	6.40	14.90	9.18	0.01434
14211	08186000	Cibolo Creek near Falls City (CR-389 downstream)	8/3/93	5/26/10	72	6.40	16.50	9.31	0.04340
15113	08167000	Guadalupe River at Comfort	7/22/03	2/17/10	24	7.20	14.20	10.01	0.13587
15998	08175000	Sandies Creek near Westhoff	11/20/97	1/27/07	32	2.87	10.90	6.72	0.28159
16580	08183500	San Antonio River near Falls City (Conquista Crossing downstream)	1/28/02	6/7/05	17	6.50	10.00	7.90	0.00728
17404	08167500	Guadalupe River near Spring Branch	10/9/01	4/6/10	36	7.50	14.80	9.61	0.00707
17406	08173000	Plum Creek near Luling	10/15/01	8/3/10	96	2.20	14.10	7.63	0.21184
20470	08173900	Guadalupe River at Gonzales	9/10/08	6/15/10	8	6.90	12.80	9.13	0.00006

gae

3.5. Geomorphology Overlay

3.5.1 Geomorphology (Sediment Transport)

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 the existing habitat conditions within the channel. These habitat conditions are required in order to meet the biological objectives of an Environmental Flow Regime. An Environmental Flow Regime will only be successful if the aquatic habitats supported by the existing channel shape are protected. 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).

There are some indications in the 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% 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%, 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 as a means 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. The analysis performed for the Guadalupe-San Antonio BBEST was performed as outlined in the SAC document including the use of the program SAMWin.

3.5.2 Study Locations

Three locations were selected by the Guadalupe-San Antonio BBEST for sediment transport analysis in support of the Geomorphic Overlay. The locations were:
San Antonio River at Goliad – USGS Gage Number 08188500, Goliad County.

- Guadalupe River at Cuero – USGS Gage Number 08175800, De Witt County.
- Guadalupe River above Comal River at New Braunfels – USGS Gage Number 08168500, Comal County.

After visiting the Guadalupe River above Comal River site, it was determined that this site is primarily bedrock. The movement of bed material plays a limited role in determining channel shape at this location. The calculation of effective discharge and average annual sediment load does not provide insight related to environmental flow requirements at this site. Therefore, the Guadalupe River above Comal River site was dropped from the analysis.

3.5.3 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, Little, and Thorne 1999). In the reaches of the Guadalupe and San Antonio River basins 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.

Annual frequency curves where developed using the USACE Hydrologic Engineering Center Statistical Software Package (HEC-SSP). This software allows the user to perform a variety of statistical analyses of hydrologic data. The current version of HEC-SSP (Version 1.1, May 5, 2009) can perform flood flow frequency analysis based on "Bulletin 17B - Guidelines for Determining Flood Flow Frequency" (IACWD 1982), a generalized frequency analysis on not only flow data but other hydrologic data as well, 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. The annual series flood frequency calculated 1 – year event can be expected to occur about every 6 months. Frequency curves for the gaged historical flow data for the San Antonio River at Goliad for 1940 – 1969 and 1970 – 2009 are shown in Figures 3.5-1 and 3.5-2, respectively. Figure 3.5-3 is the frequency curve for the Guadalupe River at Cuero for the gaged historic data from 1965 – 2009. For example, in Figure 3.5-1, there is a 50% chance (see the bottom axis) that a flood of 9,000 cfs (see the left hand axis) will occur in any year. Or, put another way, a flood of 9,000 cfs is expected to occur, on average, about once every 2 years (see the top axis). Table 3.5-1 shows both annual flood frequency calculations and the frequency when adjusted as recommended by Langbein.

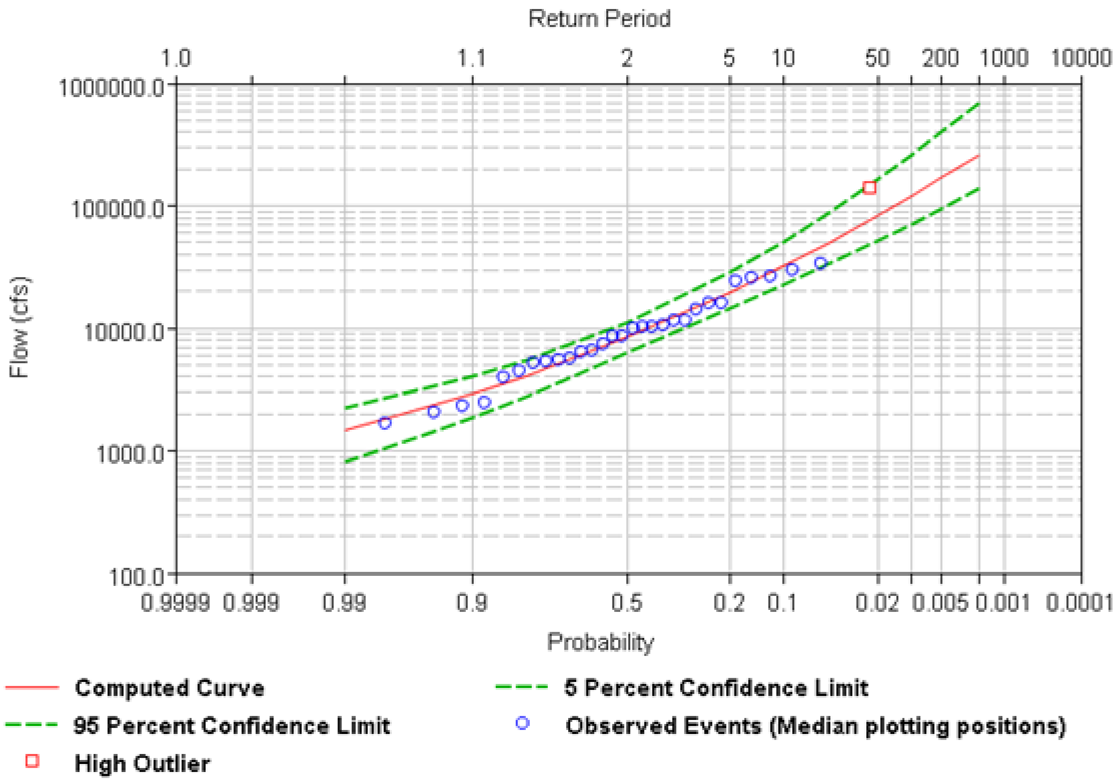


Figure 3.5-1. Annual Frequency Curve for San Antonio River at Goliad – 1940 to 1969

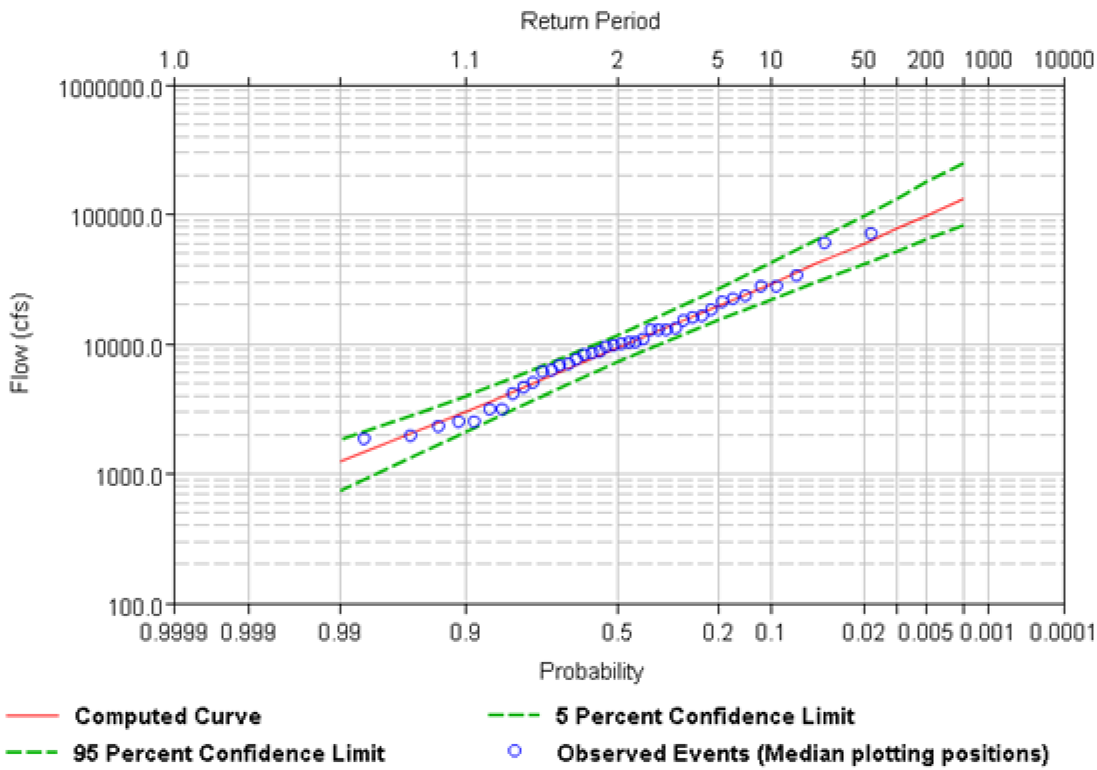


Figure 3.5-2. Annual Frequency Curve for San Antonio River at Goliad – 1970 to 2009

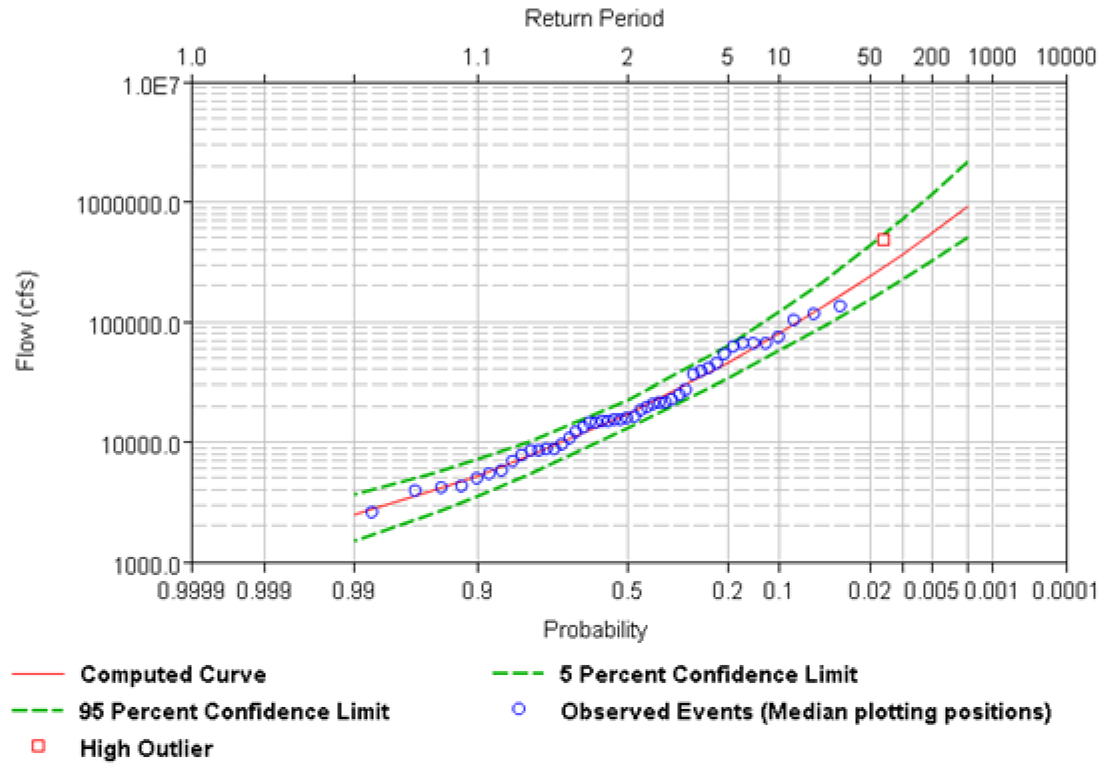


Figure 3.5-3. Annual Frequency Curve for Guadalupe River at Cuero 1965 – 2009

Table 3.5-1. Selected Annual Flow Frequencies for the Gage Locations Selected for Geomorphic Study

<table>
<tr><td colspan="8">Corresponding Return Period in Years for Annual and Partial Series (Langbein, 1949)</td></tr>
<tr><td>Partial Series</td><td>0.5</td><td>1</td><td>1.45</td><td>2</td><td>5</td><td>10</td><td>50</td></tr>
<tr><td>Annual Series</td><td>1.16</td><td>1.58</td><td>2</td><td>2.54</td><td>5.52</td><td>10.5</td><td>50.5</td></tr>
<tr><td colspan="8"></td></tr>
<tr><td colspan="3">Annual Return Period in Years</td><td>10</td><td>5</td><td>2</td><td>1.25</td><td>1.11</td></tr>
<tr><td colspan="3">Estimate Partial Return Periods in Years</td><td></td><td>4.5</td><td>1.5</td><td>0.7</td><td>0.5</td></tr>
<tr><td colspan="3">Percent Chance of Exceedence in 1 Year</td><td>10</td><td>20</td><td>50</td><td>80</td><td>90</td></tr>
<tr><td colspan="8"></td></tr>
<tr><td>River</td><td colspan="2">Location</td><td>Flow (cfs)</td><td>Flow (cfs)</td><td>Flow (cfs)</td><td>Flow (cfs)</td><td>Flow (cfs)</td></tr>
<tr><td>San Antonio</td><td colspan="2">Goliad 1940-1969</td><td>31,980</td><td>19,520</td><td>8,370</td><td>4,060</td><td>2,910</td></tr>
<tr><td>San Antonio</td><td colspan="2">Goliad 1970-2009</td><td>29,280</td><td>19,620</td><td>9,240</td><td>4,420</td><td>3,030</td></tr>
<tr><td>Guadalupe</td><td colspan="2">Cuero 1965-2009</td><td>81,000</td><td>46,200</td><td>17,700</td><td>7,800</td><td>5,420</td></tr>
</table>

3.5.4 Discharge Rating Curves

The existing channel should be analyzed to insure that it is reasonably stable and that it has adjusted to its existing hydrologic regime for the effective discharge calculation to be meaningful and provide guidance in how a future hydrologic regime might affect channel stability. One relatively simple and quick way to do this is to analyze how the long term stage – discharge curve (also known as the “rating curve”) has changed overtime. Both the San Antonio River at Goliad and Guadalupe River at Cuero are USGS field measurement sites and have adequate period of record to analyze for channel stability. Rating curves that remain stable over time are one indication that the channel in that reach of the river has remained stable. An alluvial channel that is either degrading or aggrading will show a distinct change in the stage-discharge relationship over time. Incising (degrading) channels will exhibit a decreasing gage height for the same discharge while the gage height for an aggrading channel will exhibit an increase in gage height for the same discharge.

Figures 3.5-4 and 3.5-5 are rating curves developed for the San Antonio River at Goliad. The amount of data available for this site required that the data be separated in order to detect any potential patterns. Figure 3.5-4 compares the earliest data (1939-1949) to the three decades following, i.e. through the end of 1979. Figure 3.5-5 compares the earliest data (1939-1949) to the decades beginning in 1980.

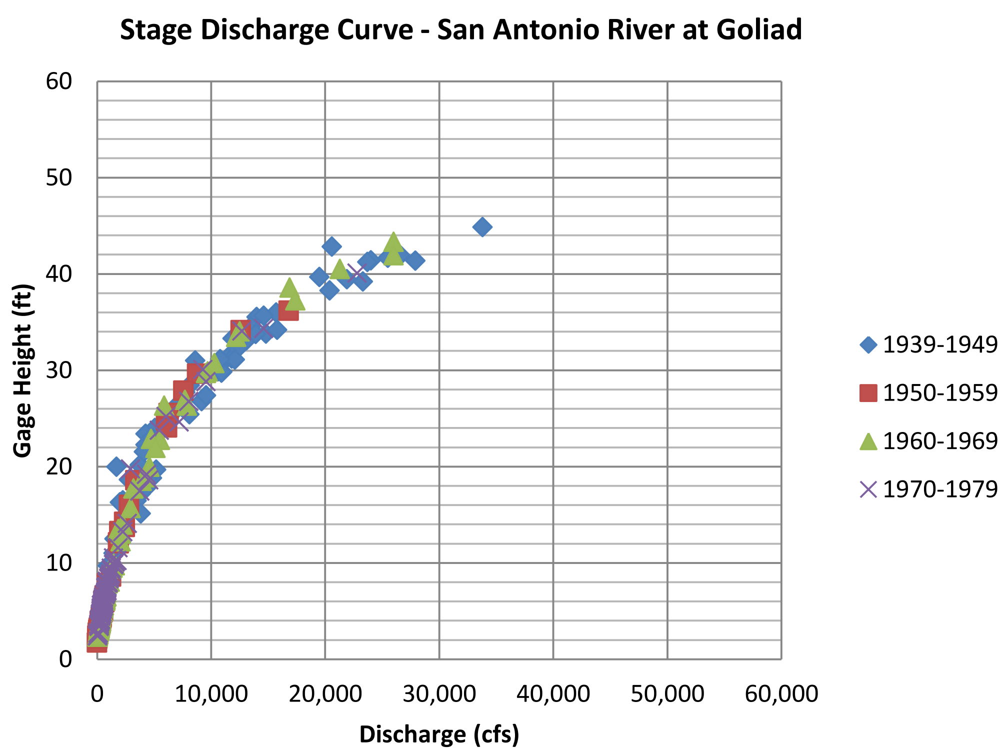


Figure 3.5-4. Discharge Rating Curve for San Antonio River at Goliad – 1939 to 1979

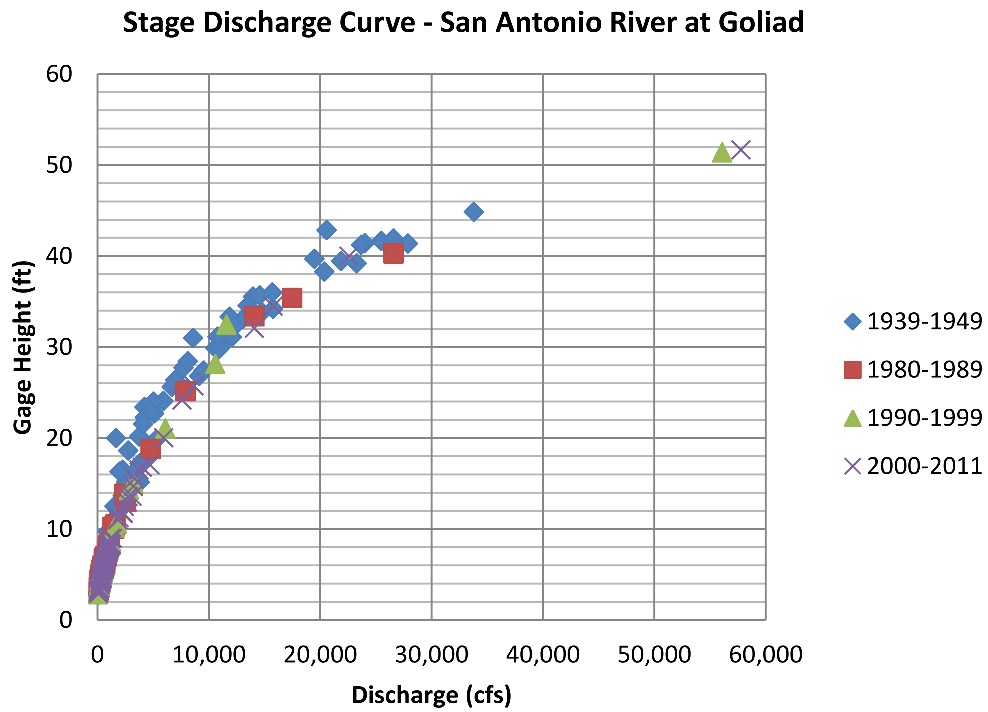


Figure 3.5-5 Discharge Rating Curve for San Antonio River at Goliad – 1939/1980 to 2011

Figure 3.5-4 shows that the channel has remained relatively stable for the range of flows and dates included on the plot. Figure 3.5-5, however, appears to show that some stream incision or degradation has occurred since the earliest time period. The plot shows approximately 1 to 2 feet of incision for flows above about 3500 cfs. This is a relatively small amount of degradation over 70 years of record and could be within the normal fluctuation expected of a stable channel. From 1980 through 2011, the data seem unchanged. This indicates that the river has adjusted to existing hydrologic conditions and, therefore, the effective discharge analysis will provide useful information regarding how the channel will react to future alterative hydrologic regimes.

To 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 sections and channel shape in this reach of the San Antonio River and consulting with 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 3.5-6 is the rating curve developed for the Guadalupe River at Cuero. This figure shows that the rating curve for the Guadalupe River at Cuero has not changed over the period of record. The channel shape does not appear to be changing at the present time, indicating the channel is stable. Therefore, the effective discharge analysis will provide useful information regarding how the channel will react to future alterative hydrologic regimes.

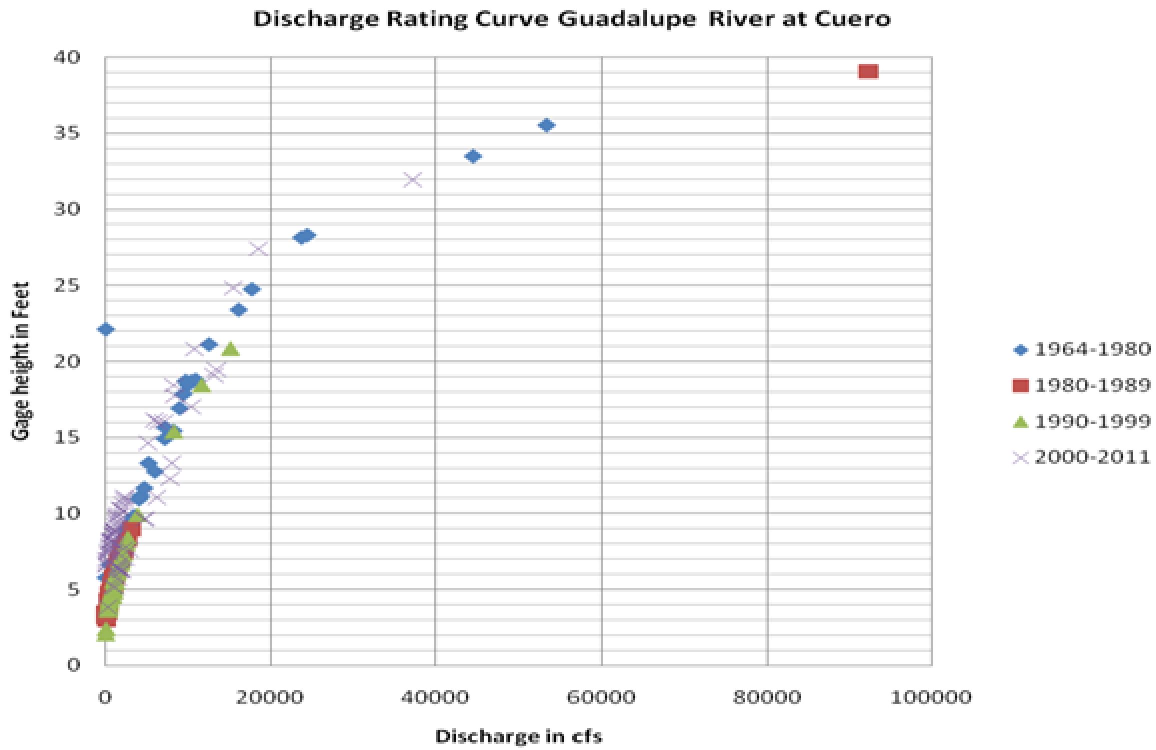


Figure 3.5-6. Discharge Rating Curve for Guadalupe River at Cuero

3.5.5 Sediment Rating Curves

Sediment rating curves estimate the amount of sediment moved by flows of various sizes. Bed material sediment data for the San Antonio River at Goliad (Haschenberger 2011) was used in the computer program SAMWin to compute the sediment rating curve for that site. For the Guadalupe River at Cuero, sediment data was not available, therefore, substrate classification and photographs from fieldwork conducted during cross-sectional surveys in support of Dr. Thom Hardy's Comparative Cross Section analysis where used to estimate inputs to the computer program SAMWin and sediment rating curves were computed based on a sediment transport function.

Channel parameters (velocity, discharge, channel width, channel depth, computed energy slopes and bed gradation) at each gage site were input into SAMWin and a sediment rating curve was computed. A number of different sediment functions were applied and the function that fit the measured data most closely was chosen as a guide for developing the sediment rating curve used in the effective discharge calculation. Figures 3.5-7 and 3.5-8 show the measured sediment data, the computed sediment rating curves, and the sediment rating curves used to compute effective discharge for the San Antonio River at Goliad and Guadalupe River at Cuero, respectively. The sediment function used is also shown on the plots. At the San Antonio River at Goliad site, the sediment data had a relatively large bed material gradation (sands to large gravels) and was best fit by the Lausen – Madden sediment function. The Ackers-White sediment function was used for the Guadalupe River at Cuero to account for the larger bed material gradation at this site (sand to small cobbles). The Ackers-White sediment function in SAMWIN accommodates 15 sediment sizes including cobble size bed material (Ackers and White 1973, Ackers 1993, Prasuhn 1993).

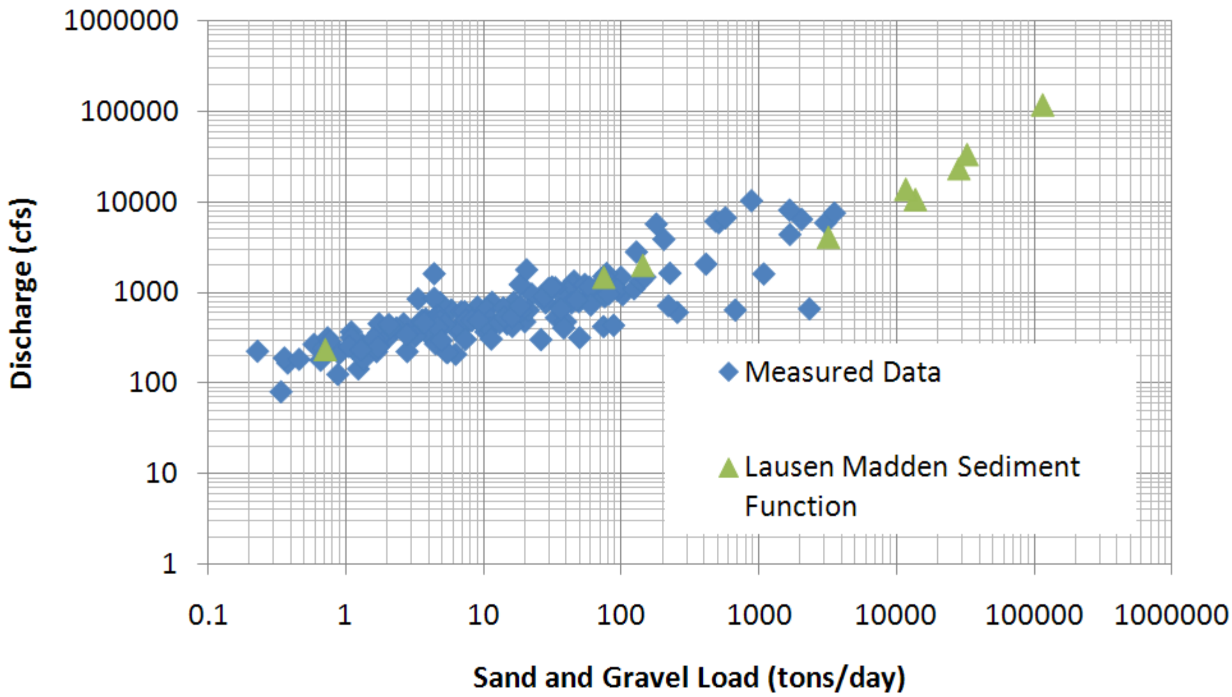


Figure 3.5-7. Sediment Rating Curve for the San Antonio River at Goliad

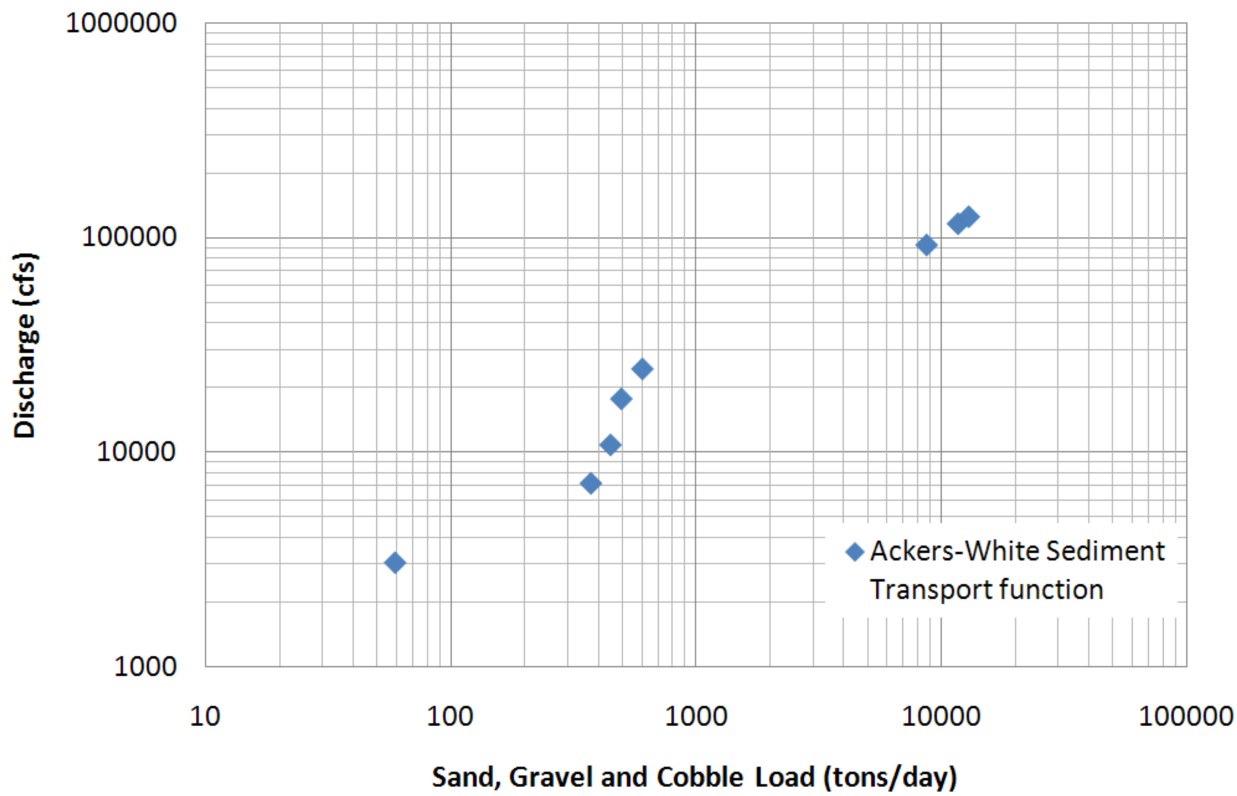


Figure 3.5-8. Sediment Rating Curve for the Guadalupe River at Cuero

3.5.6 Hydrologic Time Series

In addition to the sediment rating curves discussed in the previous section, a flow duration curve developed from a time series of flow values is required in order to compute effective discharge. The hydrologic time series can be daily, hourly, 15 minute, etc., depending on flow characteristics of the stream. Daily time step data was available at both the Goliad and Cuero sites and flow characteristics of the streams are such that the daily flow is a fairly accurate description of the flow regime. Smaller time steps are required when the flow events rise and fall within a short time span and are not accurately reflected in the average daily flow computation.

The first hydrologic scenario considered in this analysis was the baseline hydrologic condition selected by the GSA BBEST. In order to be consistent with other hydrologic scenarios, historical daily flows from the time period 1934-1989 were desired in order to represent baseline conditions at both sites. Historical gaged data is available at the Goliad site from February 1939 and the Cuero site from January 1964. Daily flow values before these dates were estimated back to 1934 for the Goliad site, but could only be estimated back to 1936 for the Cuero site. Therefore, baseline hydrologic scenarios for the sites included both estimated and gaged values for the periods 1934-1989 and 1936-1989 for the Goliad and Cuero sites, respectively.

A second hydrologic scenario for each site was analyzed, corresponding to conditions prior to substantial alteration of hydrologic conditions at each site due to human development in the basin. For the San Antonio River at Goliad, daily gaged flow values from 1940 to 1969 were used to represent this scenario. During this time period, the population of the City of San Antonio was less than half its current value; groundwater pumping was smaller, resulting in lower return flows and lower impacts on springs; and the region experienced the drought of record in the early 1950's. For the Guadalupe River at Cuero, estimated historical flow values from 1936 to 1964 were used to represent this scenario. This period occurred before completion of Canyon Reservoir in 1965, the largest impoundment in the basin. These estimated historical flow values were the same as those used by TPWD to develop the HEFR flow regime.

A third hydrologic scenario based on more recent historical conditions was analyzed for each site. This scenario was obtained from historical gaged data for the San Antonio River at Goliad from 1970 to 2009 and for the Guadalupe River at Cuero from 1965 to 2009.

A fourth hydrologic scenario was based on "Natural" flow conditions at both sites. Data for this scenario was provided by Kennedy Resource Company (KRC) based on Water Availability Model (WAM) results with monthly flow outputs converted to daily flows. Monthly flow volumes were disaggregated to daily flow values based on flow patterns from USGS gage locations, using historically gaged data or estimates of daily flow patterns during periods when gages were not active. The "Natural" hydrologic scenario corresponds to naturalized flow conditions from the WAM, with no surface water rights exercised, no return flows in the basin, and spring flow rates in the basin adjusted to remove the effects of pumpage from the Edwards Aquifer. The time period for this scenario was 1934 to 1989.

A fifth hydrologic scenario representing "Present" conditions was provided by KRC based on WAM results with current demands for all water rights, consistency with Region L planning assumptions, return flows and spring flows adjusted to reflect current conditions, and storage volumes of major reservoirs adjusted to current sediment conditions. Monthly flows were disaggregated to daily flow values covering the time period from 1934 to 1989.

A sixth hydrologic scenario representing “Region L Baseline” planning conditions was provided by KRC based on WAM results with full authorized demands for all water rights, consistency with Region L planning assumptions, return flows and spring flows adjusted to reflect current conditions, and storage volumes of major reservoirs set at their fully authorized values. Monthly flows were disaggregated to daily flow values covering the time period from 1934 to 1989.

A seventh hydrologic scenario representing the potential impact of an example water project was developed for each site. This was actually a set of scenarios that varied slightly by project configuration and environmental flow requirements. “Example Project” scenarios were based on WAM results using the same assumptions as the Region L Baseline scenario, but with the addition of an example project in either the San Antonio or Guadalupe River Basins. For the San Antonio River Basin, the example project consisted of a reservoir on the mainstem of the river near Goliad with a specified storage volume and unlimited diversion rate. For the Guadalupe River Basin, the example project consisted of an off-channel reservoir near Cuero with a specified storage volume and diversion rate. Several variations on the example project scenario were analyzed, based on different values for the storage volume for the Goliad site and different values for the maximum diversion rate for the Cuero site. Scenarios also differed by the environmental flow restrictions that were imposed. One environmental flow restriction, labeled as 2-HFP HEFR, included subsistence, base, and two levels of HFPs. Base flow and HFP requirements varied by hydrologic condition (dry, average, or wet). A second environmental flow restriction, labeled as 5-HFP HEFR, included subsistence, base, and five levels of HFPs. With these restrictions, base flow varied by hydrologic condition (dry, average, or wet) but HFPs were required whenever their trigger conditions (based on flow) were met, regardless of hydrologic condition. Differences between the various example project scenarios are shown in Table 3.5-2. Differences in the environmental flow recommendations are shown in Tables 3.5-3 and 3.5-4. With the project hydrologic scenarios, flow in the river at the Goliad or Cuero sites would be a combination of water being released to 1) supply senior water rights downstream, 2) be consistent with project limits on storage volumes or diversion rates, or 3) comply with environmental flow recommendations.

The “HEFR Only” scenarios were based on daily flows (either historically gaged or estimated) reduced to the minimum values protected by the two different environmental flow recommendations described previously. All flow recommendations included subsistence, base, and higher pulse flows. Recommendations differed by the number of higher pulse flows that would be protected and the conditions when they would be required. Differences between the various recommendations are shown in Tables 3.5-3 and 3.5-4. With the HEFR Only scenarios, flow in the river at the Goliad or Cuero sites would be limited to the amount of flow required to comply with environmental flow recommendations only (i.e. no additional amount related to supplying senior water rights downstream or spillage due to limited diversion rates or storage capacities upstream).

The flow duration curves used for the effective discharge calculations for the two study sites are shown in Tables 3.5-5 and 3.5-6. Flow duration curves for the calculations involving example water projects and “HEFR Only” scenarios were derived using the Flow Regime Application Tool (FRAT) originally developed by HDR Engineering, Inc. and substantially enhanced by Texas Parks and Wildlife Department. Electronic files documenting FRAT analyses performed at the request of the GSA BBEST to support its geomorphology overlay are included in Appendix 3.5-1.

Table 3.5-2 Example Project Scenarios for San Antonio and Guadalupe River Basins

Location	Project	Storage Volume [ac-ft]	Maximum Diversion Rate [cfs]	HEFR Levels of HFP	Hydrologic Scenario
San Antonio River at Goliad	Mainstem Reservoir	707,615	Unlimited	2	Project A
		707,615	Unlimited	5	Project B
		600,000	Unlimited	5	Project C
		500,000	Unlimited	5	Project D
		300,000	Unlimited	5	Project E
		200,000	Unlimited	5	Project F
		100,000	Unlimited	5	Project G
		80,000	Unlimited	5	Project H
Guadalupe River at Cuero	Off-Channel Reservoir	583,975	1,610	2	Project A
		583,975	3,000	5	Project B
		583,975	1,800	5	Project C
		583,975	1,610	5	Project D
		583,975	1,400	5	Project E
		583,975	400	5	Project F

Table 3.5-3. Environmental Flow Recommendations for San Antonio River at Goliad

2-HFP and 5-HFP Recommendations						High Flow Pulse 1*				High Flow Pulse 2**				5-HFP Recommendation Only				
Season	**Months**	**Subsistence Flow (cfs)**	**Dry Base Flow (cfs)**	**Average Base Flow (cfs)**	**Wet Base Flow (cfs)**	**Frequency (# per season)**	**Peak (cfs)**	**Duration (days)**	**Volume (ac-ft)**	**Frequency (# per season)**	**Peak (cfs)**	**Duration (days)**	**Volume (ac-ft)**	Overbank Flow	**Return Period (years)**	**Peak (cfs)**	**Duration (days)**	**Volume (ac-ft)**
Winter	Jan-Mar	84	169	263	336	2	782	7	6,305	1	1,610	11	16,812	1	1	8,360	23	104,363
Spring	Apr-Jun	65	143	224	308	2	1,920	9	16,119	1	4,500	14	45,161	2	2	12,600	29	172,067
Summer	Jul-Sep	62	130	178	240	2	779	6	5,541	1	2,010	11	18,176	3	5	21,000	39	320,693
Fall	Oct-Dec	81	187	250	315	2	1,130	7	8,894	1	2,930	12	28,040					

* For 2-HFP Recommendation, pulse occurs once or twice during dry or average hydrologic conditions, respectively.

** For 2-HFP Recommendation, pulse occurs only during wet hydrologic conditions.

Table 3.5-4. Environmental Flow Recommendations for Guadalupe River at Cuero

2-HFP and 5-HFP Recommendations						High Flow Pulse 1*				High Flow Pulse 2**				5-HFP Recommendation Only				
Season	**Months**	**Subsistence Flow (cfs)**	**Dry Base Flow (cfs)**	**Average Base Flow (cfs)**	**Wet Base Flow (cfs)**	**Frequency (# per season)**	**Peak (cfs)**	**Duration (days)**	**Volume (ac-ft)**	**Frequency (# per season)**	**Peak (cfs)**	**Duration (days)**	**Volume (ac-ft)**	Overbank Flow	**Return Period (years)**	**Peak (cfs)**	**Duration (days)**	**Volume (ac-ft)**
Winter	Jan-Mar	134	550	763	978	2	1,610	6	14,126	1	4,610	12	55,284	1	1	16,600	23	246,759
Spring	Apr-Jun	118	413	677	938	2	3,370	8	31,782	1	8,873	15	110,152	2	2	24,726	29	406,298
Summer	Jul-Sep	131	386	602	800	2	1,050	5	8,302	1	2,110	7	19,318	3	5	45,400	42	869,212
Fall	Oct-Dec	86	480	673	865	2	1,730	6	14,101	1	5,195	11	54,653					

* For 2-HFP Recommendation, pulse occurs once or twice during dry or average hydrologic conditions, respectively.

** For 2-HFP Recommendation, pulse occurs only during wet hydrologic conditions.

Table 3.5-5. Flow Duration Statistics for Hydrologic Scenarios for the San Antonio River at Goliad

Percent of Time Flow equaled or Exceeded	Flow %-ile	Historical Flows 1934-1989 Baseline	1940-1969	1970-2009	Natural	Present	Region L Baseline	Project A	Project B	Project C	Project D	Project E	Project F	Project G	Project H	2-HFP HEFR	5-HFP HEFR
		Flow in cfs															
100%	0%	2	2	53	4	10	10	10	10	10	10	10	10	10	10	10	10
95%	5%	92	76	167	101	102	92	84	86	86	86	86	86	86	86	65	60
90%	10%	121	102	216	144	130	113	106	110	110	110	110	110	110	110	81	76
85%	15%	148	123	246	174	152	130	126	126	126	126	126	126	126	127	84	116
80%	20%	172	142	279	202	174	147	139	134	134	134	135	136	137	137	130	128
75%	25%	198	159	309	235	194	164	151	145	146	146	147	148	151	153	138	129
70%	30%	225	178	338	268	218	183	169	154	154	155	156	158	163	166	143	134
65%	35%	250	198	371	300	240	203	178	169	171	172	174	176	180	180	169	146
60%	40%	277	218	401	327	266	225	187	180	180	180	182	186	197	198	178	154
55%	45%	306	240	438	356	293	245	209	195	197	198	198	198	200	200	178	169
50%	50%	334	263	479	388	319	271	224	198	198	198	200	200	214	223	197	180
45%	55%	367	285	524	424	345	299	240	200	200	200	210	223	243	255	224	196
40%	60%	403	310	574	470	381	329	250	211	223	223	237	258	277	284	224	198
35%	65%	452	338	641	521	423	367	263	230	251	266	275	284	298	311	240	200
30%	70%	508	376	730	579	472	417	286	272	284	284	287	311	351	362	250	200
25%	75%	578	425	841	660	542	486	315	287	287	305	356	383	421	432	253	223
20%	80%	691	506	1010	778	647	590	336	339	383	412	462	486	526	537	263	272
15%	85%	870	630	1260	956	832	750	446	502	547	564	613	639	685	694	308	284
10%	90%	1210	860	1740	1305	1184	1047	664	748	774	788	857	889	950	966	315	287
5%	95%	2170	1630	3180	2384	2232	1967	1132	1430	1485	1520	1588	1640	1772	1817	336	748
0%	100%	121000	121000	62000	121521	120134	118681	42008	31732	31744	45828	82564	87678	108498	113144	4500	23600

Table 3.5-6. Flow Duration Statistics for Hydrologic Scenarios for the Guadalupe River at Cuero

Percent of Time Flow equaled or Exceeded	Flow %-ile	Historical Flows 1936-1989 Baseline Flow in cfs	1936-1964	1965-2009	Natural	Present	Region L Baseline	Project A	Project B	Project C	Project D	Project E	Project F	2-HFP HEFR	5-HFP HEFR
100%	0%	7	7	28	1	1	1	1	1	1	1	1	1	1	1
95%	5%	165	128	351	278	94	93	93	93	93	93	93	93	86	86
90%	10%	304	210	466	401	178	175	163	163	163	163	163	163	118	118
85%	15%	407	305	548	508	262	252	231	231	231	231	231	231	131	131
80%	20%	494	367	611	603	343	329	306	307	307	307	307	307	200	202
75%	25%	564	442	686	671	404	391	372	372	372	372	372	372	362	362
70%	30%	622	511	761	733	458	442	418	420	421	421	421	426	413	413
65%	35%	692	567	822	811	516	497	478	480	480	480	480	480	445	457
60%	40%	765	619	883	893	593	574	536	544	544	544	544	550	497	512
55%	45%	832	685	970	971	666	650	602	602	602	602	602	602	553	583
50%	50%	900	752	1080	1043	736	721	649	657	657	656	656	673	602	602
45%	55%	998	839	1210	1132	821	805	677	677	677	677	677	699	646	673
40%	60%	1130	934	1350	1251	934	918	751	763	763	763	763	763	673	673
35%	65%	1272	1054	1530	1387	1068	1053	800	823	822	822	814	848	677	677
30%	70%	1440	1201	1710	1547	1225	1209	937	954	938	938	938	959	677	721
25%	75%	1634	1346	1950	1741	1425	1408	1091	1131	1109	1107	1103	1117	746	763
20%	80%	1891	1569	2260	2033	1702	1681	1381	1437	1411	1404	1407	1433	763	800
15%	85%	2273	1950	2840	2428	2090	2067	1753	1782	1777	1780	1787	1797	800	912
10%	90%	2950	2569	4310	3174	2770	2742	2417	2458	2483	2491	2495	2529	928	1050
5%	95%	5289	4414	7180	5593	4910	4869	4400	4407	4468	4496	4514	4621	978	2408
0%	100%	123141	123141	338000	123819	121374	120675	120604	120612	120619	120620	120622	120527	8873	45400

3.5.6.1 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 classes or intervals) 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 2 from 2,000 to 4,000 cfs, and so forth until bin 50, which encompasses 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 the 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 also found that in channels where the effective discharge corresponded relatively close 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. However, as a first step, the bed material load histogram can be analyzed to insure that 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 effective discharge computed flow 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 1 to 3 year return frequencies. Discharges outside the 1 to 3 year return frequency range should be queried (Biedenharn et al. 2000).

3.5.6.2 Effective Discharge Results

The results of the SAMWin computations for both sites for all hydrologic scenarios investigated are shown in Table 3.5-7. Sediment load histograms for select hydrologic scenarios are shown on Figures 3.5-9 through 3.5-16.

Table 3.5-7. Results of SAM Analysis for Hydrologic Scenarios Investigated

Flow Scenario	Avg. Annual Water Yield (ac-ft/year)	Avg. Annual Sediment Yield (tons/year)	Effective Discharge (cfs)	Sediment Load in Effective Discharge Bin (tons)	Annual Frequency of Effective Discharge	Partial Duration Frequency of Effective Discharge
San Antonio River at Goliad						
1. 1934-1989 Baseline	549,443	142,011	6,052	19,785		
2. 1940-1969	446,264	129,789	8,472	16,310	2.5	2
3. 1970-2009	750,044	166,367	5,629	12,644	1.5	1
4. Natural	615,478	153,959	6,080	22,875		
5. Present	544,885	141,036	6,016	19,032		
6. Region L Baseline	496,398	133,144	5,944	18,345		
7. Project A	329,450	59,844	4,630	3,213		
Project B	351,673	70,467	4,134	3,489		
Project C	360,832	71,678	4,771	3,357		
Project D	381,077	80,864	5,050	4,847		
Project E	404,395	104,279	7,441	9,013		
Project F	422,934	110,162	4,394	10,343		
Project G	449,811	123,832	5,435	15,781		
Project H	459,085	126,813	5,667	16,910		
8. 2-HFP HEFR	170,315	2,882	4,455	156		
5-HFP HEFR	224,936	36,401	4,728	1,072		
Guadalupe River at Cuero						
1. 1936-1989 Baseline	1,291,162	15,734	7,395	3,753		
2. 1936-1964	1,120,842	14,064	7,395	2,295		
3. 1965-2009	1,503,883	17,026	7,527	6,911	1.25	0.75
4. Natural	1,409,278	16,844	7,431	3,885		
5. Present	1,157,362	14,869	7,283	3,251		
6. Region L Baseline	1,142,206	14,699	7,242	3,225		
7. Project A	1,028,316	13,667	7,237	2,754		
Project B	1,033,748	13,565	7,238	2,654		
Project C	1,037,060	13,754	7,238	2,820		
Project D	1,037,800	13,793	7,239	2,865		
Project E	1,039,462	13,841	7,239	2,861		
Project F	1,056,514	14,089	7,183	2,977		
8. 2-HFP HEFR	434,786	615	3,373	165		
5-HFP HEFR	657,629	4503	6357	626		

3.5.6.3 San Antonio River at Goliad

SAMWin computations were completed for the hydrologic scenarios below (described previously):

1. Baseline historical (1934-1938 estimated, 1939-1989 gaged)
2. Historical gaged flow (1940 – 1969)
3. Historical gaged flow (1970 – 2009)
4. Naturalized flows from WAM model (1934-1989)
5. Present condition from WAM model (1934-1989)
6. Region L Baseline from WAM model (1934-1989)
7. Example project (mainstem reservoir near Goliad with unlimited diversion rate) (1934-1989) Scenarios Project A through H varied by storage volume and HEFR flows (see Table 3.5-2).
8. HEFR Only (1934-1989) (see Table 3.5-3)
   2-HFP HEFR: Subsistence, Base (Dry, Average, and Wet Conditions), and 2 levels of HFPs (Dry, Average and Wet Conditions)
   5-HFP HEFR: Subsistence, Base (Dry, Average, and Wet Conditions), 5 levels of HFPs and Overbank Flows

Results of computations for all scenarios are shown in Table 3.5-7. In addition, sediment histograms derived from SAMWin output for the Baseline Historical, Project H, and 2-HFP HEFR, and 5-HFP HEFR scenarios are shown in Figures 3.5-9 – 3.5-12.

The effective discharges calculated for the historical data all fall within the expected return period frequency ranges of the 1 – 3 year return period events. None of the effective discharges fall within the lowest discharge bin. All of the effective discharges calculated are below the National Weather Service (NWS) flood stage for the San Antonio River at Goliad, which is 8,200 cfs.

Neither of the proposed HEFR only scenarios by themselves provide the variability or magnitude of flows needed to maintain the current channel shape. As seen in Figure 3.5-11 (where the y - axis has been magnified 100 times compared to Figures 3.5-9, -10 and -12), the effective discharge for the 2-HFP HEFR scenario is in the highest discharge bin. This condition is due to the fact that the subsistence and base flows from the HEFR matrix do not produce enough shear stress to move even the smallest bed material sediments at the site. Only the pulse and overbank flows will produce any measurable bed sediment yield. This flow regime would result in major channel instabilities including incision in some areas and aggradation in others and most 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 within the river channel would not be maintained.

As seen in Figure 3.5-12, the sediment histogram for the 5-HFP HEFR Only scenario moves considerably less sediment than the historical baseline condition (Figure 3.5-9). This scenario represents considerable improvement over the 2-HFP HEFR (Figure 3.5-11). However, it would still result in major channel instabilities, as described for the 2-HFP HEFR scenario, and the current aquatic habitats within the river channel would not be maintained.

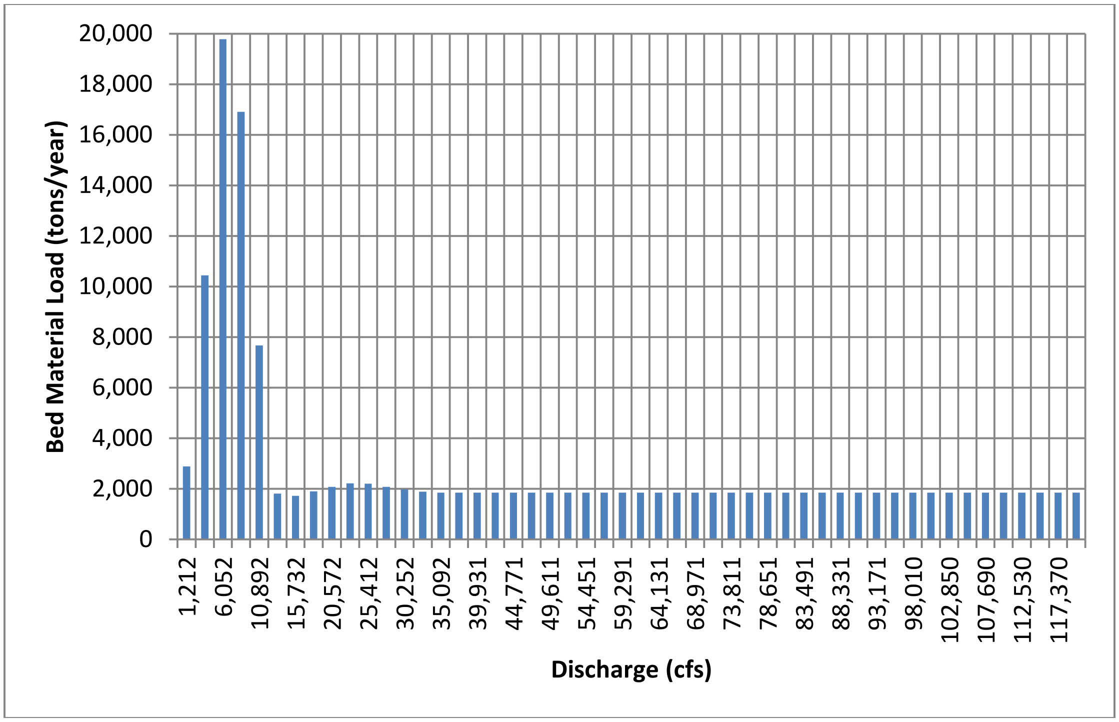


Figure 3.5-9. San Antonio River at Goliad –Baseline Condition (1936 to 1989)

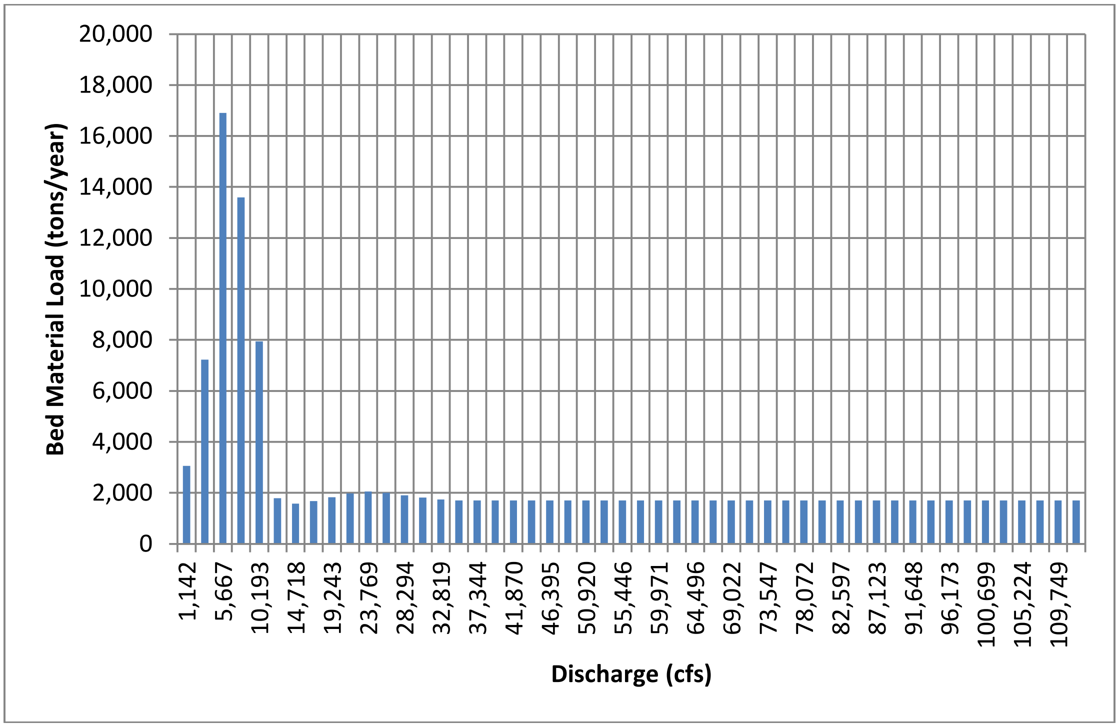


Figure 3.5-10. San Antonio River at Goliad – Example Project H (1934 to 1989)

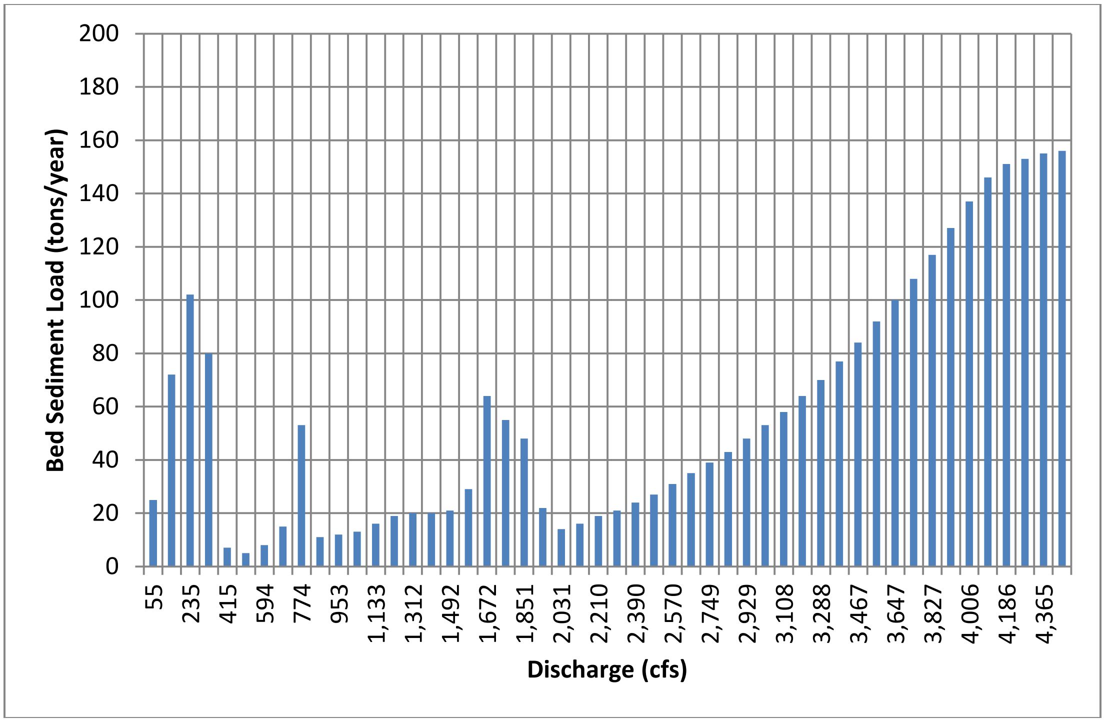


Figure 3.5-11 San Antonio River at Goliad – 2-HFP HEFR Only (1934 to 1989), y-axis magnified 100 times relative to Figures 3.5-9, -10, and -12

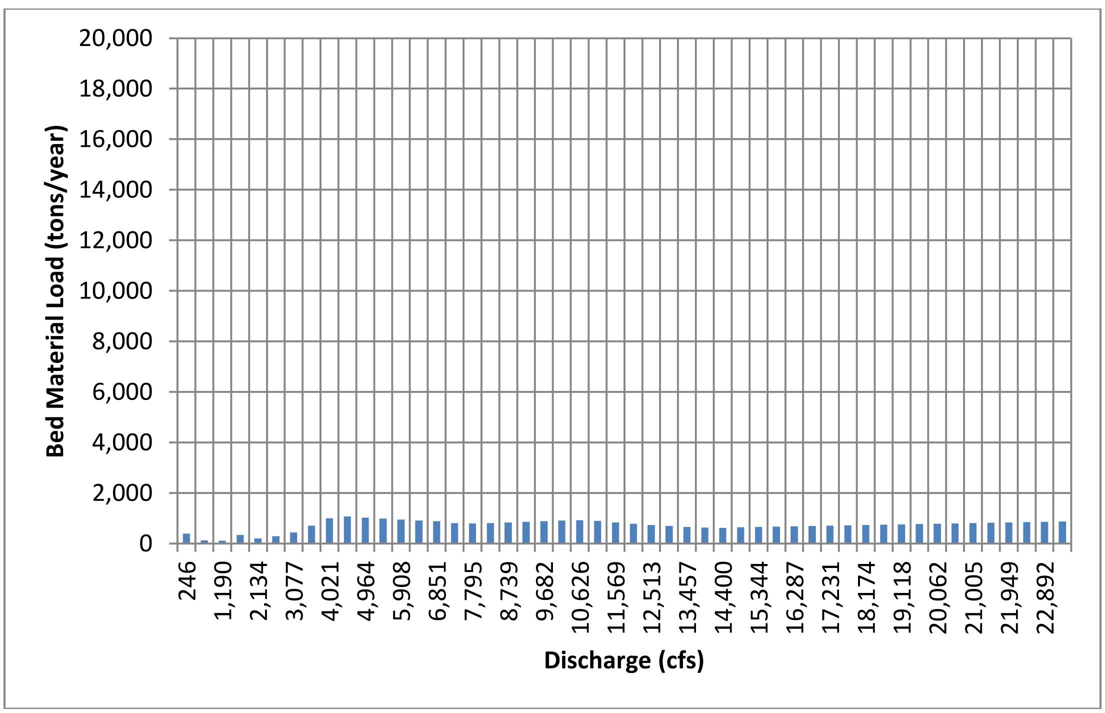


Figure 3.5-12. San Antonio River at Goliad – 5-HFP HEFR Only (1934 to 1989)

3.5.6.4 Guadalupe River at Cuero

SAMWin computations were completed for a number of hydrologic scenarios. These were:

1. Baseline historical (1936-1964 estimated, 1965-1989 gaged)
2. Estimated historical flow (1936 – 1964)
3. Historical gaged flow (1965 – 2009)
4. Naturalized flows from WAM model (1934-1989)
5. Present condition from WAM model (1934-1989)
6. Region L Baseline from WAM model (1934-1989)
7. Example project (off-channel reservoir with reservoir storage of 583,975 ac-ft) (1934-1989) Scenarios Project A through F varied by maximum diversion rate and HEFR flows (see Table 3.5-2).
8. Environmental Flow Recommendations Only (1934-1989) (see Table 3.5-4)
   2-HFP HEFR: Subsistence, Base (Dry, Average, and Wet Conditions), and 2 levels of HFPs (Dry, Average and Wet Conditions)
   5-HFP HEFR: Subsistence, Base (Dry, Average, and Wet Conditions), 5 levels of HFPs and Overbank Flows

Results of computations for all scenarios are shown in Table 3.5-7. In addition, sediment histograms derived from SAMWin output for the Baseline Historical, Project F, and 2-HFP HEFR, and 5-HFP HEFR scenarios are shown in Figures 3.5-13 – 3.5-16.

The effective discharge values calculated for the historical data from 1965 to 2009 falls within the expected return period frequency ranges of 1 – 3 year return period events. None of the effective discharges fall within the lowest discharge bin. All of the effective discharges calculated are below the National Weather Service flood stage for the Guadalupe River at Cuero, which is 14,600 cfs.

Neither of the proposed HEFR Only scenarios by themselves would maintain the current channel shape. As seen in Figure 3.5-15 (where the y - axis has been magnified 10 times compared to Figures 3.5-13, -14 and -16), the effective discharge for the 2-HFP HEFR scenario moves considerably less sediment than the historical baseline condition (Figure 3.5-13). This flow regime would result in major channel instabilities including aggradation in some areas and incision in others and most likely narrowing of the entire channel. Increased rates of channel meandering could occur in areas where channel aggradation occurs. In other areas, incision could cause bank failure due to over steepening of banks. The current aquatic habitats within the river channel would not be maintained.

As seen in Figure 3.5-16, the sediment histogram for the 5-HFP HEFR Only scenario moves considerably less sediment than the historical baseline condition (Figure 3.5-13). This scenario represents considerable improvement over the 2-HFP HEFR (Figure 3.5-15). However, it would still result in major channel instabilities, as described for the 2-HFP HEFR scenario, and the current aquatic habitats within the river channel would not be maintained.

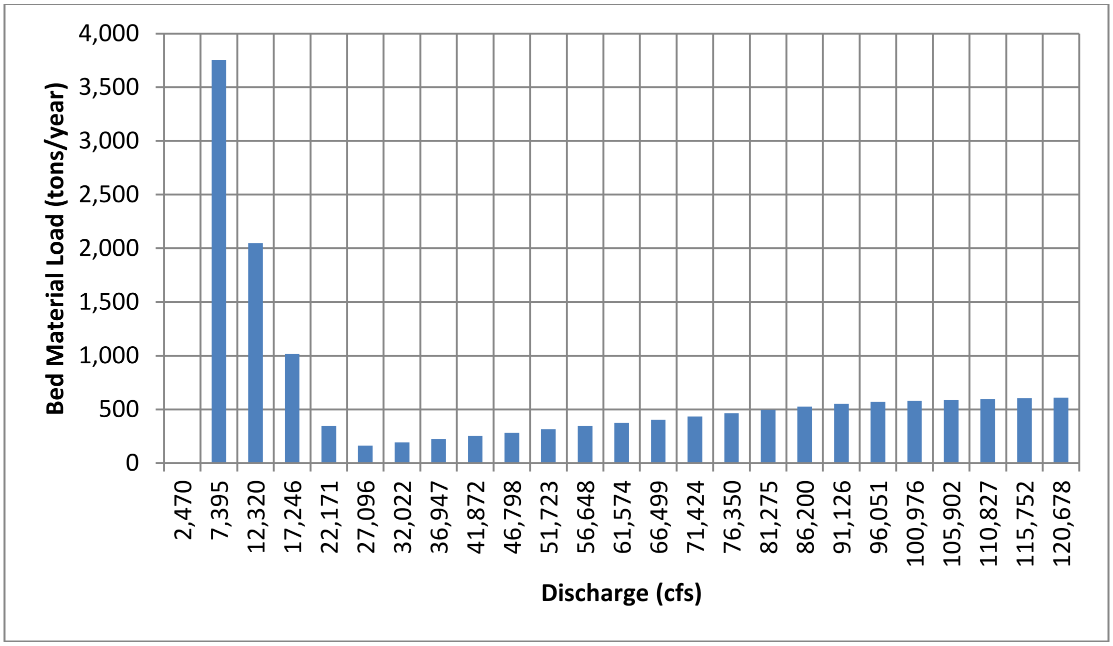


Figure 3.5-13. Guadalupe River at Cuero –Baseline Condition (1936 to 1989)

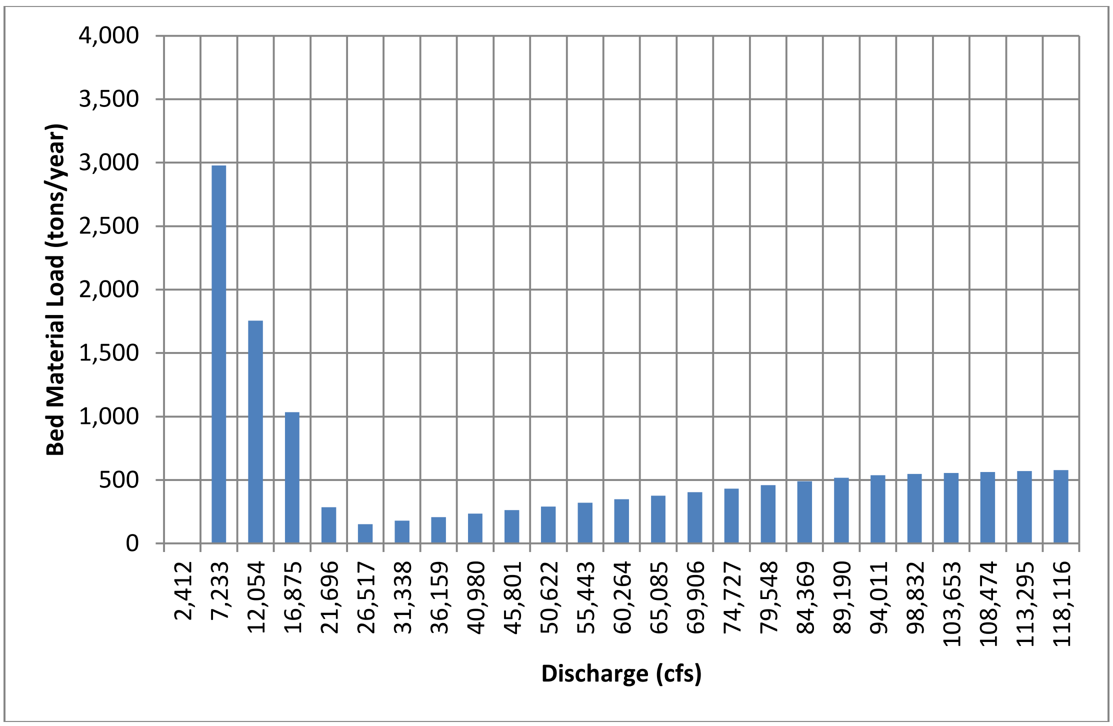


Figure 3.5-14. Guadalupe River at Cuero – Example Project F (1934 to 1989)

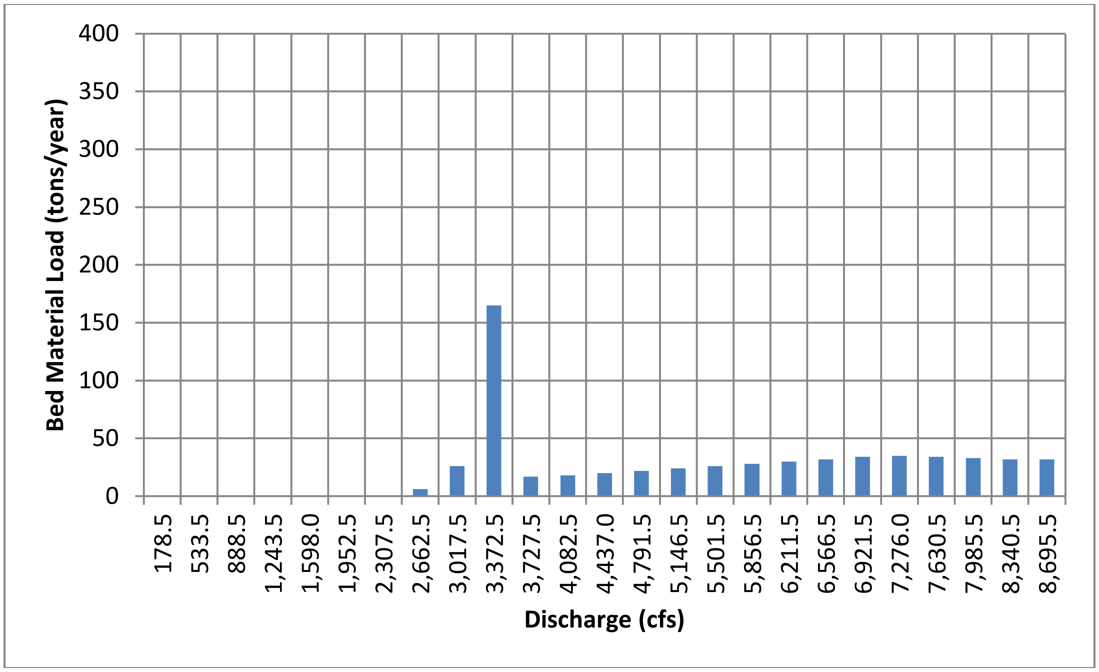


Figure 3.5-15. Guadalupe River at Cuero – 2-HFP HEFR Only (1934 to 1989) y-axis magnified 10 times relative to Figures 3.5-13, -14, and -16

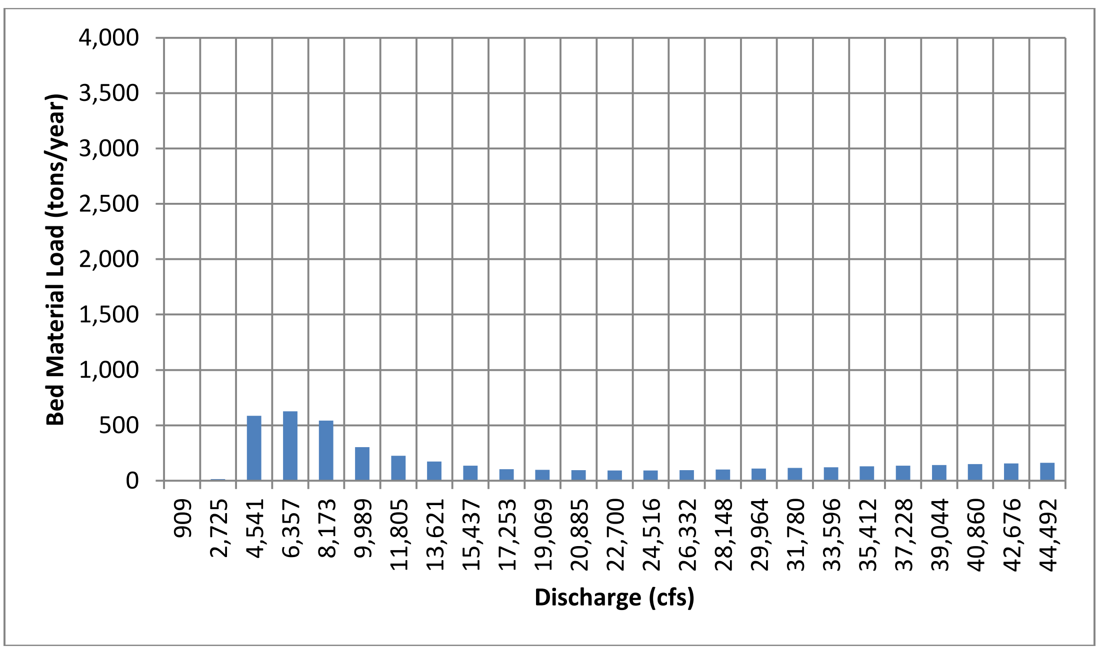


Figure 3.5-16. Guadalupe River at Cuero – 5-HFP HEFR Only (1934 to 1989)

3.5.6.5 Summary Points

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

2. The existing channels at two study sites San Antonio River at Goliad, Guadalupe River at Cuero appear to be stable.

3. A third study site, Guadalupe River above Comal, was not analyzed for this study. This reach of the Guadalupe River is a bedrock controlled channel and the calculation of the effective discharge and average annual sediment load does not provide insight related to environmental flow requirements at this site.

4. Results from the effective discharge calculations for the San Antonio River at Goliad and the Guadalupe River at Cuero show maintaining a flow regime in these reaches of approximately 80% of the average annual water yield that occurred during the hydrologic baseline time period maintains an average annual sediment yield of at least 90% of the baseline condition and maintains the effective discharge within +/- 10%. The flow volume should occur so that daily, monthly and annual regime characteristics for the Baseline Period of Record are simultaneously maintained. These computations compare favorably to recently published journal articles relating environmental flow requirements to channel stability and can be extended to other gaging sites in the Guadalupe and San Antonio River basins. The amount of flow change that each reach of the river can accommodate while remaining stable and in "dynamic equilibrium" may be refined during the adaptive management process.

5. Recommended environmental flow regimes considered adequate to provide for the biological considerations of the system (fish habitat, riparian maintenance, etc.) are not sufficient to maintain the stream channel shape (and therefore aquatic habitats) at the San Antonio River at Goliad and Guadalupe River at Cuero sites.
    a. For the San Antonio River at Goliad, the two HFPs (2 –HFP)HEFR environmental flow regime provides 31% of the average annual flow volume (reduced by 69%) and 2% of the average annual sediment yield (reduced by 98%) as compared to baseline historic gaged flow data (1934-1989).
    b. The five HFPs and overbank flows (5-HFP) HEFR environmental flow regime provides 41% of the average annual flow volume (reduced by 59%) and 26% of the average annual sediment yield (reduced by 74%) as compared to baseline historic gaged flow data (1934-1989).
    c. For the Guadalupe River at Cuero, the 2-HFP HEFR environmental flow regime provides 34% of the average annual flow volume (reduced by 66%) and 4% of the average annual sediment yield (reduced by 96%) as compared to estimated baseline historic flow data (1936-1989).
    d. The 5-HFP HEFR environmental flow regime provides 51% of the average annual flow volume (reduced by 49%) and 29% of the average annual sediment

yield (reduced by 71%) as compared to estimated baseline historic gaged flow data (1934-1989).

6. In order to adequately maintain the channel shape and therefore the aquatic habitats necessary to provide for a sound ecological environment, additional flow beyond the amount protected by environmental flow recommendations exclusively will be required. The resulting flow regime (recommended environmental flows for biological purposes plus additional flow for geomorphic purposes) should result in a similar effective discharge as the baseline condition for each site and an average annual sediment yield of at least 90% of the baseline condition (no more than a 10% decrease from baseline condition). Computations show that maintaining an average annual yield of water equal to 80% of baseline average annual yield should maintain the required sediment balance.

7. Depending on the infrastructure (storage volume and diversion rate), current configuration of senior water rights in the basin, and environmental flow criteria; this study shows that options exist for future water projects that maintain channel stability in the basin.

3.5.6.6 Conclusions

The effective discharge computations show:

1. Maintaining a flow regime of approximately 80% of the average annual water yield that occurred during the hydrologic baseline time period would maintain an average annual sediment yield of at least 90% of the baseline condition and an effective discharge within +/- 10% of that provided by the baseline condition.
2. HEFR Only flow scenarios considered adequate to provide for the biological considerations of the system (fish habitat, riparian maintenance, etc.) are not sufficient to maintain the stream channel shape (and therefore aquatic habitats) at the San Antonio River at Goliad and Guadalupe River at Cuero sites. These flow scenarios would result in major channel instabilities and would not maintain the current aquatic habitats within the river.
3. In order to adequately maintain the channel shape and therefore the aquatic habitats necessary to provide for a sound ecological environment, additional flow beyond the amount protected by HEFR Only flows would be required.
4. Depending on the infrastructure (storage volume and diversion rate), current configuration of senior water rights in the basin, and environmental flow criteria; flow scenarios representing future water projects that maintain channel stability can be developed.
5. For the San Antonio River at Goliad, hydrologic scenarios based on historical data (1934-1989, 1940-1969, and 1970-2009) and WAM output (Natural, Present, and Region L Baseline conditions) show very similar effective discharge and water and sediment yield values. For these scenarios, the channel should maintain its existing "dynamic equilibrium." Example Project scenarios show a reduction in effective discharge and water and sediment yield. By adjusting storage volume, a Project scenario that maintains effective discharge, and water and sediment yield can be developed.
6. For Guadalupe River at Cuero, hydrologic scenarios based on historical data (1936-1989, 1936-1964, and 1964-2009) and WAM output (Natural, Present, and Region L Baseline

conditions) show very similar effective discharge and water and sediment yield values. For these scenarios, the channel should maintain its existing "dynamic equilibrium." Example Project scenarios show reductions in sediment yield. By adjusting the maximum diversion rate, a Project scenario that maintains sediment yield can be developed.

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, these techniques have been utilized to the full extent that they can reasonably be expected to provide useful, valid and supportable results. As noted by Shafroth et al. (2009), approaches that account for geomorphic processes (including models of sediment transport, channel migration and sediment budgets) hold great potential for advancing efforts to link flow variables and flow regime changes to changes in channel geometry, aquatic habitats, and biotic responses, thereby strengthening the scientific basis of environmental flow assessments and implementation strategies. The development of basin-wide sediment transport models should be considered in order to more accurately account for geomorphic processes during future study efforts.

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 for the Guadalupe and San Antonio basins are unknown at this time. Those details may greatly influence the flow regimes (particularly the pulse and overbank flow components) that are actually achieved at locations within the basin and therefore the extent to which channel change may or may not occur. Analysis of HEFR Only flow scenarios at select sites in the basin has determined that these flows alone would not be sufficient to maintain the current physical characteristics of the channel. Failure to maintain the physical characteristics of the channel would inherently alter the aquatic and riparian habitats within the basin. However, depending on the scheme used to implement environmental flows, there is a high probability that in the future the channel would continue to receive considerable flow in excess of the HEFR Only flows. It is unknown at present what the future flow regime may look like, and therefore, it is unknown if it would be sufficient to maintain the physical characteristics of the channel.

3.6 Riparian Biological Overlay

3.6.1 Overview of Approach

The primary intent of this process involves developing an environmental flow regime parameterized for these basins that will support a sound ecological environment, which may be described as a *resilient, functioning ecosystem characterized by intact, natural processes, and a balanced, integrated, and adaptive community of organisms comparable to that of the natural habitat of a region.* See Section 1.3 for the GSA BBEST definition and discussion of sound ecological environment. To achieve this goal *requires maintaining the ecological integrity and conserving the biological diversity of a riverine ecosystem*. In the context of riparian corridors, maintaining connectivity between the stream system and adjacent floodplain is imperative as they naturally function and development in an integrated manner. This section is organized to provide the following: a general overview of riparian systems using available published literature, synthesis of published accounts evaluating riparian shifts in structure and function in response to natural and altered hydrologic flow regimes, and an introduction to the limited published studies and datasets to characterize and compare the San Antonio, Guadalupe, Mission, and Aransas watersheds.

3.6.2 Riparian Definition and *Importance*

Riparian ecosystems are generally defined as being situated along river and stream courses, occurring in the transition zone between the aquatic and upland areas in the landscape (Figure 3.6-1). They are often related to their linear configuration, and variously described as riparian corridors. Their position and orientation is closely tied to their function and value in the landscape. The physical structure of the riparian zone is usually defined in relation to the vegetation composition, where a distinct assemblage of woody species tolerant of periodic flooding occurs or, alternatively, where woody species that can also occur in upland areas exhibits increased productivity and size as a result of more dependable water availability (Naiman and Décamps 1997). Riparian and wetland communities within the floodplain have been differentiated using hydrology. Both communities are affected by overbank flooding, however, water generally drains off of riparian areas, whereas, standing water may be retained in the depressional wetlands for prolonged periods of time (Arthington and Zalucki 1998).

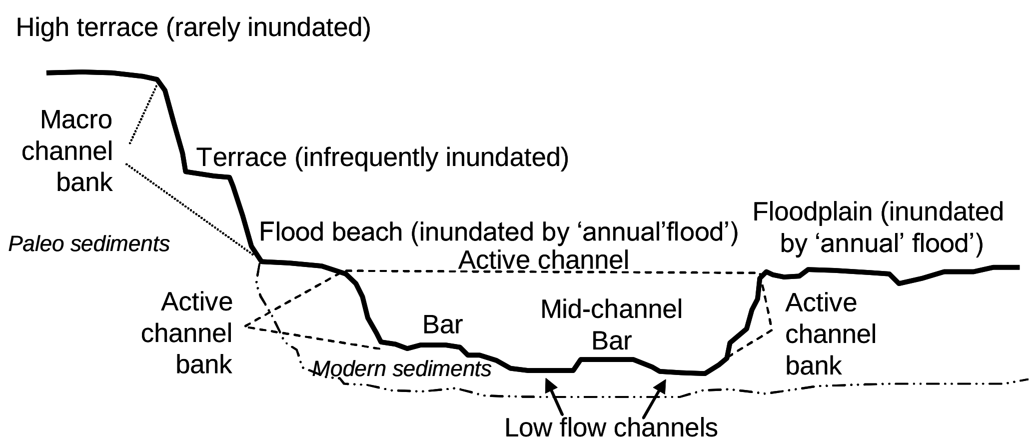


Figure 3.6-1. Cross-section morphology of conceptual river valley depicting two terrace levels, flood beach, and floodplain where riparian communities would develop (modified from King et al. 2003).

In general, riparian ecosystems occur in the western half of the United States, where semi-arid conditions prevail and flooding may not occur every year. This definition provides a general distinction from bottomland hardwood ecosystems in the eastern portion of the country, which receives periodic flooding and prolonged duration at some point during the growing season.

Several processes have been described for riparian ecosystems determining the successional progression and distribution limits of riparian vegetation including the configuration of geomorphic structures (Naiman et al. 2010), tolerance of waterlogged soils, frequency of flood disturbance (Auble et al. 1994, 1997), and effect of stream flow on organic matter redistribution within the riparian zone (Minshall et al. 1985; Naiman and Décamps 1997). Sediment erosion and deposition processes have been considered one of the most important factors contributing to river morphology (Hupp and Osterkamp 1985; Heitmuller and Hudson 2009), whereas geology and climate have been proposed as the most constant factors influencing the formation of watersheds, upland landforms, and riparian landforms. The structures, patterns, and processes that form, reshape, and maintain riverine ecosystem vary across time and space (Table 3.6-1). These processes form diverse mosaic patterns of riparian associations that may differ from each other and upland environments. Since the riparian zone is part of the drainage floodplain, this system may exhibit a complex mosaic of channels, islands, ridges and swales, cut-off channels (oxbow lakes, resacas), and terraces (Naiman and Décamps 1997).

One of the simplest examples of riparian vegetation establishment relates to the movement of water through the river channel. Even in channels with little sinuosity, the thalweg (deepest water in the channel) moves from one side to the other and sediment is alternately scoured and deposited along the stream channel (Figure 3.6-2a). These depositional areas provide new sediment where subsurface water is available for wetland and riparian vegetation establishment. In areas where elevation gradients are low (as in coastal plains), sinuosity increases and point bar formation can be extensive. A cross-section profile of the point bar area reveals the steep bank of the eroding side of the channel and wider floodplain of the accreting point bar (Figure 3.6-2b) (Leopold 1994). Environmental flow regimes (subsistence, base, pulse, and overbank) are associated with the elevation profile and surfaces flows of the river (SAC 2009). The accretion of the point bar over time is a result of continual channel migration, eroding the steep banks and depositing sediments on the point bars (Figure 3.6-2c) (Leopold 1994). Channel migration is essential to maintain diverse habitats within the stream channel and adjacent floodplain, and variable flows are essential to maintain a sound ecological environment.

Table 3.6-1. Major phenomena responsible for driving processes and resulting structural patterns in riverine systems (adapted from Ward et al. 2003).

Time Scale	Phenomenon
Seasonal	Spates, flow pulses, channel expansion/contraction
Annual	Flood pulse, seedling establishment, animal migration, reproduction, shallow ground water exchange
Decadal	Drought cycles, episodic events (extreme floods, debris flows), lateral channel migration, channel avulsion, island formation, channel abandonment
Centennial	Floodplain formation, hydrosere and riparian succession, deep ground water exchange
Millennial	Terrace formation, glaciation, climate change, sea level fluctuation, orogeny

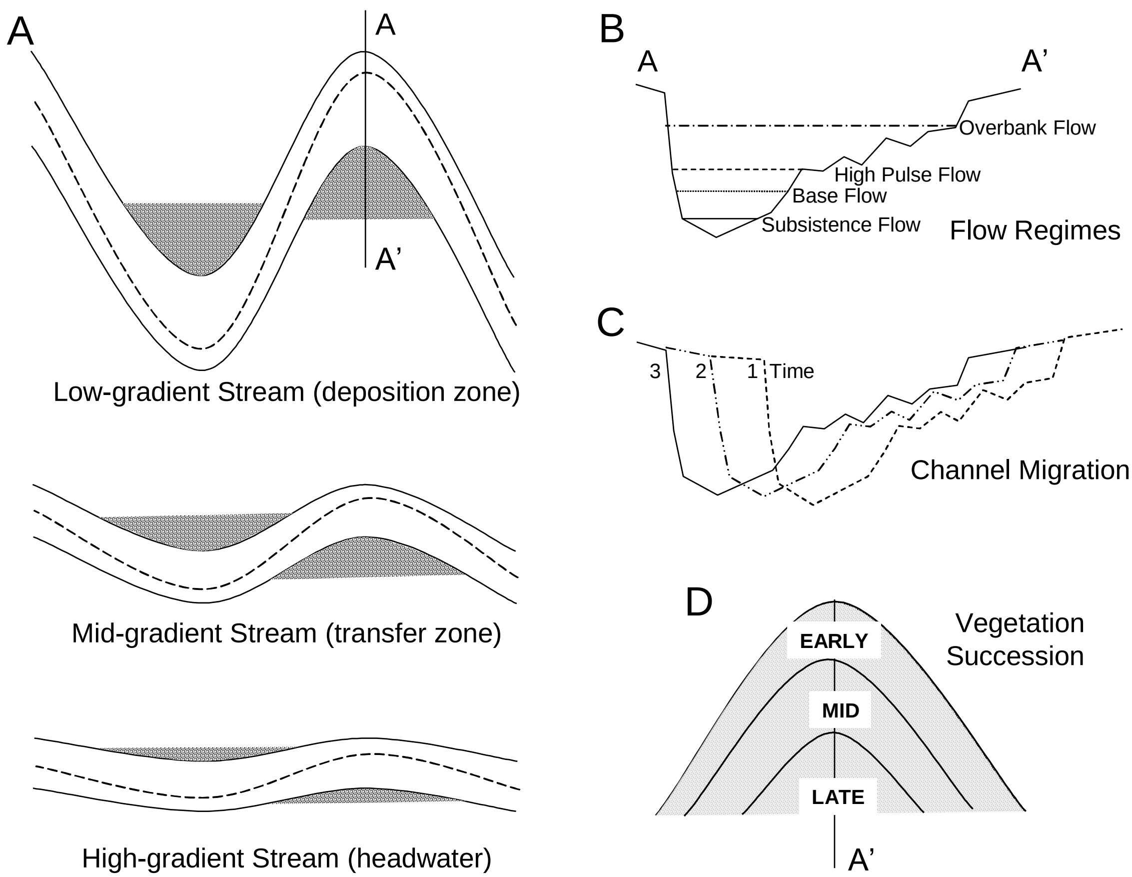


Figure 3.6-2. Geomorphology of river systems describing a) various degrees of river sinuosity and development of point bars on which riparian vegetation will establish, thalweg (deepest part of river channel) is shown as dotted line; b) profile view of a low-gradient stream meander with associated flow regime levels; c) time-lapse scenarios illustrating the continual channel migration at meander bend (modified from Leopold 1994); and, d) riparian vegetation establishment on the point bar over time relating to channel migration (Day et al. 1988).

These geomorphic features provide the physical topography and hydrologic energy to drive successional phases at different rates and levels of maturity (Naiman et al. 2010). In areas along the river bank that have been recently created as a result of sediment deposition, colonizing vegetation quickly can become established (Figure 3.6-2a, d) (Leopold 1994). Willow and cottonwood species often comprise the initial woody vegetation establishment (Johnson et al. 1976; Day et al. 1988; Auble et al. 1997; Boudell and Stromberg 2008), where seedlings receive high light and saturated soil conditions to establish, saplings are resistant to moderate flooding, and competition from other species for resources is minor (Naiman et al. 2010). As the point bar accretion occurs over time and new sediment is deposited, riparian vegetation succession continues in areas landward of the new point bars. Under natural conditions, mature riparian communities may develop in the older point bar depositions (Figure 3.6-2d) as a result of increased fertility of soils, increased elevation from sediment deposition during flooding, and relative protection from high-velocity floodwaters (Day et al. 1988). Several factors can limit community succession progressing to late stages including repeated flooding and prolonged submergence, removal by herbivorous animals, or lowering of alluvial water table during summer and droughts.

Successional processes can follow two pathways that are dependent on the flow regimes and hydrological patterns of the watershed. Cyclical succession typically occurs where the natural flooding regime periodically creates erosion and deposition of sediments within the floodplain, and either removing or burying existing vegetation. These processes effectively set back the maturation and replacement of short-lived, colonizing species with long-lived, competitive species. Directional succession usually occurs on terraces farther from the active river channel where repeated flooding events are less frequent. Successional stages can often be expressed within point bars, with each stage following the ridge and swale topography of a migrating meander feature (see Figure 3.6-2d). Earlier succession species predominate on the geomorphically younger bars, with later successional species expressed on the older bars nearer the terrace or upland. When hydrologic regimes shift to a lower or more regulated level in a river system, this meander migration can cease resulting in more mature forests in the riparian zone (Johnson et al. 1976; Arthington and Zalucki 1998). Long-term shifts in vegetation composition may occur with more upland species establishing in the riparian zone, reducing the transitional zone width between the river and the upland (Arthington et al. 2006).

The habitat diversity provides biological and ecological links between the terrestrial and aquatic ecosystems (Gregory et al. 1991). Ecotones are defined as areas where two habitat types intergrade; the land-water ecotone that characterizes the riparian zone provides the potential of higher densities and diversity than that of the adjacent upland area (Odem 1978). Temperate riparian zones have been described as exhibiting high level of biodiversity in relation to marked successional dynamics as a result of hydrological disturbance and concomitant changes in landscape structure (Naiman and Décamps 1997, Tabacchi et al. 1998, Gould and Walker 1999, Mouw and Alabak 2003, Ward et al. 2003). Riparian zones have also been recognized as susceptible to invasion, in part for the same reasons stated above as well as from human activities (e.g., river regulation, urbanization, agriculture Tabacchi and Planty-Tabacchi 2003).

High species richness has been documented in riparian landscapes (Bornette and Amoros 1996; Mouw and Alabak 2003). The relationship between distance from river and degree of inundation is often not simple (due to presence of ridge and swale topography, oxbow lakes and sloughs, cutoff channels, etc.), which also increases the complexity of vegetation zonation across the floodplain. Landscape diversity is generally highest along the main channel riparian zone and lower in secondary channels and tributaries (Minshall et al. 1985). Species composition also changes longitudinally, since floodplain width decreases upstream with concomitant deceases in moist, fine-textured sediments. Species that are associated with these characteristics reduce in abundance and may not occur in lower-order streams (Hupp 1986).

Riparian zones act as buffers that can improve water quality from non-point source pollution and water quantity, stabilize stream banks, reduce force, height, and volume of floodwaters (Narumalani et al. 1997; Tabacchi et al. 2000); provide habitat for fish and other wildlife species, and may also serve as indicators of environmental change (Naiman and Décamps 1997). High riparian plant diversity can positively affect the quantity and quality of nutrients available for the instream ecosystem (Gregory et al. 1991). Riparian buffers are generally defined as permanently vegetated areas located between the pollutant sources and water bodies and provide an effective means to attenuate pollutant impacts in stream systems; establishment of riparian buffers zones can be an essential component of a water quality management plan. Their filtering functions can include absorption, uptake, and deposition (Narumalani et al. 1997).

Two key nutrients, nitrogen and phosphorus, can be removed from the water in a variety of ways. Nitrogen removal is facilitated by denitrification and storage in woody vegetation, and has been measured to remove large amounts of nitrogen within riparian buffers (Lowrance et al. 1985; Mayer et al. 2006). In a review of the efficiency of riparian buffers in removing nitrogen, results varied widely in surface waters and were partially related to buffer width; however, removal in subsurface waters was not related to buffer width (Mayer et al. 2006). In studies evaluating surface waters, wider buffers (>50 m) were more efficient, although other factors, such as soil type, watershed hydrology (soil saturation, groundwater flow paths) and subsurface biogeochemistry (organic carbon supply, high nitrate inputs) may be more important. Over half of the phosphorus in a stream system was removed via plant uptake (Lowrance et al. 1985) as well as over 85% transported with small soil particles in the sediment (USDA 1991). In agricultural landscapes, soil erosion within croplands is highest after harvesting and during heavy rainfall events. These sediments are often retained within the riparian buffer during flooding events, and thus removed from further transported downstream into the water column and receiving waters (i.e., lakes, estuaries, open ocean) (USDA 1995).

Riparian buffers provide these soil and water quality functions through mechanical, chemical, or biological means. The presence of vegetation cover in the buffer effectively slows flooding velocities, and allows sediments to become deposited within the buffer. Additional benefits are realized in reductions of streambank erosion as a result of lower flow velocities. The chemical conversion of pollutants can also be achieved through interactions with biological processes facilitated by organisms such as bacteria and fungi. The conversion of these pollutants into usable forms by vegetation allows the uptake and storage of the chemicals in the riparian buffer. The effectiveness of a riparian buffer is dependent upon several factors including zone configuration, vegetation species composition, adjacent land uses, soil type, topography and slope, hydrology, and microclimates within the area (Trimble and Sartz 1957; USDA 1991). While all factors are important and often interrelated, buffer width has been the subject of much debate and values range from 3-200 m. A review of the literature evaluating buffer function and recommended widths provide some general recommendations (Figure 3.6-3) (Castelle et al. 1994). Continuity of the buffer, or corridor length, has also been recommended to ensure the buffer functions for the entire length of the receiving stream. At this watershed level, the use of remote sensing and modeling techniques can be valuable in determining effectiveness of riparian buffers (Delong and Brusven 1991; Xiang 1993; Narumalani et al. 1997).

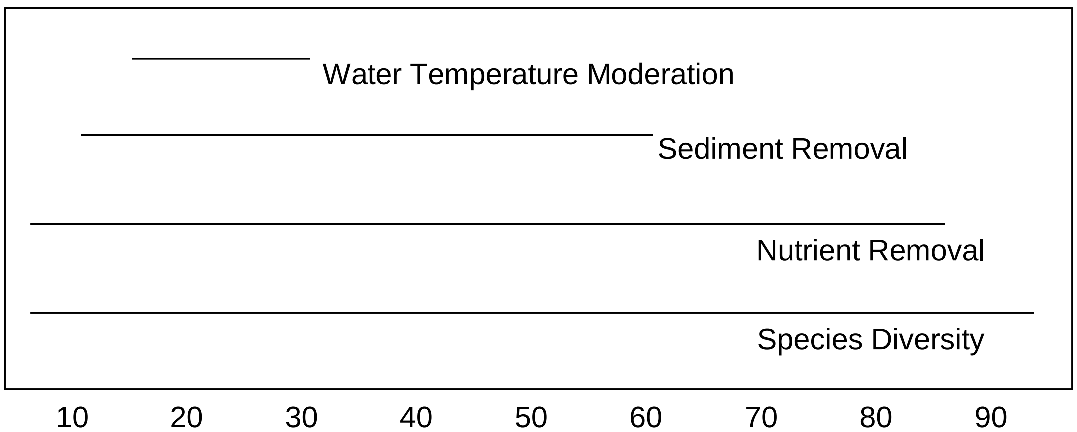


Figure 3.6-3. Range of buffer widths for providing specific buffer functions (adapted from Castelle et al.1994).

USDA Forest Service (1991) provided recommendations on riparian buffer characteristics and management in the early 1990s. Width should be determined by drainage area, soil hydrologic grouping, and soil capability class. Natural vegetation preservation was essential to maximizing buffer functions, and riparian corridor should include both forest and grassland. Tree species should be located adjacent to the streams and extending away from the banks for a minimum width of 23 m, transitioning into grassland that would extend inland to adjacent upland land uses (e.g., agricultural or urban). In a study delineating buffer width using remote sensing (soil capability classes, land use/land cover data) in Iowa, most riparian buffers were continuous along the main channels, but fragmented or completely cleared in the tributaries. Therefore, much of the small stream networks were left unprotected throughout the upper reaches of the watershed (Narumalani et al. 1997).

3.6.3 Exotic Species

Riparian lands are composed of a variety of landscape factors and connected to uplands by the hydrology of the river. Through river connectivity, these habitats act as a dispersal network for plant species; consequently, riparian corridors are one of the most sensitive habitats to plant invasion. A study conducted within the riparian zone determined that exotic species comprised 24% of 1396 species along the Adour River and 30% of 851 species of the riparian zone along the McKenzie River, Oregon, USA (Planty-Tabacchi et al. 1996). In Washington, USA, riparian patches had high exotic plant percentages ranging from 24-28%, whereas the associated upland forests were not affected (Planty-Tabacchi et al. 1998).

In general, invasion of exotic species appears to be lower in less disturbed small tributaries and most disturbed secondary channels, which may be explained using the Intermediate Disturbance Hypothesis (Connell 1978; Sousa 1984; White and Pickett 1985; Resh et al. 1988). Conversely, higher cover estimates were recorded for exotic species in areas of intermediate disturbance. Increases in resource availability may contribute to the increase in both native and exotic species richness (Davis et al. 2000; Williams and Wiser 2004). Several descriptive factors have been promoted to evaluate disturbance, such as frequency, duration, magnitude and recurrence (Sousa 1984). These approaches can be used when evaluating how natural disturbance affects riparian structure, as well as when considering alterations relating to natural flow regimes.

In general, a plant community is more susceptible to non-native species establishment when resources are available to both native and non-native species (i.e., light, nutrients, water) (Davis et al. 2000), as non-native species are usually better adapted to quickly capitalize on those resources. For example, invasive species typically produce seeds that are carried by water and air, are produced in abundance, and can reproduce vegetatively once established (Thompson et al. 1995). Often a disturbance event will release these resources through setting back native vegetation and creating an opportunity for non-native species establishment. Since disturbance is an integral part of the riverine system, other factors must be satisfied for the non-native species to establish, including presence upstream of site, viable seeds available in flood waters or debris, and timing appropriate for germination (Davis et al. 2000).

Several species that invade riparian areas have been planted in urban areas (e.g., chinaberry, Chinese tallow, ligustrum, etc.) or planted as erosion control along drainages (e.g., salt cedar), therefore, most conditions are satisfied for establishment. Most of these species' seeds or propagules either exhibit a prolonged germination season or can withstand long periods of drought before sprouting under good conditions (Kolar and Lodge 2001). Differential water use also can be an important factor in establishing and outcompeting native species over time. Salt cedar effectively utilizes available water in the alluvial soils as well as tapping into deeper groundwater. In addition, this species continues to maintain higher levels of transpiration during dry periods, when native species effectively reduce water uptake.

The invasion of non-native species is a concern because they affect native species diversity as well as reduce species structure and composition in riparian corridors (Renofalt et al. 2005; Barrow et al. 2005). Furthermore, non-native species threaten economically important species and disrupt the structure and/or distribution of physical habitats (Wasson et al. 2002). Salt cedar species comprise an aggressive group that invades riparian areas throughout North America, and consequently, covered over 0.5 million hectares of riparian corridors by 1990. Salt cedars often colonize and maintain higher densities than native species they replace, particularly along stream reaches where water flow is regulated at more uniform levels (Beauchamps and Stromberg 2007). Chinese tallow is also a widespread, invasive species that has naturalized in south Texas since its introduction to the United States in 1784.

3.6.4 Flow-Ecology Relationships among Physical Processes and Riparian Habitat

Riparian habitats and the communities they support are an integral component of the riverine system. Under natural flow conditions riparian dynamics are linked to the structure and function of the river, and the riparian community is adapted to the temporal patterns of the river flows (Poff et al. 1997). As global populations increase, freshwater resource management has become complex between balancing human needs and maintaining sound ecological environments (Rosenberg 2000). Understanding the relationship between flows and the physical (geomorphology), chemical (water quality, nutrient cycling) and biological (ecology) components of riparian corridors is essential to the environmental flow regime process. Ecological integrity of a riverine system is dependent on flow regime and associated components (Poff et al. 1997). Modifications to the natural flow regime can result in diminishing the sound ecological environment (Figure 3.6-4).

Natural flows are dynamic, varying seasonally and annually, and the riparian corridors reflect that variability and availability of water in their vegetation composition and diversity. In general, natural fluctuations result in high species richness, diversity, and fairly dense vegetation within the riparian zone (Johnson et al. 1996; Poff et al. 1997; King 2003). Environmental gradients produce shifts in riparian structure and function as a response to fluvial dynamics, floods, and soil moisture availability (Minshall et al. 1985; Naiman and Décamps 1997; Ward et al. 2003). Two gradients have been identified as driving these shifts both perpendicular (or transverse, away from the river through the floodplain), and longitudinally (along the river): stress gradient related to moisture availability, and disturbance gradient in response to the dynamic fluvial geomorphology occurring with various flow levels (Gill 1970; Malanson 1993; Bendix 1994). In the former, both standing and subsurface waters affect species presence and abundance, and soil permeability strongly affects water availability. In the latter, riparian species must be adaptable to erosion and deposition within the floodplain as well as lateral movement of channel banks to physically tolerate floodwater and soil movement as well have the ability to recolonize on the ever-shifting floodplain surface (Gill 1970).

Stream flow is a major factor in the distribution and abundance of riverine species (Poff et al. 1997) and, therefore, has been attributed as a key driver in the succession of riparian plant communities and ecological processes (Gregory et al. 1991). Stream flow regime is dependent on river size and geomorphic variation in climate, geology, topography and even vegetative cover (Poff et al. 1997). Stream flow derives primarily from precipitation reaching a stream through surface water, soil water, and ground water. Variability in stream flow influences flow magnitude, frequency, duration (hydroperiod), and timing. This variability in flow within the channel and along the floodplain develops a varying physical environment (King 2003). The rate of sediments transported by stream flow is associated with flow fluctuations, discharge, and availability of transportable material. These processes form a wide range of geomorphic features such as river bars, riffles, and floodplains (Poff et al. 1997). Different physical landforms cause diversity in the composition of riparian plant communities (Osterkamp and Hupp 2010; Pettit et al. 2001; King 2003).

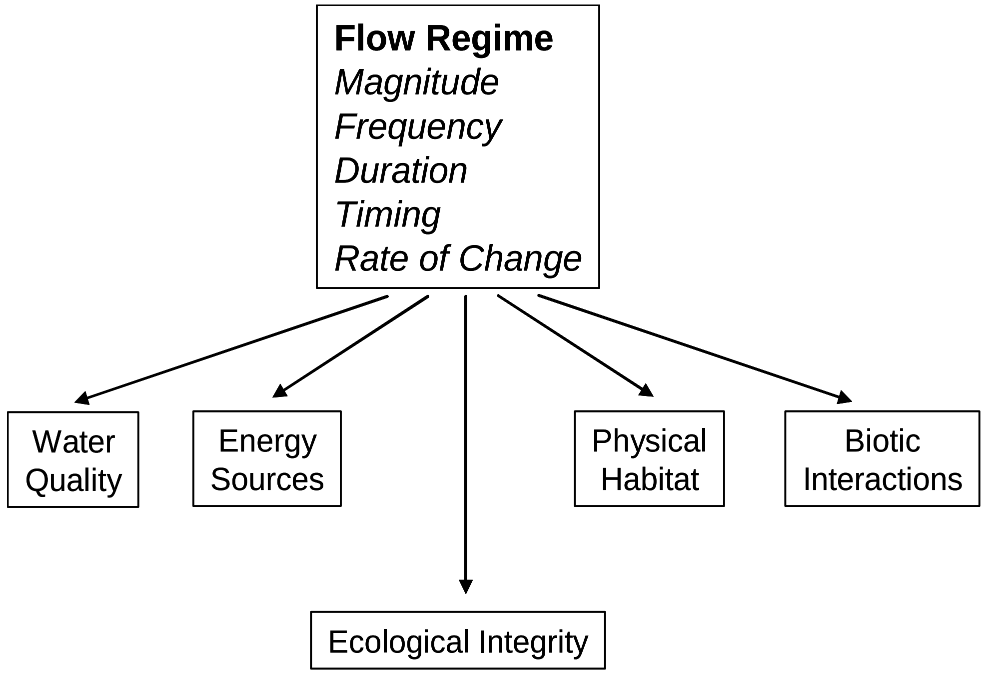


Figure 3.6-4. Ecological integrity of a riverine system is dependent on flow regime and associated components (Poff et al. 1997); modifications to the natural flow regime can result in diminishing the sound ecological environment.

Over time a variable stream flow regime consistently provides diverse habitat types that are exploited by unique aquatic and riparian species adapted to this dynamic environment (Poff et al. 1997). Riparian vegetation depends on water availability from the riverine and groundwater systems for survival and growth (Brinson et al. 1981, Goodwin et al. 1997; Stromberg and Patten 1991); some riparian species would not be able to flower, disperse seeds, germinate, or maintain seedling growth without the environmental influence of varying stream flow events, such as flooding or drought (Poff et al. 1997; Stromberg 2001). Consequently, the natural flow regime of a river can be related to patterns of vegetation development and plant community in riparian zones (Pettit et al. 2001).

Additionally, high-and low-flow events are important to stream flow dynamics as they stimulate stressors or opportunities for a variety of riverine species (Poff et al. 1997). High flow events and floods transfer materials, depositing sediments at different depths above the water table and at different locations of light exposure with varying soil properties. The resulting geomorphic diversity supports different assemblages of plants within and along a river. Floods also contribute to plant community changes as a result of river channel migration across the floodplain and creating new micro-habitats that initiate ecological succession (Richter and Richter 2000; Stromberg 2001). Nutrient availability also increases which may maintain high riparian zone productivity (Stromberg 2001). In addition, flood waters flush out salts that inhibit the growth of riparian vegetation when present in high concentrations, as well as remove accumulated woody debris or leaf litter (Busch and Smith 1995).

Riparian corridor structure is highly dependent on physical habitat conditions which are shaped by flow regimes (Johnson et al. 1976; Boudell and Stromberg 2008). Floodplains of arid regions are vegetated by a mixture of upland and wetland dominated communities (Mouw and Alaback 2003) and these two groups probably respond differently to spatiotemporal metacommunity dynamics. Flood pulses disperse both upland and wetland seed propagules across the floodplain creating a homogenous propagule bank; germination of either upland or wetland species will then occur in a particular location within the floodplain dependent on "local" and current environmental conditions (Boudell and Stromberg 2008). These dispersal techniques effectively provide a propagule bank (and, thus, regeneration insurance) across the floodplain that is capable of responding to variety of drought/wet cycles and decreased the likelihood of local species extinction from short-term unfavorable conditions. Disruption of a regional propagule pool can occur through changes in flood pulsing and/or reduced connectivity of the riparian corridor from habitat fragmentation.

3.6.5 Flow Regimes and Associated Environmental Relationship to Riparian Systems

Flow regimes are divided into four levels: subsistence, base, high, and overbank flows (Figure 3.6-5) (SAC 2009). Each of these levels has a varying effect on structure and function of riparian corridors. Subsistence flows maintain longitudinal connectivity within the stream channel, and provide minimal subsurface water to the alluvial groundwater within the floodplain.

Base flows maintain water quality conditions within the stream and are a main contributor to alluvial groundwater that supports the riparian habitat by maintaining water tables and providing soil moisture (SAC 2009). While base flows provide minimal support to riparian corridors, water stored in the floodplain from previous overbank flows in the hyporheic zone (shallow region of surface and groundwater interaction) is gradually released to sustain base flows (Todd 1955). Shading provided by the riparian zone reduces evaporation of the hyporheic zone, and water temperatures flowing into the stream are generally lower. In addition, addition of this water into stream can increase water quality conditions (Squillace 1996; Tabacchi et al. 1998).

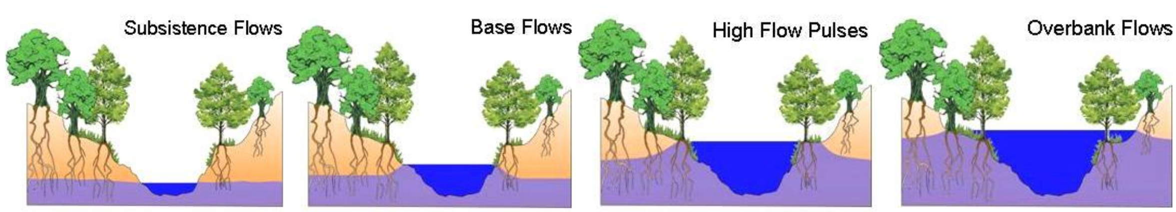


Figure 3.6-5. Conceptual models surface and subsurface water levels under four environmental flow regimes (Nichols, 2008).

High pulse flows may recharge alluvial groundwater tables, particularly after prolonged subsistence or base flow periods, as well as improve instream water quality through return flows. Depending on soil type, high pulse flows may also provide connectivity to oxbows and wetlands in the floodplain through subsurface lateral water movement. In addition, high pulse flows provide a maintenance function by preventing encroachment of riparian plants into the stream channel (Bilby 1977; Henry et al. 1994; Bendix 1994; SAC 2009).

Overbank flows are extremely important to maintaining riparian structure and function by transporting sediment and nutrients with flood water over the floodplain surface. These flow events are responsible for maintaining balance and diversity among aquatic and riparian communities. They recharge floodplain aquifers and provide lateral connectivity between stream channel and floodplain and water source for riparian plants for months following an event. In addition, overbank flooding transports plant seeds and propagules, provides new areas for colonization, initiates life cycle cues, and supports fish/biota that require floodplain habitats at some point in their life cycle. When flood waters recede, organic debris and nutrients flow back into the stream channel, and provide sediment and nutrients to bays and estuaries along the coast (SAC 2009). Riparian vegetation is dependent on the moist substrate along the streambank and overbank flows (Stromberg and Patten 1991; Rood and Mahoney 1995). These infrequent, but important, flows have the most influence on the geomorphology of the river system and are responsible for lateral migration of the channel within the floodplain and, or eroding adjacent upland bluffs. Meander migration provides new substrate and, thus, colonization sites for certain riparian plants. This continual shifting of sediments over time in conjunction with plant establishment creates more biodiversity across the floodplain and throughout the river basin (Everitt 1968; Nanson and Hickin 1974). Individual trees that are removed from the riparian corridor create more habitat diversity in the stream channel (Keller and Swanson 1979; Montgomery and Buffington 1997) and provide woody debris for decomposition and nutrient cycling (Keller and Swanson 1979; Arthington and Zalucki 1998).

Overbank flows provide the connectivity necessary to maintain the coastal basin integrity. The movement of sediment, organic material, and nutrients from the floodplain and riparian corridor is hydrologically driven by overbank flow events. These materials are essential for the maintenance of river deltas as well as providing detritus and nutrients to the bays and estuaries. Flood waters temporarily stored in the floodplain are slowly released back to the stream channel, ameliorating flow velocities within the channel and to receiving deltas and bays downstream. The presence of woody vegetation within the riparian corridor increases hydraulic roughness and further reduces flow velocity (Naiman and Décamps 1997).

3.6.6 Flow Variations and *Timing*

Whereas physical systems are not sensitive to seasonal timing of flooding to maintain geomorphology, timing is essential to maintain riparian vegetation diversity (Bradley and Smith 1985; Johnson 1997; Arthington et al. 2006). Each species responds to a slightly different window of opportunity and seedling establishment occurs during these favorable periods. Diversity is maintained within the riparian community by the natural irregularity of flooding, resulting in vegetation patterns across the floodplain and throughout the stream valley (Johnson et al. 1976; Auble et al. 2005). Therefore, it is important to understand the linkages between hydrology and geomorphology governing the patterns observed in biological communities. These drivers are responsible for organizing the successional sequences and rates of vegetation communities (Johnson et al. 1976; Amoros et al. 1987; Day et al. 1988; Amoros et al. 2000).

Several flow components and hydrologic conditions should be considered when evaluating their biological significance for riparian systems (SAC 2009). Upper and lower limit thresholds are important for maintaining physical features and connectivity between the instream and riparian zones. These thresholds drive community diversity and maintain habitat quality and quantity throughout the floodplain. While one of the primary functions that riparian vegetation provide includes increasing bank stability, lower limit thresholds should be designed such that flows are maintained and limit riparian vegetation encroachment in the stream channel (Arthington and Zalucki 1998). In temperate streams, encroachment would not occur if floods recurred within 1-2 years; however, in subtropical areas growing seasons are extended and plant productivity higher, therefore, encroachment could occur at a more rapid rate. In addition, since channel width is maintained by flow, reduction or maintenance of lower flows will effectively reduce channel width over time. An increase in higher limit thresholds would result in an increase in channel width and concomitant loss of existing bank vegetation. If the riparian bank zone is restricted (either because of narrow floodplain or management practices), then increased erosion and downcutting may occur in the floodplain. In addition, if exotic species are present in the riparian corridor or adjacent urban areas, the probability of their establishment is increased.

In coastal basins, the importance of maintaining low flows is important in both long and short time scales. Rivers that flow through the coastal plain and into an estuary provide the sediments to maintain river deltas and tidal channels as well as eventually fill the bays with sediments. High flow thresholds should be maintained at a level that periodically flush out these channels and provide sediment and nutrient loads to estuarine habitats. In coastal rivers where tidal water mixes with freshwater in the lower river channel, a salt wedge often develops in which the denser salty water is located along the bottom with fresh water at the surface. Low flow thresholds should be developed to ensure that the salt wedge does not migrate up the river channel and impact instream habitats or streambank riparian vegetation (Arthington and Zalucki 1998).

The small and large flood recurrence intervals also maintain connectivity between instream channel and riparian areas. While both scenarios provide water and nutrients to the floodplain and associated swales and oxbow lakes, they each may be used differently to stimulate spawning cues in aquatic species and provide temporary habitats for use in reproduction and protection from instream predators (SAC 2009). Small floods that occur at sufficient intervals are valuable for removing fine sediment from the channel bed surface, moving smaller cobble and rubble, and limiting vegetation encroachment (Arthington and Zalucki 1998). Larger floods maintain channel form dynamics by eroding and depositing sediments along the stream channel and across the floodplain. These events maintain riparian vegetation community diversity by setting back succession and providing new areas of colonization along the stream banks. By setting both small and large flood recurrence intervals at a natural frequency, channel morphology and habitat diversity can be maintained both within the stream channel as well as in the riparian and floodplain zone.

Riparian vegetation depends on a variety of water sources, including stream water, rainwater, surface runoff, and groundwater from alluvial soils and valley sides (Whiting 2002). Changes in the hydrologic regime can produce shifts in riparian plant communities, and flow alterations can reduce species richness and vegetation cover (Décamps et al. 1995; Nilsson et al. 1997). These shifts often result in different responses in relation to the flow type altered (King et al. 2003). Flow regime changes which exacerbate drought stress often will affect older trees, seedling, and decrease germination (Décamps 1996). Trees often exhibit reduced productivity and slowed growth in relation to reduced flow and groundwater recharge (Johnson et al. 1976; Stromberg and Patten 1990). In extreme cases, local extinction of certain species can occur that are dependent upon a particular water regime for sustenance or germination (Rood and Mahoney 1995). In some regions, relationships between vegetation dynamics and alterations of flows have been modeled to predict changes in the riparian corridor (Franz and Bazzaz 1977; Auble et al. 1994, 1997, 2005; Primack 2000; Friedman and Auble 1999).

Long periods of reduced stream flow over time result in less diverse riparian vegetation leading to more simplified floodplain communities (Stromberg 2001). Studies to determine the effect of reduced stream flow on vegetation within riparian zones have mostly been conducted along streams and rivers affected by anthropogenic activities such as construction and groundwater withdrawals (Auble et al. 1994; Busch and Smith 1995; Poff et al. 1997; Rood and Mahoney 1990; Stromberg 2001). These activities not only reduce water availability and nutrients that support riparian plants but also decrease floodplain area (Busch and Smith 1995), increase non-native vegetation (Poff et al. 1997), and impede downstream flows of sediments. The loss of sediment for downstream habitats reduces native plant biodiversity and, therefore, associated riparian community productivity.

3.6.7 Riparian Characterization for Guadalupe, San Antonio, and San Antonio-Nueces Coastal Basins

Few studies have been published focusing on riparian characterization within the Guadalupe - San Antonio River Basin and the San Antonio-Nueces Coastal Basin. Along the San Antonio River in Wilson County, Texas (Bush and Van Auken 1984), Texas sugarberry exhibited the highest density in the riparian corridor, followed by box elder and cedar elm. Importance values for cottonwood, black willow, and box elder were high along the berm closest to the stream channel, with only box elder extending into the middle and interior regions of the riparian corridor.

A study along the Aransas River (Longfield 2001) reported that the most important species within the riparian corridor was sugar hackberry followed by chinaberry, anacua, cedar elm, Texas persimmon, and colima. Hackberry species had the highest relative dominance for all transects along the Aransas River followed by anacua, cedar elm, black willow, chinaberry, and pecan. Chinaberry, an invasive species, had the greatest relative density for all transects along the Aransas River followed by hackberry species, anacua, Texas persimmon, colima, pepperbark, and cedar elm.

In one of the few studies that evaluated succession in the riparian community within the Guadalupe - San Antonio River Basin demonstrated the colonization by early successional species (primarily huisache, retama, mesquite, and hackberry) (Figure 3.6-6) (Van Auken and Bush 1985). As they mature, huisache becomes the earliest dominant tree and Roosevelt weed is the predominant shrub. In drier areas, spiny hackberry and anaqua grow into trees as hackberry replaces huisache as the dominant species in the lower riparian zones. The emergence of later successional trees occurs, including pecan, box elder, bumelia as well as the exotic species chinaberry. Both cedar elm and American elm become a predominant part of the riparian zone, and may be the next dominant group in the later successional stages.

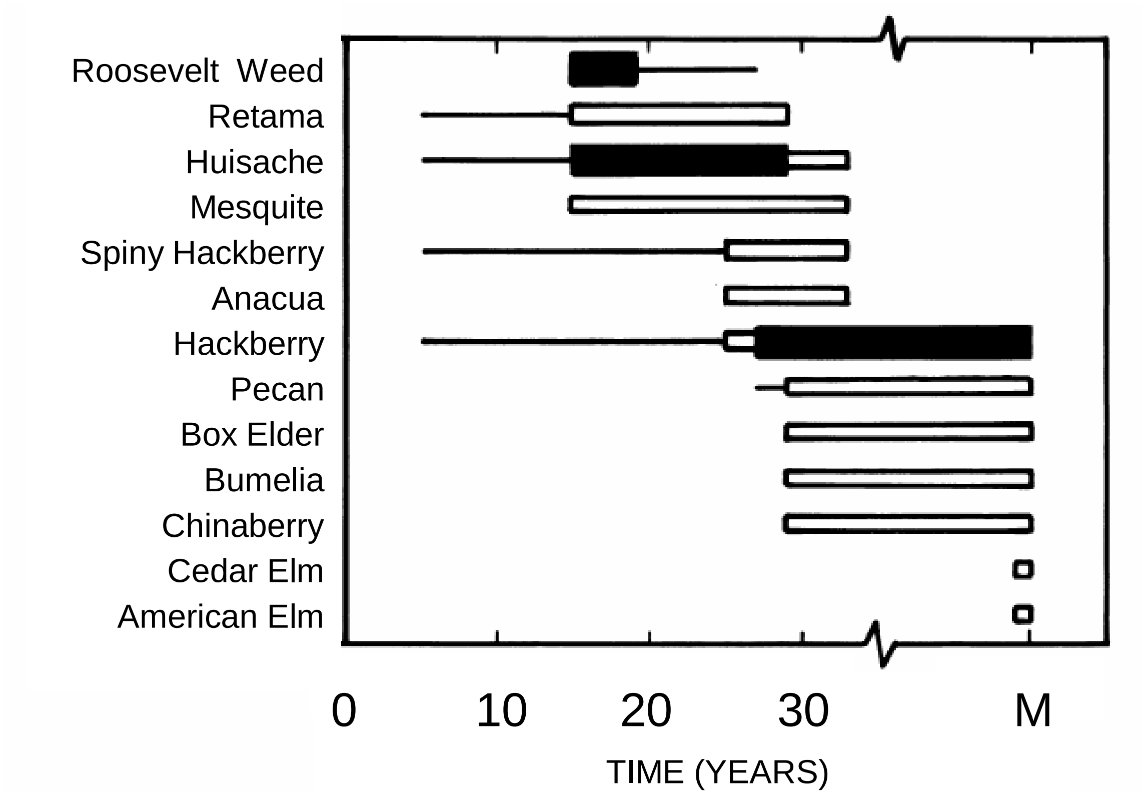


Figure 3.6-6. Successional sequence of riparian species on San Antonio River, Texas; saplings are denoted by lines, open bars tree stage, black bars as dominants in the riparian community (Van Auken and Bush 1985).

Three studies currently underway provide valuable information on species composition, successional patterns, and life history stages of woody riparian species in the Guadalupe Basin (TWDB and TPWD, unpublished data), lower San Antonio Basin (Texas Instream Flows Program, unpublished data), and Mission River in the San Antonio-Nueces Coastal Basin (Nicole Davis, unpublished data). In the Guadalupe Basin, 20 species were documented as part of a more detailed channel profile study (Table 3.6-3), whereas 33 species were recorded in both San Antonio Basin (Table 3.6-2) and Mission River (Table 3.6-4) in a more comprehensive floristic survey approach. In all studies, a range of mid- to late-successional species were located, including sugar hackberry, box elder, pecan, and cedar elm. American elm was found at all sites in the Guadalupe and San Antonio basins, but was not present in the Mission River site. Bald cypress was only found at one of five sites in both Guadalupe and San Antonio, and was absent on the Mission River site. Green ash was also found at all sites in Guadalupe and San Antonio basins whereas Mexican ash was found on Mission River. Black willow, a species characteristically found along the river banks, were located on three of five sites on Guadalupe and four of five sites on San Antonio, indicating an active channel bank morphology. Cottonwood was also found in three San Antonio sites, but only documented at one of sites surveyed on Guadalupe and is minor in occurrence on Mission River site.

Regeneration of individuals comprising the characteristics species in the riparian zone is essential in maintaining species diversity and density. Overall, most common species encountered on all three rivers were documented in the three life history stages. Black willows on the Guadalupe were noted most as trees, whereas on the San Antonio and Mission river sites all stages of regeneration were recorded. This species usually colonizes the stream bank first, and are replaced by later successional species if little disturbance occurs. Green ash and box elder were both documented as regenerating stands and are indicative of moist soil conditions. Sugar hackberry and cedar elm typify more variable water availability conditions, and were also documented in all three life history stages. These data potentially illustrate that present flow regimes are sufficient for both seedling germination and sapling establishment was well as tree maturation and most sites were exhibiting a mid- to late-successional trend.

Two exotic species were documented in each basin: chinaberry and Chinese tallow. Both species have seeds that are abundantly produced and float, and are extensively planted in urban areas. Chinaberry was found at one site in Guadalupe Basin and noted as established (tree), and at two sites in San Antonio Basin as established and regenerating (all three life history stages). This species was also regenerating in Mission River site. Similar findings were documented for Chinese tallow, although sites were not the same in which chinaberry were found Guadalupe and San Antonio basins. Chinaberry typically established on terraces whereas Chinese tallow is tolerant of both drier and moist soil environments. In addition, Chinese tallow can sprout from suckers along the roots and is capable of monopolizing riparian woodlands and herbaceous wetlands once established.

Fieldwork for these studies has only recently been completed (Winter 2010-2011) and data on basal area, density, and dominance will be calculated and compared among sites within the Texas Instream Flow Program for LSAR and on the Mission River upon completion of a master’s thesis. The use of transects and plots located perpendicular to the river in each system will provide a detailed baseline for future assessments with flow regime recommendation implementation.

Table 3.6-2. Life history stages of woody riparian species documented at selected sites within the San Antonio Basin (summarized from TWDB and TPWD unpublished data).

Common Name/Site	Scientific Name	Trees	Saplings	Seedlings
Acacia	*Acacia berlandieri*			
Goliad			x	
Falls City		x		x
American elm	*Ulmus americana*			
Calaveras		x	x	x
Goliad		x		x
Hwy 77		x	x	x
Cibolo		x	x	x
Anaqua	*Ehretia anacua*			
Hwy 77		x	x	x
Bald cypress	*Taxodium distichum*			
Falls City		x		
Black willow	*Salix nigra*			
Calaveras		x	x	x
Goliad		x	x	x
Hwy 77		x	x	x
Cibolo		x	x	
Box elder	*Acer negundo*			
Calaveras		x	x	x
Goliad		x	x	x
Falls City		x	x	x
Hwy 77		x	x	x
Cibolo		x	x	x
Brasil	*Condalia hookeri*			
Bur oak	*Quercus macrocarpa*			
Hwy 77		x		x
Buttonbush	*Cephalanthus occidentalis*			
Falls City			x	
Cibolo			x	x
Cedar elm	*Ulmus crassifolia*			
Calaveras		x	x	x
Goliad		x	x	x
Falls City		x	x	x
Hwy 77		x	x	x
Cibolo		x	x	x
Chinaberry	*Melia azedarach*			
Calaveras			x	x
Cibolo		x	x	x
Chinese Tallow	*Sapium sebiferum*			
Goliad			x	
Hwy 77		x	x	x
Colima	*Zanthoxylum fagara*			
Cottonwood	*Populus deltoides*			
Calaveras		x		x

Falls City		x	x	x
Cibolo		x		
Deciduous holly	*Ilex decidua*			
Goliad			x	
Falls City			x	x
Hwy 77			x	x
Cibolo			x	
Desert hackberry	*Celtis pallida*			
Falls City		x	x	x
Flameleaf sumac	*Rhus copallinum*			
Falls City			x	x
Hwy 77			x	x
Cibolo		x	x	x
Green ash	*Fraxinus pennsylvanica*			
Calaveras			x	
Goliad		x	x	x
Falls City			x	
Hwy 77		x	x	x
Cibolo		x	x	x
Gum bumelia	*Bumelia lanuginosa*			
Calaveras			x	x
Goliad			x	
Falls City			x	x
Hwy 77				x
Cibolo		x	x	x
Honey mesquite	*Prosopis glandulosa*			
Falls City		x	x	x
Huisache	*Acacia farnesiana*			
Live Oak	*Quercus fusiformis*			
Mexican buckeye	*Ungnadia speciosa*			
Hwy 77		x	x	
Cibolo				x
Osage orange	*Maclura pomifera*			
Goliad			x	x
Cibolo				x
Pecan	*Carya illinoensis*			
Calaveras		x		x
Goliad		x	x	x
Falls City		x		x
Hwy 77		x		x
Cibolo		x	x	x
Red mulberry	*Morus rubra*			
Calaveras			x	x
Falls City		x		x
Hwy 77		x		
Red Oak	*Quercus falcata*			
Retama	*Parkinsonia aculeata*			
Roughleaf dogwood	*Cornus drummondii*			

Hwy 77		x	x	x
Roosevelt weed	*Baccharis neglecta*			
Falls City			x	
Sabal palm	*Sabal texana*			
Sugar hackberry	*Celtis laevigata*			
Calaveras		x	x	x
Goliad		x	x	x
Falls City		x	x	x
Hwy 77		x	x	x
Cibolo		x	x	x
Sycamore	*Platanus occidentalis*			
Goliad			x	
Falls City		x	x	
Hwy 77				x
Cibolo		x	x	
Texas hawthorn	*Crataegus texana*			
Falls City				x
Texas persimmon	*Diospyros texana*			
Calaveras				x
Falls City		x	x	x
Cibolo			x	x
Wafer ash	*Ptelea trifoliata*			
Cibolo		x	x	x
Western soapberry	*Sapindus saponaria*			
Calaveras		x	x	x
White mulberry	*Morus alba*			
Goliad			x	x
Yaupon holly	*Ilex vomitoria*			
Hwy 77				x
Yucca	*Yucca torreyi*			
Falls City		x		

Table 3.6-3. Life history stages of woody riparian species documented at selected sites within the Guadalupe Basin (summarized from Texas Instream Flows Program unpublished data).

Common Name/Site	Scientific Name	Trees	Saplings	Seedlings
Acacia	*Acacia berlandieri*			
American elm	*Ulmus americana*			
Blanco @ Wimberly		x		
Plum Ck near Luling		x	x	x
San Marcos @ Luling		x	x	x
Sandies Ck near Westhoff		x	x	
Guadalupe @ Cuero		x		
Anacua	*Ehretia anacua*			
Bald Cypress	*Taxodium distichum*			
Blanco @ Wimberly		x	x	x
Ashe juniper	*Juniperus ashii*			
Blanco @ Wimberly			x	
Black Willow	*Salix nigra*			
Plum Ck near Luling		x		
Sandies Ck near Westhoff		x		
Guadalupe @ Cuero		x	x	
Box Elder	*Acer negundo*			
Blanco @ Wimberly				x
Plum Ck near Luling		x	x	
San Marcos @ Luling		x	x	x
Brasil	*Condalia hookeri*			
Bur Oak	*Quercus macrocarpa*			
Plum Ck near Luling		x		
San Marcos @ Luling		x		
Buttonbush	*Cephalanthus occidentalis*			
Blanco @ Wimberly		x	x	
Cedar Elm	*Ulmus crassifolia*			
Plum Ck near Luling		x	x	x
San Marcos @ Luling		x	x	x
Chinaberry	*Melia azedarach*			
Plum Ck near Luling		x		
Chinese Tallow	*Sapium sebiferum*			
San Marcos @ Luling		x		
Colima	*Zanthoxylum fagara*			
Cottonwood	*Populus deltoides*			
Plum Ck near Luling		x		
Deciduous holly	*Ilex decidua*			
Desert hackberry	*Celtis pallida*			
Flameleaf sumac	*Rhus copallinum*			
Green ash	*Fraxinus pennsylvanica*			
Blanco @ Wimberly		x		
Plum Ck near Luling		x	x	
San Marcos @ Luling		x	x	x

Sandies Ck near Westhoff		x		
Guadalupe @ Cuero		x		
Gum bumelia	*Bumelia lanuginosa*			
Honey mesquite	*Prosopis glandulosa*			
Plum Ck near Luling		x		
Guadalupe @ Cuero		x	x	
Huisache	*Acacia farnesiana*			
Live Oak	*Quercus fusiformis*			
Blanco @ Wimberly		x	x	
Guadalupe @ Cuero		x		
Mexican buckeye	*Ungnadia speciosa*			
Osage orange	*Maclura pomifera*			
Plum Ck near Luling		x		
Pecan	*Carya illinoensis*			
Blanco @ Wimberly		x	x	
Plum Ck near Luling		x		
San Marcos @ Luling		x		x
Sandies Ck near Westhoff		x		
Red mulberry	*Morus rubra*			
Red Oak	*Quercus falcata*			
San Marcos @ Luling		x		
Retama	*Parkinsonia aculeata*			
Roughleaf dogwood	*Cornus drummondii*			
Roosevelt weed	*Baccharis neglecta*			
Sabal palm	*Sabal texana*			
Sugar hackberry	*Celtis laevigata*			
Blanco @ Wimberly		x		
Plum Ck near Luling		x	x	
San Marcos @ Luling		x		
Sandies Ck near Westhoff		x		
Sycamore	*Platanus occidentalis*			
Blanco @ Wimberly		x	x	x
Texas hawthorn	*Crataegus texana*			
Texas persimmon	*Diospyros texana*			
Wafer ash	*Ptelea trifoliata*			
Western soapberry	*Sapindus saponaria*			
Plum Ck near Luling		x		
White mulberry	*Morus alba*			
Yaupon holly	*Ilex vomitoria*			
Yucca	*Yucca torreyi*			

Table 3.6-4. Life history stages of woody riparian species documented at Mission River site within the San Antonio-Nueces Coastal Basin (summarized from Nicole Davis unpublished data).

Common Name/Site	Scientific Name	Trees	Saplings	Seedlings
Acacia	*Acacia berlandieri*	x		
American elm	*Ulmus americana*			
Anacua	*Ehretia anacua*	x	x	x
Ashe Juniper	*Juniperus ashii*			
Bald Cypress	*Taxodium distichum*			
Black Willow	*Salix nigra*	x	x	
Box Elder	*Acer negundo*	x	x	x
Brasil	*Condalia hookeri*		x	
Bur Oak	*Quercus macrocarpa*			
Buttonbush	*Cephalanthus occidentalis*		x	
Cedar Elm	*Ulmus crassifolia*	x	x	x
Chinaberry	*Melia azedarach*	x	x	x
Chinese Tallow	*Sapium sebiferum*	x	x	
Colima	*Zanthoxylum fagara*	x	x	
Cottonwood	*Populus deltoides*	x		
Deciduous holly	*Ilex decidua*		x	
Desert hackberry	*Celtis pallida*		x	x
Flameleaf sumac	*Rhus copallinum*			
Green ash	*Fraxinus pennsylvanica*	x		
Gum bumelia	*Bumelia lanuginosa*		x	
Honey mesquite	*Prosopis glandulosa*	x	x	
Huisache	*Acacia farnesiana*	x		
Live Oak	*Quercus fusiformis*	x	x	x
Mexican ash	*Fraxinus berlandieri*	x	x	x
Mexican buckeye	*Ungnadia speciosa*	x	x	
Osage orange	*Maclura pomifera*	x		
Pecan	*Carya illinoensis*	x	x	x
Red mulberry	*Morus rubra*	x		
Red Oak	*Quercus falcata*			
Retama	*Parkinsonia aculeata*	x	x	
Roughleaf dogwood	*Cornus drummondii*			
Roosevelt weed	*Baccharis neglecta*		x	
Sabal palm	*Sabal texana*		x	
Sugar hackberry	*Celtis laevigata*	x	x	x
Sycamore	*Platanus occidentalis*			
Texas hawthorn	*Crataegus texana*	x		
Texas persimmon	*Diospyros texana*	x	x	
Wafer ash	*Ptelea trifoliata*		x	x
Western soapberry	*Sapindus saponaria*		x	
White mulberry	*Morus alba*			
Yaupon holly	*Ilex vomitoria*		x	
Yucca	*Yucca torreyi*			

Ecoregional diversity is high across the three river basins, encompassing over nine Level 4 ecoregions within five Level 3 ecoregions (Table 3.5-5). The Guadalupe Basin includes the most ecoregions, sharing all with San Antonio Basin with the exception of Southern Blackland/Fayette Prairie. The San Antonio-Nueces Coastal Basin is smaller and only extends across two ecoregions (Figure 3.6-7). Ecoregions were used to evaluate riparian extent throughout the basins using three datasets: alluvium and terrace deposits from geology of Texas data; various floodplain and riparian habitats from Texas Ecological System Database (TSED) (TPWD); and, woody wetland and herbaceous wetland habitats from 2001 National Land Cover (NLCD) data. Generally, TSED riparian and floodplain habitats correspond to alluvium and terrace geology and associated stream drainage, and provide more detailed descriptions of vegetation types associated within Level 4 ecoregion types (Ludeke et al. 2010). The NLCD woody and herbaceous wetland habitats more closely align with existing riparian coverage, but do not provide any community composition information.

Table 3.6-5. Ecoregions and associated ecosystem mapping units from Texas Ecological Systems Database Project (Ludeke et al. 2010).

		Basin		
Ecoregion (Level 3)	Ecoregion (Level 4)	Guadalupe	San Antonio	San Antonio-Nueces Coastal (Mission/ Aransas)
Edwards Plateau	Edwards Plateau Woodlands	X	X	
	Balcones Canyonlands	X	X	
Texas Blackland Prairie	Northern Blackland Prairie	X		
	Southern Blackland/ Fayette Prairie	X		
Southern Texas Plains	Northern Nueces Alluvial Plains		X	
East Central Texas Plains	Southern Post Oak Savanna	X	X	
Western Gulf Coastal Plain	Floodplains & Low Terraces	X	X	
	Northern Humid Gulf Coastal Plain	X	X	
	Southern Humid Gulf Coastal Plain			X
	Mid-coast Barrier Islands and Coastal Marshes			

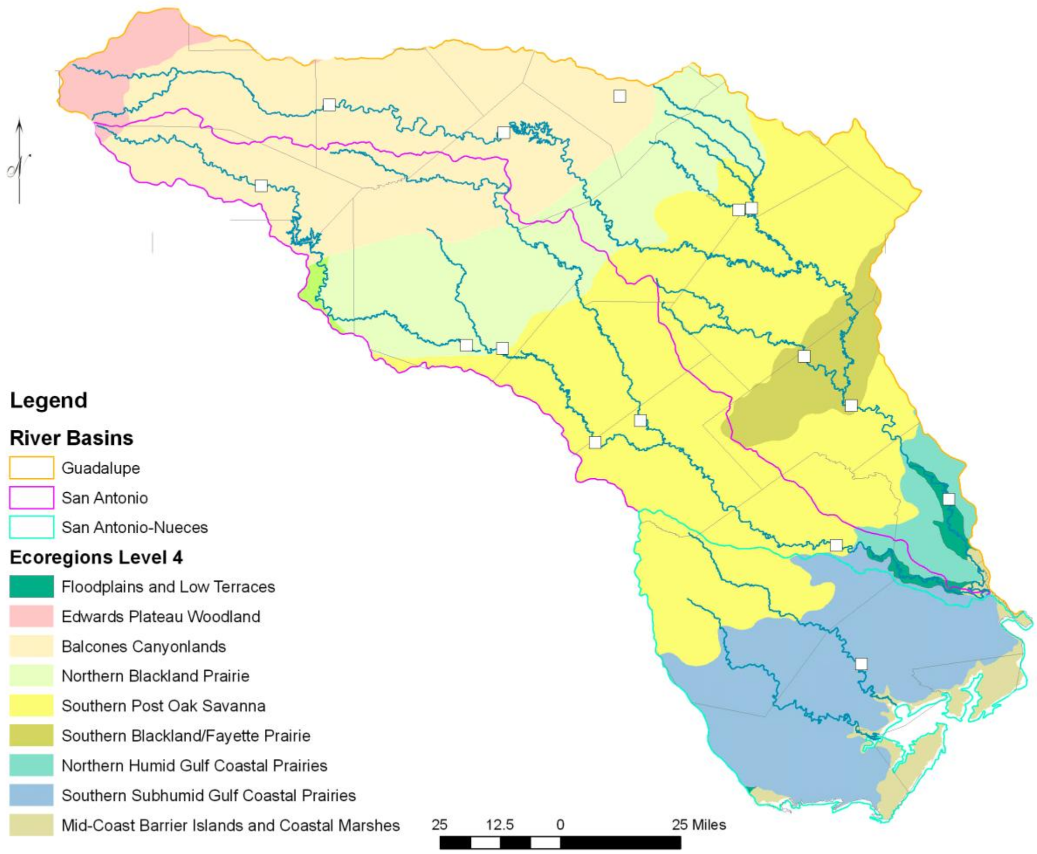
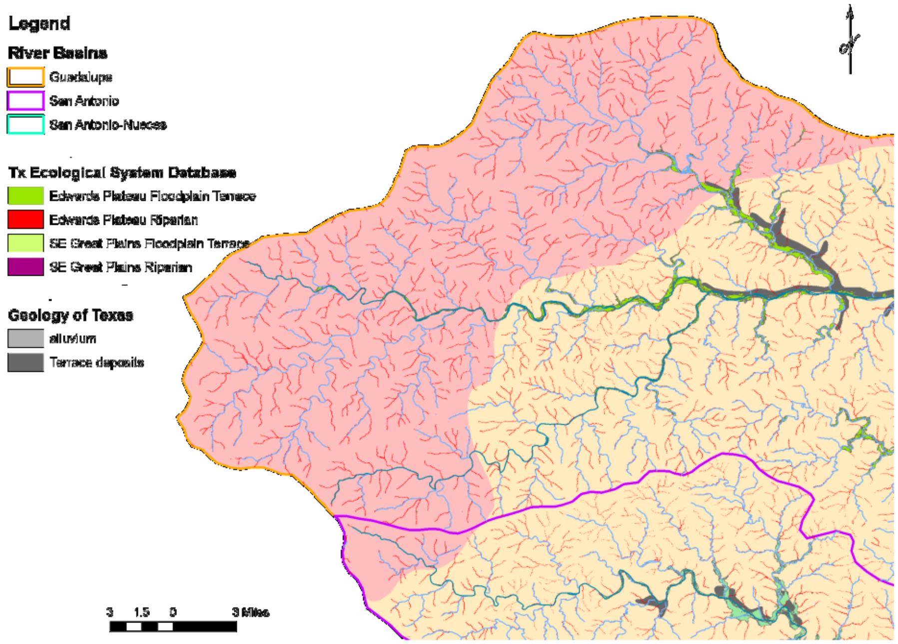


Figure 3.6-7. Ecoregions (Level 4) within the Guadalupe, San Antonio, and San Antonio-Nueces Coastal basins. White boxes correspond to USGS stream gage locations using in BBEST flow regime evaluations.

The Edwards Plateau Woodland ecoregion encompasses the headwaters of the Guadalupe and San Antonio basins. Most streams are ephemeral (no surface water present during some portions of the year, or during drought periods). No USGS stream gages were selected within this ecoregion. The terrace deposits displayed in the geology data are minor within this ecoregion; Edwards Plateau Riparian habitat follow stream and minor topographic drainage corridors in TSED (Figure 3.6-8a). However, in the NLCD data, no woody wetland or herbaceous wetland data were mapped in the Edwards Plateau ecoregion of the basins (Figure 3.6-8b).

The Balcones Canyonland ecoregion is represented by four USGS stream gages (Figure 3.6-9a). Riparian development along the main reaches of the rivers is limited, whereas Edwards Plateau riparian is still delineated along most of the tributary streams in this region in the TSED. Riparian woody wetland is not mapped to any appreciable extent in the NLCD data (Figure 3.6-9b).

A



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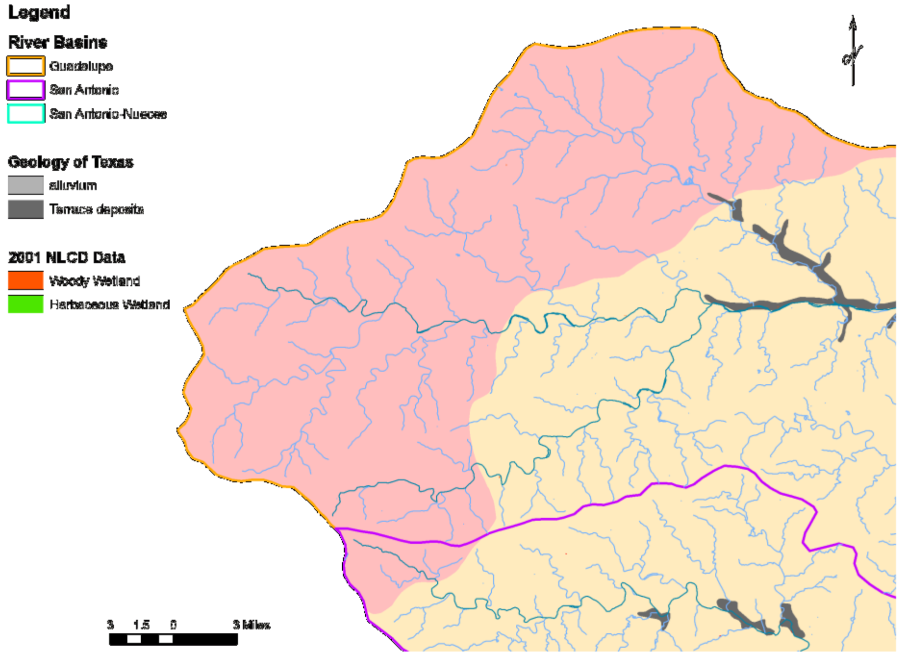
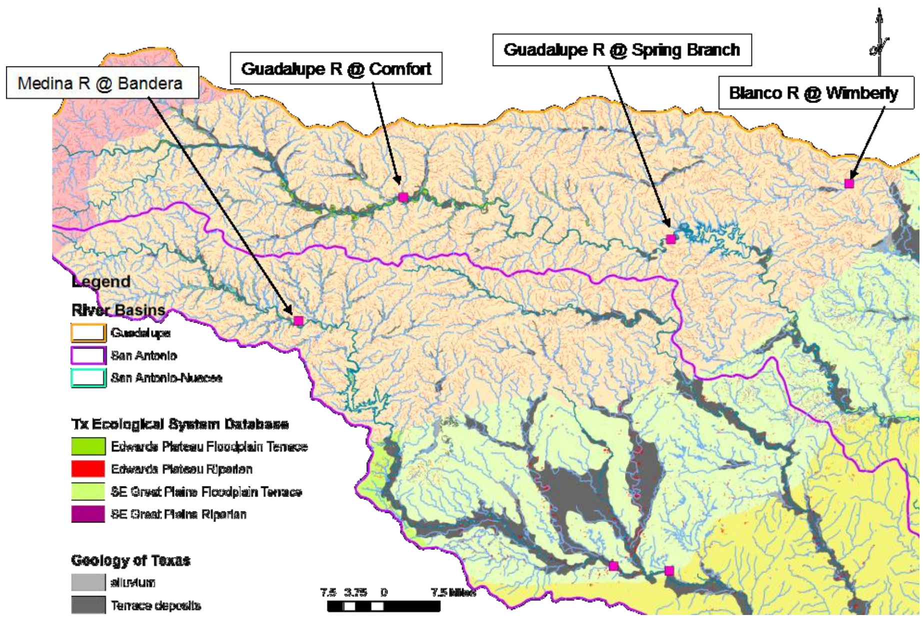


Figure 3.6-8. Riparian and floodplain habitats for Edwards Plateau Woodland Ecoregion from A) Texas Ecological System Database and B) National Land Cover Data.

A



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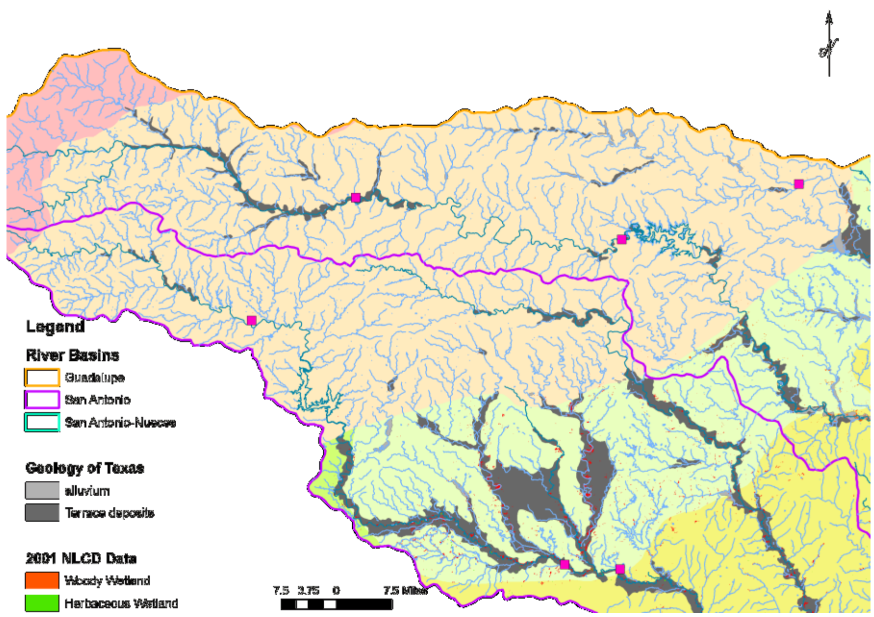


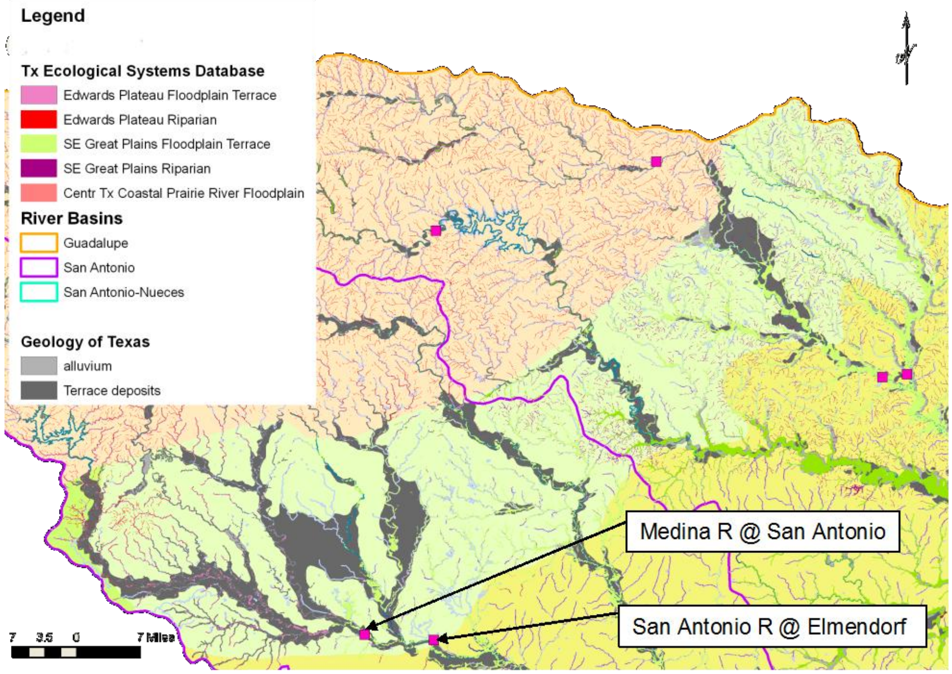
Figure 3.6-9. Riparian and floodplain habitats for Balcones Canyonland Ecoregion from A) Texas Ecological System Database and B) National Land Cover Data.

Northern Blackland Prairie exhibits more terrace deposits in the geology data, however little riparian woodland habitat is located within these terraces using TSED (Figure 3.6-10a). In addition, more Southeastern Great Plains riparian habitat overlays the tributary streams in the Guadalupe Basin than in San Antonio Basin. Two USGS stream gages are located within this ecoregion, both located in the San Antonio Basin. More extensive patches of woody wetland (generally forming a riparian corridor) are delineated within the terrace deposits located along the San Antonio and Medina rivers using NLCD (Figure 3.6-10b).

Southern Post Oak Savanna encompasses a large, middle portion of both Guadalupe and San Antonio basins and the upper extent of the San Antonio-Nueces Coastal Basin (Figure 3.6-11). In addition, Southern Blackland/Fayette Prairie ecoregions bisects the Southern Post Oak Savanna in the Guadalupe Basin and encompasses the confluence of Guadalupe River and Sandies Creek. Two USGS stream gages are located in each Guadalupe and San Antonio basins, as well as two gages within the Southern Blackland/Fayette Prairie ecoregion within the Guadalupe Basin. No gages are located in the Southern Post Oak Savanna within the San Antonio-Nueces Coastal Basin. Southeastern Great Plains riparian habitat is mapped on most tributary streams in all three basins using TESD (Figure 3.6-11a). Within the main river drainages however, Southeastern Great Plains floodplain terrace covers most of the Guadalupe terrace deposits, is patchy in distribution in the San Antonio Basin, and very limited in San Antonio-Nueces Coastal Basin. NLCD woody wetland riparian habitat is fairly continuous along tributary streams in the Guadalupe and San Antonio-Nueces Coastal basins, but less extensive in the larger stream channels in all three basins (Figure 3.6-11b). The topographic relief of these ecoregions is lower and width of terrace and alluvium deposits of the larger basins is larger. These conditions should be appropriate for some riparian corridor development, which does not appear to be delineated in either dataset.

Northern Humid and Southern Subhumid Gulf Coastal Prairies ecoregions encompass the lower portions of all three basins along the Gulf Coast (Figure 3.6-12). In the TSED, the most extensive and continuous Central Texas coastal Prairie River floodplain habitat is mapped for the confluence of Guadalupe and Coleto Creek in the Guadalupe Basin and confluence of Guadalupe and San Antonio rivers (Figure 3.6-12a). Woody wetland in the NLCD also depicts a fairly continuous riparian corridor along Guadalupe, San Antonio, and Mission rivers gradually shifting to herbaceous wetland habitat closer to the coastal bays (Figure 3.6-12b). These ecoregions support the most extensive riparian habitat within all the basin areas. The extent of the riparian coverage is more in the Guadalupe River floodplain, followed by San Antonio, and is likely a function of larger watershed area, as well as more precipitation in the drainage areas as compared to the Mission and Aransas rivers within the San Antonio-Nueces Coastal Basin.

A



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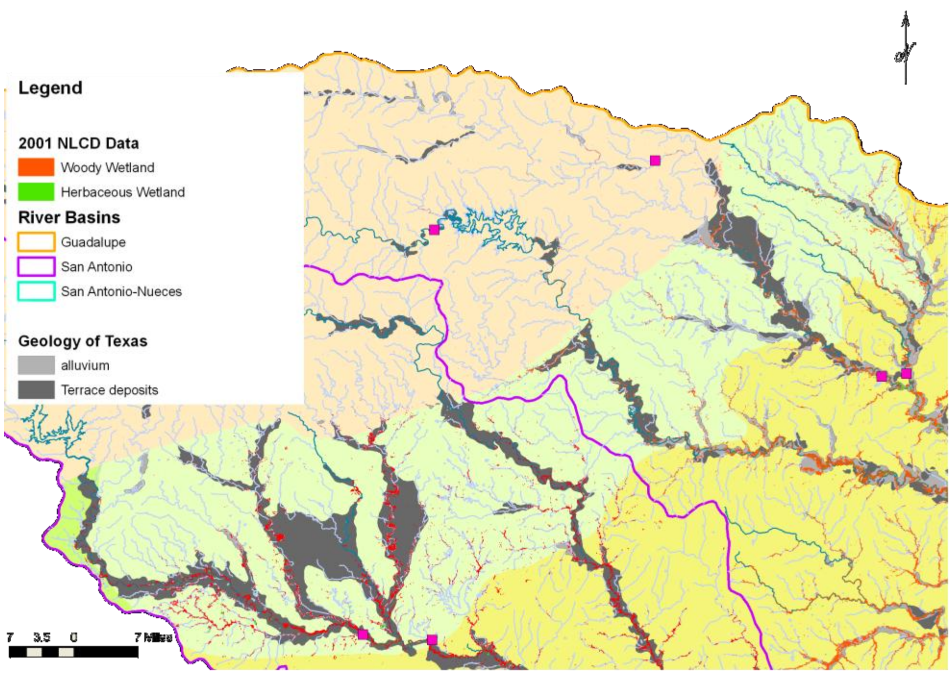
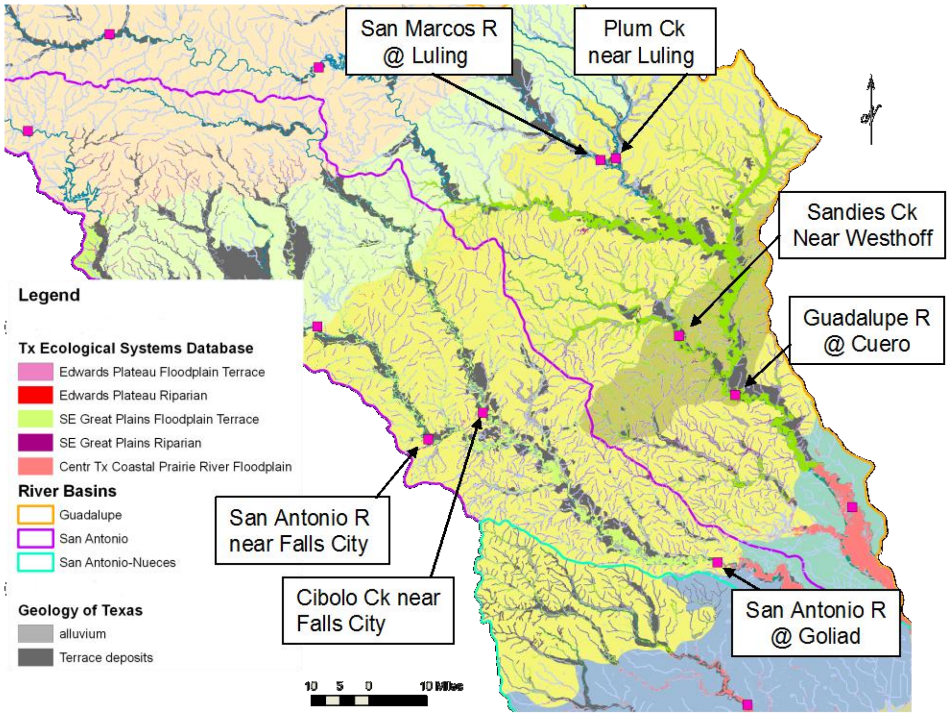


Figure 3.6-10. Riparian and floodplain habitats for Northern Blackland Prairie ecoregions from A) Texas Ecological System Database and B) National Land Cover Data.

A



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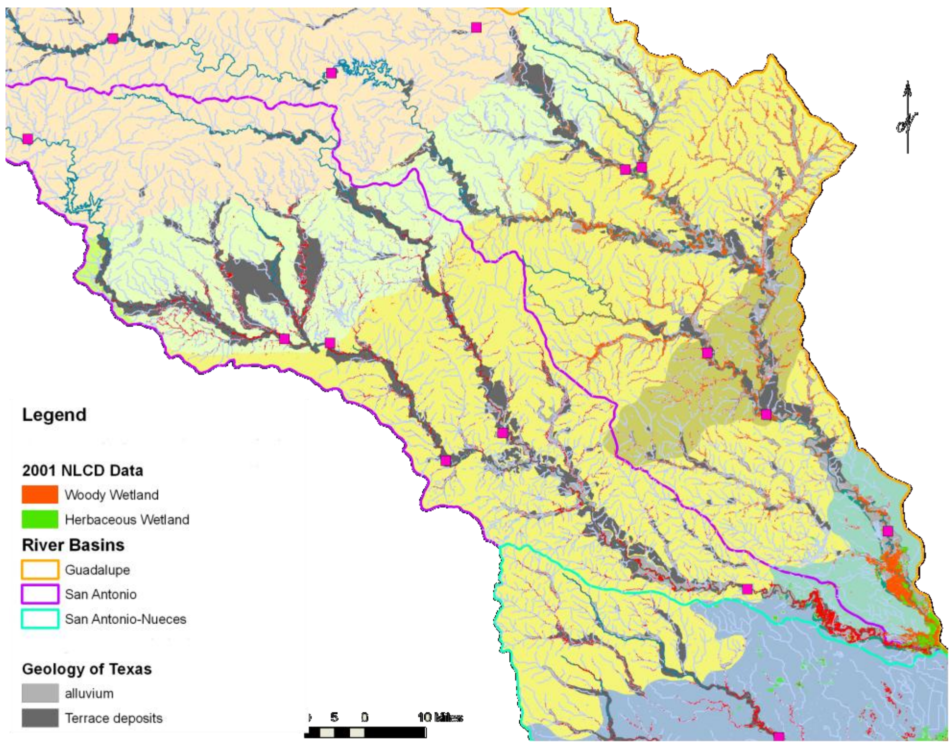
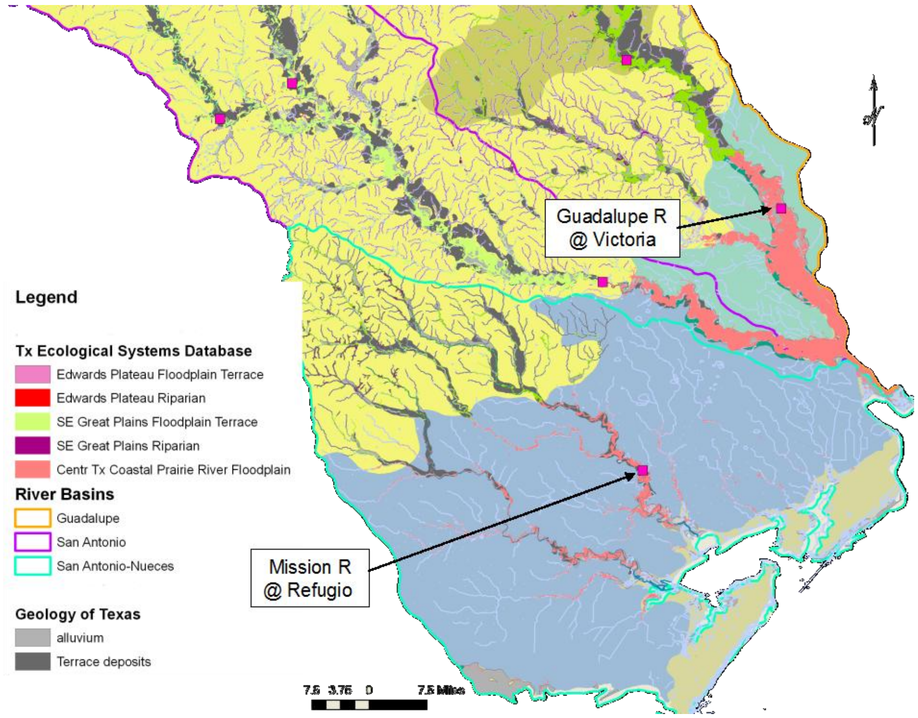


Figure 3.6-11. Riparian and floodplain habitats for Southern Post Oak Savanna and Southern Blackland/Fayette Prairie ecoregions from A) Texas Ecological System Database and B) National Land Cover Data.

A



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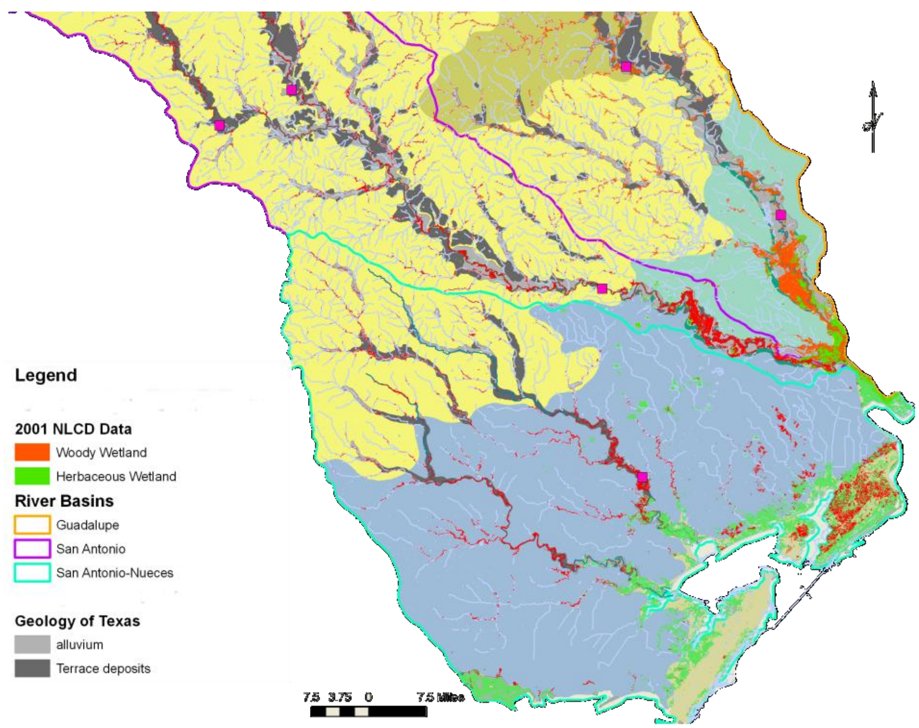


Figure 3.6-12. Riparian and floodplain habitats for Northern Humid and Southern Subhumid Gulf Coastal Prairies ecoregions from A) Texas Ecological System Database and B) National Land Cover Data.

3.6.8 Riparian Corridors in the Guadalupe-San Antonio Basin and San Antonio – Nueces Coastal Basin (Mission River): Sound Ecological Environment

Using riparian vegetation community dynamics to assess system health provides both a temporal and spatial view. While limited data exist to conduct a quantitative evaluation, qualitative assessment of species richness and stand regeneration information indicate a system which has a full complement of woody vegetation types in various stages of regeneration (see Tables 3.6-2 through 3.6-4) and succession (see Figure 3.6-6). Since this assessment only considered potential impacts on riparian health from hydrologic drivers, no effort to incorporate land management influences on riparian extent and corridor continuity was undertaken. Therefore, we consider the riparian corridors in these basins to achieve a sound ecological environmental condition.

Conducting riparian vegetation surveys can be time-effective and provide a wealth of information to assess system health, and using species' environmental requirements and responses to hydrologic change can indicate shifts in recent flow regime (although a substantial time lag occurs). As an example, using each species presence and probability of occurring in wetland conditions, a full range of species tolerant of these varying hydrologic conditions (wet to dry) were documented in each river survey (Table 3.5-6). Using this range as illustrating a sound ecological environment, predictions can be made about the riparian diversity if flow regimes change. Under a limited HFP regime, species which occurred in areas of the floodplain where subsurface water were predominantly available during the growing season are no longer a component of the community (Figure 3.6-13). In addition, upland species begin to establish at lower elevations of the floodplain, and effectively compress the riparian community width. When overbank flooding is limited as well, compression of the riparian community increases, while upland vegetation dominates the floodplain at mid- and higher elevations. As mentioned previously, exotic species are often the first to colonize in these floodplains following disturbance, further reducing species diversity. Under conditions of extended overbank flooding from severe precipitation events in the watershed or from tropical storms, upland vegetation can suffer high mortality. Often large, dead woody debris can accumulate in the stream channel during subsequent flooding and substantial amounts of sediment transported from the floodplain surface. A combination of these flow regime shifts would result in a degraded ecological environment.

Table 3.6-6. Documented woody vegetation species within riparian surveys in Guadalupe/San Antonio/Mission river systems. National Wetland Indicator abbreviations and associated probability of being located in a wetland: OBL – obligate (>99%), FACW (99<66%), FAC (66<33%), FACU (33<1%), UPL <1%), + (usually at higher end of range), - (usually at lower end of range) (Reed 1988). Color spectrum refers to Figure 14; G – Guadalupe River surveys (TWDB, unpubl. data), S – San Antonio River Surveys (TIFP and TPW, unpubl. data), M - Mission River (Davis, unpubl. data).

OBL	FACW+	FACW	FACW-	FAC+	FAC	FAC-	FACU+	FACU	FACU-	UPL
G S	G S M	M	G S M	G S M	G S	G S	G S M	M	G S M	G S M
Bald Cypress	Black Willow	Dwarf Palmetto	Box Elder	Pecan	American Elm	Bur Oak	Chinese Tallow	Huisache	Western Soapberry	Acacia
G S M			G M	G S	G S M	G M	S M	G M		G M
Buttonbush			Deciduous Holly	Red Oak	Cedar Elm	Yaupon	Live Oak	Red Mulberry		Anaqua
			G S M	G S	G S M			G S		G
			Green Ash	Sycamore	Cottonwood			Red Oak		Ashe Juniper
			M		M			G		M
			Retama		Mexican Ash			White Mulberry		Brasil
					G					G S M
					Roughleaf Dogwood					Chinaberry
					G					M
					Roosevelt Weed					Colima
					G S M					G M
					Sugar Hackberry					Desert Hackberry
					G M					G
					Texas Hawthorn					Flameleaf Sumac
					G M					G M

OBL	FACW+	FACW	FACW-	FAC+	FAC	FAC-	FACU+	FACU	FACU-	UPL
G S	G S M	M	G S M	G S M	G S	G S	G S M	M	G S M	G S M
					Texas Persimmon					Gum Bumelia
					G M					S M
					Wafer Ash					Honey Mesquite
										G M
										Mexican Buckeye
										G S M
										Osage Orange
										M
										Reticulated Hackberry
										G
										Yucca

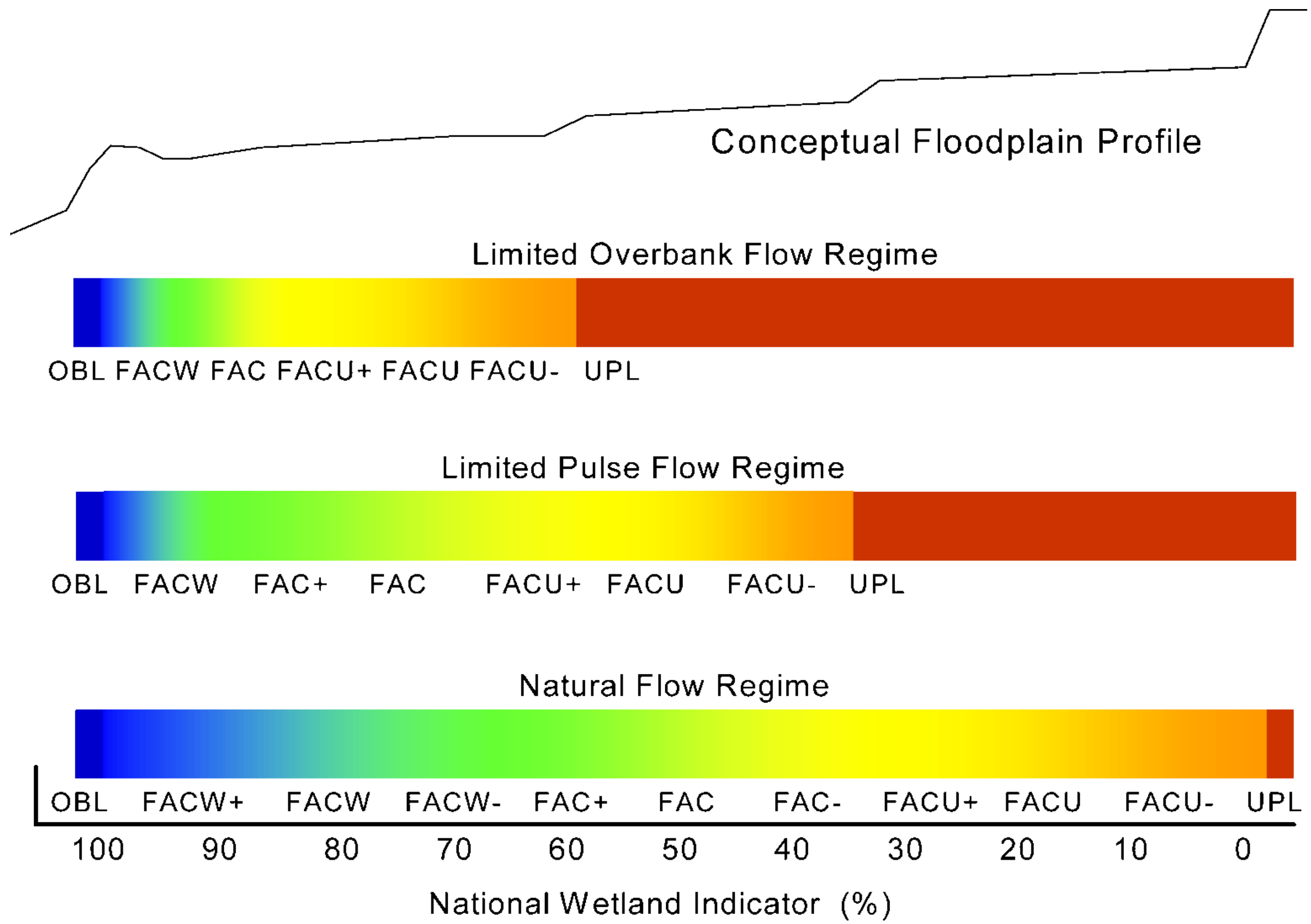


Figure 3.6-13. Conceptual diagram of distribution of vegetation arranged by National Wetland Indicator designation across the floodplain profile (see Table 6 for definitions) for natural, limited pulse, and limited overbank flow regimes.

3.6.9 Flow Regime Recommendations for Riparian Overlay

Evaluations of various physical (sediments flows), chemical (water quality), and biological overlays (instream fish and riparian vegetation communities) indicate that the GSAMA Basins and SACA Bays achieve the sound ecological environment definition. Three elements within the river basin systems that target floodplain function can be defined that will maintain the SEE conditions as well as provide benefits to the bay systems (Table 3.6-7). Floodplains systems are best defined geomorphically in that they are formed and influenced by river flows and sediment on which ecosystems develop and operate (Opperman et al. 2010). Long-duration and frequent flood pulses drive the aquatic productivity (Junk et al. 1989), whereas, riparian communities require high magnitude and less, frequent flood events to maintain geomorphic dynamics (Whiting 1998). Therefore, hydrologic connectivity between river and floodplains is essential in maintaining a sound ecological environment at a landscape scale.

The inherent variability of natural flows in the Guadalupe-San Antonio River Basin and San Antonio-Nueces Coastal Basin is a result of climate, topography, and soil diversity. The riparian vegetation that has adapted to this variability must be maintained by a flow regime that mimics that natural variability and can be adapted during dry and wet base flow conditions Since riparian and floodplain dynamics are intimately tied to sediment transport through the basin, small changes in sediment movement from altered flow regimes will result in shifts in species composition and dominance, and ultimately the sound ecological environment currently designated for these basins. Each component of the flow regime is essential to maintaining the riparian community as a sound ecological environment. In the flow regimes recommended by the GSA BBEST, each component provides a level and varying emphasis pertaining to physical, chemical, and biological processes (Figure 3.6-14). While many processes are provided to some extent by all pulse flows, the magnitude and duration of pulse levels result in different combinations of benefits. These processes and associated benefits can be parameterized to a particular site where a flow duration curve and draft flow regime recommendation has been derived (Figure 3.6-15).

Table 3.6-7. Key attributes of ecologically functioning floodplains (modified from Opperman et al. 2010).

Elements	Functions	Flow Benefits
1) CONNECTIVITY: Hydrologic connectivity between river and floodplain	Provides mechanism of exchange of flow, sediment, nutrients, and organisms	Subsistence: groundwater recharge to stream & estuary Base: groundwater recharge to stream & estuary Pulse: groundwater recharge from stream Overbank: groundwater recharge from stream; surface water detention during flooding
2) FLOW REGIME: Variable hydrograph		
Reflects seasonal precipitation patterns	Ensures timing of flow events with biological requirements	Subsistence: minimal subsurface water available for survival Base: subsurface water available for growth Pulse: subsurface water available for reproductive cycle Overbank: surface water transports sediment, nutrients, seeds, propagules, organic material
Retains a range of both high and low flow events	Supports important floodplain processes	Variability (magnitude, frequency, duration) in flow regimes maintain biodiversity
3) SPATIAL SCALE: Sufficient spatial scale		
Encompasses dynamic processes	Erosion and deposition of sediments along entire basin	Subsistence: maintain maturing riparian vegetation along streambank to stabilize bank Base: maintain seedling and sapling stages of vegetation to stabilize bank Pulse: move sediment along stream bottom to low-lying banks; limit vegetation encroachment into stream channel Overbank: maintain river meanders to increase productivity
Ensures meaningful floodplain benefits	Among terrestrial, floodplain, instream, and estuarine systems	Subsistence: maintain longitudinal connectivity along stream channel via groundwater recharge Base: maintain stream flow and water quality along stream channel via groundwater recharge Pulse: recharge groundwater for future low flow events Overbank: decrease flood flow velocity, temporarily store floodwater and discharge to stream and estuary at reduced rate

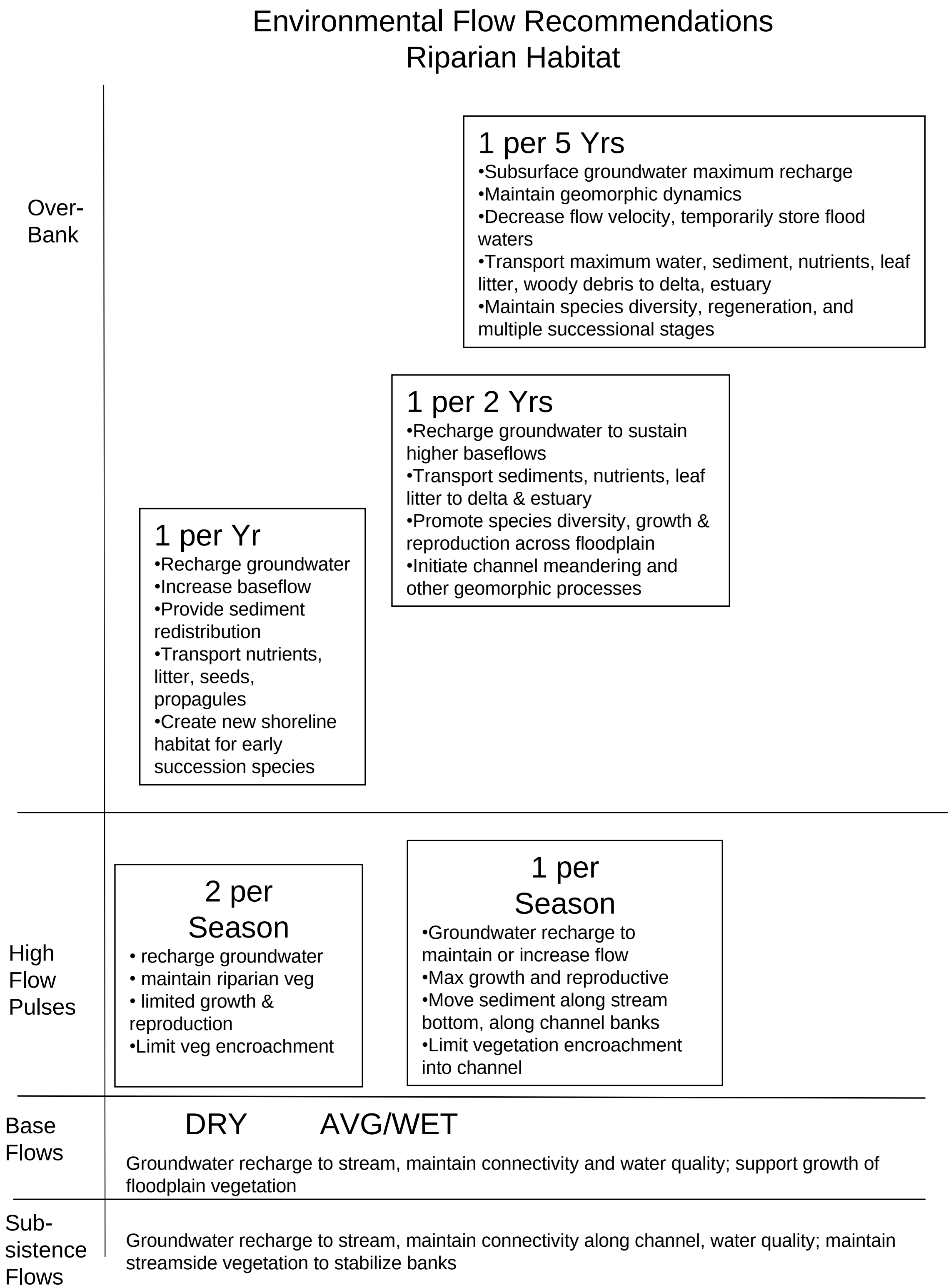


Figure 3.6-14. Environmental functions of the riparian vegetation community that will be supported by the recommended environmental flow regimes for Guadalupe-San Antonio and San Antonio-Nueces Basins that will support a sound ecological environment within the basins and San Antonio and Aransas Bay systems.

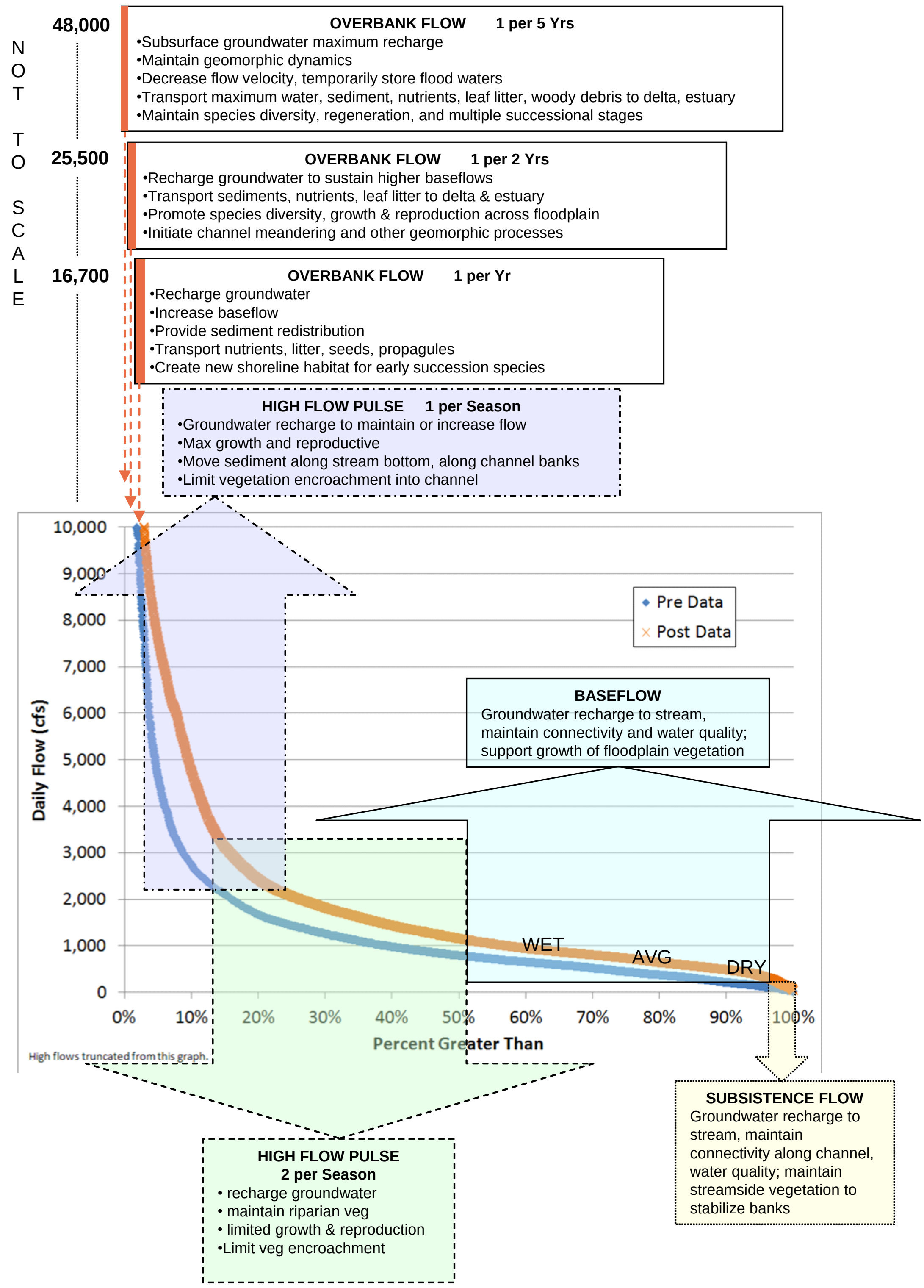


Figure 3.6-15. Conceptual example of environmental flow recommendations applied to a flow duration curve for a specified location (in this case, Guadalupe River at Victoria).

4. Freshwater Inflow Analyses

4.1 Effects of Freshwater Inflow on Estuarine Ecosystems

The critical role of freshwater inflows **(= FWI)** in estuarine ecology has long been an accepted axiom (Longley 1994, Sklar and Browder 1998, Montagna et al. 2002). Many aspects of the 'sound ecological environment' of an estuary (including distinctive salinity gradients, characteristic wetlands, other structured habitats such as oyster reefs and intertidal flats, and distinctive wildlife and fisheries species), can be attributed to the effects of FWI. The following key structural components and functional processes of estuarine ecosystems are considered critically dependent on FWI:

- <u>Estuarine Fishery Communities</u> - Freshwater inflows which maintain natural salinity gradients and bay habitats are critical for sustaining historical estuarine fisheries populations. Ninety-five (95%) of all commercial and recreational fishery species in Gulf of Mexico depend on estuarine habitats for at least part of their life cycle (McKinney 1996). As exemplified by numerous fish, shrimp, oyster and crab life cycles, most species require special estuarine nursery conditions for postlarval/juvenile stages. Spotted seatrout and oysters are two species which live exclusively in estuaries. Many non-commercial species are also required to support food webs culminated by higher trophic level species such as red drum and flounder.
- <u>Wetland Habitats</u> - Texas estuaries had approx. 540,000 acres of intertidal, saltwater wetlands in 1992, a decrease of about 10% of its emergent coastal marshes since the mid-1950s (Moulton et al. 1997). Coastwide, palustrine (freshwater) and very low-salinity (intermediate and oligohaline) marshes, which develop in the delta and upper estuary zone where salinities are non-existent to very low-brackish and must be maintained by direct FWI's, had decreased about 29% from 810,000 acres in the 1950s. Many of these sensitive fish and wildlife coastal wetlands have been impacted due to reservoir impoundments, or coastal land use conversion to agriculture. Maintenance of intermediate marshes in the upper estuary and delta requires constant flushing with freshwater, sediment-laden, inflows that occur from pulsed runoff and watershed floods.
- <u>Primary Productivity and Nutrient Assimilative Capacity</u> - This refers to the capacity of estuaries to assimilate dissolved nutrients and recycle organic matter, as well as perform water treatment, especially of anthropogenic discharges. These effects are often difficult to quantify, but the ecological and economic value of this service cannot be underestimated. Normal FWI regimes maintain balanced phytoplankton populations during specific seasons that underpin healthy estuarine food webs. Decreased river inflow (i.e. water quantity), along with no reduction or even increases in nutrient loadings, can cause serious decreases in water quality (Alber 2002). Lack of flushing of nutrients and pollutants can eventually lead to phytoplankton blooms, oxygen depletion, eutrophication and imbalanced food webs (ie. low species diversity) in estuaries. Lack of adequate FWI flushing of estuaries has contributed to more than half of Gulf of Mexico classified shellfish growing areas being closed to harvest for humans (in McKinney 1996).
- <u>Coastal Wildlife Communities</u> – Aquatic mammal and waterbird populations are typically associated with estuaries, just as fisheries are. Many waterbirds, shorebirds and marshbird species live or nest only in coastal estuaries where specialized requirements for their food and habitat are satisfied by FWI's (Gosselink 1984). In the case of waterfowl,

the so-called "waterfowl flyways" used by waterfowl migrating to the Gulf of Mexico, such as the Central flyway, funnel more than 80% of the world's population of redhead ducks to Texas estuaries to spend the winter. A recreational offshoot of this is the benefit that waterbirds and wintering waterfowl provide for recreational activities such as hunting, birdwatching, and ecotourism.

- Biodiversity and Endangered Species – Species like Whooping Cranes, sea turtles, manatees, and scallops are well-known signs of the high biodiversity of estuaries; and these often require specialized, protected, estuarine habitat, such as National Wildlife Refuges, National Parks or Coastal Preserves with seagrass beds.

Paradoxically, many of these needs and benefits of FWI's have been inferred from altered processes and climatic episodes that deprive the estuary of critical inflows which maintain healthy, productive estuarine systems. Hoese (1960) was perhaps one of the first to note this relationship. He described the effects of the 1950s drought on the lower San Antonio Bay system and then documented the subsequent ecological recovery of the Mesquite Bay area from that severe drought. Later, Copeland (1966) studied the response of Coastal Bend, Texas, bays to decreased river flow by examining ecosystem effects on estuarine phytoplankton production and nutrient cycling. Sklar and Browder (1998) further refined the concept of FWI alterations to focus on effects of shifting the salinity gradient and its resulting disturbance of estuarine biota and production. Other authors have noted detrimental effects of FWI reduction from reservoirs and water diversions in estuarine areas ranging from Texas, to the Aral Sea in Russia, to California (McKinney 1996, Montagna et al. 2002, Estevez 2002).

4.1.1 Dynamics of Estuarine Freshwater Inflow Regimes

Each of the 8 major estuaries of Texas can be characterized by its hydrology and unique assemblages of aquatic species, communities, and habitats. FWI is a major factor determined largely by the watersheds (river basins) which feed these estuaries, along with the local coastal climate. Bay communities and habitats are the result of the unique hydrology and physiography existing in those geographic regions over the North to South latitudinal gradient existing along the Texas coast (Longley 1994). The Guadalupe-San Antonio and Mission-Aransas Estuaries, shown in Figure 4.1-1, have developed their own typical, representative ecosystems (communities, suites of species, and habitats) in response to local physiography and hydrology from the Guadalupe/San Antonio/Mission/Aransas watersheds. In order to quantitatively assess the role of watershed-based FWI into Texas estuaries, both in the past and under future water management conditions, scientists primarily examine the effects of historical and predicted inflow regimes on three dynamic, physical estuarine processes directly controlled by FWI: salinity gradients, nutrient inputs, and sediment deposition (Longley 1994).

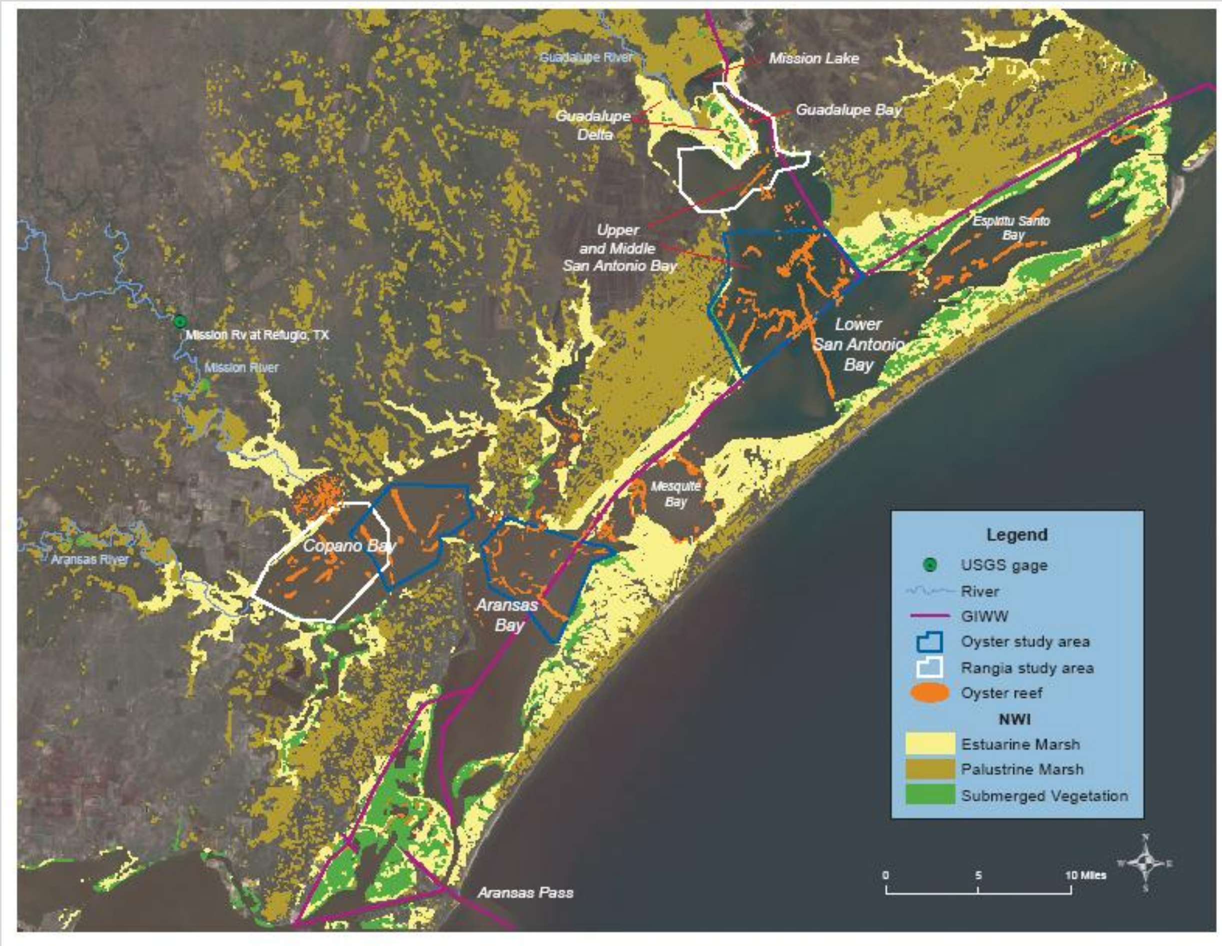


Figure 4.1-1 Map of Guadalupe/San Antonio Bays system and Mission Lake/ Copano Bay/ and Aransas Bays system, with wetlands habitats and oyster and Rangia habitats overlaid. Map prepared by Lynne Hamlin, TPWD.

4.1.1.1 Salinity Gradients

By definition, estuaries are the mixing zone where riverine freshwater mixes with saltwater from the Gulf, resulting in a salinity gradient. The most direct effect of FWI on living organisms is generally mediated through this effect on salinity, or the concentration of salt in seawater, and the resulting response to salinity of estuarine organisms. Most estuarine organisms respond to saltwater concentrations through osmoregulation, an energy-demanding process which affects metabolism and can greatly reduce growth and resulting biomass production of a species. Whether the species is a plant (primary producer) or an animal (consumer), this metabolic energy loss is a constraint on bay productivity, as well as the population of a species. Some species have a wide range of salinity tolerance (so-called euryhaline species), other species have rather narrow salinity ranges (termed stenohaline). To a large degree, where a species occurs along the salinity gradient depends on this basic physiological property of how it copes with salinity (i.e.osmoregulates).

Salinity gradients in estuaries have been described according to a classical scheme developed by Carriker (1967) and further refined for wetlands by Cowardin et al. (1979). In this scheme, the range of salinity from 0 to 35 parts per thousand (ppt) has been divided into a number of categories : oligohaline (0 – 5 ppt), mesohaline (5 – 18 ppt), polyhaline (18 – 30 ppt) and euhaline (30 -35 ppt) and hyperhaline (> 35 ppt). The spatial and temporal dynamics of these categories provides a convenient way to describe the typical salinity conditions in an estuary to FWIs. Depending on the size and volume of the estuary, salinity gradients can change gradually or quickly to fluctuations in FWI (Solis 1994). Organisms distributed along this gradient in distinct fixed communities can be considered indicators of these zones (e.g. oyster reefs, seagrasses), which often reflect the salinity tolerance capacities of such sessile organisms.

Motile organisms such as fish and shrimps, on the other hand, can move as the salinity zones expand or contract in response to hydrologic conditions. Bulger et al. (1993) suggested a different salinity zonation scheme of five zones based on biologically relevant criterion. However, Greenwood (2007) demonstrated that there were no clear and sharp changes in fish and shrimp community structure between any of the zones except at the upper and lower end where community structure changes rapidly below 2 psu ("practical salinity units", approximately equal to parts per thousand [ppt]) and above 33 psu, with relatively slow but steady change in between. The salinity gradient in estuaries is obvious but the faunal community's response to that gradient is complex and often species specific.

4.1.1.2 Nutrient Supply

Another major effect of FWI occurs through provision of nutrients (especially dissolved nitrogen and phosphorus) and organic matter to sustain nektonic (free-swimming) food webs or wetland plant growth in the estuary (Montagna et al. 2002). Primary productivity occurs either by growth of phytoplankton in the water column or by vegetative wetlands (rooted marsh plants) or submerged vascular plants (= SAV). Depending on the estuary and rate of inflow, nutrient input will produce different amounts of plant habitat assemblages, consisting of open-water (nekton), submergent (benthic SAV), and emergent (marsh plant) communities. Wetlands (consisting of SAV, saltmarshes, brackish marshes, and low-salinity to freshwater deltaic marshes) or benthic habitats, in turn produce distinctive faunal communities.

4.1.1.3 Sediment Supply

In the case of rooted wetland plants, sediments supplied by FWI inundation are also extremely critical to maintaining marsh elevations (as witnessed by wetlands loss in Louisiana coastal areas; see Visser et al. 1999). Without sediment deposition from FWI into bay delta marshes, these systems will undergo compaction subsidence and erosion, as evidenced by the Guadalupe Delta (see Fig. 1) (White and Morton 1987). Because sediment transport increases with water velocity, inflows generally appear to deliver much of this sediment to the bay deltas during floods and pulse flows (Longley 1994).

4.1.2 Physiography and Ecology of Guadalupe-San Antonio and Mission-Aransas Estuaries

The physiography of the Guadalupe-San Antonio Bays System and the Mission-Aransas-Copano Bays System on the middle Texas coast (Fig. 1) are due largely to the subtropical, subhumid region receiving 32-40 in. (91-99 cm.) average annual rainfall (Solis 1994). Inflows vary greatly, however, because of drainage area of the watersheds. The Guadalupe and San Antonio Rivers, which drain river basins of 25,977 km^2 (10,500 sq. mi.) total area, contribute a combined average gauged inflow to the system calculated at 1.8 million acre-ft per year over the period 1941-1987 (Solis 1994). Ungauged inflow from local precipitation is estimated at 0.46 million acre-ft per year. Very little of the drainage for ca 200 km inland is impeded by reservoirs, as Canyon Dam on the Guadalupe River is ca 280 km upstream from the bay and Coleto Creek Reservoir is ca 100 km upstream on a tributary of the smaller San Antonio River. With these amounts of total inflow and estimated evaporation, the net freshwater inflow to the Guadalupe-San Antonio Estuarine System ranks **fourth out of the seven** major Texas estuaries (Solis 1994). For estuaries to the south showing a net precipitation deficit, river inflows plus rainfall are much less, while evaporation is greater; for estuaries to the north, river inflows plus rainfall are much greater, while evaporation is less. The Mission-Aransas-Copano Bays system conversely **ranks last of the 7 estuaries** in annual inflow. The MAC watershed is the smallest (6,100 km^2 or 2500 sq. mi.) in comparison to other drainages, with a combined average inflow of 480,000 ac-ft per yr (Solis 1994). Thus, these 2 estuarine systems represent intermediate estuarine types compared to the other Texas estuaries.

4.1.3 Dynamics of FWI Regimes

Organisms in the two estuaries studied by this BBEST have evolved or adapted to the historical inflow regimes reported in the hydrology section (Sec. 4.2) below and the resulting salinity and nutrient gradients produced by this hydrology over fairly long periods. However motile organisms can move in response to changing environmental conditions, including FWI regimes. It is primarily fixed estuarine habitats, with their sessile (fixed) plant and faunal communities which cannot move quickly in response to changing inflow conditions and the salinity gradient, that must integrate these conditions over the long-term to survive. These fixed habitats (shown in Fig.1) range from wetlands (various marshes and submerged vegetation), to oyster reefs and benthic communities where immotile, sessile species occur.

An important concept has been propounded by Richter et al. (1996) and Estevez (2002) on the significance of hydrologic variability to aquatic ecosystems caused by extreme instream (riverine) or estuarine inflow events. **As with many dynamic biological systems, it is the extreme variations (alterations) of inflow that generally cause the largest effects on estuarine ecosystem dynamics.** (i) The first of these extremes consists of the pulses of inflow associated with significant flow or discharge events upstream or coastal tropical storms. Such episodes produce "freshets" where the estuary undergoes flushing, and increased amounts of nutrients and sediments are transported into the bay. (ii) The other extreme (low inflows) is associated with water deficit (pre-drought) periods or actual drought conditions.

Tides produce normal daily to seasonal patterns of inundation of wetlands. Superimposed on tidal cycles are these freshete inundation events caused by FWI. Freshete events in combination with tidal fluctuations are critical to flooding of wetland habitats which provides fishery species access to wetland habitat areas. River overbanking carries nutrients and sediments into the delta marsh systems and removes dead litter and nutrient material. These flooding events contribute to recharging the wetland sediments, stimulating vegetation growth (Zedler 1983, Alexander and Dunton 2002), producing more low-salinity aquatic habitat for the biota, and transporting organic matter into the bay system. Sediment accretion from freshetes is also necessary to prevent subsidence and drowning of delta marshes (Visser et al 1999).

4.1.4 Response of Delta low-salinity marsh communities to freshetes

The oligohaline/freshwater plant species found in the Guadalupe Delta of the San Antonio Bay system (Fig. 1) or the Mission-Aransas Deltas of Misson Bay and Copano Bays, respectively, can face severe water stress from 1) lack of flooding normally associated with spring or fall freshetes or 2) from flooding with water of excessive salinity (Chabreck 1972, Pulich 1991). From a resource management perspective, two questions arise: 1) What amount of inflow is necessary for a freshete to flood the Delta sufficiently to maintain favorable hydrologic conditions for growth of Delta vegetation? 2) How often does the Delta experience such high-salinity inundation events? A practical answer is to examine the average historical frequency of Delta inundation from annual inflow and tidal data.

Modeling studies by the Texas Water Development Board (TDWR 1980) led to the conclusion that actual water levels in the Delta proper are controlled by river flood events combined with tidal cycles. Their work determined that 3-4 annual Delta inundations were necessary to maintain the production of Guadalupe Delta wetlands. Pulich (1991) attempted to estimate the recent frequency of Delta inundation from Guadalupe River overbanking at the Traylor Cut streamgauge. Correlations between gauged flow and stage height at this gauge over the period 1983-87 showed that overbanking occurred at a minimum threshold stage height, depending on tides, calculated at about 3.2 ft. at the gauge. Examination of gauged flow and rainfall records for these 5 years indicated that delta inundation was quite variable, but in line with the TDWR study. During years such as ‘86 and ‘87, the delta flooded, as indicated by the stage height vs. flow relationship, around 3-4 times each spring and 2-3 times each fall. In the “wet” year of 1987, the delta was inundated for longer periods of time (up to three weeks continuously) than average years, but did not generally undergo more flood events. Thus, inundation duration, and not frequency, seemed to be the major difference between average or wet years. Conversely, during the very “dry” year of 1984, the delta was not inundated at all (0 flooding events). However, neither study examined the salinity of overlying Delta floodwaters, which is a very critical factor.

4.1.5 Life cycles of estuarine species and linkage to freshetes

The delta and upper estuary areas are well known for their function as critical nursery habitat for estuarine fauna (Zimmerman 1989). By maintaining this nursery area, freshetes support the seasonal inflow requirements of many target species’ life cycles. Recruitment of postlarval and juvenile life-stages of many species also predominately occurs during discrete seasons, especially for the target species used in FWI modeling (e.g. crab, shrimp, some finfish). For these species, the success of that year’s total production may depend on the sum of the inflows over those months (= seasons) when recruitment is occurring (Pulich et al. 2002). While individual months within a season may be important, the positive benefits of cumulative seasonal FWI in any year are probably more significant from a biological perspective. This accounts for synergism between inflows and other factors.

Without these periodic freshetes, relatively constant conditions could prevail in the estuary. Under low to moderate inflow regimes such as those produced by truncated monthly flows, a relatively narrow range of salinities (perhaps approaching marine conditions) would occur. Under these stenohaline conditions, a less diverse, more marine community with fewer species is often established. This has actually been observed for the Appalachicola River estuary in Florida by Livingston and coworkers (1997). When inflows into this system were reduced by 50% over several years, the trophic structure of the estuary changed. Fish communities changed to herbivores, detritivores, and primary and secondary carnivores, while top-level predators were virtually absent. Similar changes also occurred during the severe Texas drought of the 1950s when Mesquite and Aransas Bays developed into marine systems under hypersaline conditions (Hoese 1960). Thus, variability in salinities and other FWI-dependent factors from freshetes helps to maintain biotic diversity of the estuarine community.

The spring/early summer freshete period may be the most important in estuarine species' life cycles due to coincidence of 2 major ecological factors, <u>one physiographical and another physiological.</u> The physiography of Texas estuaries is such that a spring freshete can prepare the estuary to survive the long, hot Texas summers and early fall period, without continued major inflows. Water residence time of most Texas estuaries (Solis and Powell 1999) allows these systems to continue 2-3 months after spring floods without new runoff before the salinities become too high or hypersaline, and dessication of wetlands sets in. Floods during the late summer or fall will usually occur more unpredictably in association with tropical storms or cool fronts. The 3-4 month spring period when a freshete can occur coincides fortuitously with a physiological factor, viz. species' growth cycles, which have been alluded to previously. This spring period is often important to recruitment and immigration of postlarval and juvenile life stages. As a result of the favorable salinities and sufficient food supplies produced by spring freshetes, the fauna are provided with productive growing conditions and sheltered nursery habitat (Montagna et al 2002).

4.1.6 Inflow Stress Produced under Low Flow or Drought Conditions

Low-inflow effects can be considered over either temporary or extended periods. Short-term (lasting a few months) low-flow conditions are a source of concern that the estuary could experience stressed conditions affecting species' growth and later reproduction. When minimal flows continue for an extended period (e.g. a year or more), the stressed conditions reflect drought which will affect species' populations and survival. To provide perspective, the low inflows that occurred during 1984 and late 1980s or the mid-to-late 1990s approximate such pre-drought conditions. In comparison, the long-term drought of record (1950 – 1958) serves as a benchmark for true, severe drought. Since true drought is generally considered to be unmanageable from a climatic and hydrologic perspective, we would be most concerned about the potentially severe effects of water management scenarios under marginal, low-flow conditions, prior to true drought. Low-flow inflow analysis to verify detrimental effects on estuarine ecosystems at this stage is critical to defining a threshold for drought conditions.

Extended periods below base flows would lead to reduced, cumulative monthly flows over critical periods (such as over the spring-summer seasons of Apr-Sept). While low flows on a monthly basis would normally be considered inconsequential, the cumulative effects of low flows over the entire 6 month spring-summer-fall seasons would be critical to many estuarine biota because this comprises a major portion of their entire estuarine life cycle.

The estuary can clearly rebound from month-to–month inflow variability. But when flows are reduced or curtailed over 3-6 months in succession, the effects on bay salinity gradients, marsh soils and vegetation, and the fauna themselves become pronounced and stress effects may become catastrophic. Salinity regimes rise as the gradient is compressed into the upper estuary, and the upper estuary may even become hypersaline when FWI is decreased and evaporation increases during the summer (Pulich et al. 2002, Montagna et al. 2002). Marshes will undergo desiccation and wetland soils become salinized (Pulich 1991, Zedler 1983, Alexander and Dunton 2002). Aquatic habitat in the delta marshes can disappear altogether as summer tides drop in Texas bays and riverine inflows decline. Populations of fishery species (crabs, shrimp, some finfish) may decrease noticeably from lack of food and habitat, or unfavorable salinities (Hoese 1960). Adults of motile species will retreat to isolated refugia areas where suitable aquatic habitat remains (Norman Boyd, TPWD, pers. commun). Other species which cannot move (immotile species like oysters, or oligohaline marsh plants) may be killed from predators, parasites, or hypersalinity itself.

4.1.7 Conclusion

As discussed here, FWI regimes are dynamic and have variable effects on estuarine ecosystems. In order to understand and determine pulse (freshete) or low-flow thresholds for estuarine target species, FWI regimes should be assessed for effects on key species using various frequency and duration criteria as proposed by Richter (1996) and Estevez (2002). The impact of reduced inflow on the estuary month-by-month or for several months or years in succession is expected to be quite different due to cumulative and synergistic ecological effects.

Because of their complexity, we propose that estuarine flow conditions be evaluated in the context of a conceptual model of flow regimes analogous to instream flow regimes (Figure 4.1-2). In this model, these flows range from the low flow regimes similar to "subsistence flows", to moderate flows (similar to low and high "base flows"), which includes pulse flows, or "freshetes" in the "high" range. Environmental flow planning must assess five fundamental characteristics of historical hydrologic regimes (Richter et al. 1996): 1) the magnitude of inflows, 2) the timing of flood or drought events (especially critical seasonal periods), 3) the frequency of flooding or drought events from year-to-year, 4) the duration of time that floods or drought have occurred, and 5) the rate of change (variability) in inflow conditions. The approach taken by the BBEST will be to identify these flow regimes (both in magnitude and frequency) based on inflow and salinity requirements of target indicator species or habitats.

Holistic watershed management should allow for estuarine freshwater inflows to mimic the "natural" inflow patterns of the watershed. At high flows, flood events would pass through to the estuary, while at low flows, the estuary would need 'subsistence' flows to survive, although it would be subjected to some level of drought. Management without considering these natural hydrologic regimes ultimately leads to severe alterations in many natural functions of the estuary, as described above. Historical flow patterns of magnitude, timing, frequency, and duration should be passed through to the estuary, but they should not be artificially modified or exacerbated by water management operations.

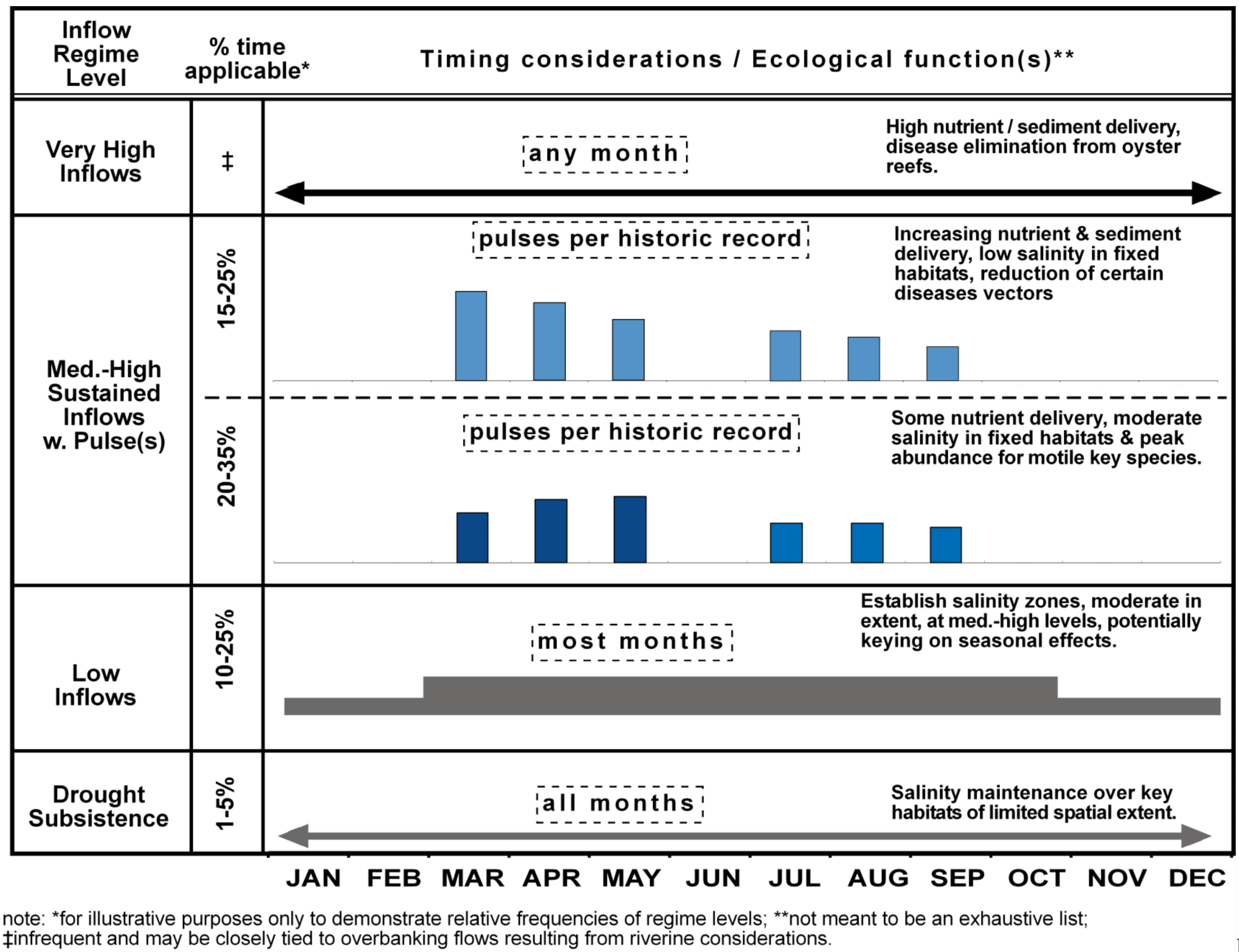


Figure 4.1-2. A conceptual model of an estuarine inflow regime, based on flow magnitude, duration, seasonality, and frequency (from N. Johns, personal communication, May 2010).

4.2 Hydrology and Salinity

The Guadalupe and Mission-Aransas Estuaries, like all Texas estuaries, are subject to a very wide range of inflow and salinity conditions. Understanding and predicting salinity patterns and dynamics in response to variations in freshwater inflow are central to the analyses that the GSA BBEST was able to pursue in the short time frame available for our work. Thus some discussion of the available data and techniques for examining the range and interrelationships of salinity and inflow is warranted.

4.2.1 Historical Inflows and Salinity Patterns

Inflows to both estuaries are a combination of measured (or "gauged") and ungauged (or "modeled") inflow estimates, plus corrections for diversions of water and wastewater returns below the gauges. Measured inflows are those from the available USGS stations (e.g. USGS gauge #8176500 on the Guadalupe River at Victoria). Estimates of inflow originating from ungauged areas are developed by the Texas Water Development Board using available rainfall data and estimates of "runoff" with a model known as TXRR. Estimates of diversions and return flows are gathered from records submitted to Texas Commission on Environmental Quality or sometimes directly from the diverters and dischargers. Overall inflow estimates for the Guadalupe Estuary were recently updated by TWDB utilizing additional diversion and return flow data gathered by HDR Engineering (TWDB 2010c). These revised estimates were considered by the GSA BBEST and TWDB as best available and utilized in all the estuary-related analyses described herein, including the efforts by the TWDB on behalf of the BBEST. Estimates of inflows to the Mission-Aransas Estuary were obtained from two TWDB data sources. For the 1941-1986 period we utilized the data published, and periodically updated, on the TWDB website3. For the 1987-2009 period we utilized the inflow data embedded in the input files for the TWDB salinity model TxBlend as further described below4. All inflow data is utilized on a monthly basis unless otherwise specified.

Figure 4.2-1 illustrates the broad range of inflows to these two estuaries. Shown in medium blue solid bars are the monthly median values, the monthly total inflow met or exceeded 50% of the time for that month. Also shown are the 25th and 75th percentile inflows for each month which are commonly used estimates of low and high inflows, respectively. The 25th percentile inflow is a level that monthly total inflow was at or below 25% of the time in that month. The 75th percentile inflow is a level that monthly total inflow was at or below 25% of the time in that month. For reference, Table 4.2-1 presents the same inflow statistics and some additional information on minimums and maximums. Much of the estuary analyses that follow will utilize inflows summed over a seasonal basis, thus Table 4.2-2 presents similar statistics as above but on a common seasonal basis (e.g. Summer = July-September).

Salinity data are another critical type of information utilized extensively in the analyses described below. There are only a few permanently monitored fixed sites in the Guadalupe and

[3] available at: http://midgewater.twdb.state.tx.us/bays_estuaries/hydrology/missionsum.txt

[4] total inflow for the Mission-Aransas Estuary for Dec. 2009 estimated based on USGS gauge data for Mission River, Aransas River, and Copano Creek scaled up by a factor of 1.5, a typical ratio of TxBlend inflows to USGS total for previous months with similar gauge totals.

Mission-Aransas Estuaries. The sites for the Guadalupe Estuary are illustrated in Figure 4.2-2 and for the Mission-Aransas Estuary in Figure 4.2-3. The Guadalupe Estuary site labeled SANT-TWDB in Figure 4.2-2 has a more-or-less continuous salinity record dating back to 1986. The Texas Water Development Board also has salinity records for a site in Mesquite Bay dating from 1986.

Before 1986 salinity data were usually from single measurements taken at various times of the year. Principal data sources for this period are summarized by TWDB and TPWD (1998). For the pre-1986 period and through today, an extensive database of salinity measurements are those of the Texas Parks and Wildlife Department (TPWD) Coastal Fisheries Monitoring Program. These are gathered monthly during fishery monitoring collections, however, the utility of this data is often limited because it is gathered on a somewhat random spatial basis and not frequently enough to establish anything more than the salinity at that moment in time (e.g. not a monthly average).

Figure 4.2-4 illustrates the very detailed salinity data (gathered on an approximate hourly basis) available from the SANT-TWDB site for a very dry period (July 1996) and an intermediate inflow period (September 1993). The analyses of salinity and inflow utilized by the GSA BBEST typically relied on these and other salinity data, but recast as monthly average values. This is illustrated in Figure 4.2-5 portraying the salinity time series using recently established (2007 and 2008) sites in the Mission-Aransas Estuary. Here, the very detailed (15 minute interval) data from the field sites in Copano Bay and Aransas Bay (see Figure 4.2-3) are recalculated as monthly averages. One very notable feature on those salinity time series is the months-long period in mid 2009 in which salinities were above 35 ppt, the salinity level of full-strength Gulf waters. Such "hyper-saline" conditions are a result of intense drought with very little freshwater inflow and high levels of evaporation leading to concentration of salinity.

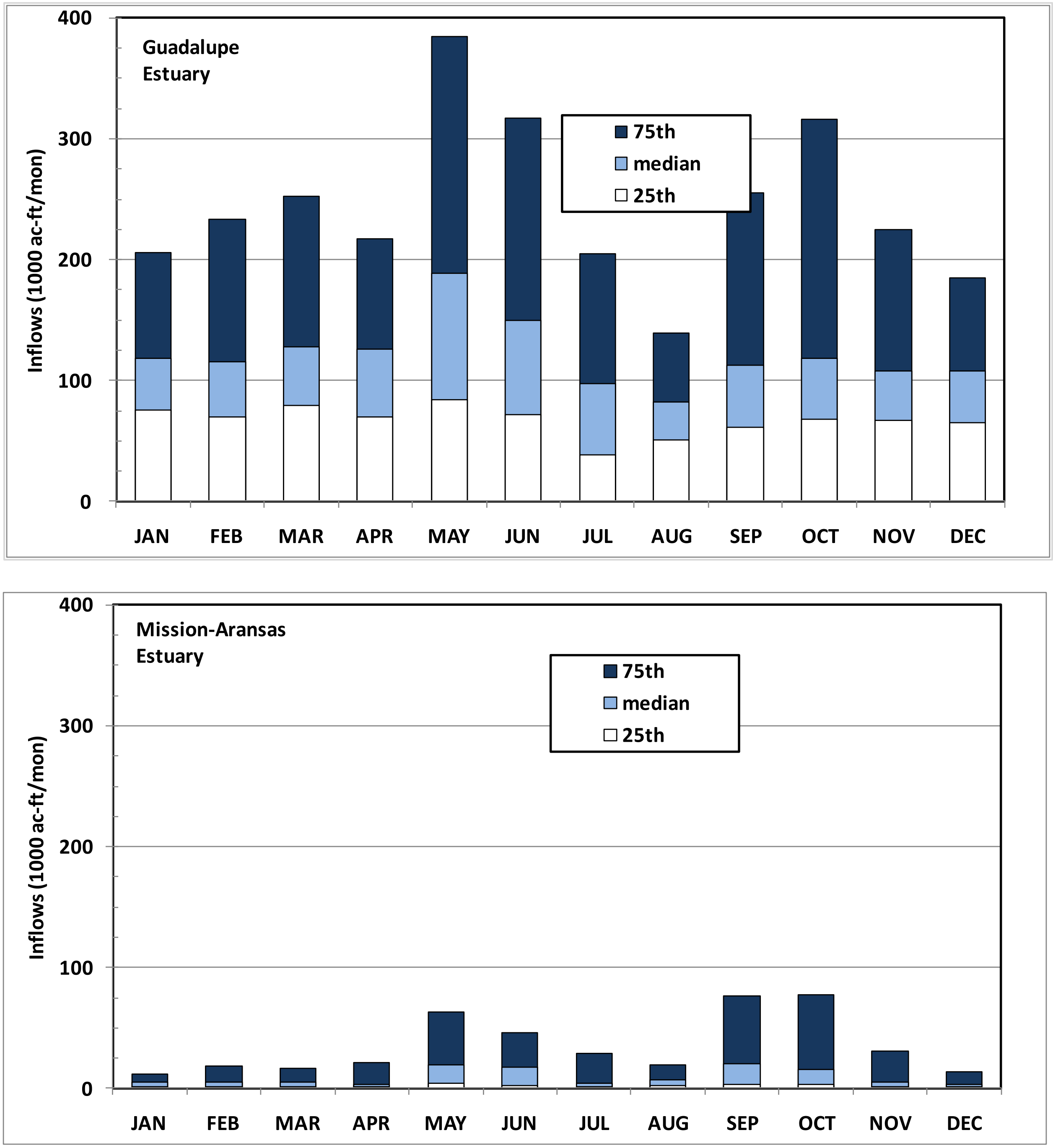


Figure 4.2-1. Illustration of monthly inflows and variability for Guadalupe Estuary (upper panel) and Mission-Aransas (lower) Estuary for the period 1941-2009.

Table 4.2-1. Monthly inflow statistics for the Guadalupe and Mission-Aransas Estuaries for period 1941-2009 (units 1000 ac-ft)

Guadalupe

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Min	14.0	20.9	16.0	14.9	25.1	0.0	0.0	0.0	0.0	16.8	11.2	18.4
25th	76	69	79	70	84	72	39	51	61	68	67	65
median	118	115	128	126	189	150	97	82	112	118	108	108
75th	206	234	252	218	384	317	205	139	255	317	225	185
max	895	1,666	959	1,085	1,240	2,478	2,073	874	2,227	2,477	1,606	983

Mission-Aransas

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Min	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.0	0.1	0.1	0.1	0.0
25th	1.1	1.1	1.7	1.6	3.9	1.9	1.5	2.6	3.2	3.3	1.8	1.4
median	4.7	5.0	5.1	3.2	19.7	17.2	4.4	7.0	20.1	15.2	4.9	3.4
75th	12.1	18.0	16.5	21.3	63	46.2	29.1	19.4	77	78	30.7	10.4
max	153	318	225	313	537	468	1,087	310	1,340	526	289	243

Table 4.2-2. Seasonal inflow statistics for the Guadalupe and Mission-Aransas Estuaries for period 1941-2009 (units 1000 ac-ft).

Guadalupe

	Winter [Jan-Mar]	Spring [Apr-Jun]	Summer [Jul-Sep]	Fall [Oct-Dec]
Min	55	52	0.0	49
25th	238	308	213	227
median	406	548	356	394
75th	683	928	630	759
max	3,520	3,072	3,081	3,634

Mission-Aransas

	Winter [Jan-Mar]	Spring [Apr-Jun]	Summer [Jul-Sep]	Fall [Oct-Dec]
Min	0.0	0.7	0.7	0.5
25th	6.7	19.0	28.5	9.0
median	29.3	63	56	42.8
75th	57	118	206	120
max	528	920	1,364	870

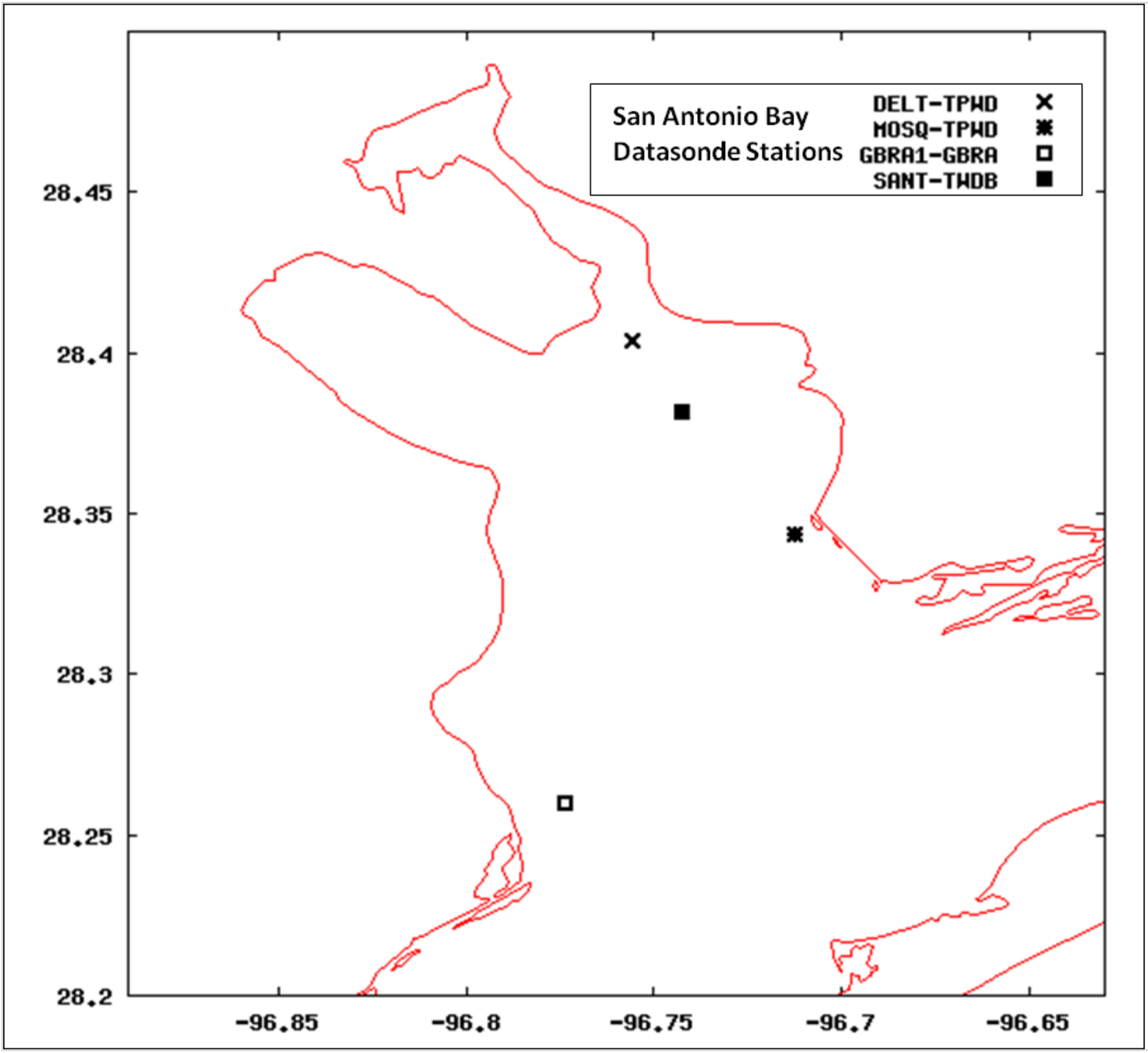


Figure 4.2-2. Salinity monitoring station locations in the Guadalupe Estuary (San Antonio Bay). DELT, MOSQ , and SANT stations are maintained by TPWD, though SANT is funded by the TWDB. GBRA1 is funded by the Guadalupe-Blanco River Authority and maintained by the Conrad Blucher Institute. (map from Texas Water Development Board).

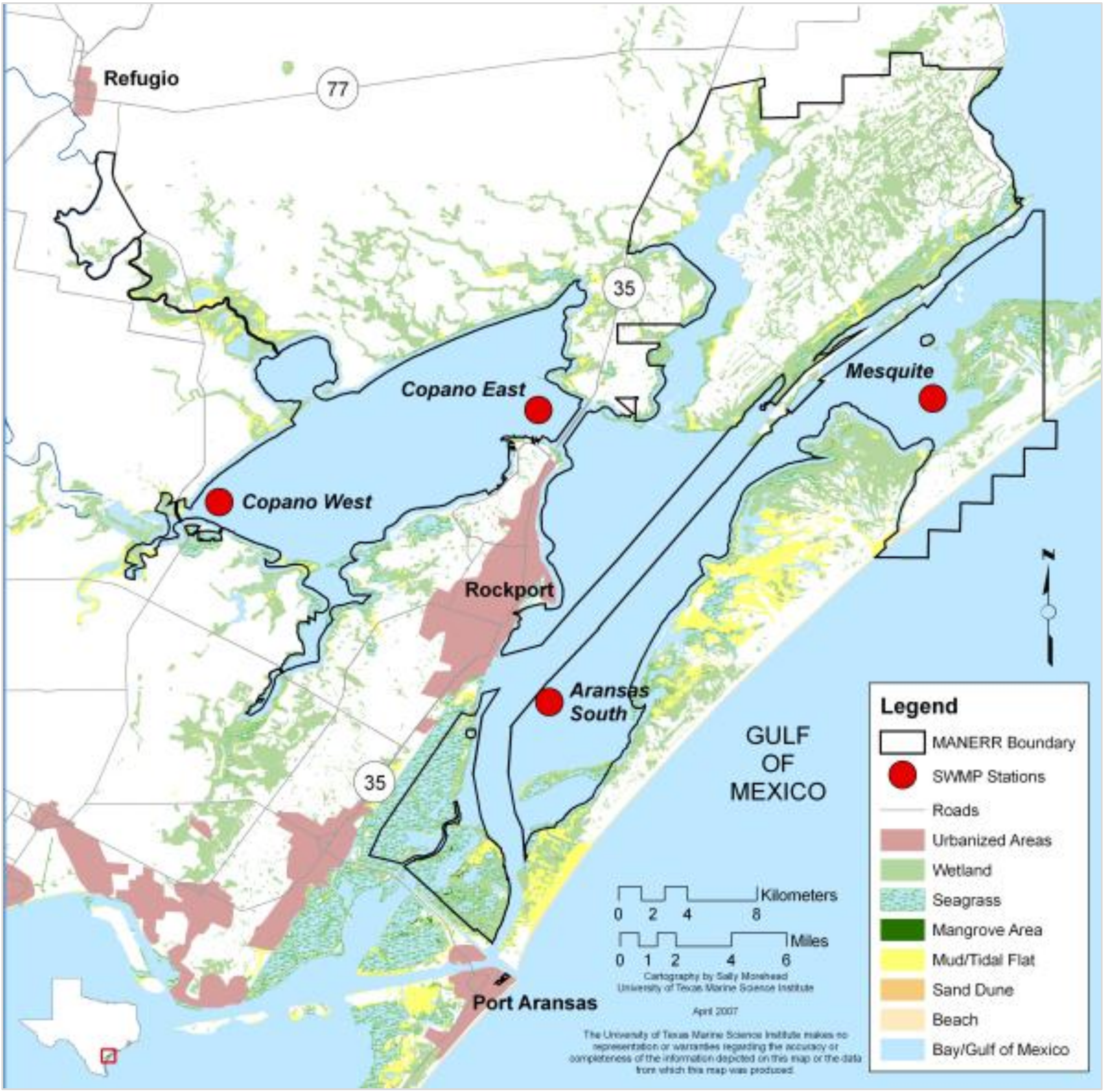


Figure 4.2-3. Salinity monitoring station (SWMP) locations in the Mission-Aransas Estuary. All the sites shown were only recently established upon creation of the Mission-Aransas National Estuarine Research Reserve (MANERR). The Mesquite Bay site dates to January 2008, while the others became functional in July 2007. (map from Mission-Aransas National Estuarine Research Reserve).

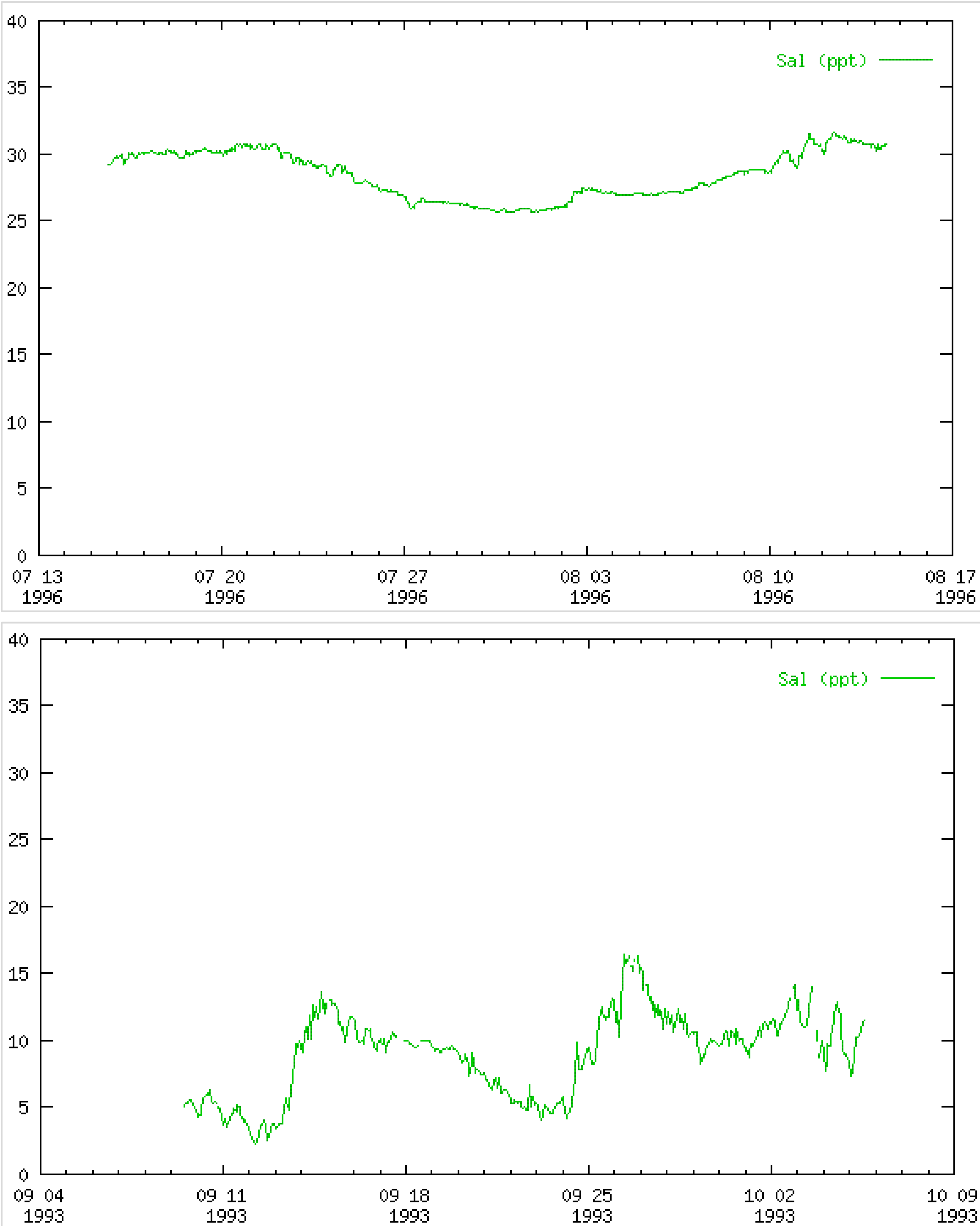


Figure 4.2-4. Illustration of the salinity data in upper Guadalupe Estuary at site SANT for the very dry period of July 1996 (upper panel) and for September 1993 (lower panel) a period of intermediate inflows. (figure modified from Texas Water Development Board).

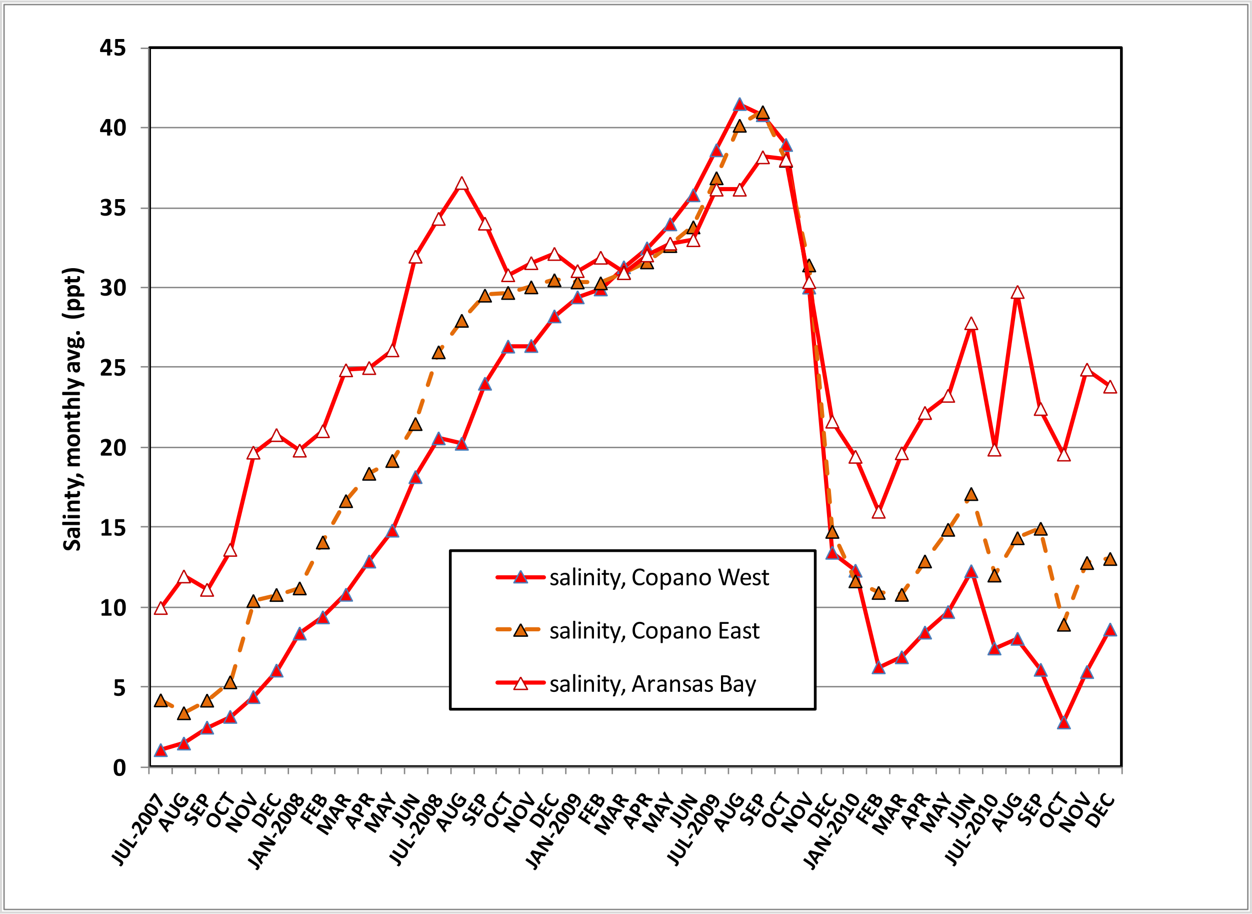


Figure 4.2-5. Illustration of the monthly average salinity data for several sites in the Mission-Aransas Estuary (see Figure 4.2-3).

4.2.2 Salinity Simulations and Prediction

The GSA BBEST had salinity data, broadly falling into three categories, available for analyses: field-gathered salinity measurements (as presented above), predicted salinities from a hydrodynamic model, and predicted salinities from statistical (regression) approaches. All of these have been utilized in the analyses that follow and thus some discussion of these data types is warranted. While actual field data would be the first choice for pursuing the analyses of the GSA BBEST, there are great limitations to this data as discussed above.

Fortunately, there are means of predicting salinities, either at times or locations where field data is not available. The Texas Water Development Board (TWDB) maintains a mathematical model, known as TxBlend, which simulates the hydrodynamics and salinity transport of the Guadalupe and Mission-Aransas Estuaries (and Matagorda Bay at the northern end) based on inflows and other variables (e.g. tides and winds) for the January 1987 - October 2009 period. This model was recently updated to include the revised inflow estimates mentioned above (TWDB 2010b). TxBlend subdivides the estuary into a fine mesh of nodes (see Figure 4.2-6) and simulates the salinity at each with a time step on the order of 30 minutes to an hour. This fine spatial and temporal scale obviously makes the computations of salinity by the TxBlend model ideal for many salinity-related tasks. TxBlend, like all simulation models, is calibrated with the aforementioned available field data. Appendix 4.2-1 contains two memos from the TWDB (TWDB 2010a, 2010b), regarding the calibration and testing of the TxBlend model in the Guadalupe and Mission-Aransas Estuaries with recently updated inflow information (TWDB 2010c). Upon updating TxBlend to incorporate the new inflow estimates, TWDB presented information to the GSA BBEST demonstrating an acceptable level of performance in the Guadalupe Estuary5. The BBEST believes that the TxBlend model performs with a level of accuracy acceptable for our work in the Guadalupe Estuary. Generally, the BBEST feels that model performance is acceptable throughout the two estuaries, with some noted concerns for portions of the Mission-Aransas Estuary as will be discussed in subsequent sections where portions of this estuary are evaluated.

The GSA BBEST relied heavily on TxBlend output covering much of the two estuaries at a time scale resolution of monthly average values. The monthly average output can be used over a broad scale as mapped in Figure 4.2-7. This figure illustrates the predicted salinities in the Guadalupe Estuary for three Septembers: 1989, 1993, and 2001. These three represent a full spectrum of inflow and salinity conditions from very dry (1989) through intermediate (1993) and finally a large flood in 2001 in which total inflows for July through September were 1.14 million ac-ft, above the 90th percentile for that season, and much of the estuary experienced salinities lower that 2ppt.

Additionally, the same TxBlend output can be recast as point-specific monthly average values, but in a time sequence. The GSA BBEST selected an initial set of points, shown in Figures 4.2-8 and 4.2-9 to track such time sequences. These time sequences proved especially useful to examine salinity-inflow trends and relationships when portrayed together over multiple months or years. Figures 4.2-10 and 4.2-11 illustrate such sequences in the Guadalupe Estuary for two recent periods: the moderate inflow to dry sequence of 1995-96 and the very wet to drought

[5] presentation by Carla Guthrie to the BBEST on October 14, 2010.

sequence of 2007-09. These plots are for the TxBlend nodes G10 near the GBRA1 datasonde (field data measurement) site shown in Figure 4.2-8. In both of these figures there is a clear response of salinity to changes in inflow. Periods of high to very high inflows such as in September 1996 and July 2007 lead to fairly immediate depression of salinity, even at this site fairly far down the estuary. Contrasting this quick response, when inflow conditions are low, the salinity response is a long multi-month rise, as the inexorable action of tides brings saline Gulf waters up the estuary in a process referred to as "intrusion." Such intrusion periods are exhibited in the low inflow period of January-August 1996 and again through most of 2008 and again in mid-2009. This TxBlend model prediction in 2009, exhibited hyper-saline conditions (> 35ppt) which is corroborated by the field data of the nearby GBRA1 site where measured salinity approached 40 ppt and was above 35 ppt for about 2 months (TWDB 2010a, Figure 41). This indicates that the TxBlend model, which has evaporation as a contributing process, is handling the combined effects of very low inflows and high evaporation to achieve reasonable predictions of high salinity in this portion of the Guadalupe Estuary.

Another type of salinity information available to the GSA BBEST are the predictions that can be made based on statistical regression analyses of the historic relationship between salinity and inflow. These statistically-derived data perform a similar functional role as does salinity from the TxBlend model: they can provide spatial coverage where not available from field data. However, unlike the TxBlend model which generally requires days to set up, execute, and extract and synthesize the results, statistical approaches, once developed, can be utilized quickly and repeatedly to predict salinity responses to inflow. Such inflow-salinity relationships can also provide a means for predicting salinity in the period of record before the initiation of field measurements in the estuaries or before the TxBlend model's simulation period.

The GSA BBEST therefore expended considerable effort developing regression equations for many points throughout the Guadalupe and Mission-Aransas Estuaries. Again, due to the lack of field measurements, we utilized the TxBlend model prediction (e.g. as in Figure 4.2-11) as a proxy for "known" salinity in order to develop the regression equations. Two suites of regression equations, one for the Guadalupe Estuary and another for the Mission-Aransas Estuary, including Copano Bay, were derived.

The regression equations for the Guadalupe Estuary took the form:

$$S^* = a + B1 \cdot \ln(Q1{:}G) + B2 \cdot \ln(Q2{:}G) \quad (1)$$

Where,
S*= the regression-predicted salinity in parts per thousand (ppt);
Q1:G = cumulative inflow volume into the Guadalupe Estuary in the current month (1000 ac-ft);
Q2:G = cumulative inflow volume into the Guadalupe Estuary in the previous month (1000 ac-ft);
and ln is the natural logarithm function. In shorthand notation this may be also referred to as S*= f(Q1:G,Q2:G), where "f" indicates generally, " is a function of".

Figure 4.2-12 illustrates the results of a Guadalupe Estuary regression equation of the type shown above for the same point near the GBRA1 datasonde as illustrated previously.

For the Mission-Aransas Estuary, because of the greater influence of the inflows from the Mission and Aransas Rivers and other local sources (e.g. Copano Creek), a more accurate form of regression equations was developed. These are of the form:

$$S^* = a + B1*\ln(Q1{:}G) + B2*\ln(Q2{:}G) + B3*\ln(Q1{:}MA) + B4*\ln(Q2{:}MA) \qquad (2)$$

Where,
S*= the regression-predicted salinity in parts per thousand (ppt);
Q1:G and Q2:G = as above;
Q1:MA= cumulative inflow volume into the Mission-Aransas Estuary in the current month (1000 ac-ft);
Q2:Ma= cumulative inflow volume into the Mission-Aransas Estuary in the previous month (1000 ac-ft).
Again, ln is the natural log function and in shorthand notation this form or regression equation can be represented as S*=f(Q1:G,Q2:G,Q1:MA,Q2:MA).

Figure 4.2-13 illustrates the results of a Mission-Aransas Estuary regression equation of the type shown above for the point A2 in central Aransas Bay (see Figure 4.2-9).

The goal of the regression equation predictions are to mimic the TxBlend line with the independent variable(s) being the Guadalupe inflow variables Q1:G and Q2:G and, for the Mission-Aransas portion, the additional inflow variables Q1:MA and Q2:MA. Thus, the difference between the regression line and the TxBlend line represents the error (residual) in the regression equation. The standard measure of the performance of a regression equation is the 'coefficient of determination' more commonly referred to as the R^2 ("R-squared"). R^2 ranges from 0 indicating no explanatory power to 1 indicating no error. The R^2 statistic explains the portion of the observed variation in the dependent variable (salinity) that is explained by the regression equation, and the higher the value the more likely the predicted values of salinity are correct. Table 4.2-3 gives the R^2 statistic for the above regression equations throughout the two estuaries at the points indicated previously on Figures 4.2-8 and 4.2-9. Generally, R^2 statistics in the vicinity of 0.8 are indicative of a regression equation with good predictive ability. Much more information on the development, and performance of the regression equations, and methods employed to address some of the residuals is found in Appendix 4.2-2 and later in this Section.

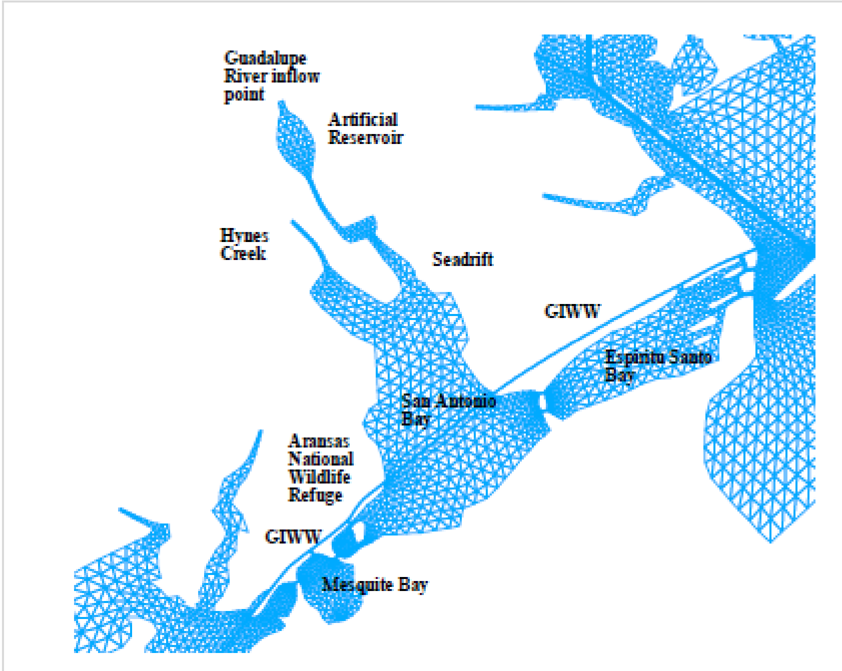


Figure 4.2-6. The TxBlend model grid, focusing primarily of the Guadalupe Estuary (San Antonio Bay). (map from Texas Water Development Board).

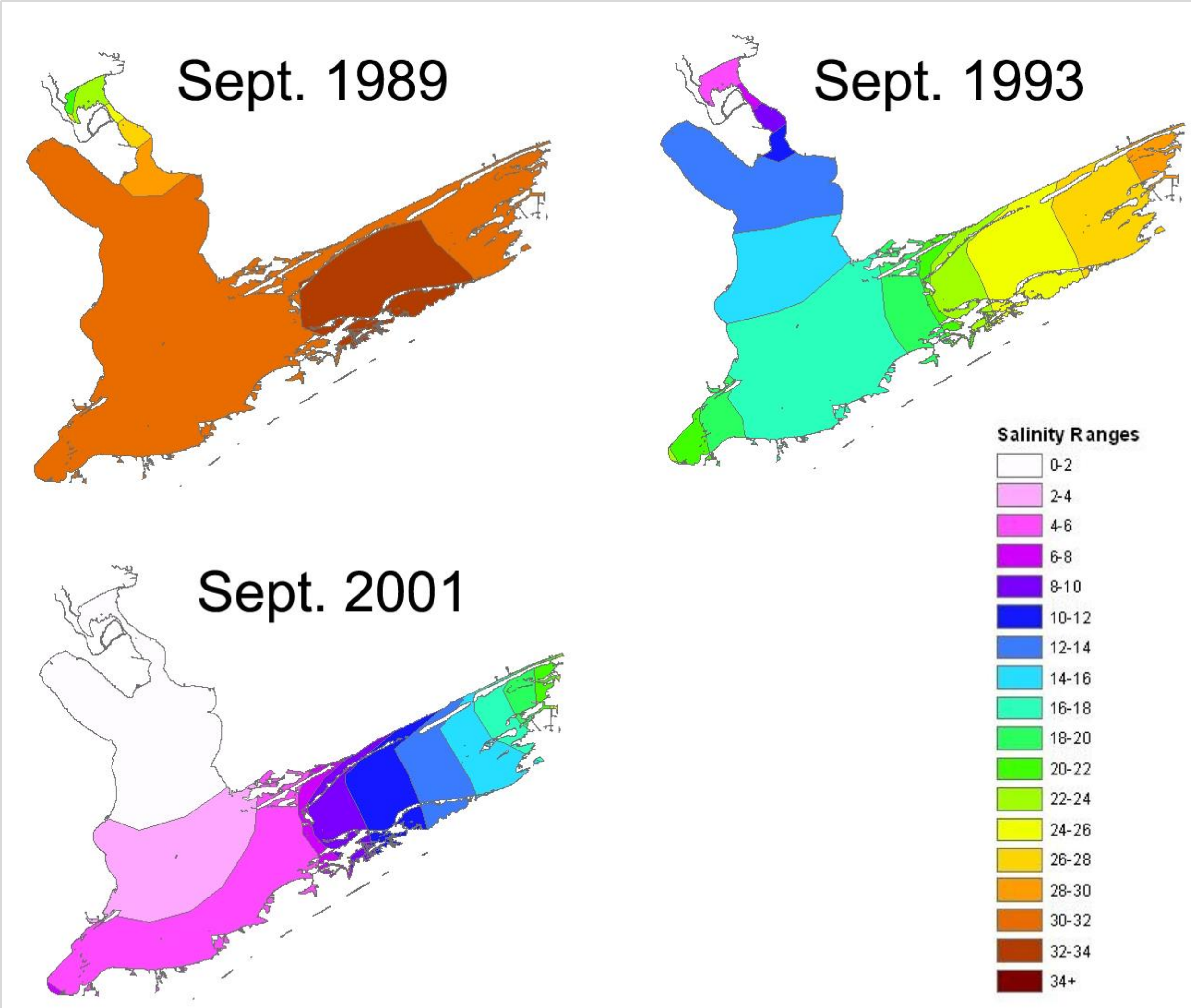


Figure 4.2-7. Maps illustrating the average monthly salinity prediction of TxBlend across the Guadalupe Estuary under a broad range of inflow conditions in three Septembers (1989 - low; 1993 - intermediate; 2001 - very high). (maps produced by TPWD and Texas State University, River Systems Institute).

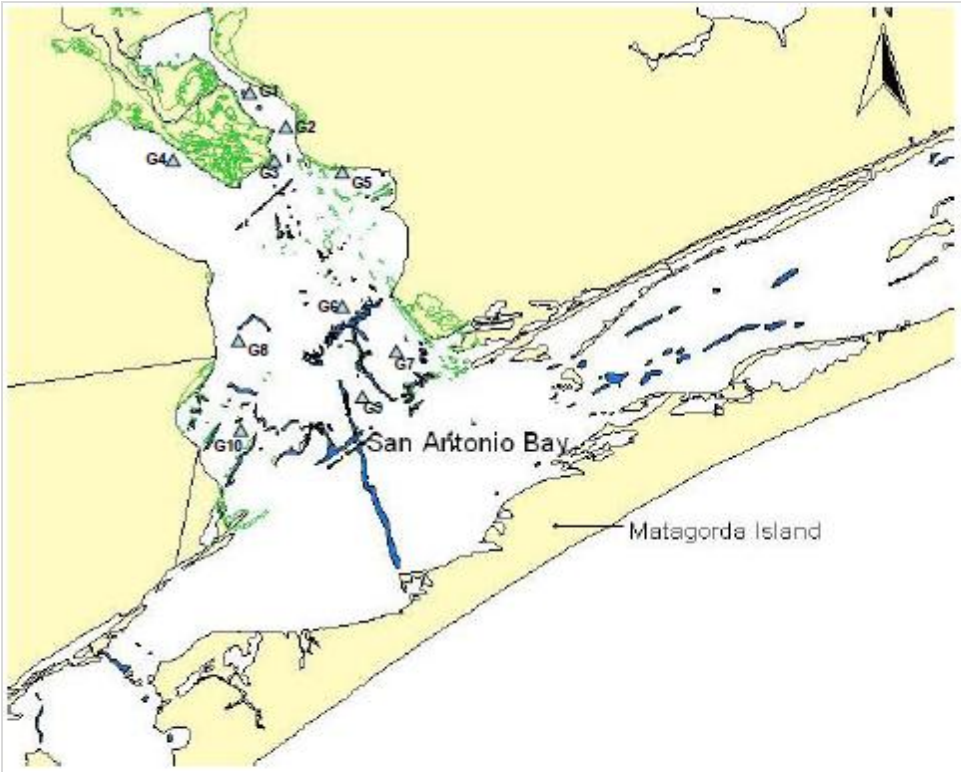


Figure 4.2-8. The initial suite of specific points (triangles) in the Guadalupe Estuary utilized by the GSA BBEST to track salinity through time as predicted by the TxBlend model.

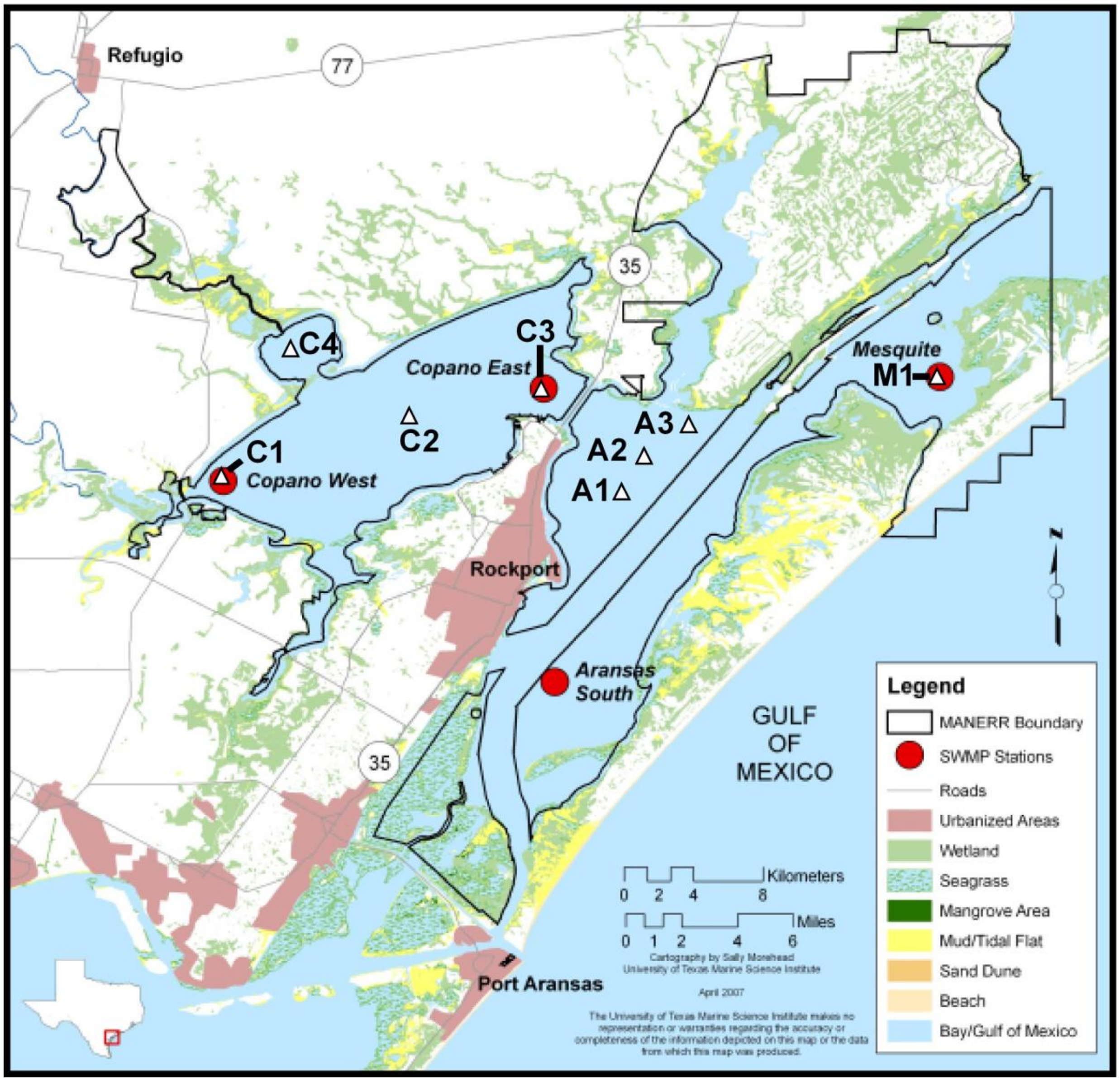


Figure 4.2-9. The initial suite of specific points (triangles) in the Mission-Aransas Estuary utilized by the GSA BBEST to track salinity through time as predicted by the TxBlend model. (base map from the Mission-Aransas National Estuarine Research Reserve).

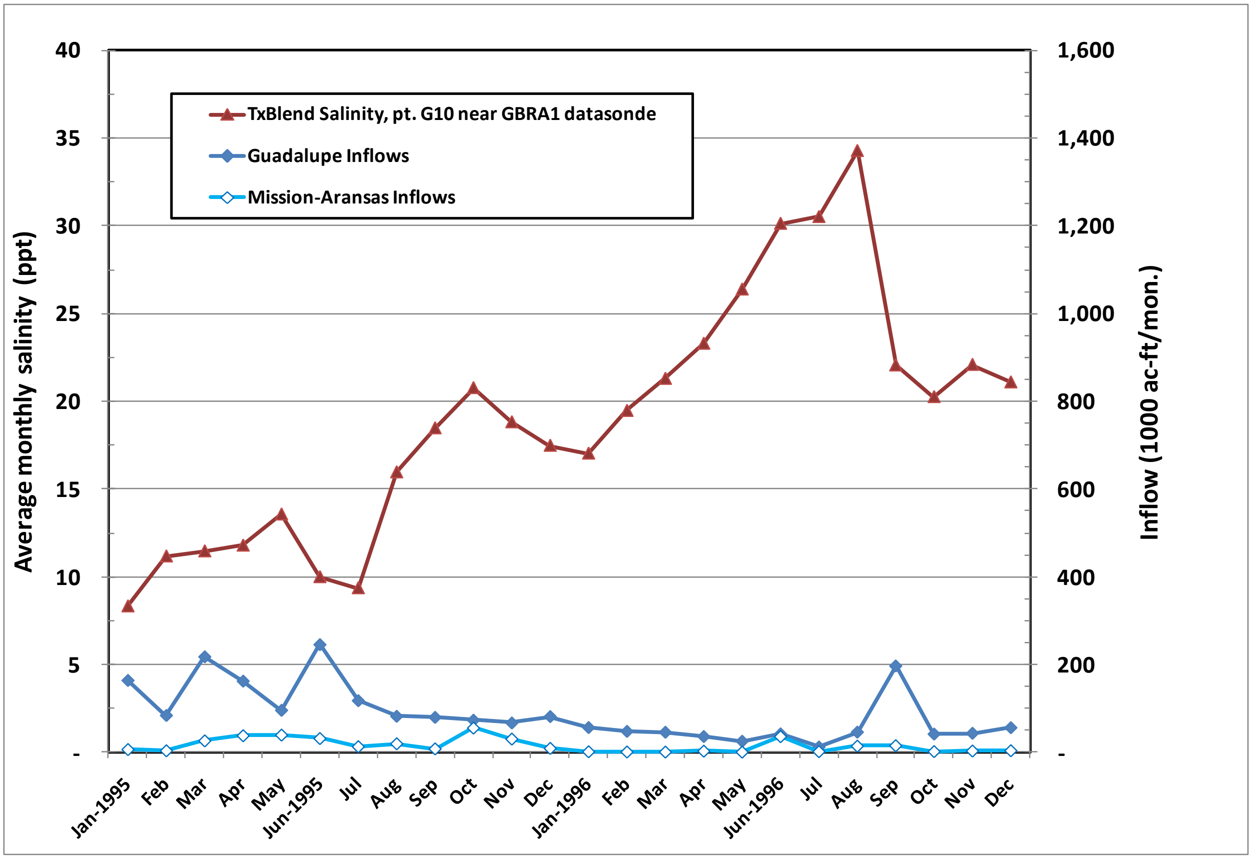


Figure 4.2-10. The TxBlend model output in time-series format at a single point G10 (see Figure 4.2-8). The moderate inflow to dry sequence of 1995-96 is depicted.

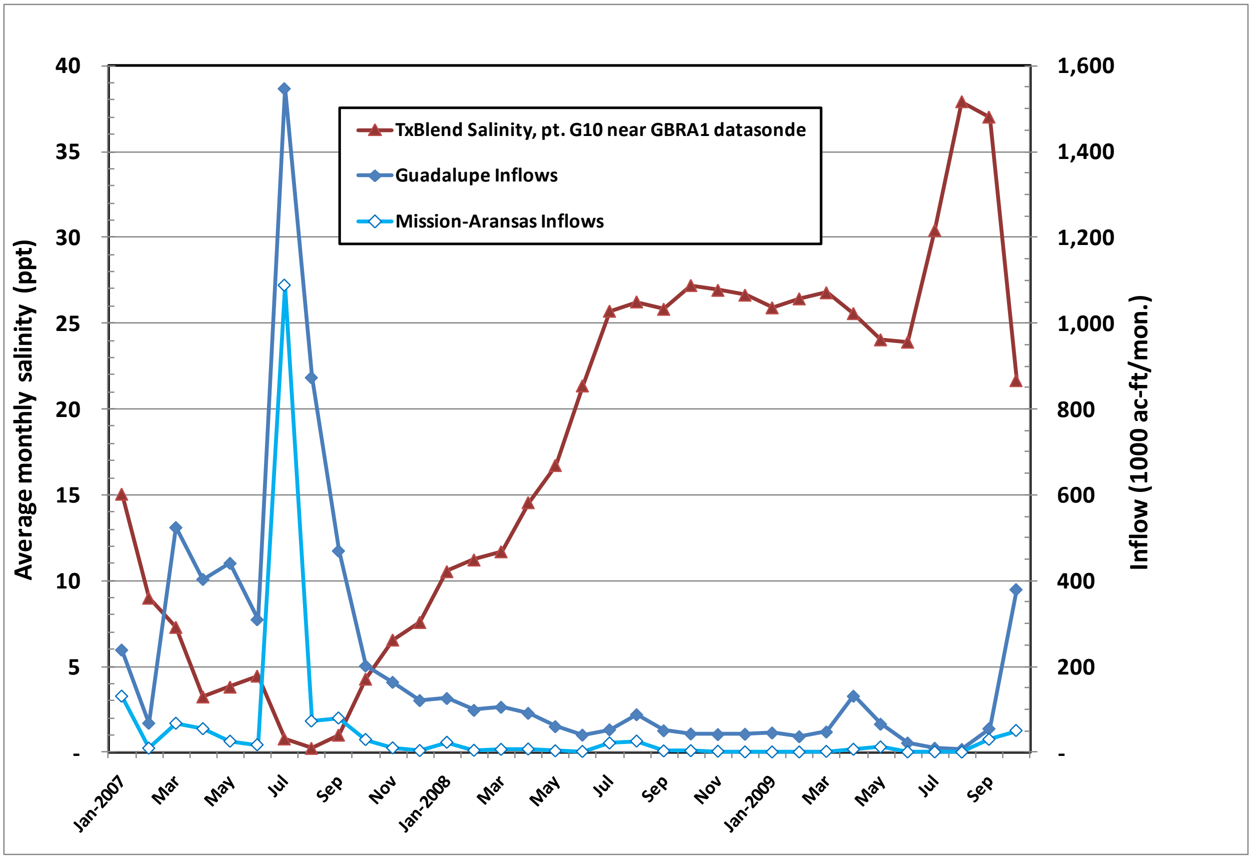


Figure 4.2-11. The TxBlend model output in time-series format at a single point G10 (see Figure 4.2-8) near the GBRA1 datasonde. The transitional very wet to drought sequence of 2007-09 is depicted.

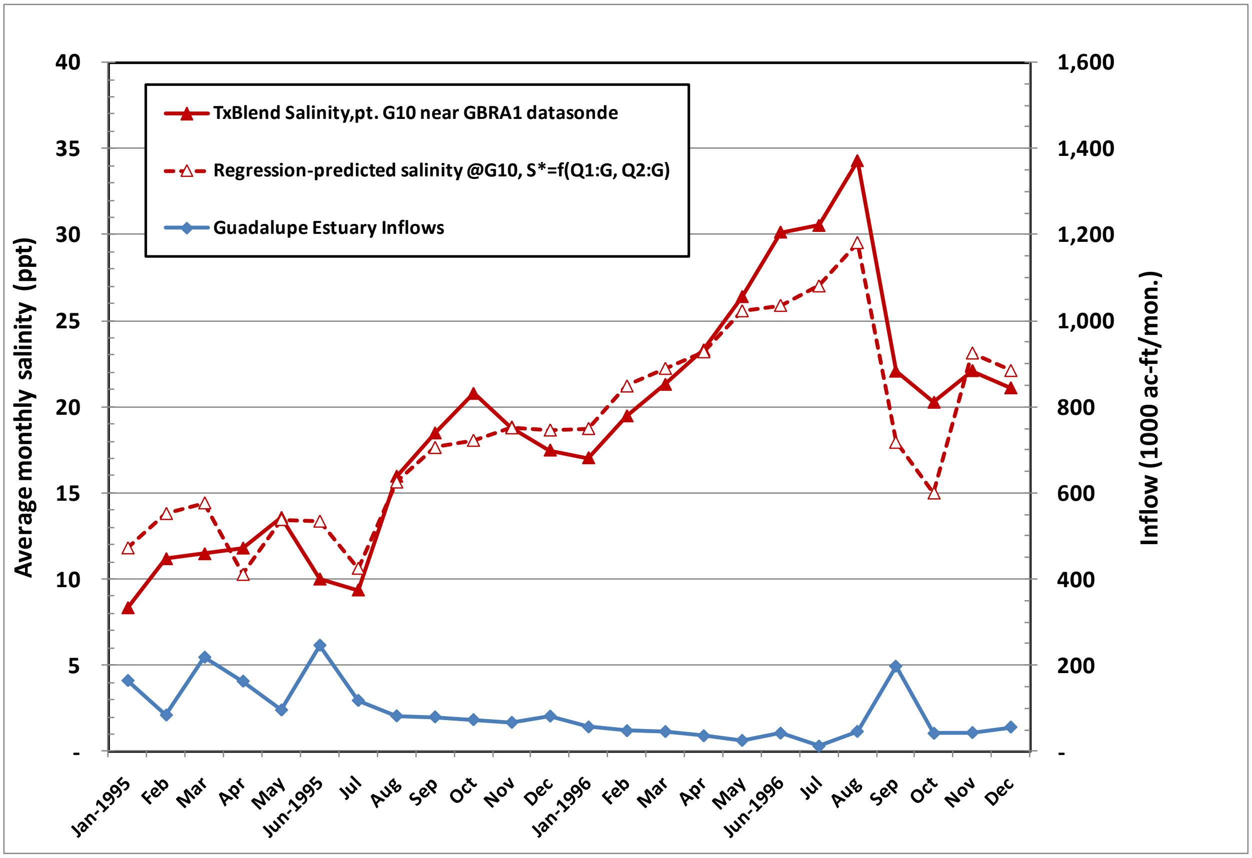


Figure 4.2-12. Results of a regression equation developed to predict salinity as a function of Guadalupe Estuary inflows at point G10 near the GBRA1 site.

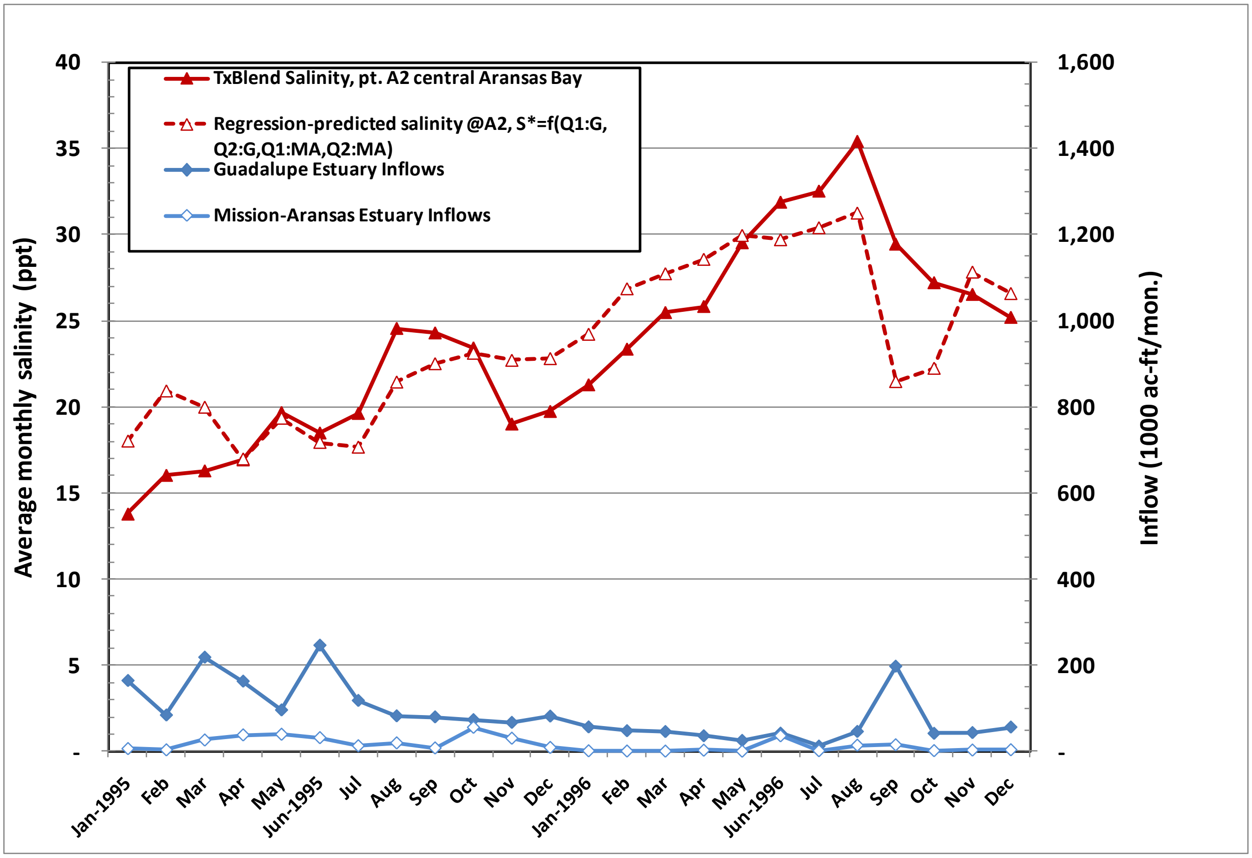


Figure 4.2-13. Results of a regression equation developed to predict salinity as a function of inflows to the Guadalupe and Mission-Aransas Estuaries for point A2 in central Aransas Bay.

4.3 Key Bay Species /Habitat and Responses to Salinity

4.3.1. Focal Species and Rationale for Selection

Introduction

In 2007, the Texas Legislature passed Senate Bill 3, directing the development of environmental flow recommendations to protect a "sound ecological environment" and to maintain the productivity, extent, and persistence of key aquatic habitats in bays and estuaries (SAC 2009). As part of the effort to develop inflow recommendations to the estuary, the Estuary Sub-committee of the Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission, Copano, Aransas, and San Antonio Bays Basin and Bay Area Expert Science Team (BBEST) met several times early in the process to discuss the options and best methods for assessing the freshwater inflow needs to the estuary as developing flow recommendations. Previous efforts to assess freshwater inflow needs in Texas (Longley 1994; Pulich et al. 2002; TPWD 2005) as well as the Science Advisory Committee's report on inflow assessment methods (SAC 2009) and elsewhere were reviewed and considered. These discussions were held in collaboration with personnel from state agencies involved in the Texas Bays and Estuary Study Program, particularly Texas Parks and Wildlife Department (TPWD) Coastal Fisheries Division, and local university researchers.

The Estuary Sub-committee considered approaches using various community metrics such as Diversity Indices [considered inappropriate for use as water quality monitoring assessment tools (Spatharis 2011)], or Biotic Integrity Indices [which are still in development (Deegan et al 1997; Borja and Dauer 2008)] and other methodologies such as Multivariate Analysis (Tolan 2009) but ultimately these were deemed not suitable for development of flow recommendations. It was ultimately decided to employ a salinity zone analysis similar to the work done by the LCRA/SAWS project in Matagorda Bay, Texas (LCRA/SAWS 2008). Briefly, the region of the bay where a given species is (or has been) found in highest abundance and/or in the best physical condition is identified and the inflows required to provide good to optimum salinities in those regions are modeled. Inflow recommendations can then be made based on model results (see section 4.4 below for details of the methodology). While salinity at any given location in the bay is not related linearly (directly on a straight-line relationship) to inflow, the relationship between inflow and salinity, especially in the middle and upper estuary, is relatively good, allowing for a recommendation of inflow to produce a desired salinity range at a given location.

Sessile species (i.e. those species living more or less fixed in in one place on the bottom like oysters or tube-building worms or rooted aquatic plants) with clear salinity requirements are the most obvious candidates for this method. Unfortunately no salinity-sensitive indicator plant species could be located in the upper San Antonio Bay area that met the requirements for our salinity-zone analysis. Such a focal species, *Vallisneria americana* (wild celery), was used by the Trinity-San Jacinto BBEST in its FWI analysis. The Estuarine sub-committee chose eastern oysters (*Crassostrea viginica*) and rangia clams (*Rangia* spp.) as the focal species for this analysis. The estuarine sub-committee also initially intended to use the method, with slight variation in its application, to motile species (i.e. species which are capable moving around in the estuary and potentially choosing appropriate or even optimum habitat). The most likely candidate for this analysis was white shrimp (*Litopenaeus setiferus*), since TPWD data showed a strong correlation with salinity and catch rate. The sub-committee also wanted to include blue crab (*Callinectes sapidus*) for similar reasons and because the species seems to have a particularly critical food chain relationship with the endangered Whooping Crane. However, after extensive reviews of the literature and consultation with numerous researchers in the field, it was determined that the salinity relationship was not a functional one but a correlation that included other confounding factors (see the detailed species descriptions below). Ultimately, it was decided to employ the analysis of the species as an corroborative overlay to the fix species analysis.

Several aspects of oysters, oyster reefs, and oyster-reef communities make their use as an environmental indicator relevant to other portions of the San Antonio and Mission/Aransas Estuaries. Oysters and oyster reefs provide a number of valuable ecosystem services that in turn can be impacted by changes in inflow levels or patterns (Volety et al. 2009). Water quality conditions that influence oysters can therefore be expected to influence other estuarine species in similar fashion (Shumway, 1996). Oysters are primary consumers relying on phytoplankton that forms a base component of food chain in estuarine ecosystems (Volety and Savarese, 2001). As such, oysters contribute to benthic–pelagic coupling through the deposition of phytoplankton and suspended detritus in the form of mucus and uneaten food (Coen et al., 1999). Many of the crustaceans and fishes that are members of oyster-reef communities are important prey for secondary and tertiary carnivores such as fishes and birds (Tolley and Volety, 2005). Furthermore, biomass and community structure of these oyster-reef communities are directly linked to hydrology and oyster-reef survival and morphology (Tolley et al., 2005, Tolley et al., 2006). The estuarine sub-committed feels that inflow recommendations providing for the wellbeing of eastern oysters and rangia clams will provide for the general wellbeing of the entire estuarine ecosystem.

4.3.1.1 Eastern Oyster (*Crassosterea virginica*)

Importance

Oysters are benthic (bottom-dwelling), sessile (stationary), filter-feeding organisms that provide ecosystem services by filtering the water column and providing food, shelter and habitat for associated organisms. They are also an important commercial and recreational species throughout much of their range. As such, the species is an excellent sentinel organism for examining the impacts of natural and anthropogenic alteration of estuarine ecosystems.
Individual oysters can filter up to 5 gallons of water in an hour, removing plankton, sediments, pollutants, and microorganisms from the water and increasing light penetration downstream for enhanced growth of benthic diatoms and even submerged aquatic vegetation (i.e. seagrasses). The reef structure creates a unique and valuable ecosystem in a bay environment that is otherwise typically void of any hard-bottom, three dimensional relief. This reef structure attracts numerous invertebrates and fishes, many of which are important forage for recreational and commercial fisheries species (Coen 1999).

Life-history

Cake (1983) provided a through overview of the life-history of eastern oysters and Barnes et al (2007) provide additional recent information. The following summary draws primarily from those two publications without including the individual references cited therein; refer to these two publications for those background references: Eastern oysters are widely distributed in the western Atlantic Ocean, occurring from at least as far north as Maine and south throughout the Gulf of Mexico to the Yucatan Peninsula of Mexico. Adult oyster are sessile and can be found attached to virtually any hard substrate. Oysters occur both in the intertidal wet/dry zone and subtidally (down to about 40 ft) and often form large reefs, particularly in open bay environments. Adult oysters are filter feeders and these subtidal reefs often develop at right angles to the prevailing current to optimize food resources. Spawning in the northern Gulf of Mexico occurs over an extended period of time (all months except December through February) with peaks occurring in late spring and early fall. Eggs and sperm are released directly into the water column and fertilization is external. The larvae are planktonic and development in the water column requires about two weeks, at which point they settle onto proper substrate and attach. This planktonic larval stage is the key to oyster colonization of existing reefs as well as dispersal to new areas in response to changing environmental conditions. The newly settled oyster is referred to as “spat” but growth at that stage is rapid and the young oyster shell soon begins to resemble that of a mature individual. The oyster matures rapidly and a spat settled in the early summer may spawn in the ensuing fall.

Salinity Relationships

As with most organisms inhabiting estuaries, oysters can generally tolerate a wide range of environmental conditions. Adults can survive in salinities as low as 1 psu (practical salinity units, approximatelyequal to parts per thousand [ppt] used elsewhere in this report) for several months and indefinitely in salinities from about 5 to 40 psu. They can survive temperatures from near freezing up to at least 90 °F but higher temperatures are often lethal. These environmental tolerances can vary by region and, importantly, the two factors can have synergistic effects. In controlled laboratory experiments, Hailmayer et al (2008) found that body condition (measured by a body condition index and by the tissue RNA:DNA ratio) in Florida oysters remained relatively high in salinities as low as 5 psu as long as temperatures remained low (below 68 °F {20 °C}). Body condition deteriorated in low salinity conditions at higher temperatures. Optimal conditions were found at salinities above 10 psu and temperatures below 72 °F. Temperatures above 77 °F were suboptimal at all salinities tested. It is important to note that predators and diseases were eliminated in these experiments.

Despite a physiological tolerance for a wide range of temperatures and salinities, oyster populations in the wild are generally limited by external factors, namely predation and disease (Ray 1966; Andrews and Ray 1988). The primary predator is the southern oyster drill and the primary disease is *Perkinsus marinus* (formally *Dermocystidium marinum*), commonly called “Dermo”, with the later described as the primary limiting factor in oyster health (Cake 1983). Both of these predators and disease organisms are limited by low salinities. Oyster drills and other similar predators are limited to salinities higher than around 15 to 20 psu and are killed, or at least displaced by lower salinities. Dermo is also limited by salinity but with an important synergistic relationship with temperature. In a controlled laboratory study, La Peyre (2010) showed that the largest decrease in Dermo cell viability occurred when exposed simultaneously to sub-optimal salinities (< 7 psu) and sub-optimal temperatures (< 50 °F {10 °C }). Cell viability of Dermo was much less affected at low salinities and high temperatures (84 °F) or low temperatures at high salinities (> 15 psu). Thus the greatest limitation of Dermo would occur in cold winters with low salinities (i.e. high inflows). However, in the environment, infection intensity is highest in summer and fall and lower in winter and spring (Soniat et al 2009), responding to seasonal temperature cycles.

Models that couple the physiological processes of both host and parasite (Hofmann et al 1995, 2001) have shown that the parasite quickly proliferates at temperatures above 68 °F and at salinities above 20 psu suggesting a focus on non-winter months. In Louisiana, Dermo disease infection intensity and salinity are correlated at a periodicity of 4 years, corresponding to the ENSO cycle (Soniat et al 2009). Several authors (Soniat et al 2009, Tolan 2007) conclude that the low winter rainfall in La Ñina years results in elevated estuarine salinities, setting the stage for high Dermo disease prevalence and intensity, due to the resultant higher salinity and temperatures, in the following spring and summer.

The combination of the physiological response of both oysters and their predators and parasites to temperature and, especially, salinity produce an optimum salinity of around 10 to 20 psu (~ppt) with the prevalent salinity having a greater effect in summer than in winter.

4.3.1.2 Atlantic Rangia (*Rangia cuneata*) and brown rangia (*Rangia flexuosa*)

Species Recognition

Two species of clams in the genus *Rangia*, Atlantic rangia (*Rangia cuneata*) and the brown rangia (*Rangia flexuosa*), occur within the Guadalupe/Mission Aransas estuary system. Both species are found primarily in upper portions of San Antonio Bay and in Copano Bay (Figure 4.3-1 and Figure 4.3-2, from the Texas Parks and Wildlife Department Coastal Fisheries Resource Monitoring Program database) and (Parker 1960, Fig 10). The available data indicate that the distribution of both species is similar in the two bay systems but brown rangia is somewhat more abundant than Atlantic rangia in the Mission Aransas estuary whereas Atlantic rangia is more abundant than brown rangia in San Antonio Bay. It should be noted however, that the sampling equipment utilized by TPWD are not designed to gather this burrowing species. Harrel (1993) points out that the clam prefers soft sediments and is dispersed. This is in contrast to oysters that form concentrated reef-like masses and are sampled by TPWD with very specific equipment for that single species. The rangia information in the TPWD database is from trawl equipment that is dragged along the bottom and occasionally digs into the sediment layer and gathers rangia specimens. Thus, the GSA BBEST's inferences on the spatial extent and abundance characteristics of these species are the best we can make at this point.

Importance

Rangia clams, as well as other bivalves like oysters, are non-selective filter feeders. In the process of feeding, they remove significant quantities of particulate matter from the water column and convert it to clam biomass. High densities of clams (> hundred g m^{-2}) in shallow water regions of an estuary and where water residence times are high (the latter two conditions, at least, being characteristic of Copano Bay and portions of upper Guadalupe Bay) can have a significant effect on water column characteristic (Officer et al 1982). For example, Phelps (1994) showed that following the invasion of an Asiatic clam that developed high densities in the Potomac River, the resultant increased water clarity led to higher seagrass densities which led to increased fish and waterfowl populations. Wong (2010) showed that rangia populations in three coastal lakes in upper Barataria Bay, Louisiana were capable of filtering the volume of each of the lakes in 1.0 to 1.5 days (mean = 1.3). Although a daily phytoplankton doubling rate of 1, a realistic rate when nutrients are abundant, would easily compensate for a bivalve clearance rate of 1.3, these authors concluded that rangia could have a significant impact on the phytoplankton populations of the lakes during certain periods (e.g. during periods of low nutrient concentrations, or periods following floods when the phytoplankton population is low) and could be effective in ameliorating the negative effects of eutrophication.

Life-history

Information on the ecology of brown rangia is quite sparse. Parker (1960), in describing the distribution of macroinvertrebates in the Gulf of Mexico, placed both species in his "River Influenced – Low Salinity" assemblage. Both species inhabit shallow subtidal zones in areas with salinities of 5-15 psu on the Mexico coast of the Gulf of Mexico (Wakida-Kusunoki and MacKenzie 2004). Foltz et al (1995) assessed the genetic structure of the two species and determined they are clearly distinct species, but stated that they are "sympatric in the Gulf of Mexico". This common co-occurrence of the two species suggests that they have similar ecological requirements. Thus, we will provide an assessment of the biology and ecology of *Rangia cuneata*, the more studied of the two, and we will provide a single inflow needs assessment of the two *Rangia* species under the assumption they have similar ecological requirements and constraints.

Salinity Relationships

Atlantic rangia (*Rangia cuneata*), often called common rangia and herein referred to as rangia, is an important bivalve in estuaries throughout the Gulf of Mexico and along the Atlantic coast from Maryland to Florida. It is a characteristic component of oligo- and mesohaline zones (0.5-5.0 and 5.0-15 psu, respectively) of the estuary (Montagna et al 2006). It is one of the few estuarine organisms to permanently flourish in this brackish water zone of the estuary. It can reach very high densities and can comprise up to 95% of the benthic biomass in some areas (LaSalle and de la Cruz 1985). Rangia can serve as a significant food source for crabs, shrimp, fish, and waterfowl (Cain 1975, LaSalle and de la Cruz 1985) and this function may be particularly important in this otherwise depauperate region of the upper estuary.

Rangia clams appear to be relatively long-lived, with age estimates ranging up to 15 years (Hopkins et al 1973). Adult clams are an indicator of the mesohaline zone [range ppt] (Montagna et al 2008) and are tolerant of salinities up to 20 psu but apparently do not maintain long-term, viable populations outside a 1 to 15 psu range (Hopkins 1970). However, Cain (1973, 1975) and Hopkins (1973) have suggested that rangia populations are controlled primarily by factors regulating larval survival rather than factors affecting adult physiology. Specifically, it has been shown that early larvae will not survive unless salinities are in the range of 2 to 10 psu over the temperature dependent larval period of a day to a week or so (Chanley 1965, Cain 1975).

Eggs and sperm are released into the water column and fertilization is external. The spawning period is protracted and may be limited primarily by temperature. Cain (1975) found ripe (i.e. ready to spawn) rangia when temperatures reached 15°C in Virginia and spawning continued through the fall until temperatures dropped to below 17°C. In Lake Pontchartrain, La., spawning occurred in March to May and again in late summer into November (Fairbanks 1963). In Mexican waters, Wakida-Kusnooki and MacKenzie (2004) found that rangia spawned year around. Through most of its range, peak spawning periods for rangia appear to occur in spring (March-May) and fall (August to November) (LaSalle and de la Cruz 1985). Cain (1973, 1975) has suggested both temperature and salinity are important for controlling spawning; temperature may set the broad seasonal cycle but a rapid change in salinity may be critical in initiating gamete release. He observed large spawning events associated with both rapid increases and decreases of around 5 psu in Virginia.

From the above assessments, based on the longevity of adults, the protracted spawning period, and the sensitivity of larvae to salinity, it would appear that the rangia population in a given area could be sustained by periodically successful reproduction/ recruitment events. The criteria for successful recruitment of settled juveniles seems to be water temperatures above 15°C, a relatively rapid rise or fall in salinity of ± 5 psu (to induce gamete release from ripe adults) and a salinity of 2 to 10 psu for several days (preferably several weeks to promote prolonged successful settlement) to provide for high survival of the pelagic larvae (i.e. those larvae still floating in the water column).

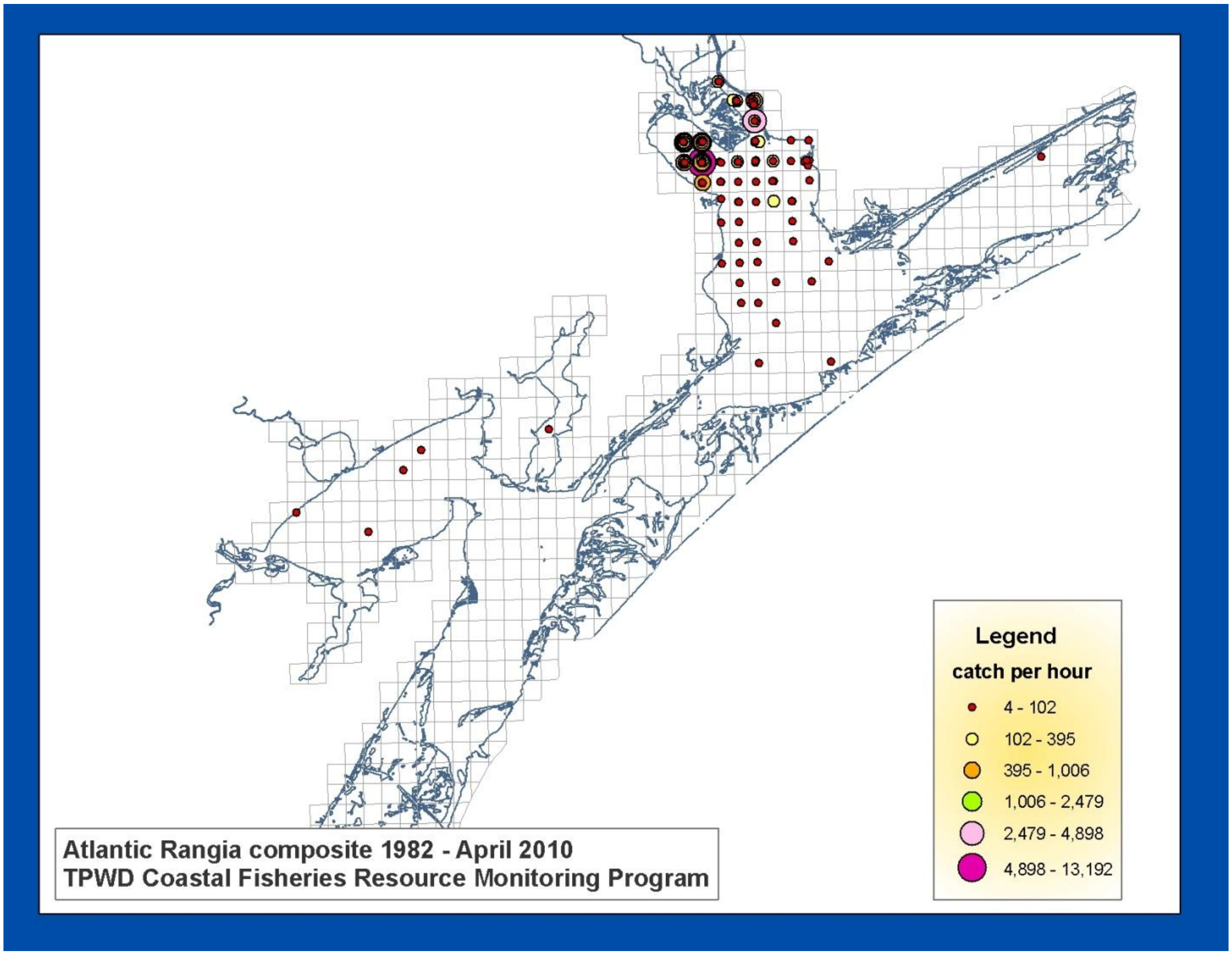


Figure 4.3-1. Distribution of Atlantic rangia in San Antonio Bay and the Mission/Aransas Estuary from Bay Trawl samples (N Boyd, personal communication, 2011).

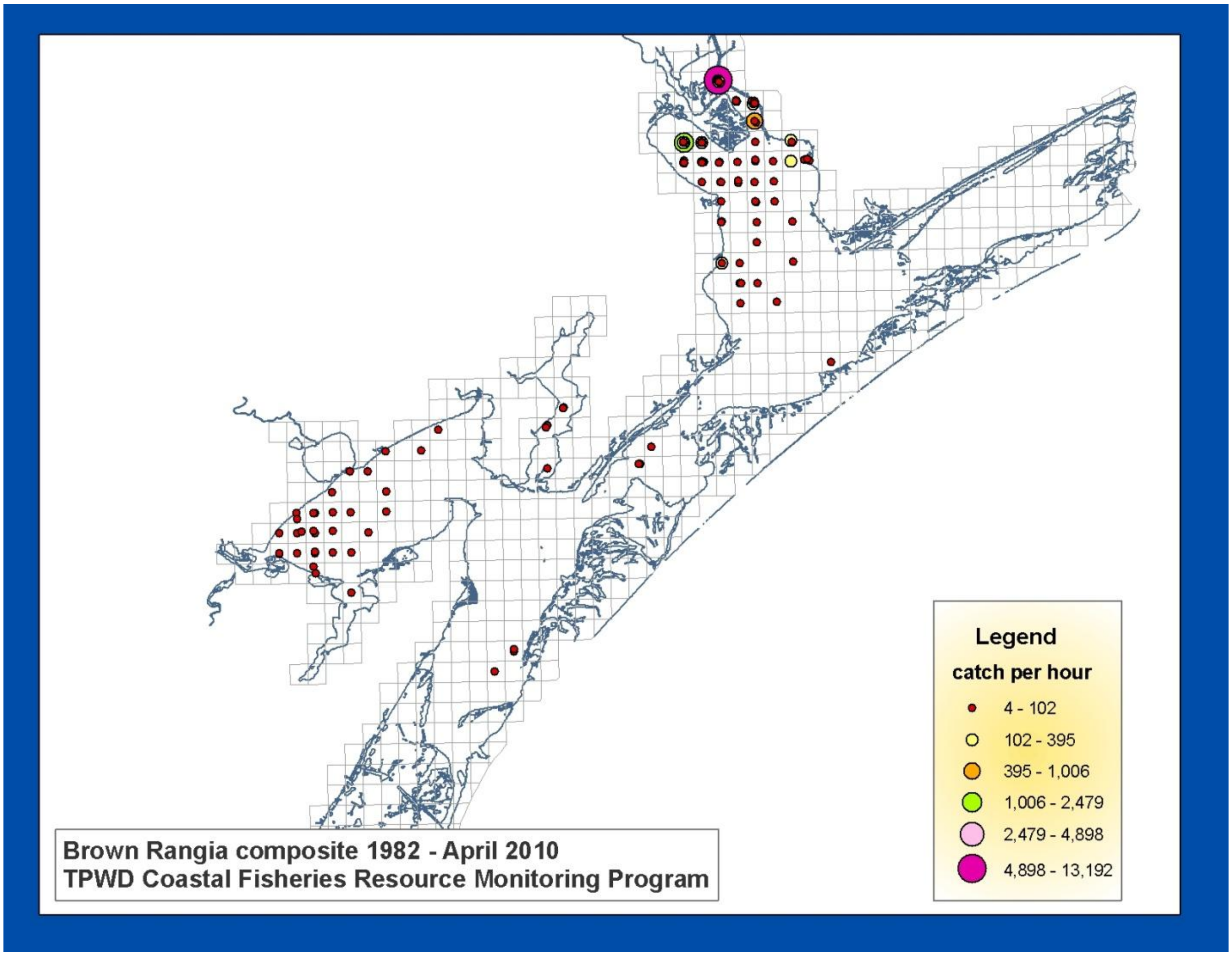


Figure 4.3-2. Distribution of brown rangia in San Antonio Bay and the Mission/Aransas Estuary from Bay Trawl samples (N Boyd, personal communication, 2011).

4.3.1.3 White Shrimp (*Litopenaeus setiferus*)

Importance

White shrimp (*Litopenaeus setiferus* is one of three penaeid species (including brown shrimp, *Farfantepenaeus aztecus*, and pink shrimp, *F. duorarum*)), (all formally in the genus *Penaeus*) which make extensive use of estuarine habitats during their juvenile stage. White shrimp was the first species of commercially important shrimp in the U.S., with the fishery for this species dating back to 1709 (Muncy 1984). The three species of penaeid shrimp (white, pink, and brown shrimp) together comprise more than 99% of the commercial landings in the Gulf of Mexico shrimp fishery. White shrimp are the second most abundant species (after brown shrimp). A total of about 110 million pounds of white shrimp were landed in U.S. fisheries in 2008, mainly off of Texas and Louisiana. Annual landings vary considerably from year to year and these fluctuations have been attributed to environmental influences. For example, white shrimp landings are much lower in years following severe winter weather. (NOAA FishWatch no year). White shrimp also support an important inshore fishery, both for table shrimp and for bait. In addition to their importance as commercial species, shrimp are important component of the estuarine ecosystem.

Finfish prey heavily on white shrimp, which serve as an important food source, link and integrator of the environment (Muncy 1984; Patillo et al. 1997).

Life-history

All three species have a similar life-history: spawning takes place in coastal waters where the offspring transition through several larval stages as they are transported towards the coast by surface currents. They enter the estuaries through tidal inlets at the post-larval stage and disperse throughout the estuary. After a period of rapid growth in the estuary, subadults migrate back to the open ocean (Howe et al 1999). Few white shrimp live as long as a year (Muncy 1984), however, mark-recapture studies have revealed that some white shrimp live from 27 months to as much as 4 years (Etzold and Christmas 1977; Klima et al. 1982). In the Carolinas, spawning occurs from May through September (Williams 1955), while further south in the Gulf of Mexico, spawning occurs from March through September. Williams (1965) reported only one spawning period for white shrimp however, Gunter (1950) suggested spring and fall spawning periods in Texas waters. Juvenile and adult white shrimp are benthic omnivores that feed on detritus, plants, microorganisms, macroinvertebrates (annelids, copepods, amphipods, snails, bryozoans, etc.) and small fish (Muncy 1984).

Salinity Relationships

Early investigators recognized the importance of low salinity estuaries as nursery grounds for the young of numerous marine species of commercial or recreational importance. Pearse and Gunter (1957) contended that salinity *per se* is important, stating "The distribution and abundance of blue crab and commercial shrimp (*Penaeus sitiferus*) … are dependent on estuarine areas. The shrimp spawn in oceanic salinities; the early stages apparently require oceanic waters, but the older juveniles must reach bay waters or perish." Assessing information on white shrimp available at the time from throughout the Gulf and Southeast Atlantic region, Lindner and Anderson (1956) state, however, that the influence of salinity on white shrimp distribution "is not clear-cut". Hoese (1960) found young juvenile white shrimp to be fairly abundant in the Gulf surf near Bolivar, Texas in the fall of 1958 where salinities were 22 – 26 ppt. Hoese (1960) also reported that young white shrimp were regularly taken along the ICWW in West Bay (Galveston) where salinities were salinities were generally 19 – 26 ppt. Lindner and Anderson (1956) tested the relationship between salinity and size of white shrimp using data from a Louisiana estuary where they had catch data from several locations throughout the estuary. The data showed an "almost perfect" correlation between size of trawl-caught shrimp and salinity, but when they eliminated the effect of location by means of a partial correlation analysis, they found the relationship between size and salinity to be non-significant.

Zein-Eldin (1963), pointing out that some authors felt that components of the estuarine habitat other than salinity might be of equal or greater importance, conducted controlled laboratory experiments on the effect of salinity on survival and growth of postlarval penaeid shrimps. The study found that the shrimp grew equally well at all salinities tested (including 2, 5, 10, 25, and 40 ppt) and the authors concluded that salinity *per se* does not limit survival or growth of young shrimp. The only study of the direct influence of salinity on juvenile white shrimp is a recent study by Rozas and Minello (2011) where the effects of salinity on shrimp growth were determined in mesocosms placed in the Intermediate (average salinity 1-3 psu), Brackish (average salinity 5-6 psu), and two regions of the Saline zones (Upper Estuary, average salinity 13-17 psu and Lower Estuary, 20-24 psu). Studies were conducted in two months (May and September) and shrimp in the experiments ranged from 32 to 72 mm TL. Half of the mesocosms had food added during the experiments while the other half did not. White shrimp grew significantly more slowly at the Intermediate (i.e. lowest salinity) location than at the other three locations. White shrimp growth rate was higher in mesocosms with food added, especially at the lower salinity sites. The authors concluded that lowering the salinity over a large portion of the available habitat (via freshwater diversions from the Mississippi River) could reduce the productivity of brown and white shrimp within the estuary.

Several other studies have added substantially to our knowledge of the ecology and life-history of penaeid shrimps and their relationship to salinity. A primary finding has been the strong affinity of all penaeid species for vegetated habitat compared to unvegated bay bottom [e.g. Zimmerman et al (1984) in Galveston Bay, preference for vegetation shown by brown shrimp but not white shrimp; Sheridan (1992) in Rookery Bay Florida, preference shown by pink shrimp; Wenner and Beatty (1993) in Charleston Harbor SC, preference shown by both brown and white shrimp; Howe et al (1999) Mobile Bay AL, all three species)]. Howe et al (1999) found however, that there was no significant positive correlation between shrimp density and vegetation density, the relationship was essentially between presence and absence of vegetation regardless of vegetation density. The vegetation relationships mentioned above are all for emergent marsh vegetation, little data exists for the relationship of postlarval and juvenile shrimps and submerged vegetation (i.e. seagrasses) which are important component of the estuarine vascular plant complex in South Texas estuaries.

Three extensive assessments of penaeid habitat/abundance relationships seem particularly relevant. Wenner and Beatty (1993) examined the temporal patterns of abundance of postlarval and juvenile penaeids among shallow marsh habitats along a salinity gradient in Charlston Harbor, South Carolina. In essence, their study looked at how young shrimps utilized various habitats (marsh surface, adjacent subtidal creek bottoms, and drainage rivulets) at sites representing low (oligohaline) (< 5 psu), medium (mesohaline) (5 – 18 psu), and high (polyhaline) (> 18 psu) salinity regimes. White shrimp postlarvae were most abundant in July and August and densities were substantially higher (86% of all postlarval white shrimp) at the high salinity site than at either the low or medium salinity site. Juvenile white shrimp were taken from July through December with highest densities at the low and medium salinity sites. White shrimp juveniles clearly made use of all habitat types within the tidal creek environment and showed a clear tendency to move onto the marsh surface at night on flood tides. There was no apparent difference in habitat use between the low and medium salinity sites, suggesting that salinity regimes did not influence habitat use. The high tidal range of the South Carolina site dictated movements of shrimps among the habitats (e.g forcing shrimp to vacate the marsh on low tide). In a recurring theme among studies, Wenner and Beatty (1993) noted that the timing of ingress of postlarvae was consistent among the three years of the study but there were significant differences in density of shrimps among years. In summary, they found white shrimp postlarvae most abundant at the high salinity site while juveniles were most abundant at the medium and low salinity sites although white shrimp vacated the low salinity site following a major flooding event.

Howe et al (1999) compared shrimp densities between adjacent vegetated and nonvegetated sites along a salinity gradient within Mobile Bay, Alabama over a three year period. As with other shrimp studies, there was an obvious seasonal pattern in shrimp occurrence. Brown shrimp were most abundant in spring, white shrimp in summer, and pink shrimp in both fall and spring. Mean salinity at the five vegetated sites ranged from around 2.5 psu at the most up-estuary site to around 19 at the most down estuary site. An analysis of the distribution of shrimps among the five vegetated sites in each of the three years of the study showed highest catches of white shrimp were consistently seen at one of the two mid-bay sites where salinities averaged around 6-13 psu, although in only one of those years were the differences statistically significant. These authors concluded that the presence of vegetation was a more important determinant of shrimp distribution and density than abiotic factors such as temperature, salinity, or dissolved oxygen.

Webb and Kneib (2002) found that white shrimp were smaller and more abundant in the upper reaches of Georgia tidal creeks than farther down in the main stem of the estuaries. They point out that this supports a "general and long-standing tenant that there are ontogenetic shifts in habitat use along estuarine salinity gradients, with smaller individuals found in lower salinity waters farther inland …". They propose however, that variation in salinity *per se* is not the only, nor perhaps even the principal mechanism controlling the distribution of juvenile white shrimp. Instead variations on the extent and physical complexity of the adjacent marsh landscape may underlie the observed patterns. If this is the case, then it may help explain the occasional occurrence of high densities of small shrimp in high salinity, down-estuary sites as described by Hoese (1960). Salinities in the Webb and Kneib (2002) study fell within the polyhaline (high salinity) regime at all sites and ranged from 18 to 30 ppt.

Finally, DeLancey et al (2008) analyzed a long-term dataset of trawl collections from a NERR site in South Carolina. They found a significant difference in catch among years with a near order of magnitude difference in abundance between the best and worst years. As with most other studies, white shrimp juveniles were most abundant and smaller at up-estuary stations. Significant relationships were seen between winter water temperatures and subsequent spring catches of larger juveniles that had overwintered in the estuary. A significant relationship was also seen between August CPUE values and July-August DO values. Relationships between CPUE and salinity and between CPUE and water temperature at time of collection were non-significant. Salinities at the study site ranged from 20 -30 ppt and increased over the 25 year study period.

NOAA's Center for Coastal Monitoring and Assessment has developed a database from which information on distribution and abundance of coastal resources can be extracted (NOAA CCMA no date). Table 4.3-1, derived from that database, shows the relative abundance of three life stages of white shrimp in relationship to five salinity zones in San Antonio Bay. Two pieces of information can be derived from this table. First, the seasonal progression shows (essentially from bottom to top in the table) that postlarvae are found all year around (indication some continuous level of larval immigration for offshore throughout the year) but are found in high abundance from March to July. Juveniles are found in highest abundance from June through November and adults from July through October. Adults almost all leave the estuary for spawning in the late fall while some late recruiting juveniles may linger over the winter (DeLancey et al 2008). The second bit of information in the table is the consistent occurrence of high abundance of white shrimp over a wide range of salinity. Post larvae are found in very high abundance in all but the lowest salinity zone, juveniles were found in very high abundance in all salinity zones, and adults were found in high abundance in all but the lowest salinity zone. In essence, none of the life-stages was limited by salinity. It is important to realize that the data for this summary were gathered from a variety of sources and encompass multiple years and provides no information on the spatial distribution within the estuary. The salinity at any given location in the estuary can vary substantially over time.

In essence, it appears that although juvenile white shrimp may often be more abundant in the lower salinity parts of the estuary, physiological constraints are not driving their distribution, but rather some other biotic or abiotic aspect of the upper reaches of estuaries provides high quality habitat that attracts juvenile white shrimp to those areas. The GSA BBEST has developed an evaluation of the relative distribution of white shrimp in San Antonio Bay in relation to inflows (which largely drive salinity) to be used as an overlay in the inflow criteria and that assessment is described in Section 4.5.3.1 of this report.

Table 4.3-1 Relative abundance of different life stages of white shrimp in San Antonio Bay within selected salinity zones (NOAA CCMA, no date)

White shrimp	San Antonio Bay												
Life Stage	Salinity zone	J	F	M	A	M	J	J	A	S	O	N	D
ADULTS	0-0.5 ppt	2	2	2	2	2	2	2	2	2	2	2	2
ADULTS	0.5-5 ppt	2	2	0	0	3	3	4	4	4	4	3	2
ADULTS	5-15 ppt	2	2	0	0	3	3	4	4	4	4	3	2
ADULTS	15-25 ppt	2	2	0	0	3	3	4	4	4	4	3	2
ADULTS	>25 ppt	2	2	0	0	3	3	4	4	4	4	3	2
JUVENILES	0-0.5 ppt	2	2	2	3	3	4	4	4	5	5	5	3
JUVENILES	0.5-5 ppt	2	2	2	3	3	4	4	4	5	5	5	3
JUVENILES	5-15 ppt	2	2	3	3	3	4	4	4	5	5	5	3
JUVENILES	15-25 ppt	2	2	3	3	3	4	4	4	5	5	5	3
JUVENILES	>25 ppt	2	2	3	3	3	3	3	3	4	4	4	3
LARVAE	0-0.5 ppt	0	0	0	0	0	0	0	0	0	0	0	0
LARVAE	0.5-5 ppt	0	0	4	5	5	4	4	3	3	0	0	0
LARVAE	5-15 ppt	0	0	4	5	5	4	4	3	3	0	0	0
LARVAE	15-25 ppt	0	0	5	5	5	4	4	3	3	0	0	0
LARVAE	>25 ppt	0	0	5	5	4	3	3	3	3	0	0	0

Legend: Relative abundance codes; 0 not present; 1 Rare; 2 Common; 4 Abundant; 5 Highly Abundant

4.3.1.4 Blue Crabs (*Callinectes sapidus*)

Importance

The blue crab, *Callinectes sapidus*, is a portunid crab native to western Atlantic estuaries from Nova Scotia to Argentina (Millikin and Williams 1984).). Blue crabs play an important role in the estuarine food web as generalist omnivores and scavengers, consuming bivalves, gastropods, fish, and other crustaceans (Virnstein 1977, Hines et al. 1990). Predation by blue crabs can regulate the structure of estuarine ecosystems (e.g. Silliman and Bertness 2002) and limit the range of certain invasive species including rapa whelps *Rapana venosa* (Harding 2003) and green crabs *Carcinus maenus* (deRivera et al. 2005). Blue crabs are also an important prey species for fish including red drum (Scharf and Schlicht 2000)) and striped bass (Tupper and Able 2000) and birds including herons, sea gulls, and endangered whooping cranes (Hunt and Slack 1989, Chavez-Ramirez 1996).

Major commercial fisheries for blue crabs exist along the Atlantic and Gulf Coasts of the U.S., making it the largest crab fishery in the U.S. (NMFS 2009). U.S. landings in 2009 totaled over 70,000 metric tons for a wholesale value of over $150 million (NMFS 2011). In Texas, blue crabs support the third largest fishery in terms of landings (Sutton and Wagner 2007), averaging 1.27 million kg annually from 2005-2009 for a value of ~$2.3 million per year (NMFS 2011) (NMFS 2011). Many states including Texas (Sutton and Wagner 2007, Mark Fisher TPWD, personal communication, 2011) have seen declines in blue crab populations in recent years. Data from the Texas Parks and Wildlife Department Coastal Fisheries Resource Monitoring Program has shown a general decline in catch rate of blue crabs on all Texas bays, including the San Antonio Bay and Mission/Aransas Bay systems over the past 20 years. (Figure 4.3-3 and Figure 4.3-4, and Figure 4.3-5)

Life history and habitat use

Blue crabs have a migratory life cycle similar to many other estuarine crustaceans. Spawning female blue crabs migrate to high salinity waters (Carr et al. 2004, Aguilar et al. 2005) where they sequentially release clutches of larvae (Hines 1982, Dickinson et al. 2006, Darnell et al. 2009). In tidally-driven estuaries, larvae are transported offshore and develop in the plankton (Epifanio et al. 1984, Millikin and Williams 1984). Following 7-8 zoeal stages, blue crab zoeae metamorphose into megalopae (Costlow and Bookhout 1959), which are transported into estuaries by surface currents and migrate to settlement sites using flood tide transport (Forward and Rittschof 1994, Welch and Forward 2001, Ogburn et al. 2009). Blue crab megalopae settle and metamorphose into juvenile crabs in structured habitats including seagrass beds and salt marsh edges (Heck and Thoman 1984, Orth and Van Montfrans 1987), where they remain until they begin to disperse throughout the estuary (Blackmon and Eggleston 2001, Reyns and Eggleston 2004). During the later juvenile stages, blue crabs begin to move into unstructured habitats, as they reach a size that provides a refuge from predation and allows increased exploitation of high prey densities (Mense and Wenner 1989, Rakocinski et al. 2003, Lipcius et al. 2005). Blue crabs typically reach maturity 10-20 months after hatching, following 18-20 postlarval molts (Millikin and Williams 1984). Although males continue to molt several more times after reaching sexual maturity, females undergo a terminal pubertal molt. Mating occurs following the terminal molt and is usually immediate, although incompletely mated females remain receptive for up to 10 days after the terminal molt (Rittschof et al., unpublished data). Molting and mating generally take place in shallow, marsh-lined tidal creeks (Wolcott and Hines 1990) and embayments (Ramach et al. 2009). Following mating, females forage for several weeks as the ovaries mature before undertaking the seaward spawning migration (Turner et al. 2003, Aguilar et al. 2005, Darnell 2009). After migrating to high salinity waters, female crabs do not return to the upper estuaries, but rather live out their lives in high salinity waters of the lower estuary and coastal ocean (Van Engel 1958, Forward et al. 2005, Rittschof et al. In Press). The typical blue crab life span is estimated to be between 2 and 5 years (Van Engel 1958, Tagatz 1968a, Darnell et al. 2009) and depends on latitudinal temperature variations, seasonal timing of hatching and settlement, and total time above a certain temperature (Darnell et al. 2009, Hines et al. In Press).

In North Carolina, the relative abundance of megalope at the coast was episodic, reflecting a relatively long spawning period, with a broad period of abundance from July through October but within the estuary, the peak period of abundance was September or October of each year (Ogburn et al. 2009). Texas Parks and Wildlife Department Coastal Fisheries Resource Monitoring Program data shows that juvenile crabs (carapace widths (cw) of 30-50 mm) are most abundant in San Antonio Bay from February to April and adults (90-100 mm cw) are most abundant from June to September (Figure 4.3-6 and Figure 4.3-7 respectively , from the Texas Parks and Wildlife Department Coastal Fisheries Resource Monitoring Program database).

Salinity tolerances and responses to salinity change

Physiological tolerance

Salinity tolerances of various blue crab life history stages can be predicted based on the life history and habitat use of each life history stage. The larval (zoeae) stages require high salinity for proper hatching and development. Hatching occurs near the mouths of estuaries, and larvae develop offshore. The optimum salinity for hatching is ~23-28 psu (Sandoz and Rogers 1944), and successful development requires a salinity above ~20 psu.

Megalopae return to estuaries and settle in submerged vegetation and other structured habitat. While transport into the estuary is due primarily to wind-driven currents (Ogburn et al. 2009), movements within estuaries to settlement sites relies on a chemical cue (humic acids) derived from freshwater inflow that causes the megalopae to alter their behavior, resulting in up-estuary movement (Forward and Rittschof 1994). Humic acids rapidly precipitate at high salinities and are unavailable as a chemical cue; freshwater inflow is thus an important component of the megalopal recruitment process. Megalopal survival is highest at salinities between 20-40 psu (Tankersley and Forward 2007). The duration of the megalopal stage (time from metamophosis to megalopal stage to metamorphosis to juvenile stage) varies based on salinity and temperature, and is shortest between ~15 psu and 35 psu (Tankersley and Forward 2007).

During the juvenile and adult stages, salinity tolerances are broad. Rapid changes in salinity can cause mortality, although given sufficient acclimation time, juveniles and adults are tolerant of both low and high salinities (Tankersley and Forward 2007). Juvenile and adult blue crabs are tolerant of a wide range of environmental conditions, having been found in habitats with ranging from freshwater (Mangum and Amende 1972, Norse 1978) to hypersaline lagoons with salinities up to 117 psu (Simmons 1957, Williams 1984). Temperature tolerance is similarly broad, ranging from <3ºC to >35ºC (Williams 1974, Tankersely and Forward 2007).

Growth and size at maturity

Both laboratory studies and field observations suggest that crab size is influenced by environmental factors including salinity and temperature. Larger crabs are frequently found in lower-salinity areas of estuaries (Tagatz 1968b). Similarly, the TPWD fishery-independent survey program found that size at maturity generally decreased with increasing salinity (Fisher 1999). Eggleston et al. (2004) observed that crabs in North Carolina were generally larger during wet years than during dry years. Growth studies have been inconclusive (Haefner and Shuster 1964, Cadman and Weinstein 1988), and the mechanistic relationship between salinity and size at maturity remains unclear. This relationship may be due to direct effects of salinity on growth, perhaps because of increased water absorption at the molt when in low salinity waters (Van Engel 1958), or may also be due to an indirect effect of salinity on food availability or predation intensity.

Blue crab size is also related to temperature. In a preliminary experiment, Rittschof et al. (unpublished data) observed decreased growth at the molt with increasing temperature, although effects were not significant likely because of low sample size. Both Fisher (1999) and Darnell et al. (2009) found that size at maturity was inversely related with water temperature. Generally, the largest crabs molt to maturity in the spring and fall, while the smallest crabs molt to maturity during the warmer summer months (Hines et al. In Press).

Relationship to Freshwater Inflow

Although there is little evidence of direct effects of salinity on blue crab physiology, there is some suggestion that inflows in general may influence population size. Wilber (1993) showed that inflow during the September through May juvenile grow-out period was correlated with commercial landings of blue crabs the following fall in Apalachicola Bay Florida. While salinity levels and freshwater inflow volumes are highly correlated, there are numerous other components of freshwater inflow, such as increased nutrients, detrital concentrations, etc. that can affect production of estuarine flora and fauna. Higher freshwater inflow might influence recruitment success by potentially reducing predation pressure or by increasing the estuaries “signal” to immigrating megalope (Wilber 1993), thereby increasing recruitment levels. However, Wilber (1993) found the correlation with harvest stronger at the low end of the inflow range and “there was no evidence that above-average flows were associated with either oyster or blue crab productivity”. Using similar analysis techniques to the Florida study cited above, Wilber and Bass (1998) found no correlation between inflow to Matagorda Bay from the Colorado River and commercial harvest of blue crabs.

Blue Crabs and Whooping Cranes

A recently completed study investigated blue crab population dynamics and habitat preferences in the Aransas National Wildlife Refuge (Slack et al. 2009). Different life stages of blue crabs preferred different habitats within the coastal marsh complex. Young blue crabs preferred shallow bay habitats whereas dispersing juvenile and adult crabs were found primarily in interior marsh ponds. Habitat preferences were also reported for small crabs (submerged vegetation and algae-dominated bay waters) and larger crabs (pond-edge habitats), and largest crabs (open-water ponds in interior marsh). Connectivity between interior ponds and open bay further defined abundance ranking; more crabs were found in connected, interior ponds than unconnected pond habitats.

These spatial habitat preferences among various life stages and sizes of blue crabs changes temporally throughout the year as well, and is tied to several environmental factors. In this study, abundance was significantly correlated with habitat type, territory and three abiotic factors: bay water level, wind speed as measured in the bay, and bay salinity (Slack et al. 2009). The study was conducted during a two-year period, when salinities were at moderate levels. In other studies, an inverse correlation was made between blue crab abundance and salinities (TPWD 1998, Hamlin 2005).

Blue crab constitutes a major portion of the diet of whooping cranes, an endangered species that migrates from Northwest Territories in Canada each fall and winters only within the San Antonio, Copano, and Aransas bay system (Allen 1952, Hunt and Slack 1989, Chavez-Ramirez 1996, Slack et al. 2009). Years where salinities are high (>28 ppt) and blue crab abundance was low corresponded to decreased vitality and increased mortality of whooping cranes (Pugesek et al. 2008, Stehn 2008). Whooping cranes will feed on other food items when available (e.g. wolfberries) or when blue crab are temporally unavailable during low tides (e.g. clams); however, blue crab provide the highest nutritional value (Nelson et al. 1996). The energy storage necessary for overwintering and preparation for the 2,500 mile migration to Canada is essential for the continued recovery of this endangered species.

Parasites and diseases with special consideration of salinity and seasonality

Despite the blue crab's ecological end commercial importance along the Atlantic and Gulf Coasts of the U.S., parasites and diseases of blue crabs have received relatively little attention in the scientific literature, especially compared to other commercially harvested species such as oysters, shrimps, or lobsters (Shields 2003, Shields & Overstreet 2007). Blue crabs can become infected or parasitized by a number of agents, including *Vibrio* spp., *Hematodinium perezi*, *Listeria monocytogenes*, *Clostridium botulinum*, *Loxothylacus texanus*, *Lagenidium callinectes*, *Octolasmis muleri*, and *Carcinonemertes carcinophila*. While several of these agents are of minor concern due to limited prevalence or relatively benign effects on the crab, others can have substantial effects on blue crab populations or present human health concerns in the seafood industry (Shields & Overstreet 2007).

An understanding of blue crab parasites and diseases may be useful for water resources management decisions because many of these agents have specific salinity requirements that limit their distributions within estuaries. Such salinity requirements can be used when making freshwater inflow recommendations. The following is a brief report on several blue crab parasites, with special consideration of (1) relationships between salinity and prevalence/intensity and (2) seasonality of these parasites. Terminology is used consistent with Shields and Overstreet (2007). *Prevalence* refers to the percentage of potential hosts in a population that are infected, while *intensity* refers to the number of parasites per infected host. For brevity, only those agents with clear relationships to salinity and/or freshwater inflow are included; this is by no means an exhaustive review of blue crab parasites and pathogens. Such a review is presented by Shields and Overstreet (2007).

Loxothylacus texanus

Loxothylacus texanus is a sacculinid rhizocephalan barnacle found the Gulf of Mexico and southern Atlantic coast states that parasitized multiple species in the genus Callinectes, including C. sapidus. Rhizocephalan barnacles have highly modified morphologies compared to the more familiar balanomorph (acorn) barnacles. Blue crabs parasitized by L. texanus can be identified by the parasite's externa, or brood sac, attached under the abdomen. These externa superficially resemble the egg mass of an ovigerous blue crab. Nauplii larvae are released from the externa and, after ~3 d, metamorphose into the cyprid larval stage. Female cyprids find a suitable host within 3-4 d, settling on juvenile soft-shell crabs. These female cyprids are attracted soft-shell crabs by a carbohydrate-based chemical cue associated with the exoskeleton of the recently-molted crab (Boone et al. 2004). Following settlement, cyprids metamorphose to a dart-like kentrogon larvae. 60-70 h after settlement, each kentrogon releases a vermigon larva which enters the crab. The parasite continues to develop for 5-9 molts of the host crab before the externa is produced (O'Brien 1999). The externa is then inoculated by a male cyprid (Glenner et al. 2000).

Parasitization by *L. texanus* has several effects on host crabs, including parasitic castration, feminization of male crabs, maturation at smaller sizes, and parasitic anecdysis, meaning that following production of the externa the host does not continue to molt (O'Brien 1999). Following production of the externa, the parasite also produced pheromones that cause infected crabs to perform abdominal-pumping behaviors characteristic of ovigerous crabs and which enhance synchronous release of *L. texanus* larvae (DeVries et al. 1989). Parasitized crabs produce only parasite larvae, and do not produce crab offspring.

The larval stages of *L. texanus* are intolerant of low salinities. O'Brien et al. (1993a, 1993b, as cited by Shields & Overstreet 2007) found that larvae were not viable below 12 ppt. Tindle et al. (2004) similarly found that that survival of nauplii is greatly reduced at 15 ppt compared to 25 or 35 ppt in acute exposure experiments. Similarly, survival is reduced at lower salinities in acclimation experiments (Figure 4.3-8). Acclimation experiments also indicate decreased nauplii survival above 35 ppt (Figure 4.3-9). Results of the same study also suggest that cyprid larvae may be unable to successfully metamorphose to the kentrogon stage at 10 ppt, although results were inconsistent, possibly due to increased tolerance of cyprid larvae compared to nauplii larvae, or perhaps differences in salinity tolerances between broods (Tindle et al. 2004).

Wardle and Tirpak (1991) reported on an outbreak of *L. texanus* in Galveston Bay, and the prevalence of infection in male and female crabs were similar, with an overall prevalence of 16.5%. Intensity of infection ranged from 1-4 externae per crab (mean = 1.2). Prevalence of infection was reduced at lower salinities, with 20.5% of crabs infected at 25-32 ppt, 23.4% infected at 20-25 ppt, and 12.1% infected at 10-19 ppt. No crabs were examined from salinities below 10 pt (Wardle & Tirpak 1991). In southwest Florida, Hochberg et al. (1992) did not find a relationship between infection prevalence and salinity, but did find that most infections occurred when the water temperature ranged from 21-25°C.

The Texas Parks and Wildlife Department fishery-independent survey program records the number of crabs bearing visible externa that are collected in bag seine, bay trawl, and gill net surveys. Survey data from 2006-2010 were examined for four major bay systems in the Texas coastal bend: Matagorda Bay, San Antonio Bay, Aransas/Copano Bays, and Corpus Christi Bay. During that time period, infected crabs were captured in the trawl surveys, but not in the gill net or seine survey. Prevalence was generally low, and less than 4% of captured crabs carried visible externa during any given month. Infected crabs were generally collected between April and October, with the exception of a single infected crab collected in January, 2010 (Figure 4.3-10).

Hematodinium perezi

Hematodinium perezi is a parasitic dinoflagellate that invades the hemolymph and tissues of blue crabs and other crustaceans including tanner crabs, snow crabs, lobsters, rock crabs, and mangrove crabs (Messick & Shields 2000). In a study conducted in the Chesapeake Bay, infection was significantly associated with high salinities; prevalence is highest at 26-30 ppt, and no infection was found below 11 ppt (Messick & Shields 2000)(Figure 4.3-11). Similarly, Messick et al. (1999) determined that exposure to water of 10 ppt salinity reduced infection intensity compared to water of 29 ppt salinity.

Prevalence of *Hematodinium* sp. infection in Chesapeake Bay generally peaks in the fall (Sept-Nov) and is virtually undetectable from March to May (Figure 4.3-12)(Messick 1994, Messick & Shields 2000). Infection prevalence in the Chesapeake is highest at water temperatures of 3-9°C (Messick & Shields 2000), although intensity decreases below 9°C (Messick et al. 1999)

Messick and Shields (2000) also examined samples from NJ, NC, SC, GA, MS, LA, and TX (Aransas Bay and Corpus Christi Bay) and found no infection below 18 ppt. Corpus Christi Bay was sampled twice, once on 11/20/96 and again on 7/23/97 and prevalence of infection was 9% (*n*=23) and 0% (*n*=8), respectively. Aransas Bay was samples on 10/30/96, and the prevalence of infection was 6% (*n*=17)(Messick & Shields 2000). Little is known of seasonal trends in prevalence and intensity of *Hematodinium* sp. infections in blue crabs in warmer climates, such as Texas.

Octolasmis mulleri

Octolasmis mulleri is a gooseneck barnacle that attaches to the gills of multiple crab species, including blue crabs. Crabs parasitized by *O. mulleri* have reduced respiratory ability and are unable to remain buried in the sediment; these crabs can often be identified by high levels of external fouling by acorn barnacles (D. Rittschof, Duke University, pers. comm.).

O. mulleri is generally intolerant of low salinities. Scarf (1966, as cited by Walker 1974) found that at 20 ppt, the barnacles have open valves and wave their cirri. At salinities of 15 ppt or below, the valves are closed; if returned to high-salinity waters 80% of barnacles exposed to 15 ppt salinity recover, while only 35% of barnacles exposed to 10 ppt salinity recovered, and 0% of barnacles exposed to 5 ppt recovered. Walker (1974) thus suggested that salinity is a major factor limiting the distribution of *O. mulleri*. No clear seasonal trends in prevalence were observed in

Seahorse Key, FL (Gannon 1990), although prevalence may be higher during the summer months in areas with greater seasonal differences in temperature (Shields & Overstreet 2007).

Carcinonemertes carcinophila

Carcinonemertes carcinophila is a nemertean worm that is parasitizes the gills and egg masses of blue crabs and is also a predator on the developing embryos. Juvenile and non-feeding adult worms live in the gills but move into the egg mass following oviposition of a clutch of eggs. At the time of larval release by the crab host, the worm moves back into the gills until oviposition of the next clutch.

Salinity tolerances of *C. carcinophila* has not been well studied, although other species of *Carcinonemertes* are limited by low salinities. Shields and Overstreet (2007) suggested that *C. carcinophila* may be intolerant of salinities below 10, although further research is necessary to determine the exact lower tolerance.

Prevalence of *C. carcinophila* infestation generally peaks in the summer and fall, likely related to the peak in blue crab reproduction, as *C. carcinophila* does not become mature until its host crab produces a clutch of eggs (Hopkins 1947, Shields 1993).

Summary

The four parasites discussed here, *Loxothylacus texanus*, *Hematodinium perezi*, *Octolasmis mulleri*, and *Carcinonemertes carcinophila*, are all intolerant of low salinities, and low-salinity areas of estuaries may serve as a refuge for blue crabs from certain parasites. Unfortunately, data on the prevalence, intensity, or seasonality of these parasites in the Texas Coastal Bend are sparse or non-existent. It is also important to note that other parasites and pathogens, such as the egg fungus *Lagenidium callinectes*, are tolerant of a much wider range of salinities.

Annual Bag Seine CPUE Blue Crabs

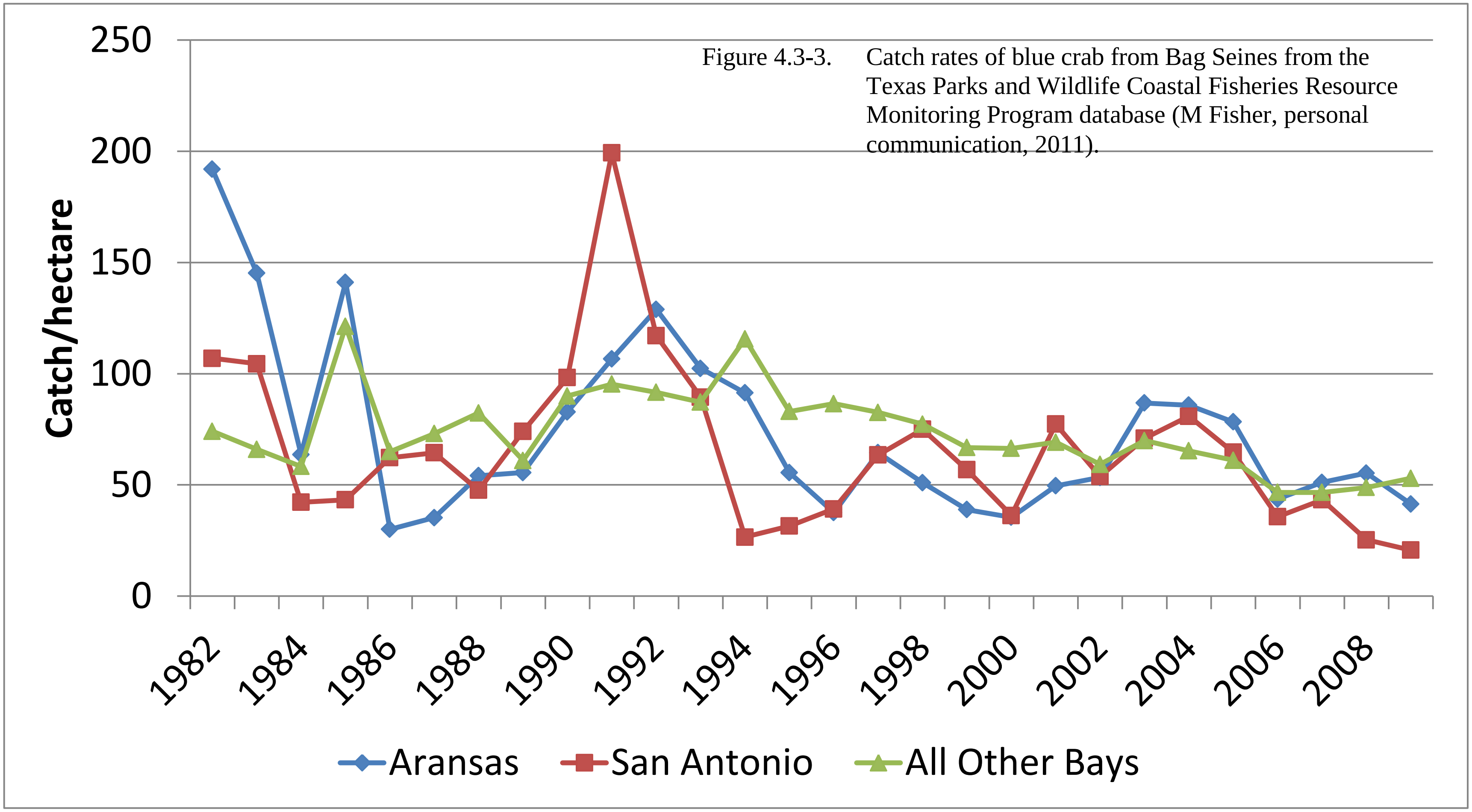


Figure 4.3-3. Catch rates of blue crab from Bag Seines from the Texas Parks and Wildlife Coastal Fisheries Resource Monitoring Program database (M Fisher, personal communication, 2011).

~20-70 mm carapace width

Annual Bay Trawl CPUE Blue Crabs

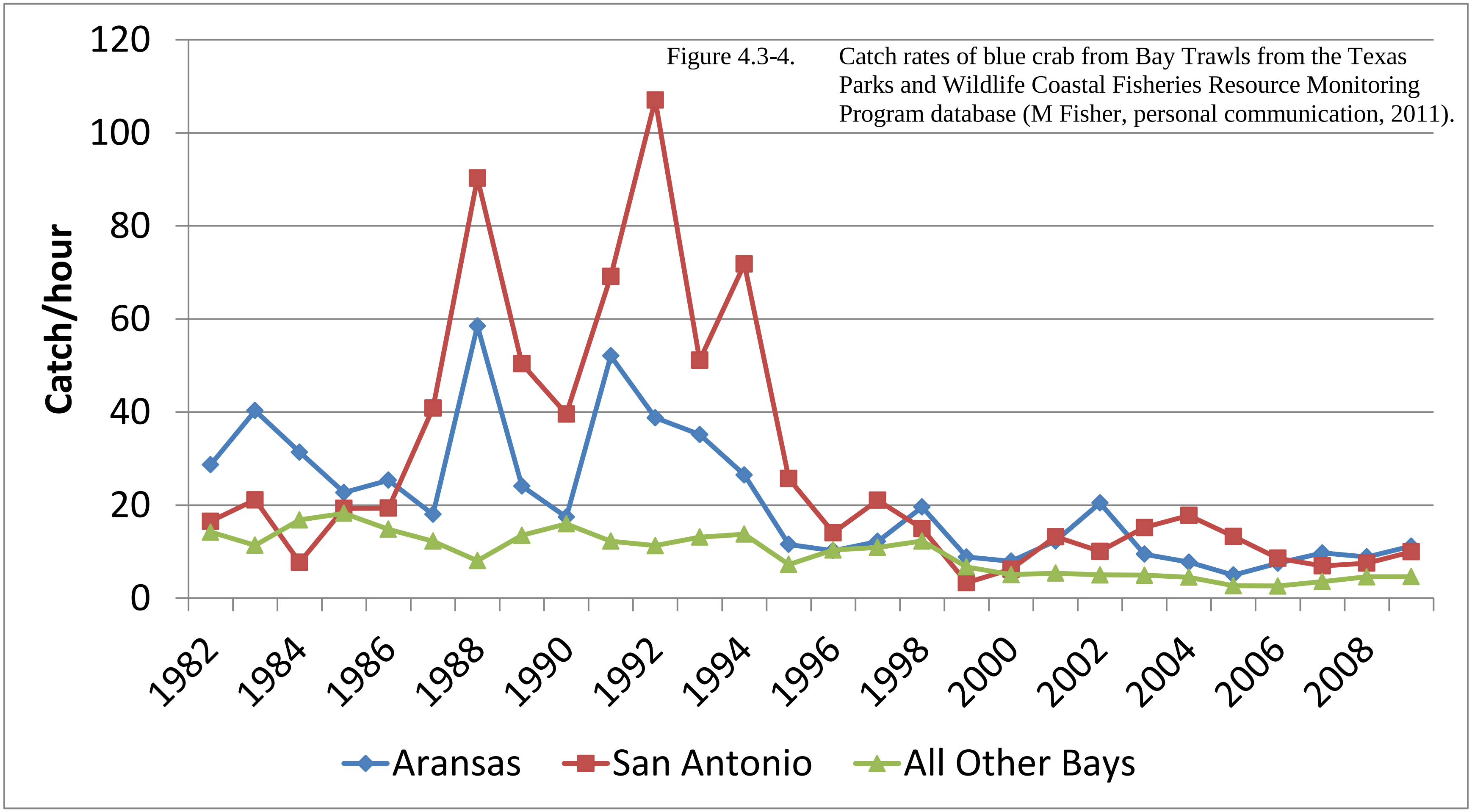
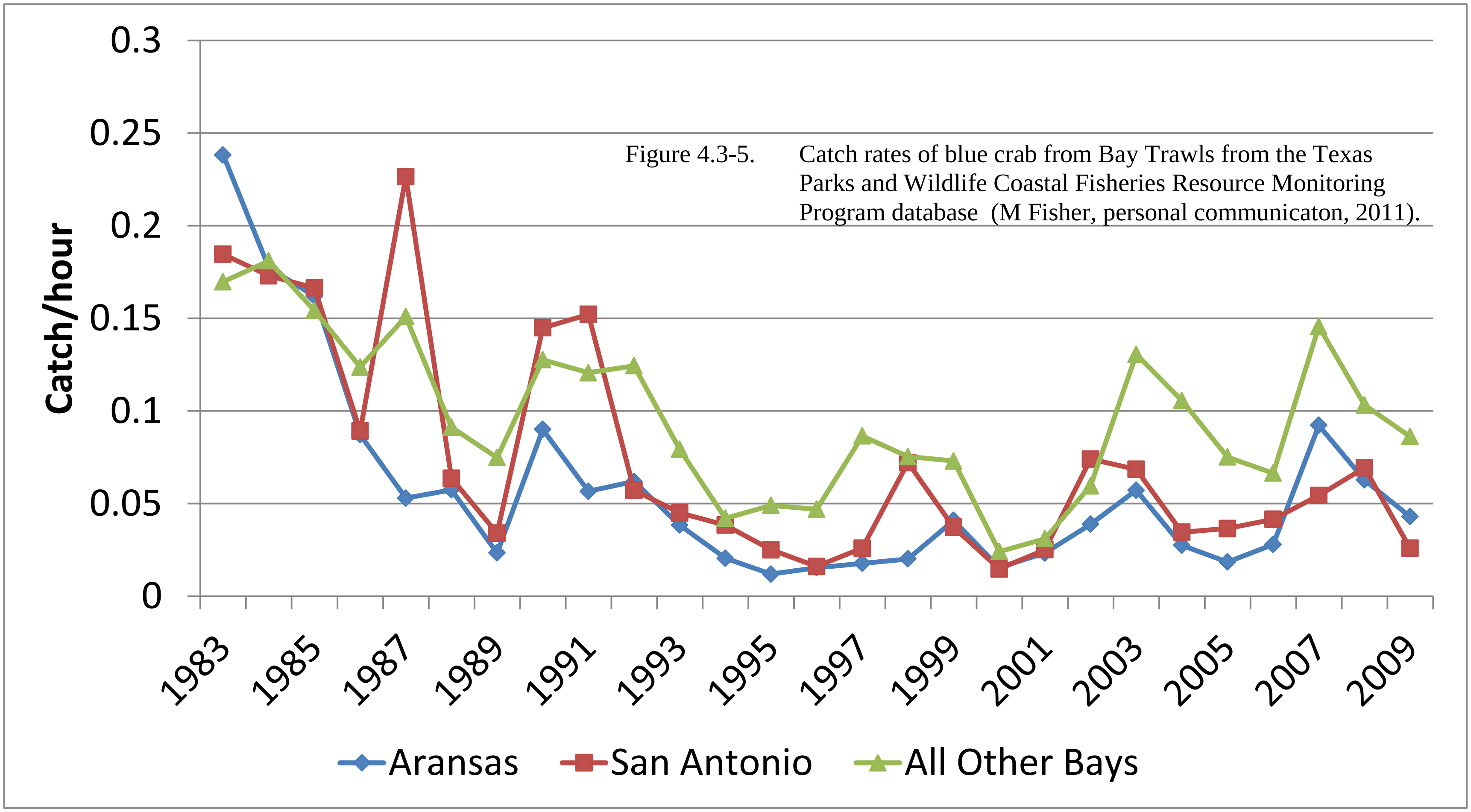


Figure 4.3-4. Catch rates of blue crab from Bay Trawls from the Texas Parks and Wildlife Coastal Fisheries Resource Monitoring Program database (M Fisher, personal communication, 2011).

~30-170 mm carapace width

Annual Gill Net CPUE Blue Crabs



>120 mm carapace width

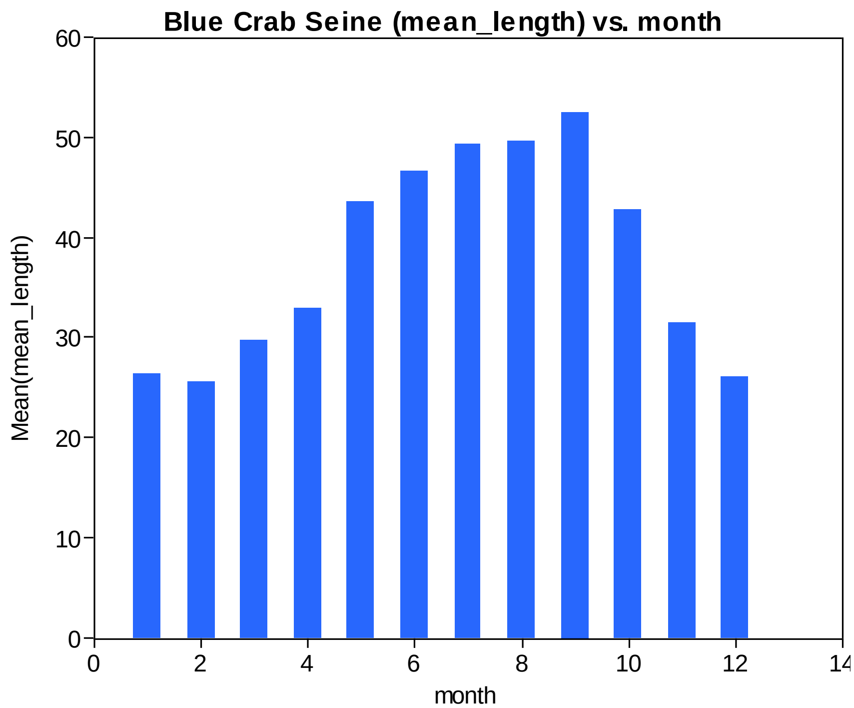


Figure 4.3-6. Mean carapace width of blue crabs in each month from Texas Parks and Wildlife Department Coastal Fisheries Resource Monitoring Program seine collections in San Antonio Bay.

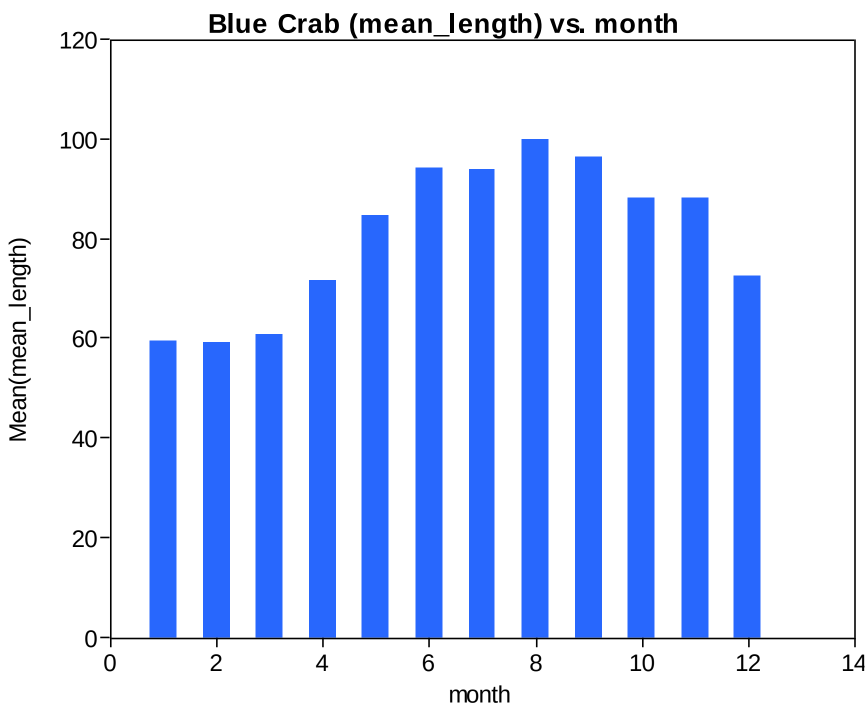


Figure 4.3-7. Mean carapace width of blue crabs in each month from Texas Parks and Wildlife Department Coastal Fisheries Resource Monitoring Program trawl collections in San Antonio Bay.

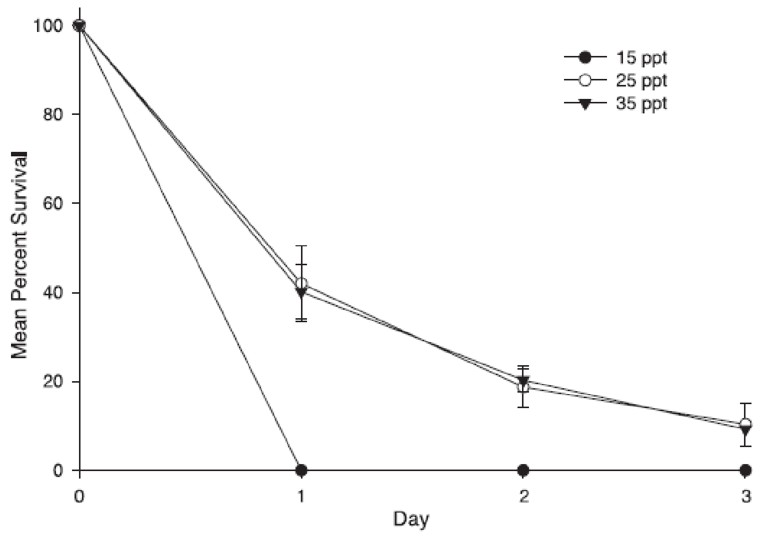


Figure 4.3-8. Percent survival of *L. texanus* larvae from release (Day 0) through development to the cyprid stage (Day 3) at three test salinities, all acute responses. Data points are means ± S.D., *n* = 5. From Tindle et al. 2004.

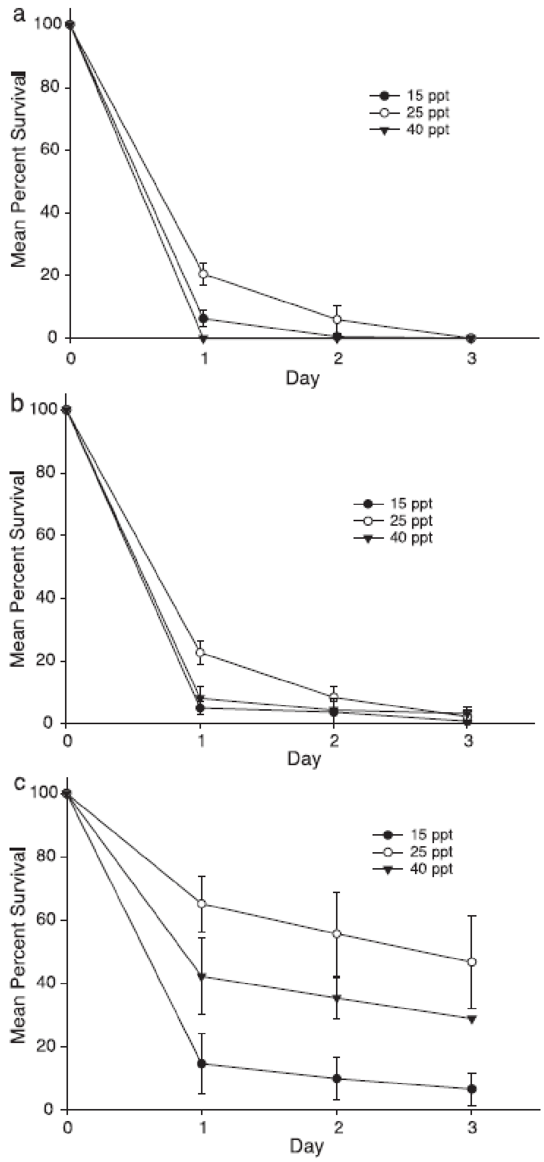


Figure 4.3-9. Percent survival of *L. texanus* larvae from release (Day 0) through development to the cyprid stage (Day 3) at three test salinities under three acclimation conditions: (a) 15 ppt, (b) 25 ppt, and (c) 40 ppt. Data points are means ± S.D., $n = 5$. From Tindle et al. 2004.

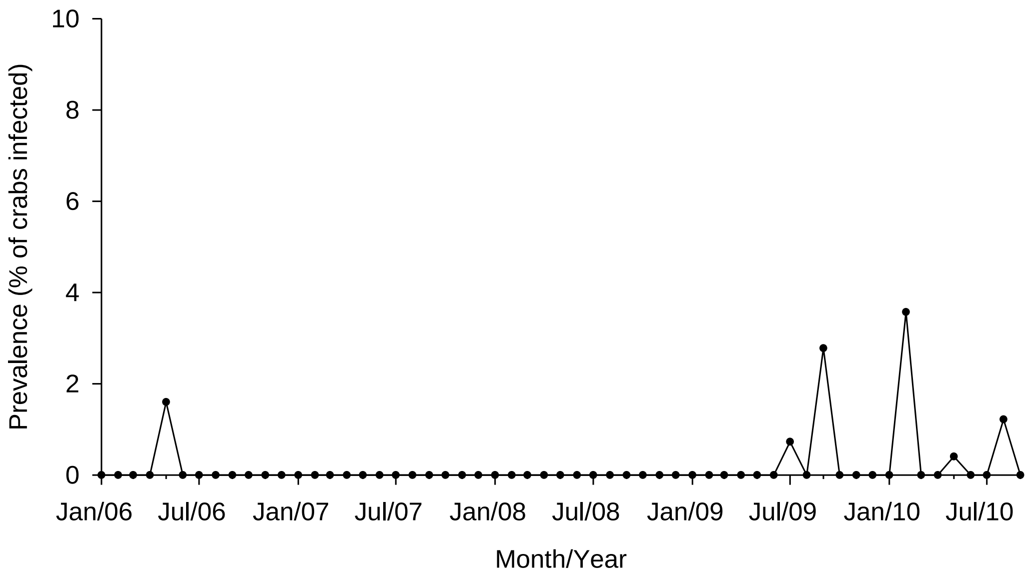


Figure 4.3-10. Prevalence of *L. texanus* infection in Matagorda, San Antonio, Aransas/Copano, and Corpus Christi Bays from January 2006-September 2010, from the TPWD bay trawl survey. Data are from the four bay systems combined.

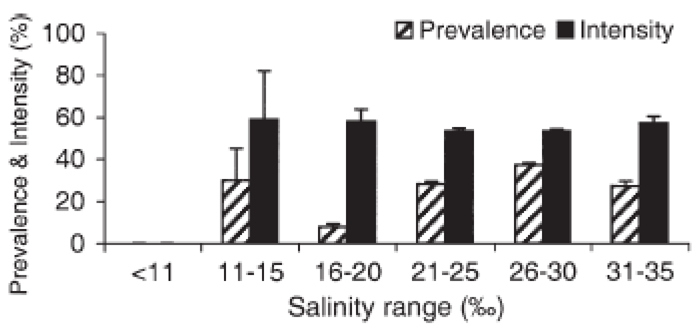


Figure 4.3-11. Comparison of mean prevalence and mean intensity of *Hematodinium* sp. infections among blue crabs collected from different water salinity ranges within coastal bays of Maryland from 1992-1998. Error bar ± SE. From Messick and Shields 2000. Intensity was calculated as: 100 × (# of parasites)/(# of cells + # of parasites).

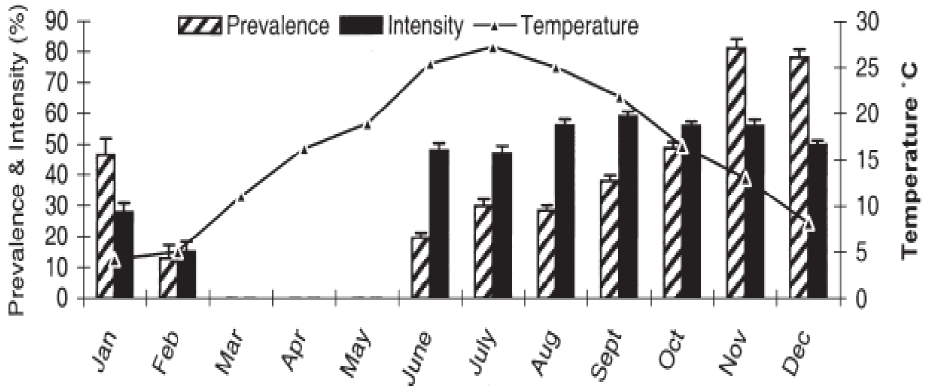


Figure 4.3-12. Seasonal variation in mean prevalence and mean intensity of H*ematodinium* sp. infections in blue crabs collected among different water temperature ranges within coastal bays of Maryland from 1992-1996. Error bar ± SE. From Messick and Shields 2000.

4.3.2 Selection of Fixed Habitat Target Areas

The GSA BBEST relied heavily upon a salinity zone approach (discussed in more detail below) in which specific subareas / habitats of the estuary are delineated due to a concentration of the key species of concern. The selection of these areas for the Guadalupe and Mission-Aransas Estuaries was accomplished with several resources. The GSA BBEST relied heavily on the data of the Texas Parks and Wildlife Department (TPWD) Coastal Fisheries Resource Monitoring Program, available maps of habitats, and the expert opinion of TPWD personnel who are routinely in the field performing sampling.

4.3.2.1 <u>Eastern Oysters</u>

Oyster habitat areas were selected through a combination of habitat maps and expert opinion. For the Guadalupe Estuary, an oyster-rich area in the lower portion of the bay was selected and is shown in Fig. 4.3-13. This area was chosen based largely on the field experience of TPWD's Norman Boyd (personal communication, July 07, 2010). Similarly, areas in the Mission-Aransas Estuary with substantial oyster reef concentrations were selected largely based on the expert opinion and maps of habitat areas (TPWD's Karen Meador, personal communication August 2010).

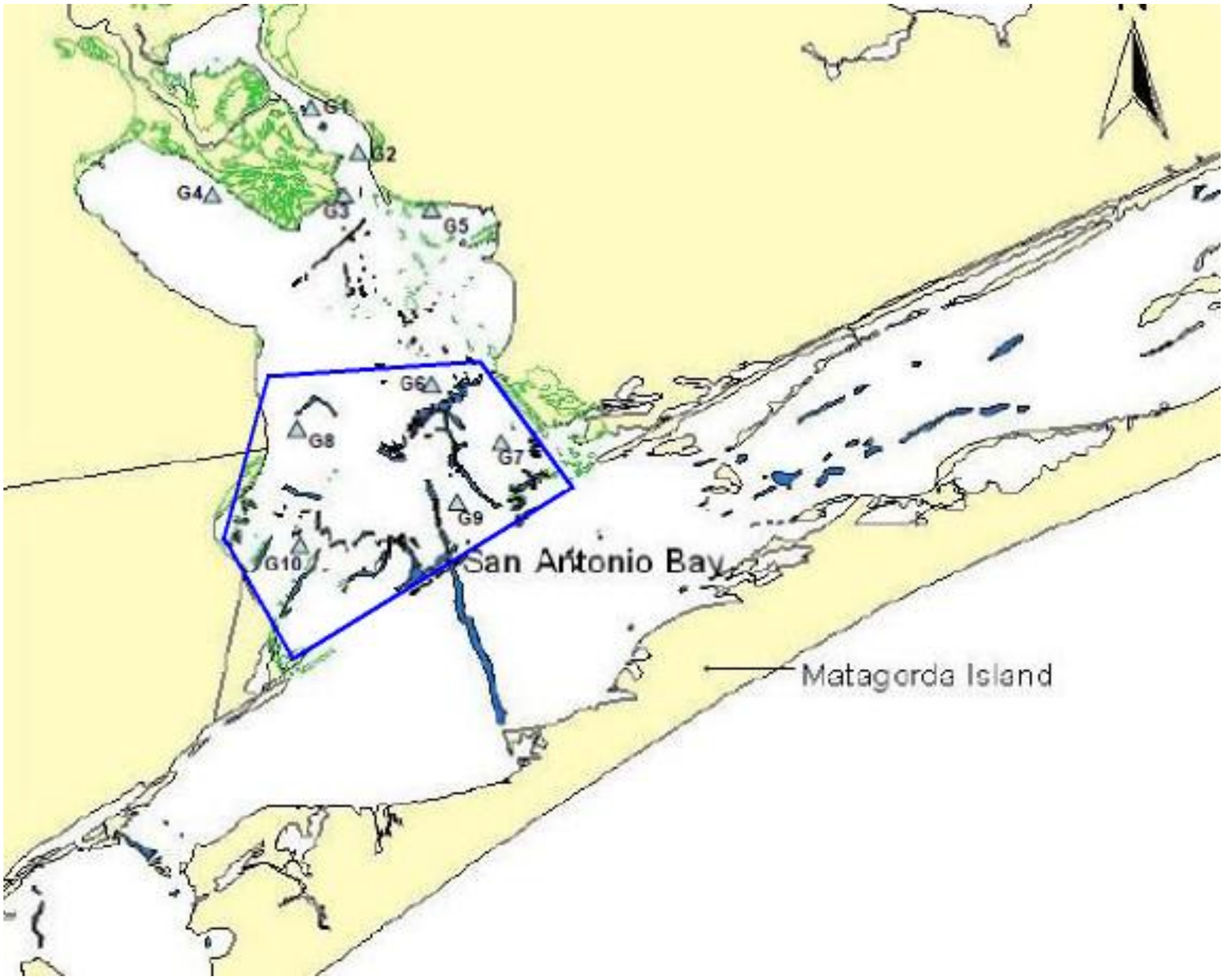


Figure 4.3-13. The portion of the Guadalupe Estuary selected for the oyster fixed habitat area, totaling approximately 24,000 acres.

4.3.2.2 Rangia

Rangia habitat areas were selected based on analyses of the TPWD Coastal Fisheries Resource Monitoring Program. In the Guadalupe Estuary, members of the GSA BBEST and TPWD personnel analyzed the available data in the upper portion of the estuary. A core area of both high abundance and a reliably high frequency of rangia being caught was selected, although there are occasional catch of rangia further down the estuary. This abundance and catch frequency data from the Coastal Fisheries Monitoring Program are shown in Figures 4.3-14 and 4.3-15. Synthesis of these two led the science team to select a "core" rangia fixed habitat area as shown of Figure 4.3-16. For the Copano Bay portion of the Mission-Aransas Estuary, the rangia area was selected with reference to TPWD's Coastal Fisheries Monitoring Program data and is shown in Figure 4.3-17 Finally, Figure 4.3-18 shows all five of the selected fixed habitat areas used by the GSA BBEST in the Guadalupe and Mission-Aransas Estuary system.

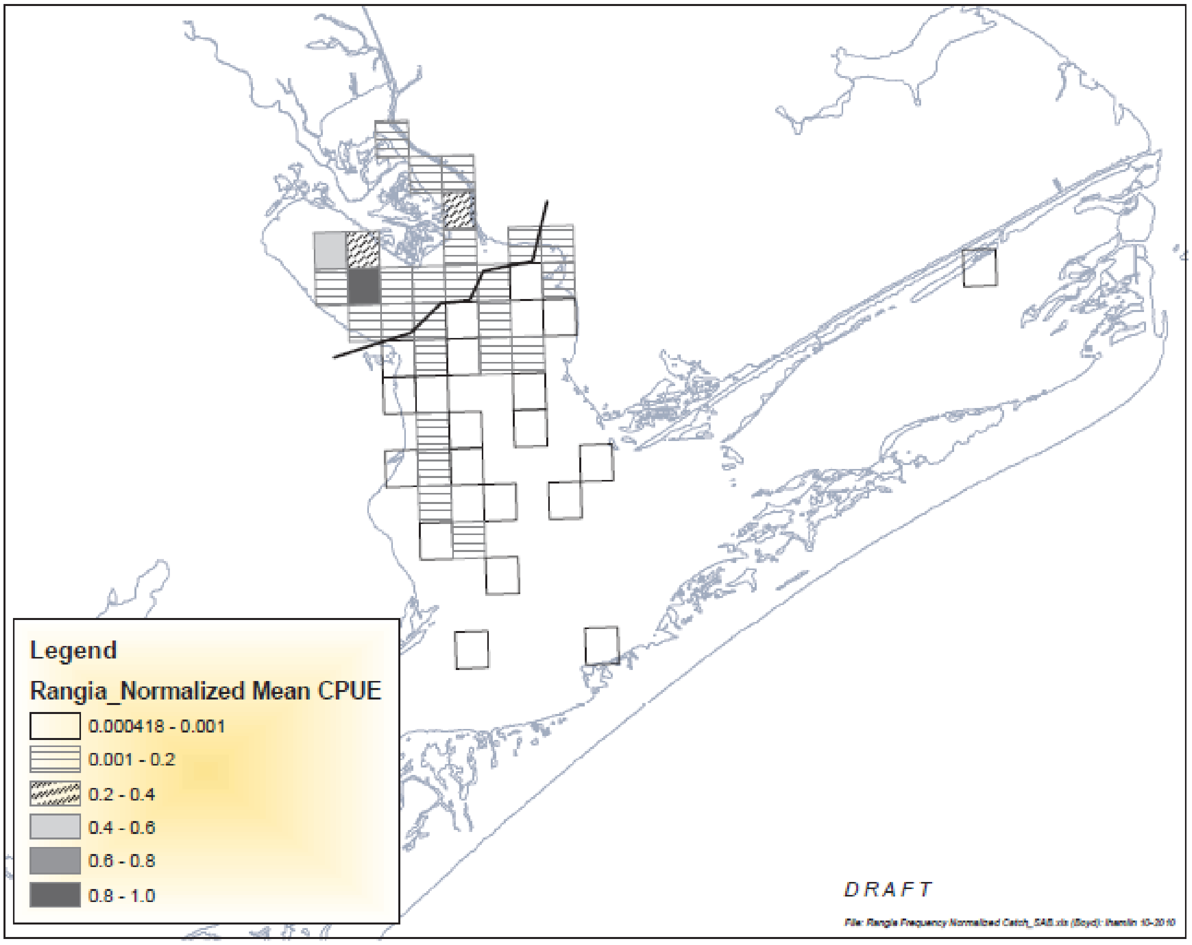


Figure 4.3-14. Map of the Atlantic Rangia catch per unit effort, a measure of abundance, in the upper portion of the Guadalupe Estuary. Data is from the TPWD Coastal Fisheries Resource Monitoring Program. (map courtesy of Lynne Hamlin, TPWD).

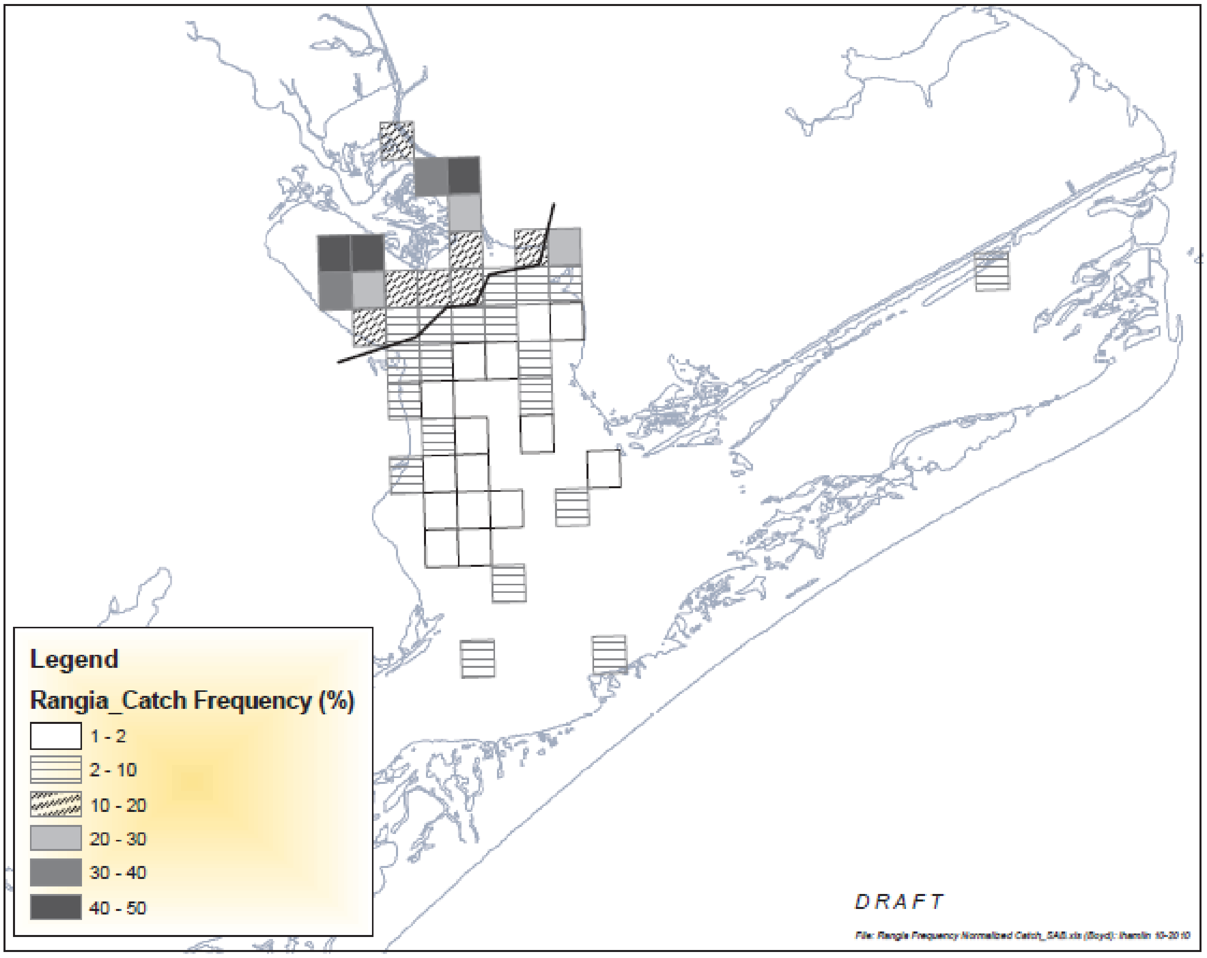


Figure 4.3-15. Map of the Atlantic Rangia catch frequency, a measure of the reliability of repeatedly finding rangia, in the upper portion of the Guadalupe Estuary. Data is from the TPWD Coastal Fisheries Resource Monitoring Program. (map courtesy of Lynne Hamlin, TPWD).

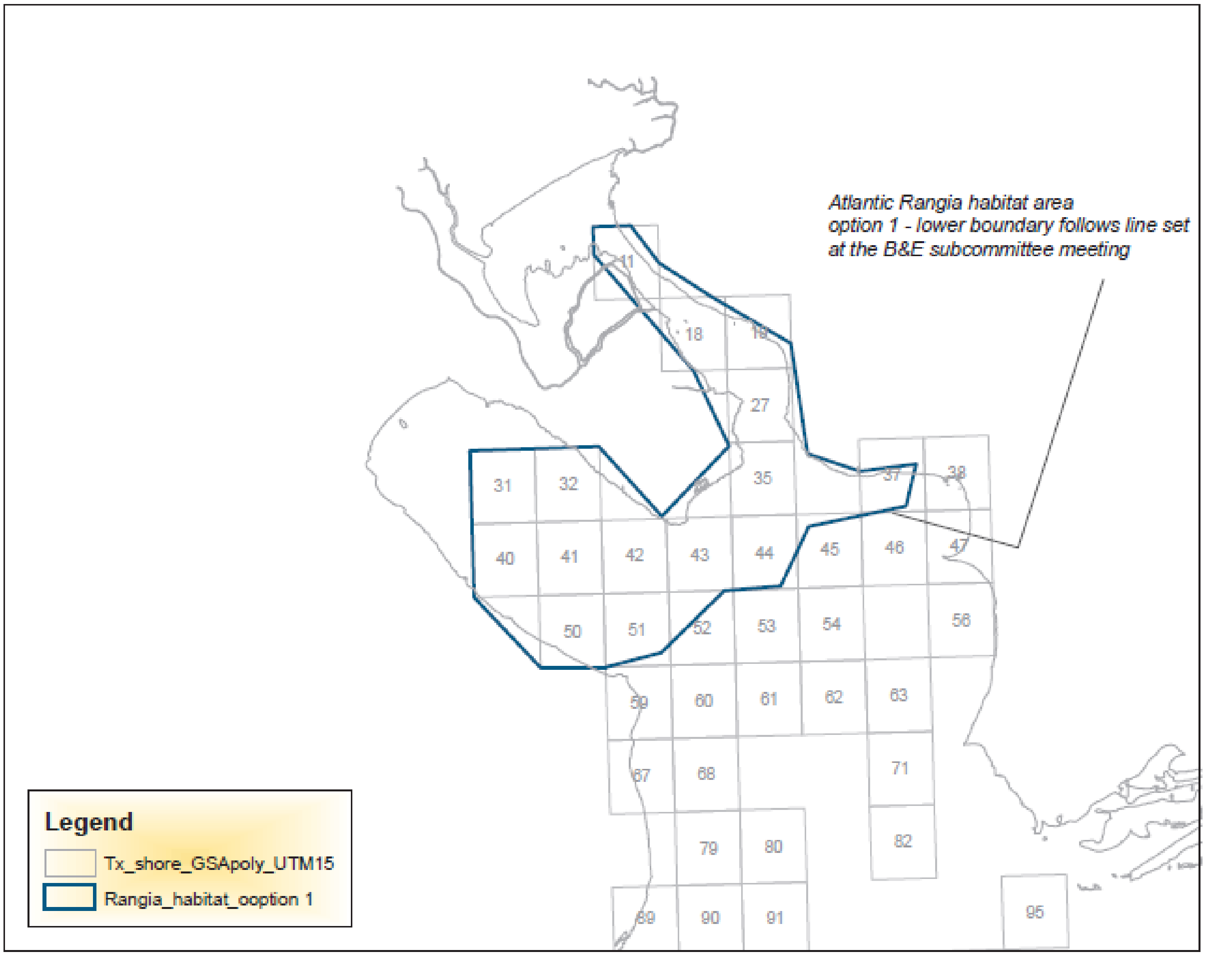


Figure 4.3-16. Map of the selected "core area" of Atlantic Rangia in the upper portion of the Guadalupe Estuary. (map courtesy of Lynne Hamlin, TPWD).

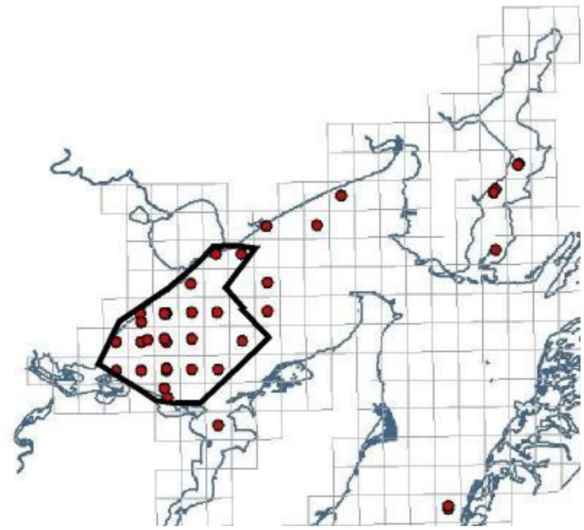


Figure 4.3-17. Map showing rangia collections (dots) in the Mission-Aransas Estuary, Copano Bay and the BBEST selected habitat area. Data is from the TPWD Coastal Fisheries Resource Monitoring Program. (map courtesy of Lynne Hamlin, TPWD).

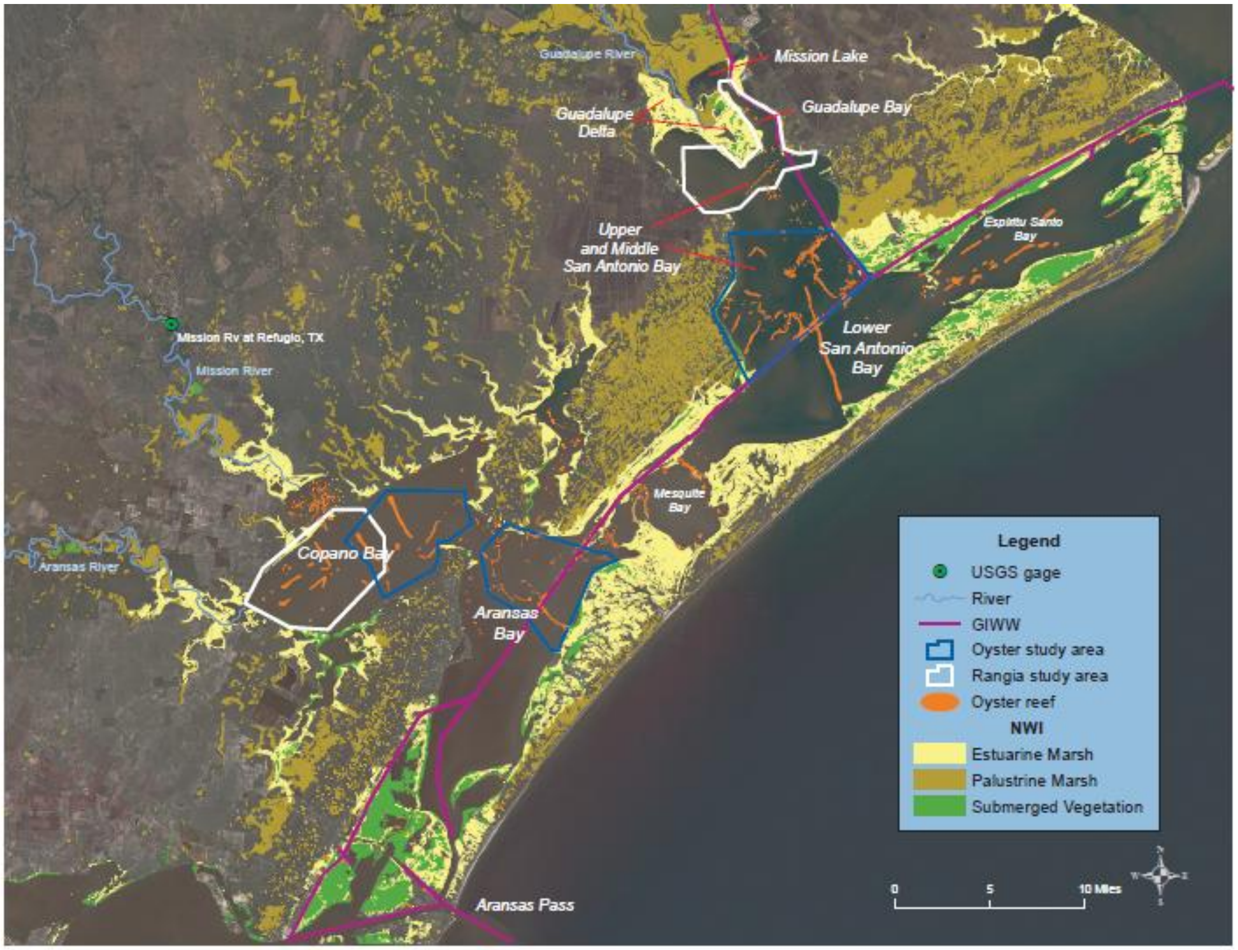


Figure 4.3-18. The 5 selected fixed habitat areas used by the GSA BBEST in the Guadalupe and Mission-Aransas Estuaries. (map courtesy of Lynne Hamlin, TPWD).

4.3.3 Focal Species - Other Important Species

4.3.3.1. <u>Guadalupe Delta Plant Species as Indicators of FWI Effects</u>

Historical changes within the Guadalupe Delta (designated in Figure 4.1-1 in Sec. 4.1) indicate that Delta wetlands have responded dramatically to variations in Guadalupe River inflow regimes over the last 75 years. The largest factor has undoubtedly been the dredging of Traylor Cut in 1935 which now carries more than half the discharge of the Guadalupe River into Mission Lake (Longley 1994) where a new subdelta lobe is forming. Prior to this, most Guadalupe River flow emptied directly into upper Guadalupe Bay through the north and south forks of the river. On high flows, much of this water overbanked into the old lobes of the lower Delta from the South fork. Since Traylor Cut was opened, most of the water and sediment formerly carried into the southern Delta lobes has decreased dramatically and this area is subsiding as it is deprived of sediment. In addition to Traylor Cut, levee construction along the north and south forks associated with agricultural operations (mostly livestock grazing but some rice farming in early '70s; Benton et al. 1977) exacerbated these hydrologic alterations such that lower Delta wetlands have consistently been receiving less freshwater inflow, and more bay water from tidal and wave action. White and Calnan (1990) found that vegetation coverage in the lower Delta (especially interior water bodies and lakes) had decreased by 307 ha (759 acres) from 1930 to 1979 based on aerial photography analysis, as a result of erosion and subsidence.

A variety of aquatic plant species still found in the Guadalupe Delta can potentially serve as indicator species for evaluating these FWI effects. These include several wetland species which require freshwater to very low-salinity water (oligohaline conditions) for survival and growth, for example:

- Submerged species – *Najas guadalupensis* (Water-nymph). Tolerates up to 4 psu water, declines and dies around 6-10 psu (Haller et al. 1974)
- Marsh species – *Sagittaria lancifolia* (Arrowhead) Tolerates up to 4 psu water, but dies at 6 psu (Chabreck 1972; Spalding and Hester 2007); *Paspalum vaginatum* Tolerates well up to 6 psu water (Chabreck 1972).
- Floating species - *Eichhornia crassipes* (Water hyacinth) Tolerates well up to 2 psu water, but dies at 2.5 - 5 psu (Chabreck 1972; Gopal 1989). Despite being a noxious, invasive species, it is an excellent low-salinity indicator plant.

An additional category of emergent marsh species are considered indicators of oligohaline to moderately mesohaline marshes .

- Mesohaline species – *Spartina patens* (Marsh hay cordgrass). Productivity decreases above 6 psu, death generally above 20 psu (Spalding and Hester 2007); *Bulboschoenus (Scirpus) maritimus* (Saltmarsh bulrush) generally is most frequent and productive between 4 – 20 psu (Chabreck 1972; Zedler 1983).

In 1976, Benton et al.(1977) surveyed and mapped the distribution of Delta brackish and freshwater marsh communities and determined dominant species composition. At that time, a predominately low-salinity system extended south into the middle of the old Delta lobes, and a freshwater community occurred along the North and South forks of the Guadalupe River. Frequent freshwater species listed were: palmetto *(Sabal minor),* arrowhead *(Sagittaria graminea),* and water hyacinth *(Eichhornia crassipes).* Hyacinths were considered more abundant in this delta compared to all other river deltas in Texas. *Phragmites australis* was observed throughout the lower Delta lobes along relict river bayous and interior lakes. *Typha* was a co-dominant in some of these interior bayou associations. *Distichlis*, *Borrichia*, *Spartina patens, S. spartinae,* and *Cynodon dactylon* were mapped as abundant brackish marsh species over much of the delta. All these species are characteristic of lower-salinity or higher elevation brackish marsh zone. Several saltmarsh species of low elevations appeared notably scarce or absent in the Delta proper based on the Benton et al. (1977) report. Smooth cordgrass (*Spartina alterniflora*) was not mentioned, while saltmarsh bulrush (*Scirpus [Bulboshoenus] maritimus*) was described as, at most, a minor component.

A later study by Pulich (1991) reported that in the late 1980s , the lower Guadalupe Delta had developed a higher salinity habitat with significant *Spartina alterniflora* and saltmarsh bulrush. *Ruppia maritima* which proliferates under moderate to even high salinities (10 – 25 psu), had also replaced *Najas* as the dominant submergent species in the lower Delta. However, in the upper Delta, oligohaline habitat species were still present and common. These included *Sagittaria* and *Paspalum vaginatum* along the eastern Delta shoreline which is directly exposed to Guadalupe River inflows and bordered by upper Guadalupe Bay water, and *Najas* in the interior Delta lakes. A few additional oligohaline species not recorded by Benton et al. (1977) were observed along the edge of upper Guadalupe Bay (*Scirpus californicus* and *Paspalum vaginatum*). Just recently in August 2010, a survey trip into the Redfish Bayou region of the lower Delta resulted in a noteworthy range extension of two other low-salinity requiring marsh plant species. A population of *Spartina cynosuroides* (Big cordgrass), the southernmost stand along the Texas coast, was recorded here, in association with another species, *Amaranthus cannabinus* (tidal marsh amaranth), the first record for Texas and previously found only from Mississippi (Jason Singhurst/ Nathan Kuhn, TPWD, personal communication).

These observations demonstrate that the upper and eastern Guadalupe Delta, the parts of the Delta directly influenced by the discharge of the Guadalupe River into Guadalupe Bay, still comprise habitats with low salinity-sensitive plant species. These species, with salinity tolerance limits around 4-6 psu, can respond dramatically to changes in river inflow and inundation (flooding) regimes. While it has been difficult in the past to directly monitor these areas using datasondes, and thus collect sufficient salinity data, obviously salinity and inundation conditions are normally required at oligohaline or lower levels for these aquatic plant species to persist. From salinity tolerance data listed above, it would be expected that inflow regimes needed would parallel the range of some fauna in the upper bay such as *Rangia*. The population dynamics of these plant indicator species should therefore be monitored in future inflow management programs to document effects of low inflow regimes.

Time series correlation analyses between flood stage of the Guadalupe River and salinity of overlying Guadalupe Delta flood waters would be most informative. Analyses should be performed by relating stage height and salinity at a stream gauge above Traylor Cut with water levels and salinity values at similar gauges in Mission Lake and various bayous (such as Redfish Bayou and Lucas Lake) leading into the lower Delta from Guadalupe Bay. In conjunction with bay tide gauge and salinity records already being collected in upper San Antonio Bay, this critical continuous salinity and water level monitoring data would allow inundation events and corresponding salinity regimes in the Delta to be determined and correlated with riverine FWI regimes.

4.4 Salinity Zone Methodology

The recent SB 3 Science Advisory Committee report (SAC 2009a) on methods for establishing an estuarine inflow regime recognizes a variety of potential approaches. The goal of these approaches is to link freshwater inflows, and its various attributes such as timing and volume, to the biologic response of the estuary. One of the principal methods for characterizing the biota of the estuary is recognized by the SAC as the "Key Species" method. For the purposes of establishing an estuarine inflow regime, the SAC goes on to state that:

> "The utility of key species is enhanced if they exhibit sensitivity to inflow-controlled parameters such as salinity or nutrient concentrations."

Approaches focused on key species with specified salinity tolerance ranges, so called "salinity suitability relationships," are in widespread use with a variety of methods for coupling the species' biologic response to the inflow-salinity patterns. For example, the work of Doering et al. (2002) focused on rooted plants with established salinity preferences to design a freshwater inflow range for a major southern Florida estuary. A recent Texas example would be the efforts of the Trinity and San Jacinto SB3 BBEST to derive elements of an estuarine inflow regime for Galveston Bay (Tr-Sj BBEST 2009). That science team focused on several specific species in fixed habitats with known salinity preference characteristics (some of these organisms were described above: rangia clams and oysters). While both of these examples focused on organisms in fixed habitats, the salinity zone approach has also been applied to mobile organisms, with the most prominent Texas example being the work on Matagorda Bay related to the proposed LCRA-SAWS project (LCRA-SAWS 2008). The application of a salinity zone approach to mobile species assumes that through provision of the right combination of physical habitats and salinity ranges, the species will occupy the habitat and certain life-cycle needs will be meet.

This science team utilized a salinity zone approach focused on organisms in fixed habitats and with well-defined salinity needs during a certain portion of their life cycle in the Guadalupe and Mission-Aransas Estuaries. We primarily focused on habitat areas with abundant populations of rangia clams and oysters as shown in Figure 4.3-18. Some additional cross-checks based on requirements of other species were performed and will be discussed subsequently. By focusing primarily on these two species with specific salinity requirements or preferences during two distinct seasons, we were able to cover much of the calendar year. Furthermore, a multi-tiered suite of inflow criteria are proposed, with various tiers differentiated based on how well or how often they satisfy the specific salinity needs of the organisms. We believe that maintaining such variability is essential ecologically, is cognizant of the risk of focusing on too narrow of a band of inflows given significant scientific uncertainties, and also comports with the SB3 charge of deriving an inflow regime that reflects seasonal and year-to-year variation.

4.4.1 The Methodology Utilized for Guadalupe and Mission-Aransas Estuaries

This section is focused on the methodological aspects used by the GSA BBEST using an oyster-rich area in the Guadalupe Estuary as a illustrative example. More specific results-oriented discussion including the initial suites of inflow criteria for the five fixed habitats derived through this method are presented in Section 4.5.

The development of a specific methodology for application to the estuaries in the GSA BBEST's purview was based on consideration of available data, models, and other technical resources, as well as agency and contract personnel available to execute the steps of the method. This required a considerable degree of planning and coordination among parties; as shown in Figure 4.4-1.

The salinity zone approach used by the BBEST begins by selecting the specific subarea / habitat of the estuary in which the key species is concentrated. The selection of these for the Guadalupe and Mission-Aransas Estuaries was presented previously in Section 4.3.2. As shown above on Figure 4.3-13, an oyster-rich area was selected in the lower portion of the Guadalupe Estuary. This area was the first analyzed with the science team's salinity zone approach.

After selection of a specific habitat/species region of the estuary, there are several sequential steps needed to examine salinity patterns in that area and relate these to inflow levels capable of satisfying the specific salinity needs of that species. The first of these is the necessity of relating salinity response in this specific portion of the estuary to inflows. Clearly, the first choice for pursuing this task would be to use actual field salinity measurements, but as discussed previously there are severe limits to the available data. Also, the salinity zone approach needs salinity data thoroughly covering the entire habitat extent, reflecting variations therein. This is a requirement for a robust data set far beyond what is available from field collections.

Fortunately, as presented in Section 4.2.2, there are other methods available for predicting salinity: a) the Texas Water Development Board's TxBlend model and, b) regression equations. As previously noted TxBlend subdivides the estuary into a fine mesh of nodes (see Figure 4.2-6) and provides a simulated salinity at each node many times per day. This fine spatial coverage obviously makes the computations of salinity of the TxBlend model ideal for the salinity zone approach. The salinity zone approach utilized TxBlend output at the monthly average time scale in a spatial map format and in a time series format as discussed in Section 4.2.

While the TxBlend model is executed, output data of monthly average salinity at each node in the model is computed and recorded for each month of the Jan. 1987-Nov. 2009 period. This monthly average data is analyzed sequentially, for how much of the habitat area is within specific salinity ranges and during specific critical times of year. For oysters the time window was chosen to cover the high temperature time of year July- September when the "dermo" parasite can be problematic at high salinities (see Section 4.3). This process is accomplished in two steps. First, the raw TxBlend output over the whole Guadalupe and Mission-Aransas Estuaries spatial domain was contoured, through the contributed efforts of TPWD personnel, into 2 part per thousand (ppt) salinity zones (e.g. 10-12 ppt, 12-14 ppt, …). Next, through the application of geographic information system technology (GIS), the portion of the fixed habitats that were within these specific salinity ranges was determined (e.g. acres in the 10-12 ppt range, …). This step was performed by personnel at Texas State University on contract to the GSA BBEST. Table 4.4-1 illustrates a portion of the data derived from this method for the oyster habitat area of the Guadalupe Estuary and the complete data is given in Appendix 4.4-1.

After determination of the area within specific salinity ranges, the salinity zone analysis turns sharply towards species-specific salinity requirements in order to assess how well the specific biologic needs of the key or “focal” species were met during each time period. For this step we rely heavily on scientific literature to derive, or use previously derived, “salinity suitability curves” (also know as salinity preference curves). Figure 4.4-2 illustrates the salinity suitability curve for Eastern oysters used by the GSA BBEST. This curve was derived via a synthesis of much available literature on oysters and presented in Cake (1985). A primary determinant of the shape of this curve, especially the 10-20 ppt ideal level (suitability = 1.0) and the decline above that is the increasing incidence of the “dermo” parasite as discussed in Section 4.3. The portion of the curve with zero suitability below 5 ppt, is primarily driven by the observed high mortality that oysters suffer when salinities are severely depressed, which is amplified if this occurs in the summer with warm water temperatures. These effects have been both observed in the field, including the Guadalupe Estuary, and examined in great detail in a controlled laboratory setting (Loosanoff 1953). Thus the GSA BBEST feels that this salinity suitability curve is a good representation of the needs of the oysters in the Guadalupe Estuary during the summer window, although we should point out that other slightly different curves have been derived by other authors (e.g. Barnes 2007).

With the combination of the salinity suitability curve and the previously derived salinity-acreage information it is possible to ‘grade’ or ‘weight’ the salinity within the fixed habitat in regard to how well it meets the needs of the focal species within. Each acreage in a specific salinity range is weighted according to its position on the salinity suitability curve. For instance an area with salinity anywhere in the 10-20ppt range would have a suitability of 1.0 and thus is ‘weighted’ at 100%. By contrast, an area with salinity in the 25-36 ppt range would have a suitability of approximately 0.7 and thus this area would be ‘weighted’ at 70% of actual area. By summing these individual area components in each month, weighted with the salinity suitability curve, the total is known as the “weighted useable area” (WUA). The determination of WUA was repeated for each July, August, and September in the TxBlend simulation period covering 1987-2009 (23 years). The WUA derived for any given month or season is a direct indicator of how suitable the salinity conditions in the fixed habitat were for the focal species. The next step is to relate these results to the observed freshwater inflows that generated these conditions.

As illustrated in Figure 4.4-3, simply graphing WUA versus inflows in the same month leads to a plot with little apparent relationship between the two variables. There are months with very low inflows months (0-40,000 ac-ft/mon., with 40,000 being between the 12th and 27th percentile for these months) that exhibit both high and low WUA results (Aug. 2000 vs. Aug 2009). There are Intermediate to high inflow months, in the range of 100-400,000 ac-ft/mon. [roughly the 40th - 80th percentile range] that also range widely. Only very wet months (> 400,000 ac-ft/mon.) seem to consistently rate low in terms of WUA.

There are two principal causes for the “noisy” relationship between inflow and weighted useable area. First is related to the fundamental shape of the salinity suitability curve for oysters in Figure 4.4-2. Since salinities varying from 10-20ppt are ideal for oysters, this means that a broad range of inflows would be expected to give equal WUA results. Thus, one is assured at the outset that there is going to be a range of inflows which will provide similar WUA results.

The other source of the “noisy” relationship of WUA and inflow is the fact that salinity in the estuary does not depend only on the inflows of the current month; there is a pronounced “memory” of recent past inflows (also called “antecedent” inflows). Figures 4.4-4 and 4.4-5 illustrate in more detail the month-by-month salinity, inflow, and WUA characteristics of portions of 2000 and 2009, respectively. Although the inflows in the Jul.-Sept. period were similar, totaling, respectively, 88,000 ac-ft and 73,000 ac-ft in 3 months [these are in the 7-9th percentile range], clearly the salinity and WUA response of the two years are vastly different. This level of inflow was insufficient to keep salinity from rising in the Jul-Sept. period; both years exhibited a rise of approximately 12 - 15 ppt from July through September. The reason for the differing WUA results is clearly the conditions in the months leading up to the Jul.-Sept. oyster analysis period. In year 2000 higher inflows in the preceding months were sufficient to depress salinity by June to just below 10 ppt, whereas in year 2009 the June salinity already stood at 23 ppt. Thus, one of the more significant recognitions of the GSA BBEST, was that the utilization of the salinity zone approach for designing an estuarine inflow regime within a season must be done with due attention to antecedent condition inflows.

To streamline our criteria into seasonal values, the GSA BBEST also found that using a seasonal total basis for examining inflows and WUA response was adequate, again with attention to antecedent conditions. Figure 4.4-6 illustrates the same derived WUA data for the Jul.-Sept. period as shown in 4.4-3 but in this case the average WUA and the total inflow, both for the Jul.-Sept. period are presented. Some particular years are highlighted which illustrate the interacting roles of current seasonal (Jul.-Sept.) inflows and antecedent inflows. The years 1989, 2000 and 2009, for example, have very similar low Jul.-Sept. inflow sums (64, 88, and 73,000 ac-ft), but are differentiated in WUA performance due to the difference in antecedent condition. Another illustrative group (1988, ’94, ’99, and 2008), with Jul.-Sept. inflows right around 200,000 ac-ft are also highlighted. As before it is the difference in the antecedent condition that is differentiating these in terms of WUA, although not as markedly as the lower tier. Figure 4.4-7 illustrates the similar interacting role of current seasonal and antecedent inflows, but in this case with similar antecedent condition and varying seasonal totals. Here the increasing seasonal total leads to increasing WUA in this inflow range.

The interacting role of both the seasonal and antecedent inflows upon WUA suggest an analyses technique of arraying these inflows into a two-dimensional matrix with WUA performance filling the columns and rows. This is illustrated in Table 4.4-2, in the lower portion. Rather than average acreage as shown previously on the preceding figures, which are rather large and unwieldy numbers, the average acreage is divided by the maximum (approximately 24,000 acres) to arrive at much more succinct and manageable fractions of the maximum ranging from 0 to 1. The year(s) that fall within certain current season (Jul.-Sept.) inflow and antecedent (June) inflow brackets are indicated in the upper portion of the table, while the lower portion shows the corresponding WUA performance for each of those years. Although the WUA results are not perfectly ordered, in synthesis, there is a strong indication of a high-performance range, running somewhat diagonal, over a broad combination of the two inflow variables. Off that diagonal, WUA performance, falls due to either the current seasonal inflows and/or the antecedent condition level being to low (upper left) or too high (lower right).

The blank cells in Table 4.4-2 represent antecedent and current season inflow combinations that were not experienced in the fairly short (1987-2009) period of record of the TxBlend salinity model[6]. Thus, exact inferences on necessary magnitudes of inflow combinations and corresponding WUA performance are challenging given the sparseness of this matrix. To address this challenge, the GSA BBEST developed another method for complementing the limited information available from the 1987-2009 historic record. As illustrated in Figure 4.4-8, along the upper path, the original manner of obtaining the information covering the 1987-2009 historic record was via a TxBlend-GIS route. However, as presented in Section 4.2.2 another method of predicting salinity is available to the science team, namely, statistically-derived regression equations relating salinity to inflow, including antecedent condition inflow. The GSA BBEST realizes that the derived regression equations are not perfect predictors of salinity (i.e. the R^2 values are less than 1) and their use introduces some error into the determination of salinity and therefore WUA. However, as will be demonstrated, employing this method of "filling in" the matrix and the resulting indications of necessary inflows for a regime are highly valuable. As a precaution, the 'synthetic' WUA values will also be subjected to some cross-checks against the TxBlend-GIS derived values, as will be shown.

In order to get more accurate results from the 'synthetic' approach, the oyster habitat area presented earlier was more finely subdivided and regression equations relating salinity to inflow developed at the midpoint of each subarea. Figure 4.4-9 shows the subdivision of the oyster area in the Guadalupe Estuary. After the regression equations are developed it is then possible to predict salinity within all of these subareas, and thus weighted useable area, for any combination of inflows. In order to put the results in the seasonal format, as in Table 4.4-2, there is one further assumption necessary: the distribution of the inflows by month within the Jul.-Sept. season. The GSA BBEST decided to go with the simplest approach and divided the seasonal sum equally among the three months.

Table 4.4-3 presents the results of this exercise for the Guadalupe Estuary oyster area with similar inflow combinations as in Table 4.4-2 (each is set to the midpoint of the ranges of the previous table). Obviously, this technique overcomes the "sparseness" of Table 4.4-2 and provides a full specification of the WUA performance as a function of the antecedent condition and seasonal inflows. Some differences in the values of these two tables are due to the use of brackets or ranges in Table 4.4-2 to capture individual similar years, whereas in Table 4.4-3 exact inflow values are specified. For instance 2009 in the upper left corner of Table 4.4-2 had June and Jul.-Sept. inflows of 22k and 73k ac-ft/mon., respectively (where 'k' connotes thousands). The upper left cell of the later table has these inflows set to 45k and 75k. If the exact values of 2009 (22k / 73k) as well as the historic month-to-month inflow distribution for Jul.-Sept. are substituted directly into the regression-based approach, the WUA result is 0.38. This compares very favorably to 0.33 for the actual historical value derived via the TxBlend-GIS route, with the remaining discrepancy due to the errors in the regression equations, which somewhat under-predict salinity at low inflows and thus slightly over-estimate the suitability and weighted useable area. Figure 4.4-10 presents a rigorous comparison of the avg. WUA results of the TxBlend-GIS route versus the regression equations-based route for the 23 years available for direct comparison.

As mentioned, the regression equations tend to under-predict high salinity and often over-predict more moderate to low salinity as shown in Figure 4.4-11 (and previously in Section 4.2). The

[6] Additionally, there are several "flood" years (1987, 2002, 2007) that are outside the range limits of the table.

GSA BBEST believes that the errors, or in statistical jargon the “residuals”, in the regression equations during periods of high salinity are due to the fact that the regressions are based solely on inflows, whereas other processes influence salinity. As evident Figure 4.4-11 and in previous figures, during very low inflow drought periods, the process of evaporation has a strong influence on salinity. The several-month period in 2009 at this site with hyper-saline conditions (salinity greater than 35ppt of Gulf waters) is clearly due to the evaporation process. Because of the inability of the regressions to track this process, and in order to avoid over-predicting the suitability of low inflows, as measured by the WUA results, the GSA BBEST decided to apply moderate adjustments or “corrections” to the regression equations at each of the points in the oyster habitat (shown if Figure 4.4-9). These corrections adjust salinity upward by approximately 2ppt when total June-Sept. inflow is less that 75,000 ac-ft, a very low level. The corrections also adjust salinity downward if June-Sept. inflow levels are above 225,000 ac-ft. In between these levels, the adjustment is pro-rated. A full discussion of the derivation of these corrections and the application thereof is discussed in Appendix 4.2-2. Table 4.4-4 illustrates the final weighted useable area results of both regular and “adjusted” regression equations as compared to the results of the TxBlend - GIS approach. As evident there is some improvement in the overlap of the GIS and regression-based approaches with the salinity adjustments in dry years (e.g. 1989, 2004 and 2009). At moderate inflows (e.g. 1995, 1999, 2005) there is little change and at very high inflows again an improvement in many cases (e.g. 1987, 1997).

Clearly, the GSA BBEST expended considerable effort to develop and refine the regression equations-based (or “synthetic”) approach to derive weighted useable area as a function of inflows. Once developed the BBEST was able to extensively utilize this method to examine the effects of various inflow levels and combinations thereof, on the salinity suitability of the oyster habitat in the Guadalupe Estuary as well as the other fixed habitats. The BBEST developed a graphical manner of portraying the results of this “synthetic” approach that proved very useful for translating the WUA results into a multi-tiered suite of inflow criteria. As shown in Figure 4.4-12, using the regression equations approach, WUA can be derived and plotted as a continuous function of the two inflow variables, antecedent June and seasonal Jul.-September. For the derivation of the salinity underlying each of the WUA isolines, the Jul.-Sept. inflow total was assumed to be distributed evenly among the three months. Also illustrated are the position of many recent years and some prominent severe drought years (e.g 1956, 1984) and some other drought years (e.g. 1989, 2009). Slight discrepancies between the plotted position of any given year relative to the WUA isolines is due to the assumption of equal Jul.-Sept. monthly distribution of the ‘synthetic” inflows underlying the WUA curves. For example, the 1.0 WUA isoline plots near the inflow position of 1996, although in reality the WUA determined by either the GIS or regression equations approach was 0.57 or 0.77 for this year (Table 4.4-4). This discrepancy is due to the actual very uneven distribution of inflows that occurred in 1996 as evident on Figure 4.2-12

In spite of a few caveats associated with the use of the regression equations approach, the GSA BBEST feels that this approach vis-à-vis the very sparse inflow-WUA information available from the limited historic record, is of very great value in the derivation of inflow criteria. Upon inspection of Figure 4.4-12 there are several prominent trends. First, it is evident that categories of inflow that will provide similar WUA performance, suggesting a multi-tiered suite of criteria. For instance in the range of Jul.-Sept. inflows from about 175,000 to 450,000 ac-ft the salinity conditions for oysters in the chosen fixed habitat of the Guadalupe Estuary would be nearly optimal, almost without regard to antecedent conditions. Below that level of inflow, other lesser values of WUA are obtainable. In the range of Jul.-Sept. inflows of about 50,000 to 150,000 ac-ft the WUA isolines change rapidly as a function of the antecedent condition, suggesting the need to be cognizant of this in the design of inflow criteria categories covering this inflow spectrum. Finally at very low Jul.-Sept. inflows, generally less than about 50,000 ac-ft, reflective of drought, very poor suitability for oysters are evident in the very low WUA values. At this low level of seasonal inflows, the antecedent conditions, at least in the range examined, are not very important once again. The following section tracks the application of these concepts as applied to the five fixed habitats in the Guadalupe and Mission-Aransas Estuaries.

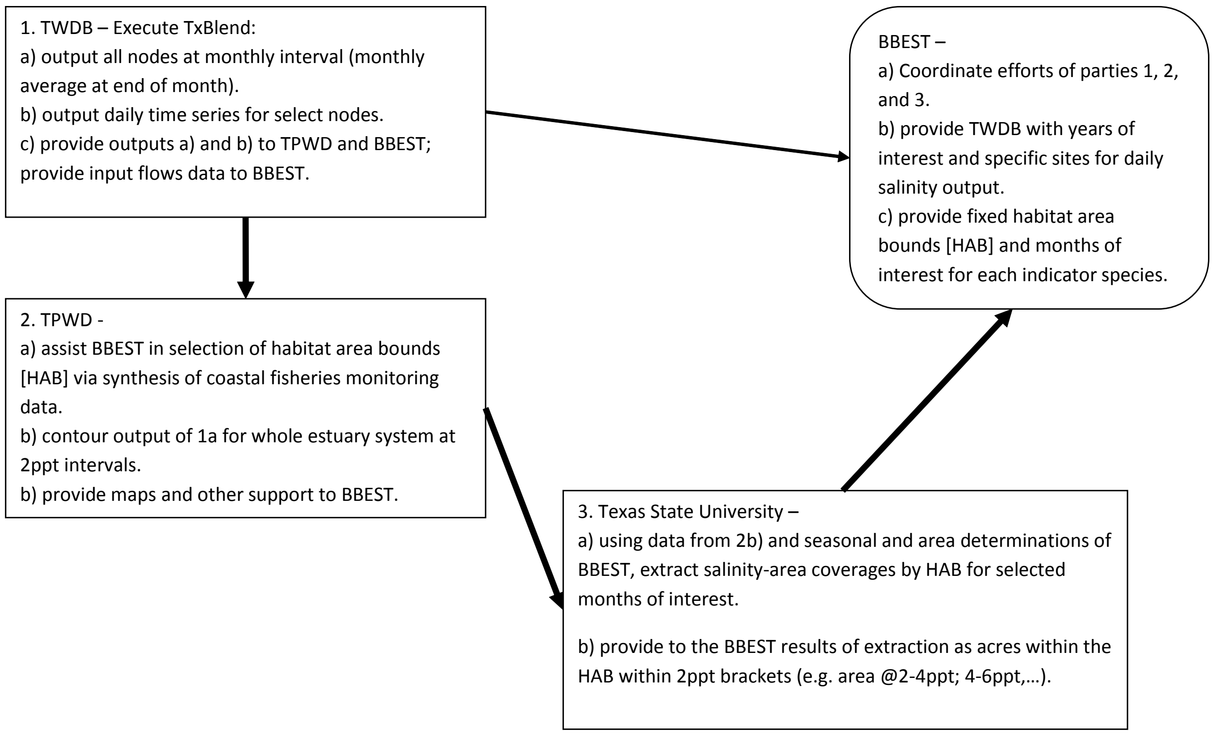


Figure 4.4-1. The flow of information and the relative roles of key contributors to the salinity zone approach of the GSA BBEST.

Table 4.4-1. Excerpt of the salinity - area coverage determined via the TxBlend-GIS method in the Guadalupe Estuary oyster fixed habitat area for the months of July-Sept. and years 1987-2009.

		Salinity Range (ppt) / Coverage in Range (acres)												
Year	Month	0 - 1.99	2 - 3.99	4 - 5.99	6 - 7.99	8 - 9.99	10 - 11.99	12 - 13.99	. . .	28 - 29.99	30 - 31.99	32 - 33.99	> 34	Total
1987	July	23930							. . .					23930
1987	Aug.	15475	8455						. . .					23930
1987	Sept.			11716	11970	245			. . .					23930
1988	July								. . .					23930
1988	Aug.								. . .					23930
1988	Sept.								. . .					23930
1989	July								. . .					23930
1989	Aug.								. . .	97				23930
1989	Sept.								. . .		23930			23930
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
2005	July						7864	15920	. . .					23930
2005	Aug.						30	14319	. . .					23930
2005	Sept.								. . .					23930
2006	July					2487	19302	2142	. . .					23930
2006	Aug.						15625	8305	. . .					23930
2006	Sept.							2974	. . .					23930
2007	July	23930							. . .					23930
2007	Aug.	23930												23930
2007	Sept.	23866	65											23930
2008	July													23930
2008	Aug.													23930
2008	Sept.													23930
2009	July									8797	15133			23930
2009	Aug.												23930	23930
2009	Sept.												23930	23930

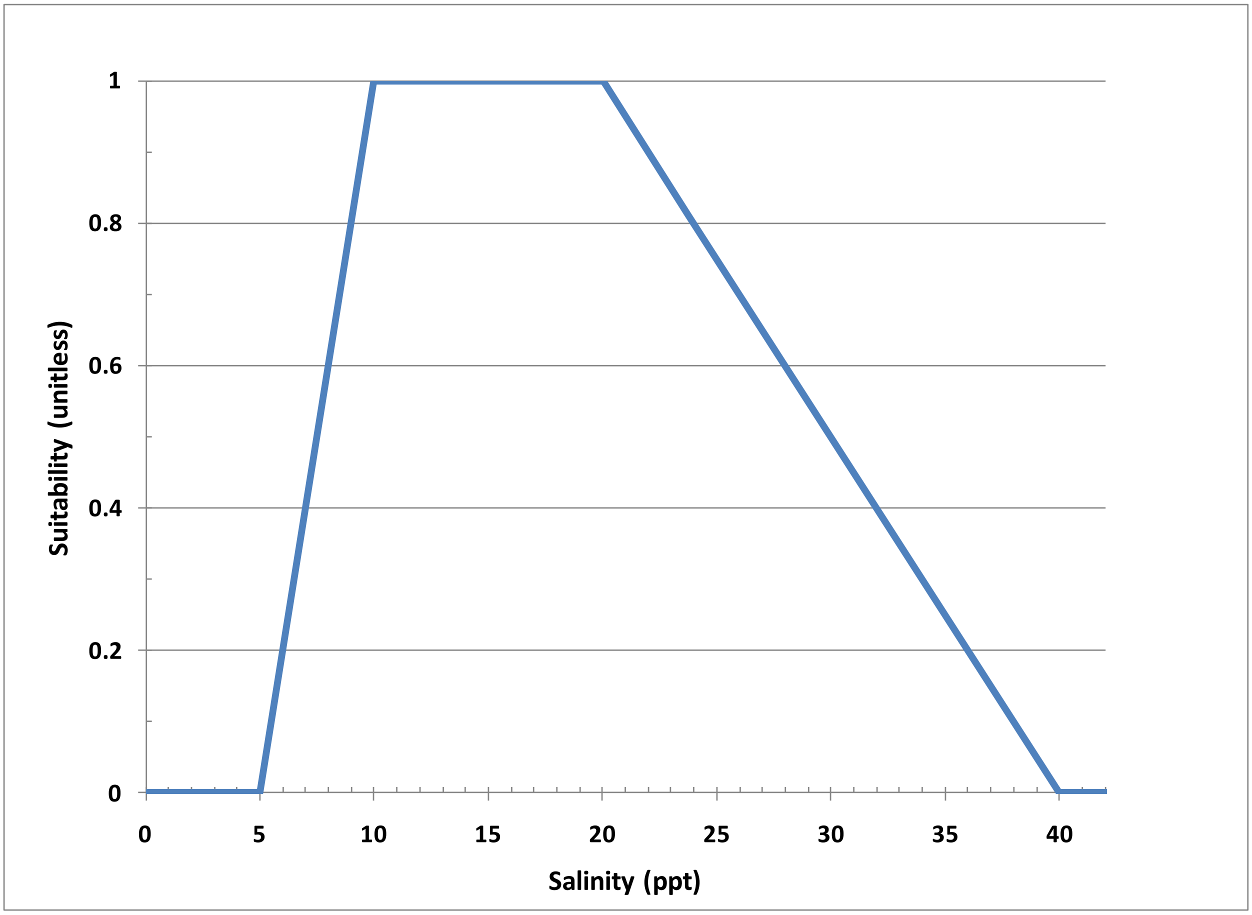


Figure 4.4-2. The salinity suitability curve for Eastern oysters utilized in the salinity zone analyses in the Guadalupe and Mission-Aransas Estuaries. An index of 1.0 indicates optimum salinity conditions and 0 indicates very bad conditions. This curve is from Cake (1985).

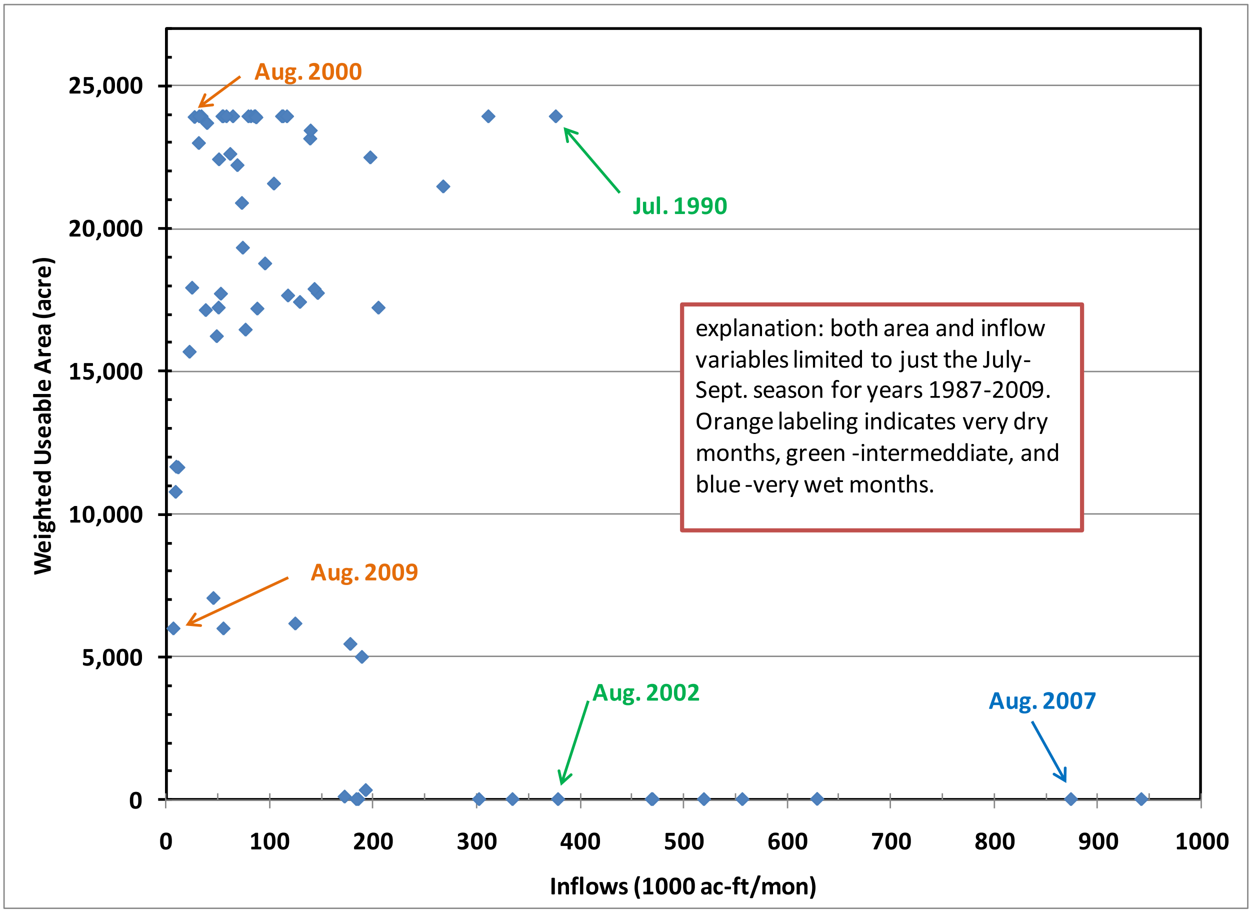


Figure 4.4-3. The weighted useable areas determined for the oyster fixed habitat are of the Guadalupe Estuary and associated monthly inflows, with some particular months highlighted.

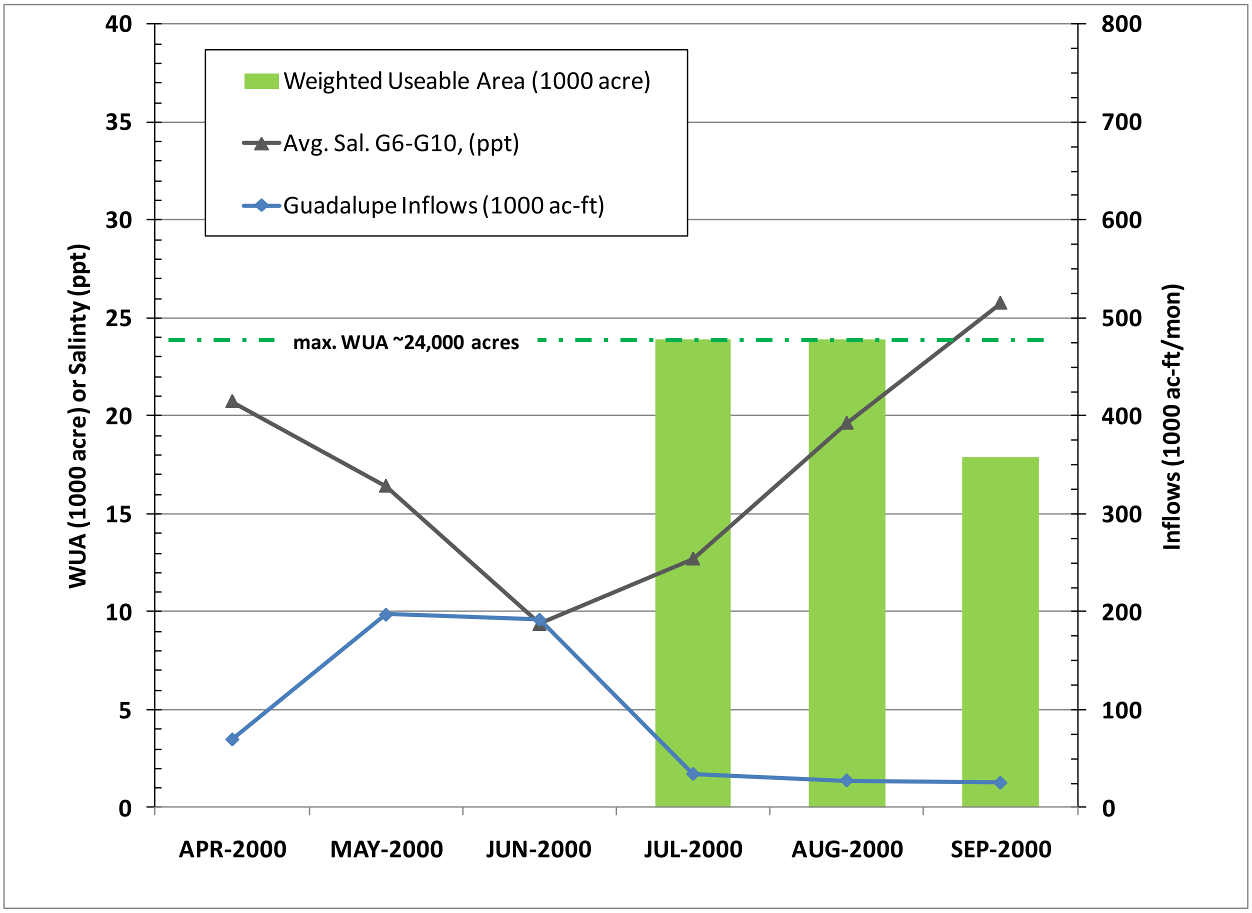


Figure 4.4-4. The time series of inflows, average salinity over the oyster-rich area, and weighted useable area results in the Guadalupe Estuary for year 2000.

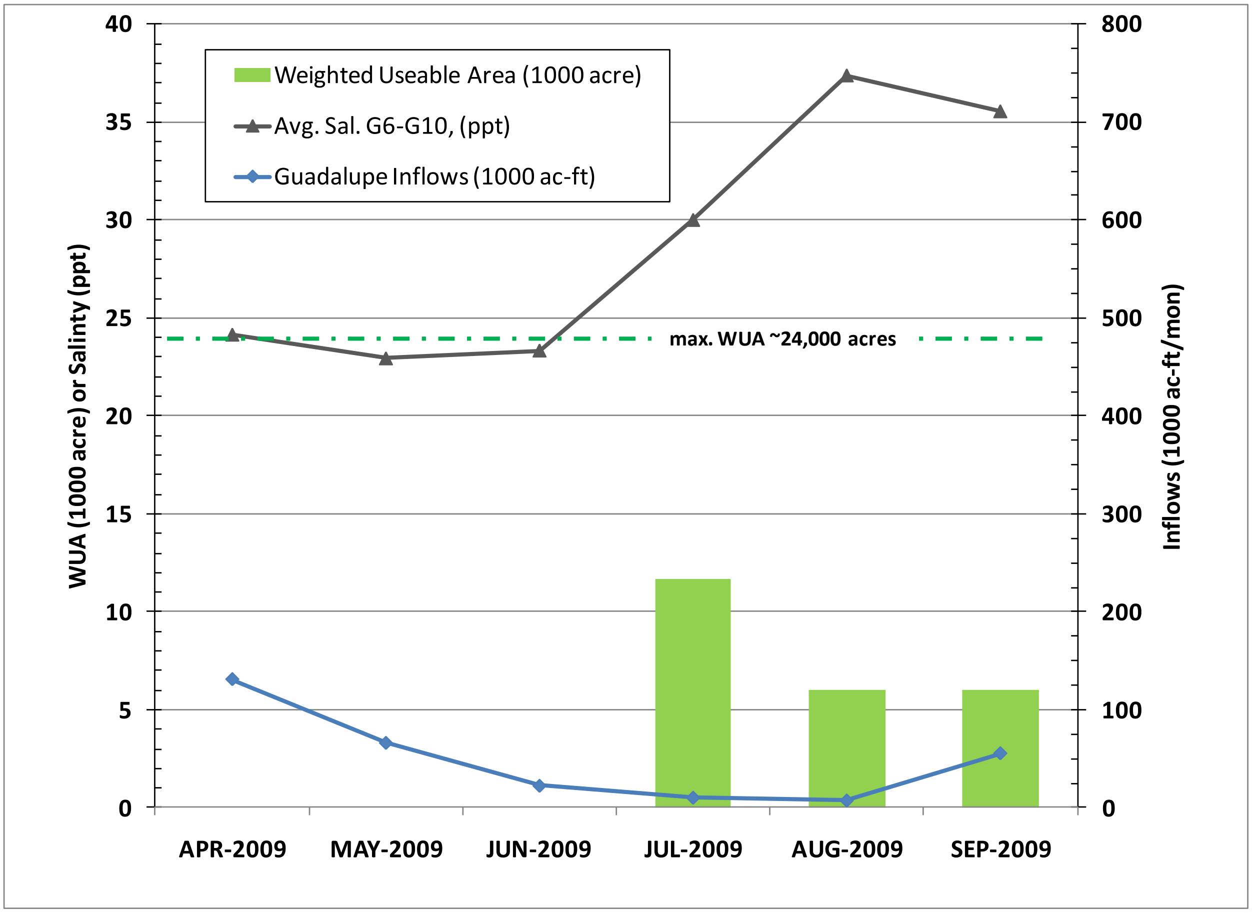


Figure 4.4-5. The time series of inflows, average salinity over the oyster-rich area, and weighted useable area results in the Guadalupe Estuary for year 2009.

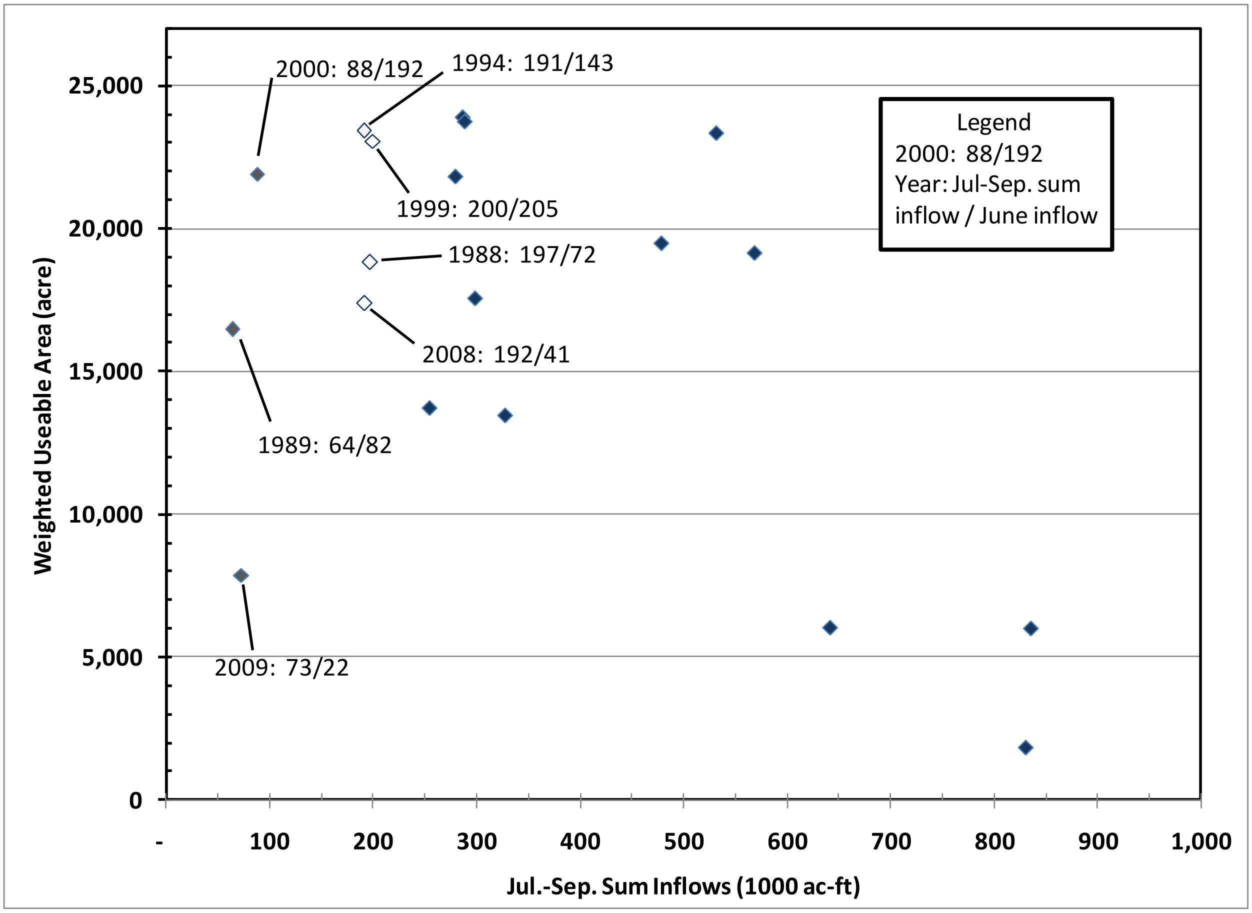


Figure 4.4-6. Seasonal depiction of average weighted useable area and total inflows. Highlighted year groups (e.g. 1989, 2000 and 2009) all have similar Jul.-Sept. inflow but varying antecedent condition June inflows, with the antecedent condition exhibiting a strong influence on WUA performance. This illustrate the interacting roles that current season and antecedent condition inflows have on WUA performance.

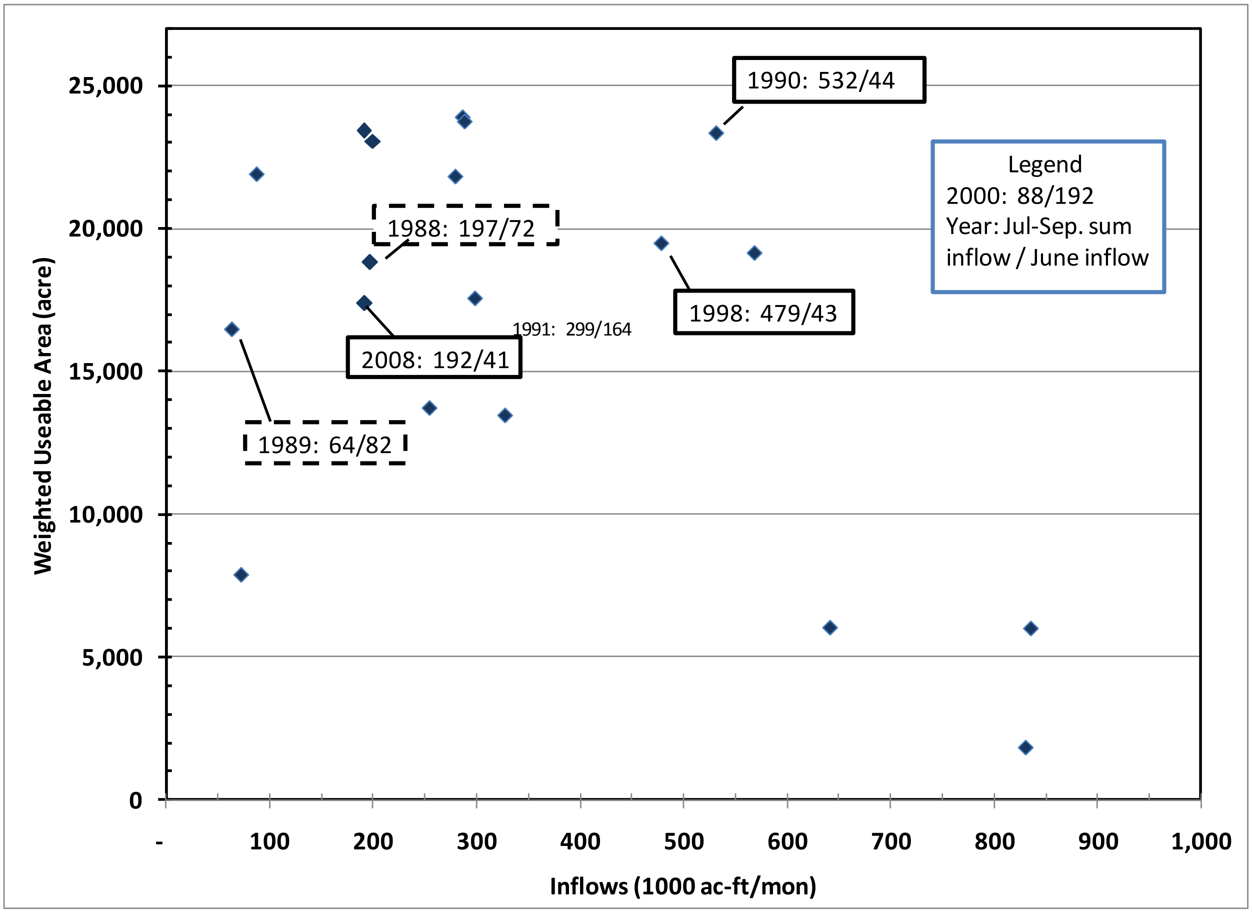


Figure 4.4-7. Seasonal depiction of average weighted useable area and total inflows. Highlighted year groups (e.g. 1988 and 1989) all have similar antecedent condition June inflows but WUA performance increases with increasing Jul.-Sept. inflow totals through this range. This illustrate the interacting roles that current season and antecedent condition inflows have on WUA performance.

Table 4.4-2. Results of the Guadalupe Estuary oyster weighted useable area analyses arrayed with antecedent June inflows and current July-September inflow totals.

	Total July - September Inflow (1000 ac-ft)									
June Inflow (1000 ac-ft)	50-100	100-150	150-200	200-300	300-400	400-500	500-600	600-850	850-1100	1100-1350
20-70	2009	-	2008	1996	-	1996	1990	-	-	-
70-120	1989	-	1988	-	-	-	-	-	-	2001
120-170	-	-	1994	1991,2006	-	-	2003	-	-	-
170-220	2000	-	1999	-	-	-	-	-	-	-
220-270	-	-	-	1995	-	-	-	-	-	-
270-400	-	-	-	-	-	-	-	-	-	-
400-550	-	-	-	-	-	-	-	-	-	-
550-700	-	-	-	-	-	-	-	-	-	-
700-850	-	-	-	-	1993	-	-	2004	-	-
850-1000	-	-	-	-	-	-	-	1992,1997	-	-

	Total July - September Inflow (1000 ac-ft)									
June Inflow (1000 ac-ft)	50-100	100-150	150-200	200-300	300-400	400-500	500-600	600-850	850-1100	1100-1350
20-70	0.33	-	0.73	0.57	-	0.57	0.98	-	-	-
70-120	0.69	-	0.79	-	-	-	-	-	-	0.66
120-170	-	-	0.98	0.73,0.99	-	-	0.8	-	-	-
170-220	0.92	-	0.96	-	-	-	-	-	-	-
220-270	-	-	-	0.91	-	-	-	-	-	-
270-400	-	-	-	-	-	-	-	-	-	-
400-550	-	-	-	-	-	-	-	-	-	-
550-700	-	-	-	-	-	-	-	-	-	-
700-850	-	-	-	-	0.56	-	-	0.25	-	-
850-1000	-	-	-	-	-	-	-	0.25,0.08	-	-

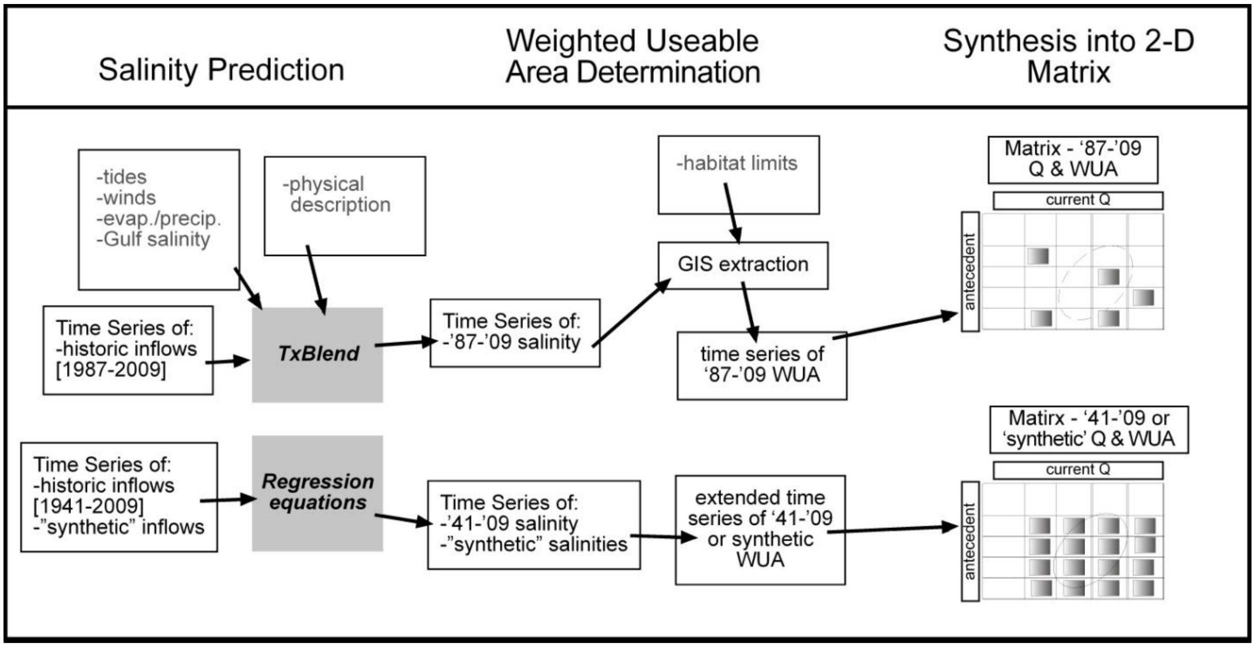


Figure 4.4-8. Options available to the GSA BBEST for deriving weighted useable area as a function of inflows. The upper route using TxBlend and GIS extraction is limited to just the 1987-2009 period, while the lower route using salinity-inflow regression equations may be extended to the longer 1941-2009 period or may examine other inflow levels not rigorously in this record.

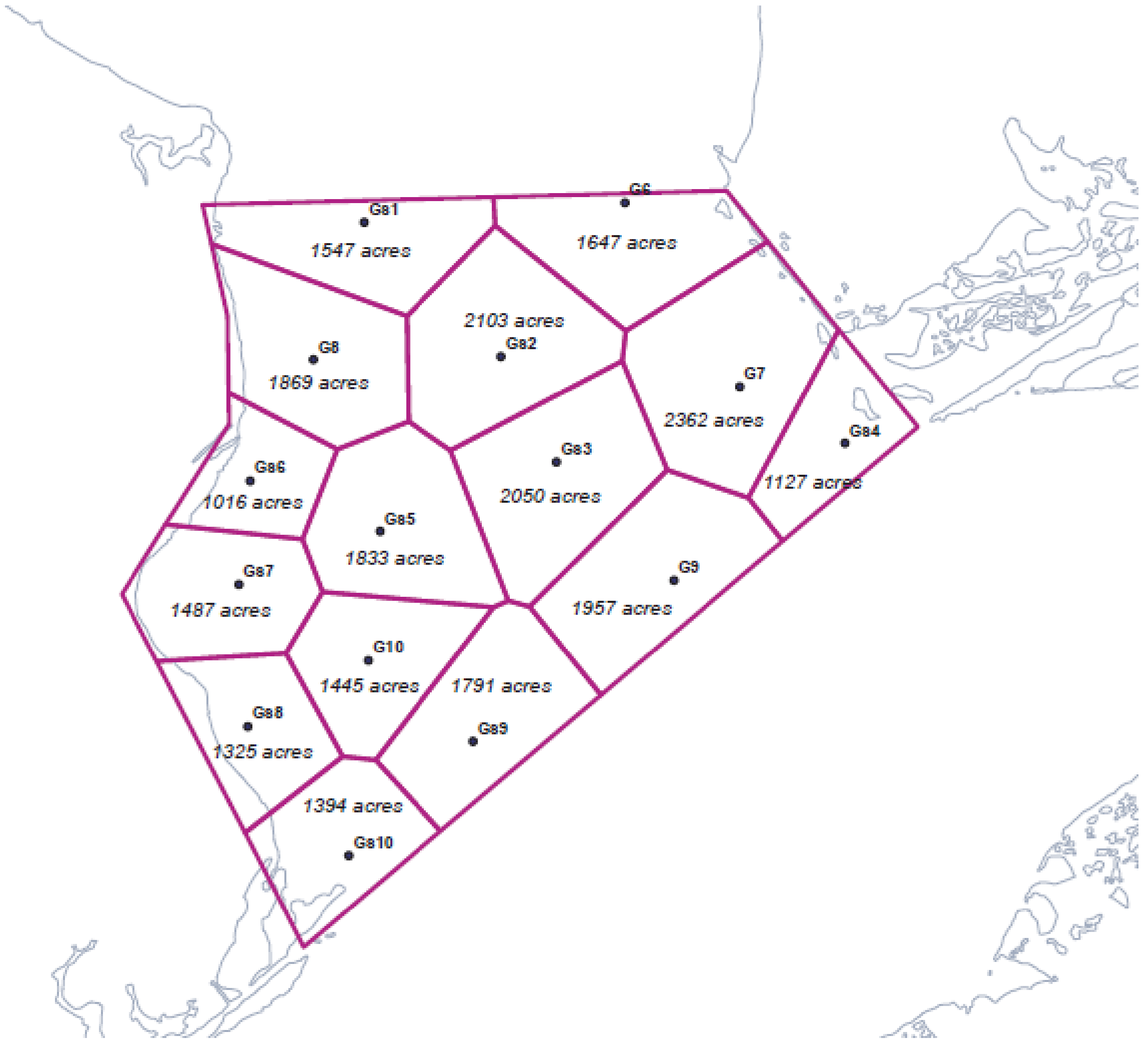


Figure 4.4-9. A finer spatial subdivision of the Guadalupe Estuary oyster habitat for use in the regression equations based approach to determining weighted useable area as a function of inflows. (map courtesy of Lynne Hamlin, TPWD).

Table 4.4-3. Results of the Guadalupe Estuary oyster weighted useable area analyses derived with the regression equations based approach, arrayed with antecedent June inflows and current July-September inflow totals.

		Total July - September Inflow (1000 ac-ft)									
		75	**125**	**175**	**250**	**350**	**450**	**550**	**725**	**975**	**1225**
June Inflow (1000 ac-ft)	**45**	0.63	0.85	0.98	1.00	1.00	1.00	0.93	0.65	0.37	0.33
	95	0.75	0.93	1.00	1.00	1.00	1.00	0.93	0.65	0.37	0.32
	145	0.79	0.93	1.00	1.00	1.00	1.00	0.93	0.63	0.3	0.22
	195	0.79	0.93	1.00	1.00	0.99	0.98	0.88	0.55	0.21	0.12
	245	0.79	0.93	1.00	0.99	0.97	0.92	0.81	0.47	0.13	0.05
	335	0.79	0.93	0.99	0.93	0.86	0.81	0.7	0.37	0.05	0.00
	475	0.79	0.89	0.89	0.82	0.74	0.7	0.61	0.32	0.04	0.00
	625	0.76	0.8	0.79	0.72	0.68	0.66	0.6	0.32	0.04	0.00
	775	0.69	0.73	0.72	0.67	0.67	0.66	0.6	0.32	0.04	0.00
	925	0.63	0.66	0.68	0.67	0.67	0.66	0.6	0.32	0.04	0.00

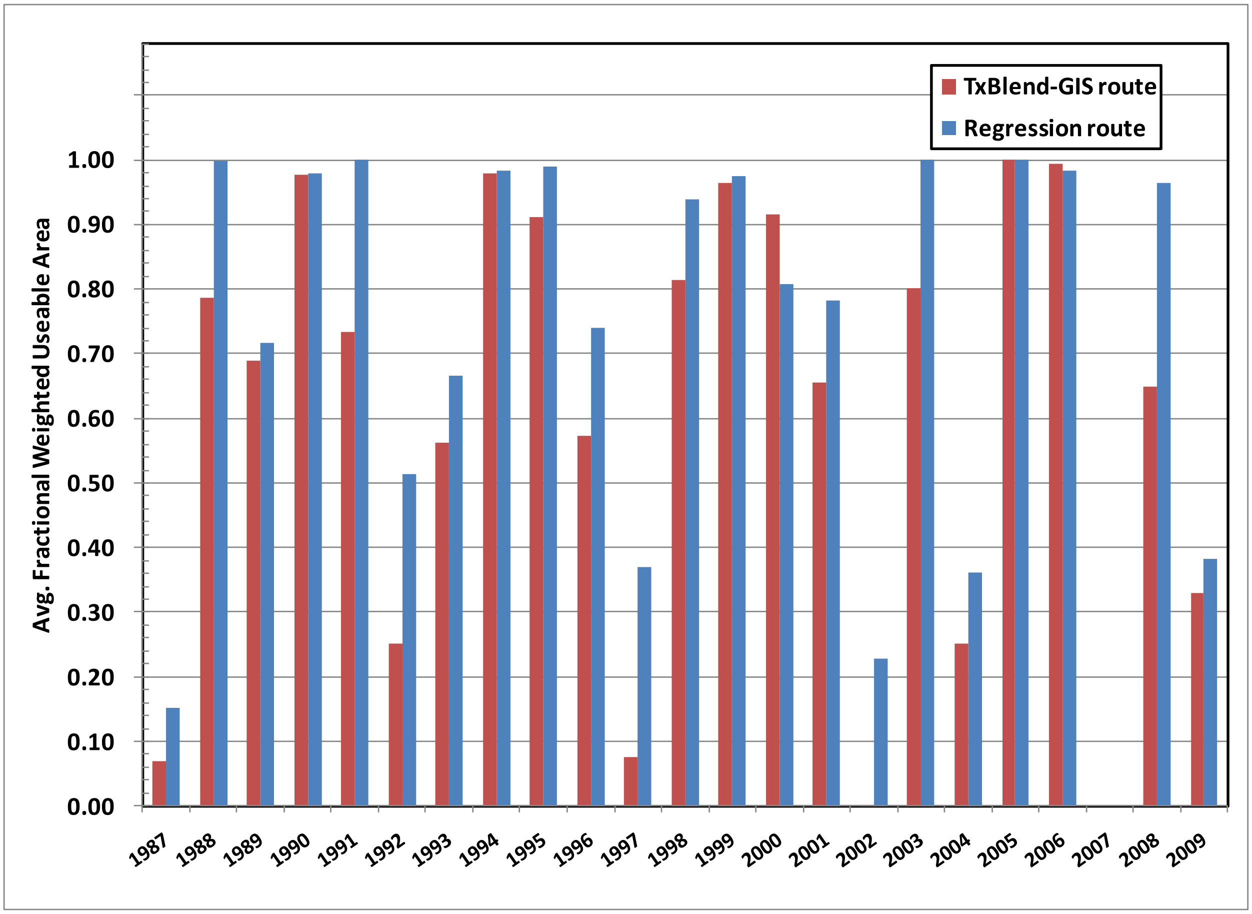


Figure 4.4-10. A comparison of the avg. WUA values determined by the TxBlend-GIS route versus the regression equations-based route for the 23 years available for direct comparison

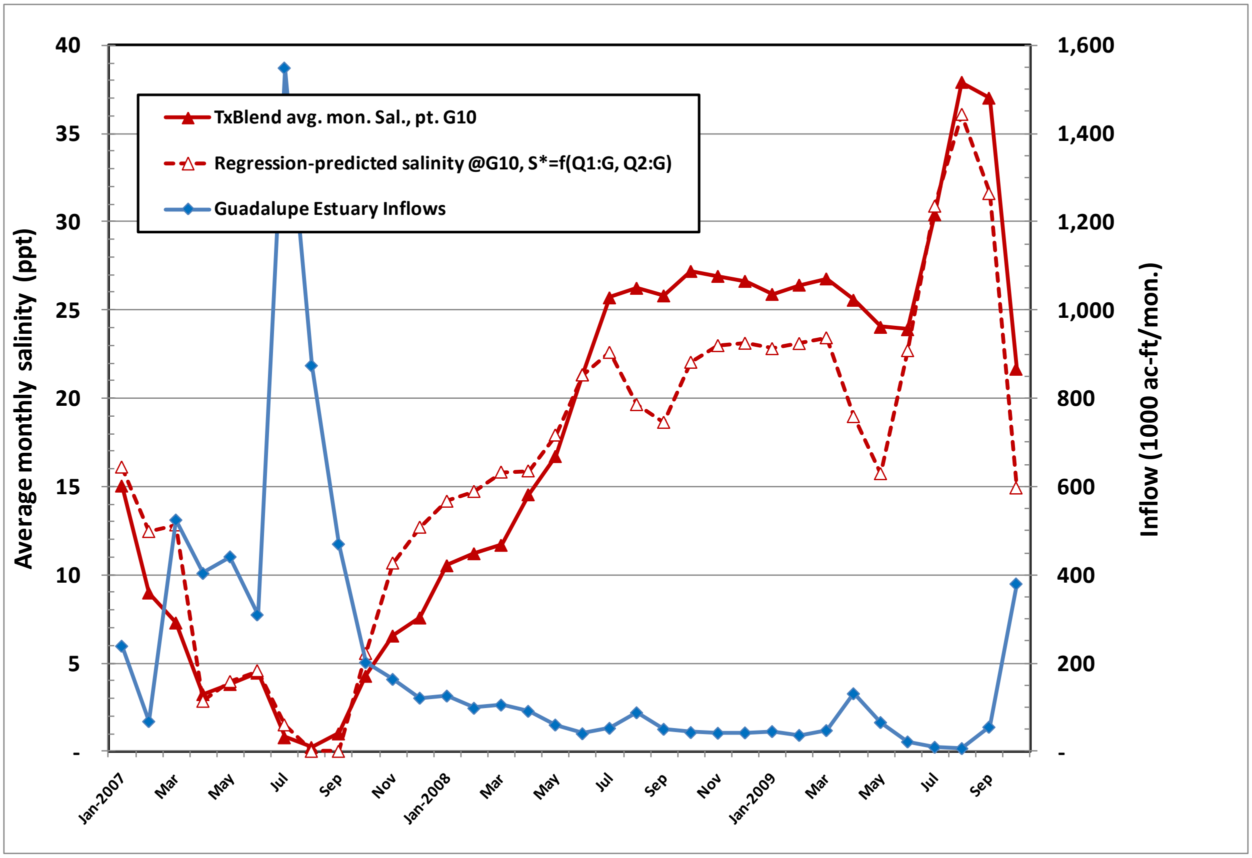


Figure 4.4-11. Regression predicted salinity at point G10 (near GBRA1 data site)versus that of the TxBlend model, showing the under-prediction of high salinity and over-prediction of moderate to low salinity.

Table 4.4-4. Comparison of the weighted useable area values for 1987-2009 in the Guadalupe Estuary oyster area determined via the TxBlend-GIS route, the regression equations-based route, and an 'adjusted' regression equations-based route.

	Inflows (1000 ac-ft)		Weighted useable area determinations		
year	Antecedent June Q (k ac-ft)	Seasonal Jul-Sept. Sum Q (k ac-ft)	GIS-based	Regression, no salinity adjustment	Regression, w. salinity adjustment
1987	2,478	1,081	0.07	0.15	0.10
1988	72	197	0.79	1.00	1.00
1989	82	64	0.69	0.72	0.68
1990	44	532	0.98	0.98	0.93
1991	164	299	0.73	1.00	1.00
1992	911	642	0.25	0.51	0.44
1993	805	328	0.56	0.67	0.67
1994	143	191	0.98	0.98	0.99
1995	246	280	0.91	0.99	0.96
1996	42	255	0.57	0.74	0.77
1997	888	831	0.08	0.37	0.31
1998	43	479	0.81	0.94	0.93
1999	205	200	0.96	0.98	0.98
2000	192	88	0.92	0.81	0.83
2001	82	1,140	0.66	0.78	0.74
2002	63	3,081	0.00	0.23	0.17
2003	129	569	0.80	1.00	1.00
2004	710	836	0.25	0.36	0.33
2005	146	287	1.00	1.00	1.00
2006	141	289	0.99	0.98	0.99
2007	310	2,891	0.00	0.00	0.00
2008	41	192	0.65	0.96	0.98
2009	22	73	0.33	0.38	0.30

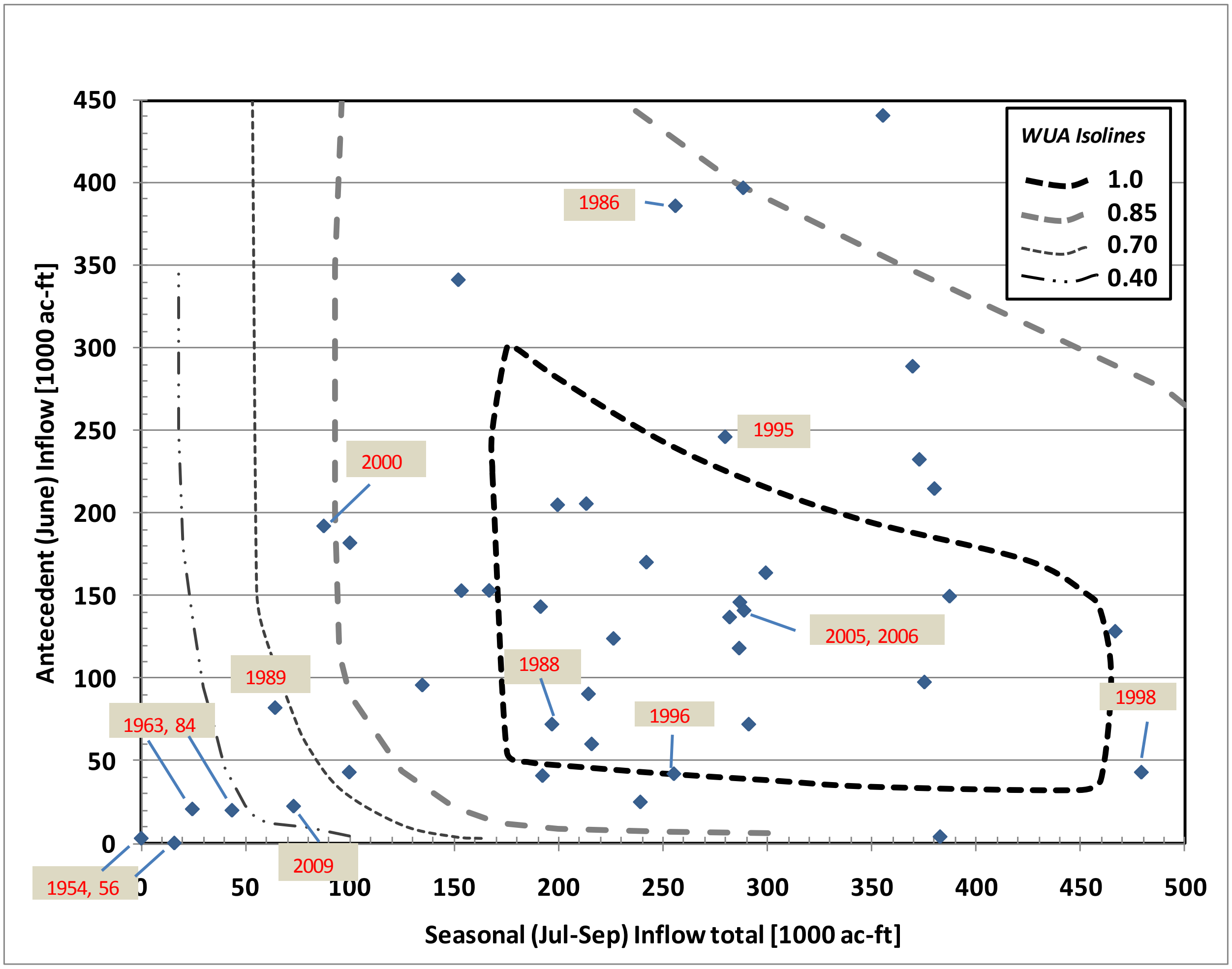


Figure 4.4-12. Illustration of the relation of weighted useable area in the Guadalupe Estuary oyster habitat to inflows in June and combined inflows in July-September.

4.5. Analyses for Focal Species

The salinity zone methodology described above was applied successively to the five fixed habitat / focal species areas shown on Figure 4.3-18[7]. As will be demonstrated, a multi-tiered suite of criteria were derived for the spring and summer periods utilizing this approach. Additional information on salinity and / or inflow needs of other mobile species was also utilized as important 'overlays' to examine and reinforce the results of the salinity zone approach.

Also, an important note regarding nomenclature for the criteria derived below at multiple locations in two estuaries. The GSA BBEST adopted a naming convention so that it is easy to differentiate (or less likely to confuse) among the 5 suites of potential criteria, covering 2 seasons and 5 locations. Thus, in the Guadalupe Estuary the prefix "G" is attached to each criteria while in the Mission-Aransas Estuary this prefix is "MA." An additional prefix, a number, indicates the season that the criteria addresses (and hence the focal species from which derived). Thus, prefix "G2" refers to the Guadalupe Estuary / 2nd season, where summer is defined as June-September and is the 2nd season. Spring is the 1st season, spanning Feb.-May for the purposes of the estuary analyses8. Table 4.5-1 summarizes the seasonal, geographic and focal species and nomenclature conventions.

Table 4.5-1. The array of geographic, focal species, and calendar year coverage of the salinity zone analysis utilized for the Guadalupe and Mission-Aransas Estuaries.

Estuary	Calendar year coverage	Focal species	basic salinity objectives	criteria reference
Guadalupe	Spring Feb-May	Rangia clams	2-10 ppt to support reproduction, at least 1 month Mar.-May	G1
Guadalupe	Summer June - Sept.	Eastern oysters	10-20 ppt best to control "dermo" parasite, 3 months Jul.-Sep.	G2
Mission-Aransas Aransas Bay	Summer June - Sept.	Eastern oysters	"	MA2
Mission-Aransas Copano Bay	Spring Feb-May	Rangia clams	2-10 ppt to support reproduction, at least 1 month Mar.-May	MAC1
Mission-Aransas Copano Bay	Summer June - Sept.	Eastern oysters	10-20 ppt best to control "dermo" parasite, 3 months Jul.-Sep.	MAC2

4.5.1 Salinity Zone Application – Guadalupe Estuary

As presented above and in Figure 4.4-12 it is possible to array the determined weighted useable area (WUA) as a function of the antecedent condition and seasonal inflows, which for the oyster

[7] Appendix 4.5-1 Contains the files utilized in each of the 5 fixed habitats for the salinity zone approach.
[8] For the estuary, the seasons are Spring, season 1, from Feb-May; Summer, from June-Sept.; season 3, Winter from Oct-Jan.

example were those of June and July-September, respectively. As also suggested above, the information of that figure suggest multiple-tiers of inflow. Before moving to the discussion of each fixed habitat and the process of employing those methodological steps for deriving inflow criteria, there are some key considerations that are common to all salinity zone approach analyses that were used by the BBEST:

a) it is assumed that the inflow criteria should be multi-tiered reflecting the variability of the historic inflow and salinity record. We believe that is consistent with the charge of SB3 to develop flow and inflow regimes that reflect seasonal and year-to-year variability. Thus in the process below, this is reflected in criteria designed to achieve or satisfy various levels of suitability for the focal species of consideration, ranging from near ideal to very poor (the ideal condition e.g. 100% suitability for oysters, 75% suitability, etc.).
b) any chosen inflow criteria, and the associated salinity conditions, should reflect conditions that occurred periodically in the historic record and are anticipated to occur again, thus warranting consideration of their implications for maintaining a sound ecological environment.

4.5.1.1 <u>Oysters, Guadalupe Estuary</u>

This fixed habitat, shown on Figure 4.3-13 was utilized as an example above to develop the important conceptual components of the BBEST's salinity zone approach. Thus, here the discussion turns quickly to the process of employing those methodological steps to deriving a suite of inflow criteria. Figure 4.5-1 presents this same basic information as in 4.4-12, but with multiple inflow criteria levels also indicated by the green lines. The criteria levels and several important attributes of each tier are described in Table 4.5-2.

For the Guadalupe Estuary, the top criteria is "G2-A" which provides very good conditions for oysters over a broad range of total inflows in Jul.-Sept. from 275-400 thousand ac-ft. These are medium to fairly high inflows with 400 thousand ac-ft as a seasonal total being just above the median for Jul.-Sept. (see Table 4.2-2.). The WUA would be generally in the vicinity of 100%. As explained in notes to Table 4.5-2, and visible on Figure 4.5-1 a very broad range of antecedent conditions in June, including very low values, still provide high WUA performance and salinities in the 11-18 ppt range, thus the GSA BBEST felt that for simplicity the specification of an antecedent condition could be relaxed. As can be seen in columns under "occurrence" this inflow level occurred 16 years (of 69) in the 1941-2009 historic record spanning all antecedent conditions.

Criteria level G2-B spanning the range of 170-275 thousand ac-ft total in the Jul.-Sept. period, still provides good conditions for oysters, but not quite as good as G2-A (these inflows span the range above and below the 25th percentile as shown in Table 4.2-2). The WUA ranges from 85-100% and salinities range from 13-23 ppt depending on the inflow level primarily on Jul.-Sept., but also to some degree on June inflows. As can be seen in Figure 4.5-1 however, and as detailed in the notes to the table, good conditions would prevail over a broad range of antecedent condition, even very low June inflows, thus again the BBEST opted to relax the specification of an antecedent condition for simplicity. This inflow level occurred 12 years (of 69) in the 1941-2009 historic record, spanning all antecedent conditions.

Taken together criteria levels G2-A and G2-B occurred a total of 28 years, or 41% of the years in the 1941-2009 historic record. Because inflows in this range have occurred rather frequently, and do provide good conditions for the abundant oysters in this broad portion of the Guadalupe Estuary, the GSA BBEST feels that these inflow levels are important to maintain with some high frequency going into the future. Thus, with regard to a recommendation we believe that taken together categories G2-A and G2-B should not decline in overall occurrence by more than 25% as measured in the long-term, or stated another way, should occur at least 21 years in the long term. Furthermore, to maintain the variability that the GSA BBEST thinks is essential, the G2-A criteria should be met 12 of those years in the future. More on how these "attainment goals" should be evaluated follows in Section 6.

Arriving at a recommended future attainment levels is based on the best collective scientific judgment of the BBEST. There are just a few examples in the published literature which provide some insights into how this type of recommendation was handled in other locales. A national inventory of ecosystem status, prepared by the Heinz Center, compared changes in the magnitude and timing of four key hydrological events in streams across the nation (Heinz Center 2002). For each of the four events, a change of less than 25% compared to the baseline was considered 'low' alteration. Greater than 75% change from baseline conditions was considered 'high' alteration. Secondly, the Environmental Protection Agency's (EPA 2004) used a variety of water quality, sediment toxicology, and fish-contaminant measures to categorize coastal areas' environmental conditions. Breakpoints of 5%, 5%-15%, and greater that 15% were used to rank estuarine sediment-contamination measures as 'good', 'fair', and 'poor'.

Category G2-C covers a much lower Jul.-Sept. inflow range of 75-170 thousand ac-ft which encompasses the 8th - 18th percentile of historic inflows in this season. This category was subdivided into two sections which the BBEST felt necessary due to the increasing importance of antecedent condition in this range. As can be seen in Figure 4.5-1, the WUA isolines in this range of Jul.-Sept inflows begin to exhibit increased influence of the antecedent condition. In fact, for category G2-C the WUA maximum of 100% is not possible at the lower end of this Jul.-Sept. inflow range. At the upper end of this range, at 170 thousand ac-ft in Jul.-Sept., the 100% WUA is achieved only if June inflows are at least 50 thousand ac-ft/mon, roughly the 20th percentile of inflows in that month. Category G2-CC, although it has been rare in the historic record, represents a portion of the WUA-inflow relationship that may become important. As visible in Figure 4.5-1 and in Table 4.5-2, this lower C category can include some fairly poor conditions with salinity as high as 39 ppt and WUA as low as 36%. For the recommended occurrence in the future, these two C categories function as something of a bridge between the good G2-A and G2-B categories and the drought "D" levels below. The acceptable 25% reduction in the long term occurrence of G2-A and G2-B inflow levels should lead to an increase in G2-C and G2-CC occurrence given that the drought conditions below this should not increase (discussed below). Thus the increase in frequency of both C categories is acceptable if the conditions on G2-D and G2-DD drought level criteria are also met. Furthermore since the lower, G2-CC, includes some fairly poor conditions for oysters, the BBEST feels that this category, historically 1/7 of the total of the C categories could increase up to 1/6 of the total in the long term, again representing about a 25% increase in frequency.

The categories G2-D and G2-DD cover moderate and severe drought conditions, respectively. As evident in Table 4.5-2 such low inflow conditions lead to very high salinities over the oyster habitat. In sum, these inflow conditions occurred a total of six times in the 1941-2009 period, including two recent years (1989 & 2009) in category G2-D. The GSA BBEST recognizes that droughts will continue to occur but believes that over the long-term there should be no increase in the occurrence of such conditions and no worsening of moderate drought (G2-D conditions) to severe droughts (G2-DD). Thus the recommendations here are for those categories of inflow to have the same occurrence level as in the historic record. Again, how such attainments should be assessed is discussed below in Section 6.

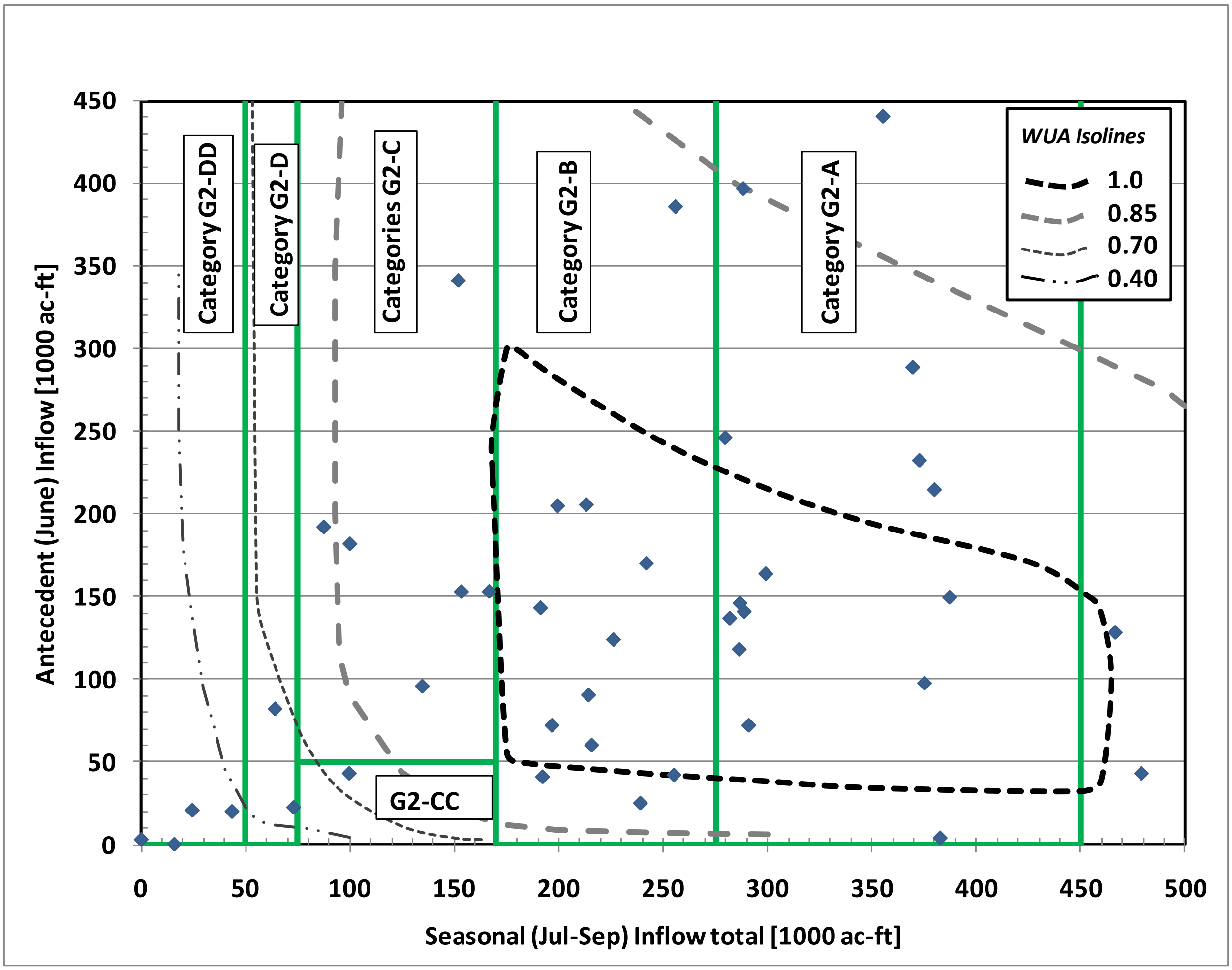


Figure 4.5-1. Employing the weighted useable area response in the oyster habitat of the Guadalupe Estuary to derive a multi-tiered suite of inflow criteria.

Table 4.5-2. A multi-tiered suite of inflow criteria covering the June-September period in the Guadalupe Estuary oyster area determined via the salinity zone approach.

<table>
<tr><th rowspan="2">Criteria level</th><th colspan="2">Inflow ranges (1000 ac-ft) [cfs equivalent]</th><th colspan="2">Salinity and Weighted Useable Area objectives, Jul-Sep</th><th colspan="2">Occurrence [/ Co-] of seasonal [/and antecedent]</th></tr>
<tr><th>July-Sept. total inflows</th><th>June inflows if applicable</th><th>WUA within oyster habitat.</th><th>Approx. avg. salinity (ppt.)</th><th>No. years 1941-2009 [% yrs]</th><th>example years</th></tr>
<tr><td>G2-A</td><td>275-450 [1507-2466]</td><td>-</td><td>100% WUA[1]</td><td>11-18</td><td>16 / 23.2%</td><td>'06,'05,'95</td></tr>
<tr><td>G2-B</td><td>170-275 [932-1507]</td><td>-</td><td>85-100% WUA[2]</td><td>13-23</td><td>12 / 17.4%</td><td>'08,'99,'96</td></tr>
<tr><td colspan="6">Criteria levels G2-A & G2-B, total historic occurrence 28 years (41%).</td><td></td></tr>
<tr><td colspan="6">Recommended occurrence in future:
Criteria levels G2-A and G2-B total occurrence >= 21 years (30%)[3];
Criteria level G2-A occurrence >= 12 years (17%)[3].</td><td></td></tr>
<tr><td>G2-C</td><td>75-170 [411-932]</td><td>>=50 [>=840]</td><td>65-100% WUA[4]</td><td>16-27</td><td>6 / 8.7%</td><td>'00,'82,'69</td></tr>
<tr><td>G2-CC</td><td>75-170 [411-932]</td><td><50 [<840]</td><td>36-99% WUA[4]</td><td>20-39</td><td>1 / 1.5%</td><td>1955</td></tr>
<tr><td colspan="6">Criteria levels G2-C & G2-CC, total historic occurrence 7 years (10%).</td><td></td></tr>
<tr><td colspan="6">Recommended occurrence in future:
Overall occurrence of Criteria level G2-C and G2-CC may increase beyond 7[5] years (10%)if the constraints on other categories are met, and G2-CC comprises no more than 1/6 of total. .</td><td></td></tr>
<tr><td>G2-D</td><td>50-75</td><td>-</td><td>39-73% WUA</td><td>25->40</td><td>2 / 2.9%</td><td>'09,'89</td></tr>
<tr><td>G2-DD</td><td>0-50</td><td>-</td><td>0-43% WUA</td><td>31->40</td><td>4 / 5.8%</td><td>'84,'63,'56</td></tr>
<tr><td colspan="6">Criteria levels G2-D & G2-DD, total historic occurrence 6 years (9%)</td><td></td></tr>
<tr><td colspan="6">Recommended occurrence in future:
Criteria level G3-D and G3-DD together should occur no more than a total of 6 (9%)years;
Criteria level G3-DD should occur no more than 4 (6%)years.</td><td></td></tr>
</table>

Notes:

1. WUA of 100% is strictly only achieved over the range of June antecedent inflows of40-156 thousand ac-ft/mon. However, 95-100% is achieved over a very broad range of antecedent conditions ranging from 21 to 224 thousand ac-ft/mon. in June. The stated salinity range corresponds to the later broad June antecedent condition inflow range. Inflows as low as 2 thousand ac-ft/mon. in June, would still provide approximately 75% of WUA, though salinities would rise to about 22. The "Number of years total" column includes all potential antecedent conditions.
2. For Category G2-B, the range of WUA from 85%-100% is achieved with a broad range of antecedent conditions from 13 - 400 thousand ac-ft/mon. in June. The stated salinity range corresponds to that antecedent condition range. Even with June inflows as low as 4 thousand ac-ft/mon., the WUA would still be approximately 74% while salinity would rise to about 25ppt. On the high end of the scale, with June inflows as high as 650 thousand ac-ft/mon., the WUA would still be 70% while salinity would drop to 12 ppt. The "Number of years total" column includes all potential antecedent conditions.
3. The change from the historic occurrence is calculated with up to a 25% drop in frequency of attainment of these elements.
4. For category G2-C the WUA maximum of 100% is not possible at the lower end of this Jul.-Sept. inflow range. At the upper end of this range, at 170 thousand ac-ft in Jul.-Sept., the 100% WUA is achieved if June inflows are at least 50 thousand ac-ft/mon. and up to 285 thousand ac-ft/mon.

5. It is anticipated that the acceptable reduction in the long term occurrence of G2-A and G2-B inflow levels will lead to an increase in G2-C and G2-CC occurrence. This is acceptable if the conditions on G2-D and G2-DD drought level criteria are also met. Furthermore since G2-CC includes some fairly poor conditions for oysters, the BBEST feels that this category, historically 1/7 of the total C categories could increase up to 1/4 of total.

4.5.1.2 Rangia, Guadalupe Estuary

As summarized in Table 4.5-1 and detailed in Sec 4.3 the ecologically important rangia clam was used as a focal species for the Spring period of Feb.-May. Literature and field experience led the BBEST to select Mar.-May as the target window in which rangia would probably be able to reproduce, with February likely being too cold. However, analogous to oysters, February is the antecedent condition month for the salinity zone analyses of rangia. The utility of using rangia clams as a key species is that the larvae, released into the water directly, need salinity in the range of 2-10 ppt for about 20 days to survive. For the purpose of these analyses, using monthly average values of salinity, the BBEST assumes that a monthly average in the 2-10ppt range would likely include an approximate 20 day window in that range. This salinity suitability curve is illustrated in Figure 4.5-2. The very sharp edges of this curve, as compared to the smooth transitions of the oyster curve, lead to some very precipitous changes in suitability in the habitat area as inflows are changed but little, as will be shown.

Figure 4.5-3 illustrates in more detail this habitat area and the subareas within it that were utilized for the regression equations-based approach. Finally, this overall rangia habitat was subdivided into an upper and lower portion. As shown if Figure 4.5-4, the upper portion of this habitat has a fairly different salinity-inflow response than the lower. As in the case for oysters, the salinity-inflow regression equations were ‘adjusted’ to compensate for apparent prediction errors (see Appendix 4.2-2). For illustrative purposes, these salinity response curves in Figure 4.5-4 were generated under the rather narrow assumption of the February antecedent condition inflow being equal in monthly magnitude to the Mar.-May level (= 1/3 Mar.-May total). This salinity prediction is useful though as it illustrates the rather narrow range of inflow over which the entire habitat would have the ideal conditions of 2-10ppt.

If the full suite of subareas and regression equations are utilized in conjunction with a fully varying suite of antecedent condition and seasonal inflow combinations, the full-fledged WUA isoline plot is as shown in Figure 4.5-5. This plot is analogous to, but significantly different from, that for oysters presented earlier. As before, example years from the 1941-2009 historic record are highlighted. The differences in WUA isolines are related to fundamental information pointed out in Table 4.5-1 (and in Section 4.3), namely, the scientific literature on rangia indicate that reproduction can occur within about a 1-month window. Thus the best combination of inflows on this plot (labeled “upr&lwr=3 @1”) represents those cases where the entire upper and lower areas have 100% suitability for reproduction over the entire 3-month season (Mar.-May). As also evident from the example years indicated on the figure, this perfect combination is fairly rare. The rarity of this perfect combination and the fact that there is a very significant population of rangia in the upper Guadalupe Estuary, provides two things to the GSA BBEST. First, this is pretty strong corroborating evidence that the scientific literature, almost all of it based on studies from other states, is reasonably accurate and that rangia do not need the entire season to reproduce successfully. This also provides an opportunity to specify inflows of somewhat lesser levels that would still provide opportunities for rangia reproduction, hence the other variety of isolines on Figure 4.5-5.

As antecedent and / or Mar.-May inflows are lowered, other threshold levels emerge as indicated by other dotted lines with symbols (e.g. triangles). First as inflows are decreased from the ideal combination area, there is an immediate movement to conditions in which less than 3 months of reproduction over 100% of the area are supported (including 3 months, but partial area coverage). Eventually a threshold is reached where only 1-2 months over the entire upper and lower area support reproduction. This is indicated by the line labeled "lwr ≥1@ 1". The portion of this curve with solid symbols indicates 2 months, the open symbols indicate just 1 month. Inflow combinations to the lower left from this threshold now enter a region in which some or all of the lower area, shown previously, rises above 10ppt and thus only the upper area can be completely within the 2-10ppt range, but not for 3 months. This is indicated by the line with triangles labeled "upr ≥1@ 1" and a similar convention for solid versus open symbols. At lower levels of inflow even more restricted areas of just the upper portion of the habitat become suitable for reproduction (the lower area would not be favorable for reproduction). The line labeled "upr 33%@1" indicates the threshold were just one third of the upper portion of the rangia habitat would support reproduction for one month. Similar lesser performing levels are also shown, until at very low inflow levels, essentially just a refugium area in the upper portion of the habitat would support rangia reproduction.

As with oysters, this variation in salinity suitability as inflows vary is the basis or designing a multi-tiered suite of inflow criteria to support rangia reproduction in the upper Guadalupe Estuary. As before, the underlying precepts for the multi-tiered approach are: a) a range of inflows and associate ecological condition, reflecting natural annual and seasonal variation; b) criteria levels that reflect fairly frequent occurrences in the historic record. The criteria derived by the BBEST, are illustrated in Figure 4.5-6 and presented in Table 4.5-3.

The upper tier G1-A with Mar.-May total inflows in the range of 375-550 thousand ac-ft (36th - 53rd percentiles of historic levels) represents the best possible conditions for rangia. Figure 4.5-6 shows that in this level of Mar.-May inflows, even a very low antecedent condition inflow would still yield fairly good reproductive support for rangia. At that level of inflow, more-or less regardless of the antecedent inflow, all of the upper and lower portions of the habitat would support rangia reproduction for between 2-3 months.

With the next tier down, G1-B, inflows are in the range of 275-375 thousand ac-ft total for Mar.-May (spanning the 27th - 36th percentiles). By examining Figure 4.5-6 it is evident that within this range of Mar.-May inflow there is some variation based on the antecedent condition. At very low antecedent conditions the lower area would not support rangia reproduction, however in the historic record there have been only a handful of Feb. inflows below 50 thousand ac-ft in combination with this Mar.-May level. Even at a nearly zero antecedent condition the upper area would have 24% area in good conditions for rangia reproduction. Thus, the BBEST couches this criteria with no attached antecedent condition.

The “C” categories, with Mar.-May total inflows in the modest 150-275 thousand ac-ft range (9th - 27th percentiles for this seasonal total), cover a broad range of conditions that would be described as very bad at the lower end to good at the upper end, if the higher antecedent condition occurred as well. As was the case with oysters, the “C” categories are in a region of the WUA-inflow relationship with big changes as a function of antecedent condition, thus the GSA BBEST specified two levels, G1-C and G1-CC, that differ based on being above or below 75 thousand ac-ft/mon. Feb. inflows (the 30th percentile inflow level for that month). The lower G1-CC criteria would, at best, support rangia reproduction over just 33% of the upper habitat area for 1 month. The higher G1-C level would in some combinations of antecedent condition and Mar.-May inflows support reproduction over the entire upper and lower areas for at least 1 month.

Finally, the lower drought category, G1-D, would not support rangia reproduction to any great extent unless an unusually high antecedent condition inflow occurred. However, the years in the actual historic record to date that have Mar.-May inflows in this low range also tend to be accompanied by very low Feb. inflows. Four of these six previous low Mar.-May years, shown on Figure 4.5-6, also had Feb. inflows less that 50 thousand ac-ft/mon., the 11th percentile for that month.

As also shown on Table 4.5-3, the GSA BBEST made recommendations for future attainment of these inflow categories. This process was similar to that for oysters in that the historic attainments of the various levels served as the beginning point, since today’s environment, a product of that long record was deemed “sound” early on by the BBEST. Categories G1-A and G1-B, representing excellent and good conditions for rangia reproduction occurred a total of 17 years in the historic 1941-2009 record, the G1-A occurring 11 of those. With the same 25% reduction rule employed previously for oysters, this translates to a future attainment recommendation of 12 years overall , and 8 for the upper G1-A criteria. As for oysters, the GSA BBEST believes there should be no increase in the occurrence of the drought G1-D condition for rangia. In between, therefore, the G1-C and G1-CC conditions, in total, may increase, but that there should still be relative frequency somewhat like the historic relationship among these two with G1-CC comprising no more that 2/3 of the total.

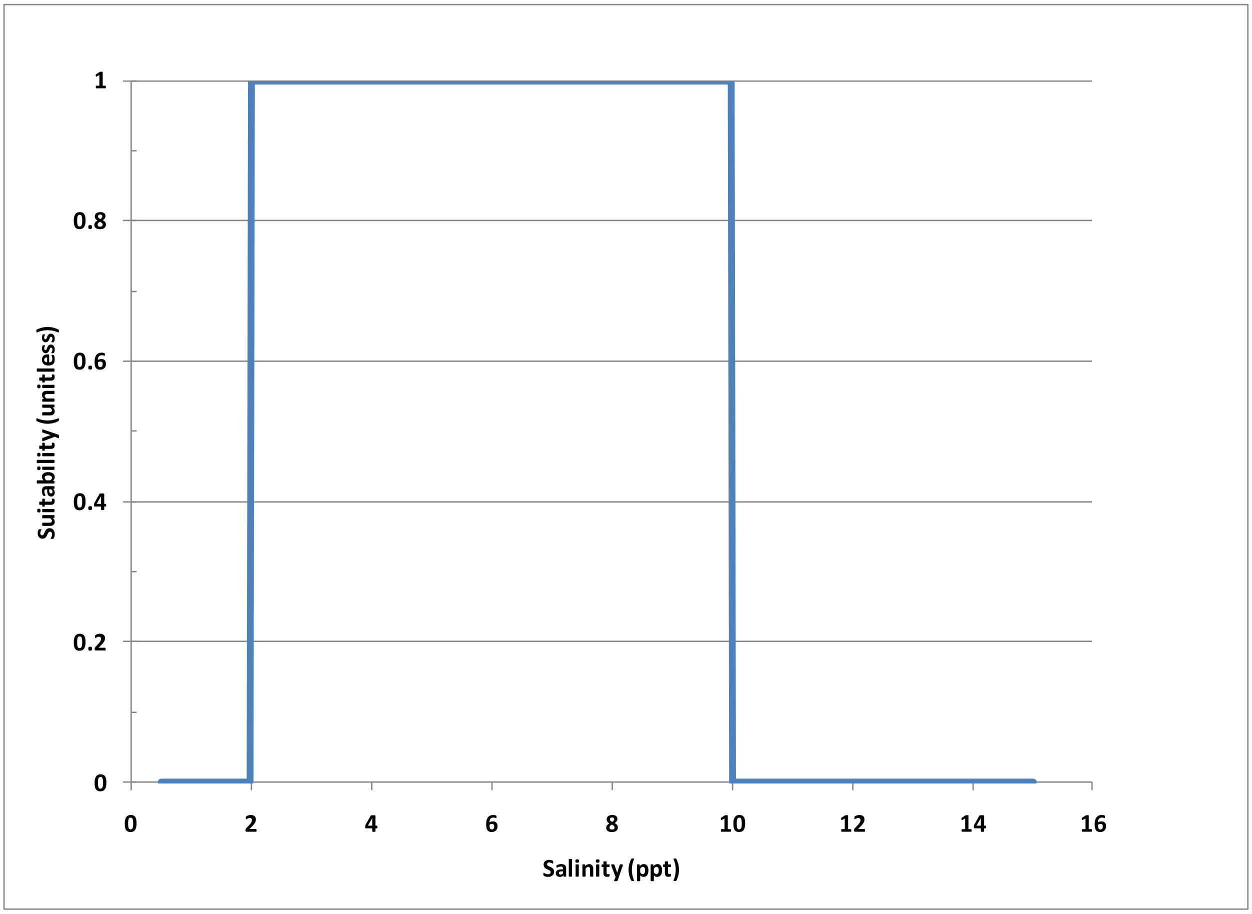


Figure 4.5-2. The salinity suitability curve used by the GSA BBEST in the evaluations of rangia for determining inflows that support reproduction.

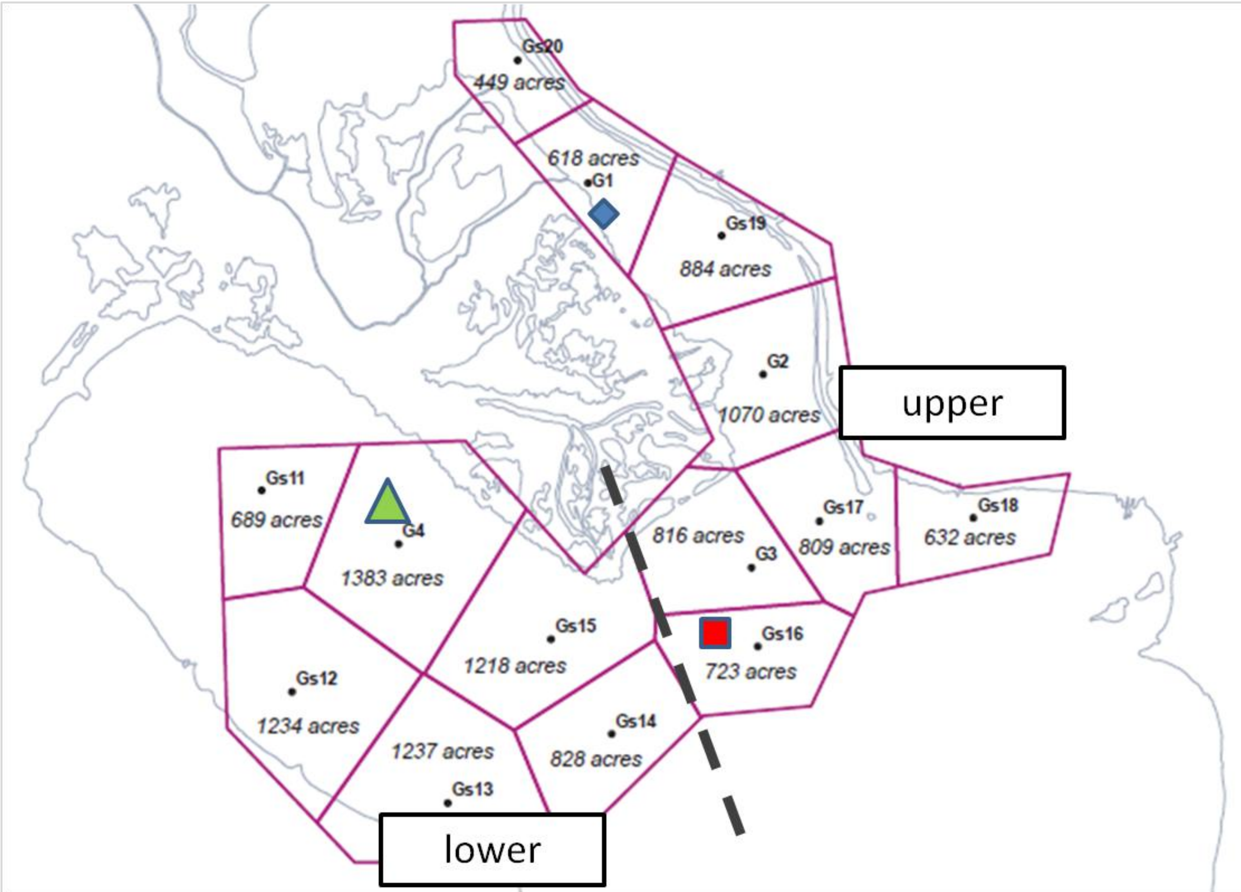


Figure 4.5-3. The area of the upper Guadalupe Estuary utilized for rangia analyses. Also shown are the subareas and points at which salinity-inflow regression equations were developed. Finally, this habitat was also subdivided into an upper and lower portion for analyses.

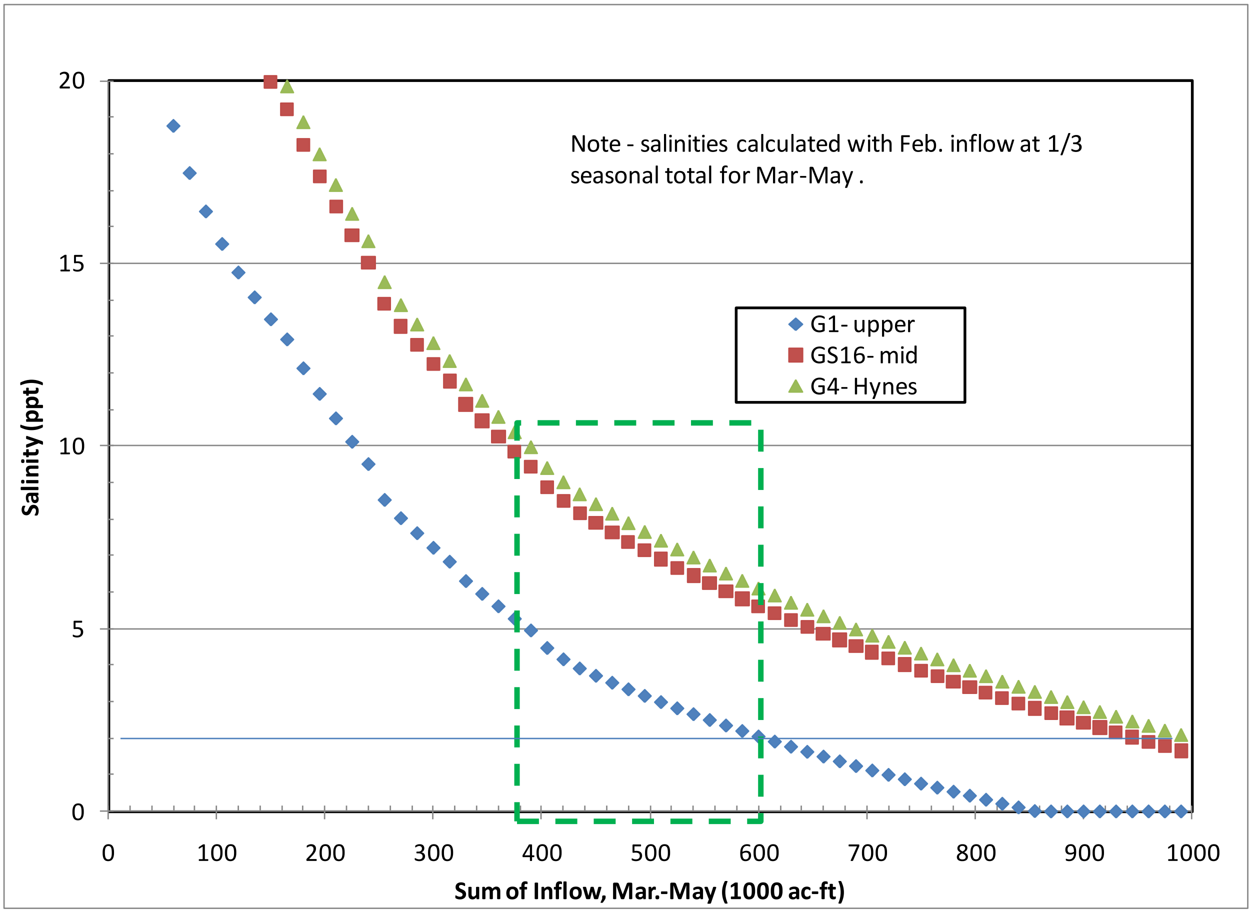


Figure 4.5-4. Illustration of the difference in salinity response to varying inflow at the three highlighted sites of Figure 4.5-3. The box generally illustrates the narrow range over which both the upper and lower portions of rangia habitat are in ideal conditions.

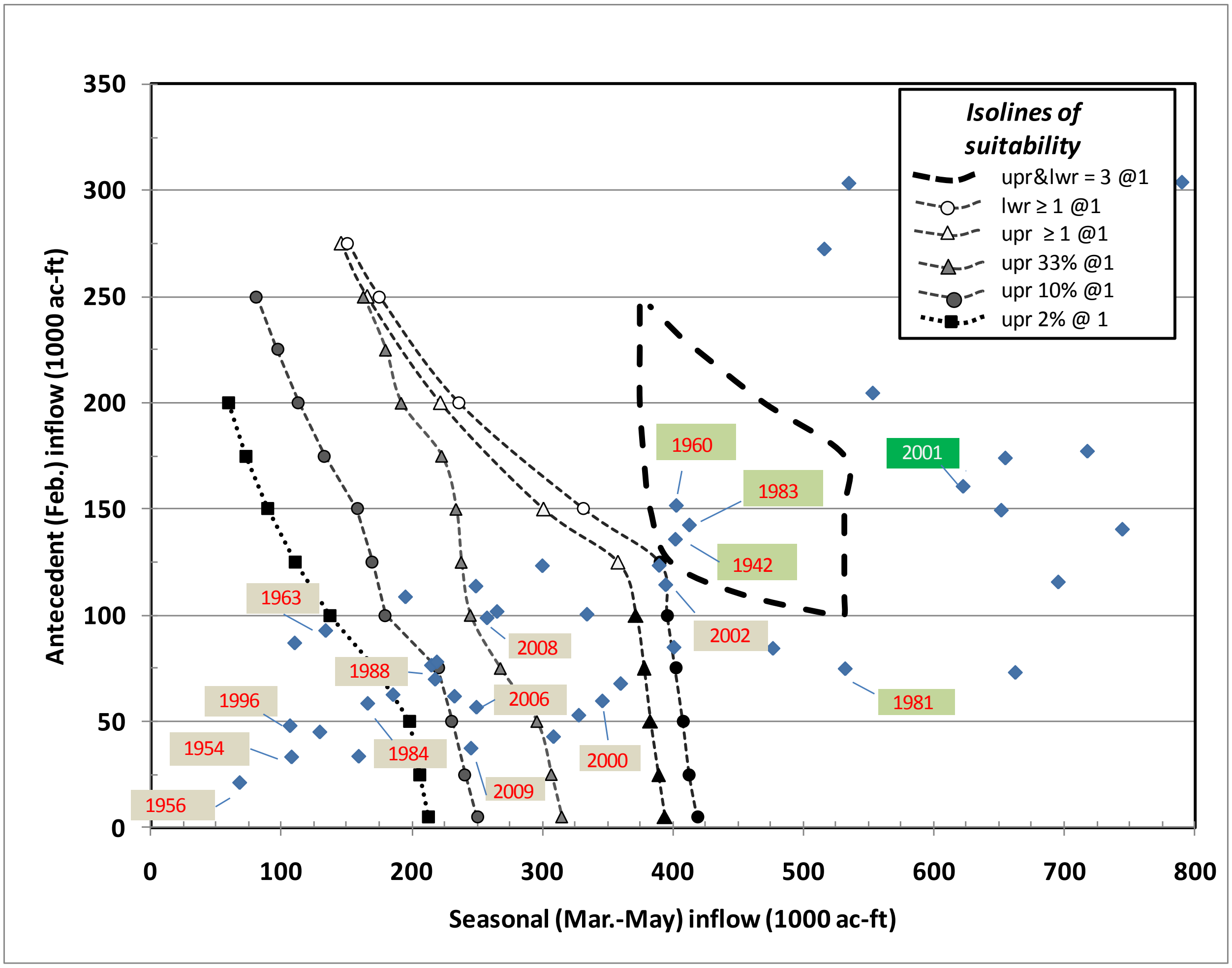


Figure 4.5-5. The weighted useable area response in the rangia habitat of the Guadalupe Estuary as a function of antecedent condition February and total Mar.-May inflows.

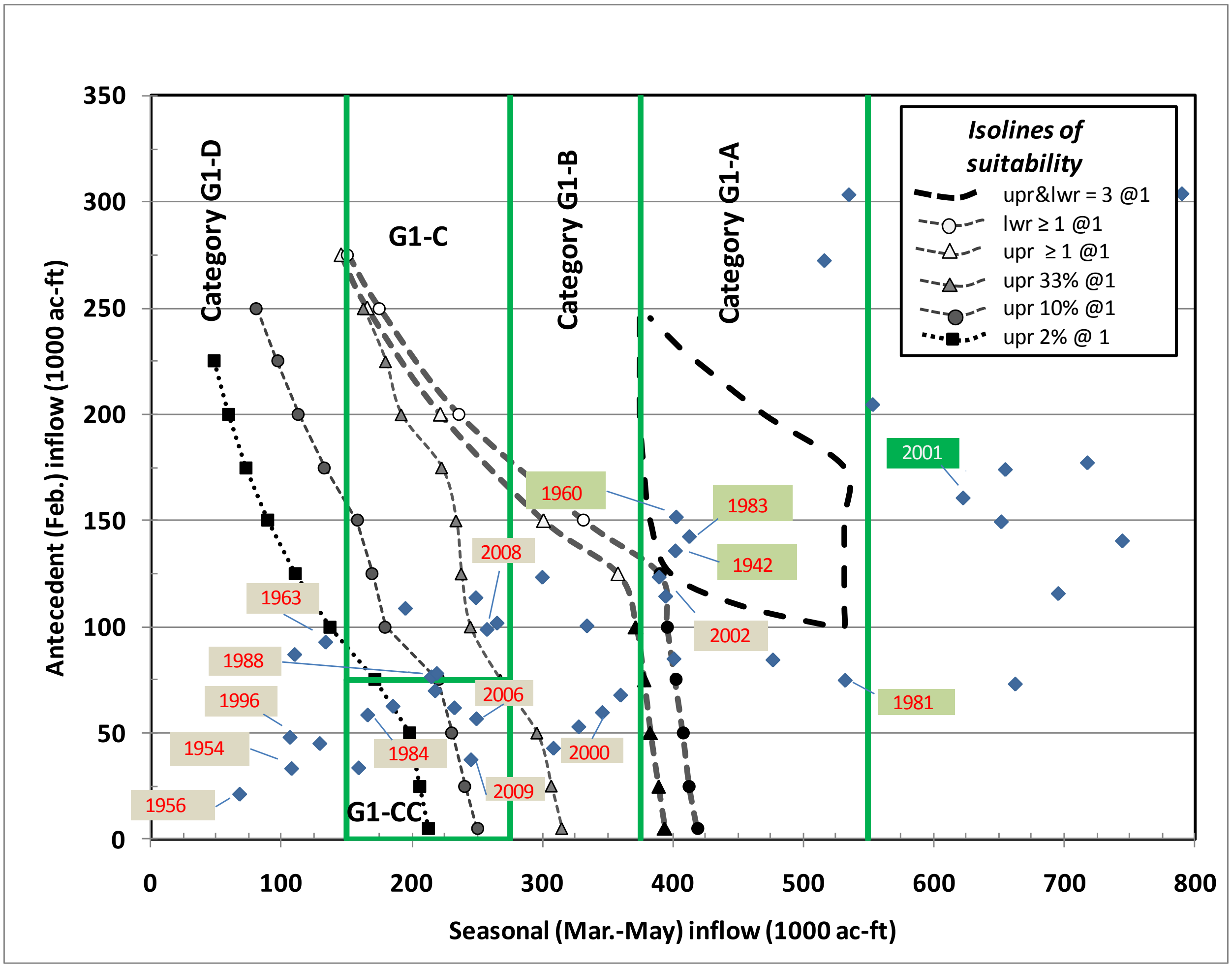


Figure 4.5-6. Employing the weighted useable area response in the rangia habitat of the upper Guadalupe Estuary to design an multi-tiered inflow criteria.

Table 4.5-3. A multi-tiered suite of inflow criteria covering the February - May period in the Guadalupe Estuary rangia area determined via the salinity zone approach.

Criteria level	Inflow ranges (1000 ac-ft) [cfs equivalent]		Salinity-biology objectives, Mar.-May [upper / lower areas]			Historical occurrence [/ Co-] of seasonal [/and antecedent]	
	Mar.-May total inflows	Feb. inflows if applicable	No. mons. whole area supports reproduction	Avg. monthly area supporting reproduction	Approx. avg. salinity (ppt.)	No. years 1941-2009 [% yrs]	example years
G1-A	375-550 [2055-3014]	-	2-3 upper / 2-3 lower	~100% upper / ~100% lower	3-10 upper 5-14 lower	11 / [16%]	'02,'99,'98
G1-B	275-375 [1507-2055]	-	0-3 upper / 0-2 lower	24- 100% upper / 0 - 100% lower	6-12 upper 9-16 lower	6 / [9%]	'00,'90,'86
Criteria levels G1-A & G1-B, total historic occurrence 17 years (25%).							
Recommended occurrence in future: Criteria levels G1-A and G1-B total occurrence >= 12 years (17%); Criteria level G1-A occurrence >= 8 years (12%).							
G1-C	150-275 [822-1507]	>75 [>1350]	0 - 1 upper / 0 - 1 lower	0 - 61% upper / 0 - 33% lower	7-17 upper 9 - 20 lower	6 / [9%]	'08,'88,'78
G1-CC	150-275 [822-1507]	0 - 75 [0 - 1350]	0 upper / 0 lower	0 - 33% upper / 0% lower	11 - 22 upper 14 - 27 lower	7 / [10%]	'09,'06,'89
Criteria levels G1-C & G1-CC, total historic occurrence 13 years(19%).							
Recommended occurrence in future: Overall occurrence of Criteria level G1-C and G1-CC may increase beyond 13 years(19%) if the constraints on other categories are met, and G2-CC comprises no more than 2/3 of total.							
G1-D	0 - 150 [0-822]	-	0 upper / 0 lower	0 - 2% upper / 0% lower	15 - 40 upper 19 - 40 lower	6 / [9%]	'54,'56,'96
Criteria level D total historic occurrence 6 years (9%).							
Recommended occurrence in future: Criteria level D should occur no more than a total of 6 years (9%).							

4.5.2 Salinity Zone Application – Mission Aransas Estuary

The evaluations of inflow needs of the Mission-Aransas Estuary was again based on the important life-history needs of the focal species rangia and oysters. However, the fact that this estuary is influenced by inflows from both the Guadalupe River to the north and the more local Mission and Aransas Rivers and coastal basins led to some important considerations. As shown early in Section 4.2 (see Figure 4.2-1 and Tables 4.2-1 and 4.2-2) the inflows from the Guadalupe River dwarf those of the Mission-Aransas system.

Thus the first step in the suite of analyses for the Mission-Aransas Estuary was to assess the relative importance of these two inflow sources on the salinity characteristics here. For this step, the regression equations described earlier provide important information. Figure 4.5-7 compares the original regression equations that utilized just Guadalupe River inflow terms (of form S*= a + B1*ln(Q1:G) + B2*ln(Q2:G) as explained in Section 4.2.2) compared to the fuller form using both Guadalupe and Mission-Aransas inflow variables (of form S*= a + B1*ln(Q1:G) + B2*ln(Q2:G) + B3*ln(Q1:MA) + B4*ln(Q2:MA)). As is evident on the map if Figure 4.5-7 there is only marginal improvement in the explanatory power of adding the local Mission-Aransas inflow terms. In other words, most of the behavior of salinity in this area, as related to inflow, is dominated by the influence of Guadalupe River inflows.

Figures 4.5-8 and 4.5-9 illustrate the salinity - inflow relationships in the fixed oyster habitats of this area during with the recent 2007-09 transition from very wet to drought conditions. As shown in Figure 4.5-9 Copano Bay often tracks about 5ppt less saline than the habitat in Aransas Bay which is under much more influence of the Gulf of Mexico and tidal exchange through Aransas Pass.

Because of the high level of influence of the Guadalupe Estuary's inflows on the habitats of this region, the BBEST chose to perform a slight alteration of the salinity zone approach. The inflow criteria established for the Guadalupe Estuary were taken as the starting point and then tested in combination with a wide range of Mission-Aransas Estuary inflows. This is illustrated in Figure 4.5-10 for the evaluations of oysters in the Jul.-Sept. window. The vertical green lines are the established Guadalupe inflow criteria breakpoints. Also shown are the very broad bands of Mission-Aransas Estuary inflows that were entertained, ranging up to the 68th percentile (100 thousand ac-ft) for the Jul.-Sept. period. The pairings of Mission-Aransas Estuary inflows with the Guadalupe criteria are such that the upper limit is roughly equal to the upper percentile of the respective Guadalupe inflow criteria. For instance, the G2-A criteria maximum of 400 thousand ac-ft over three months was just above the median (Table 4.2-2).

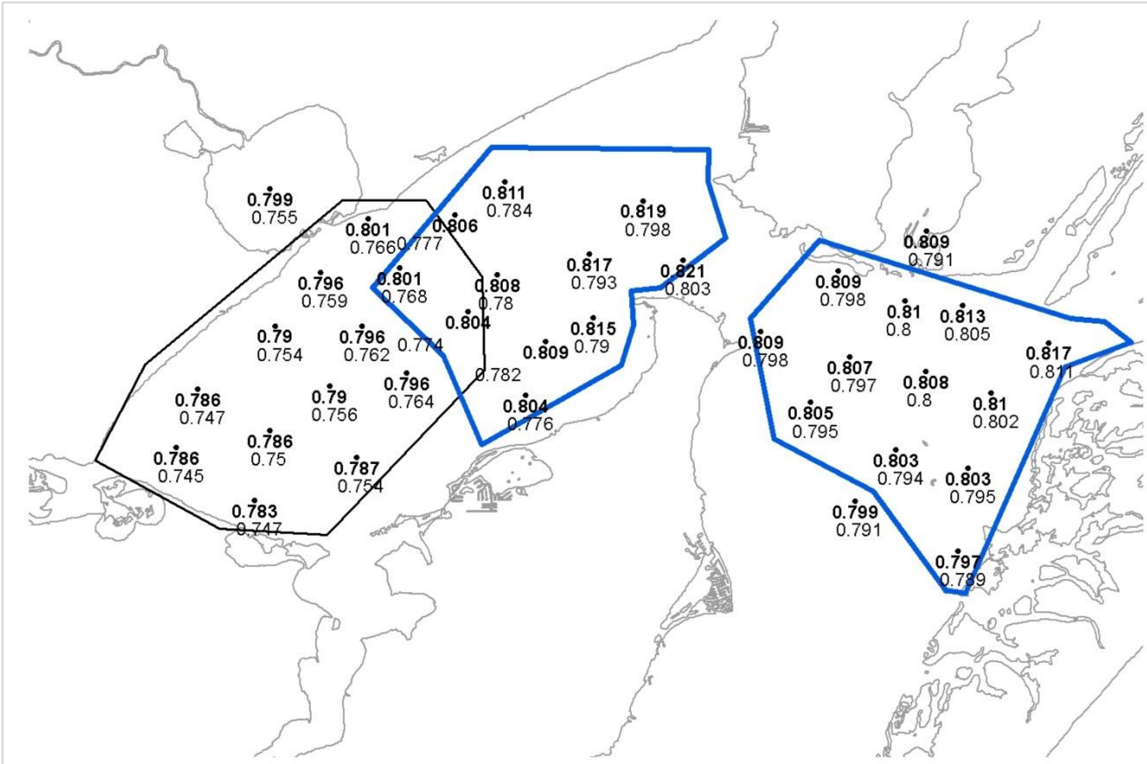


Figure 4.5-7. Comparing the R^2 statistics for two types of salinity-inflow regression equations applied to points in the Mission-Aransas Estuary. Bold font indicates regressions with both Guadalupe and Mission-Aransas inflow terms, while the regular font indicates regressions with just Guadalupe terms. (map courtesy of Lynne Hamlin, TPWD).

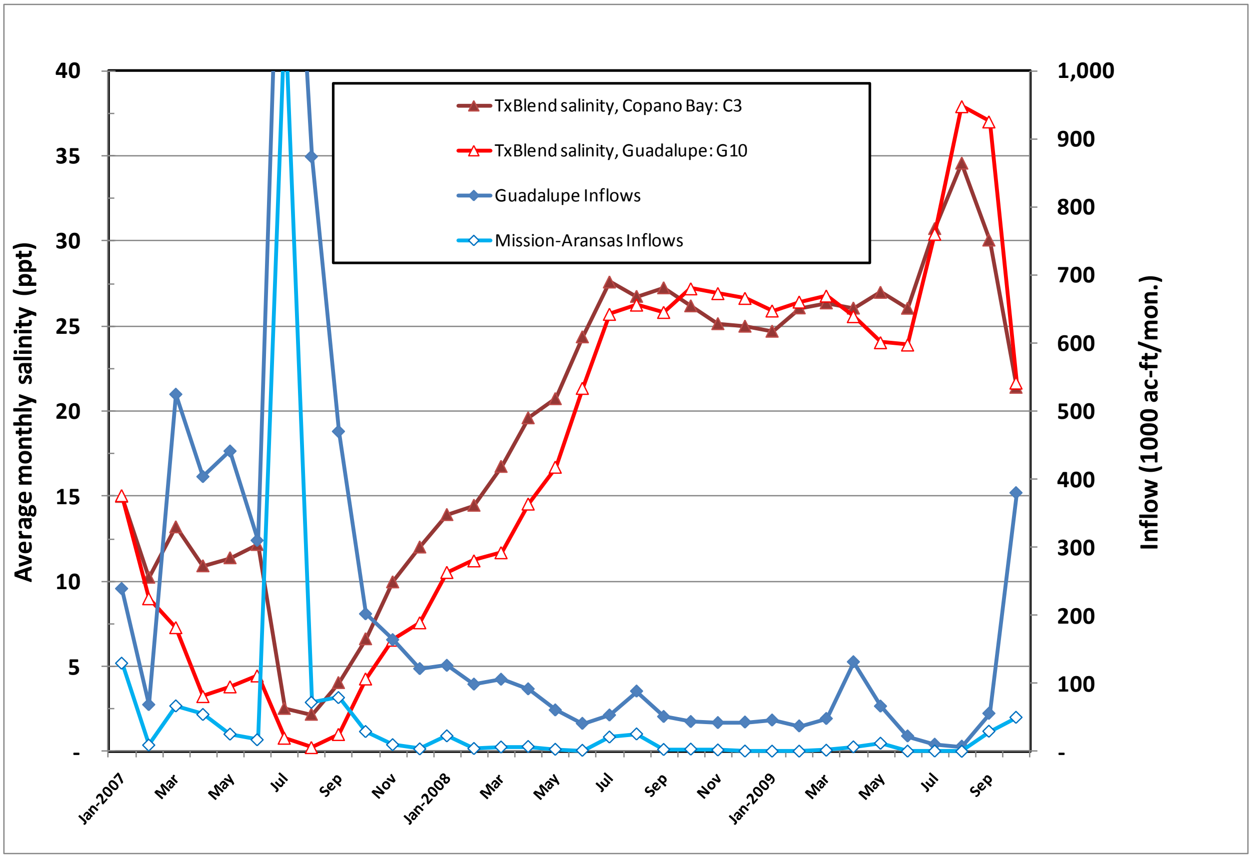


Figure 4.5-8. Salinity inflow behavior at a point in the oyster habitat of Copano Bay (C3) compared to that at a similar point in the Guadalupe oyster are (G10).

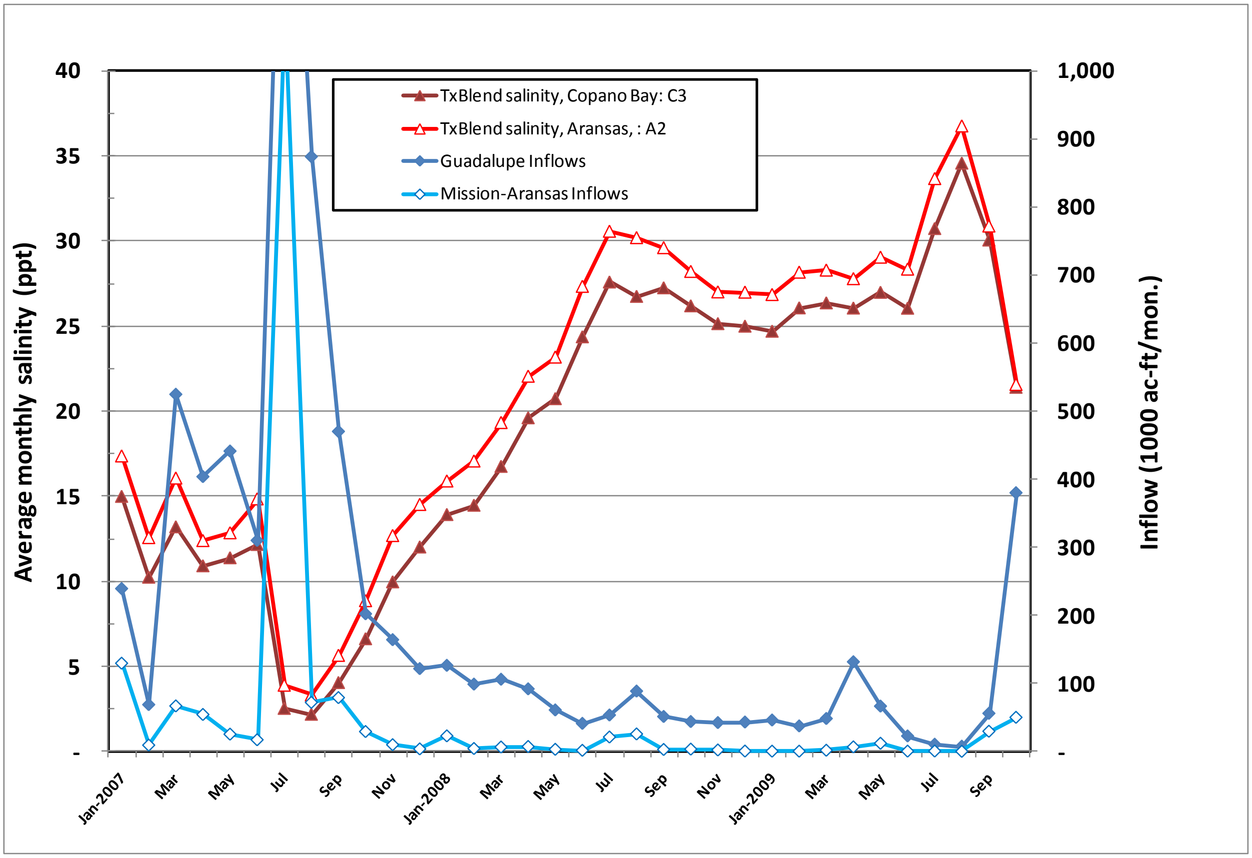


Figure 4.5-9. Salinity inflow behavior at a point near the center of oyster habitat of Aransas Bay (A2) compared to that at a similar point in Copano Bay (C3).

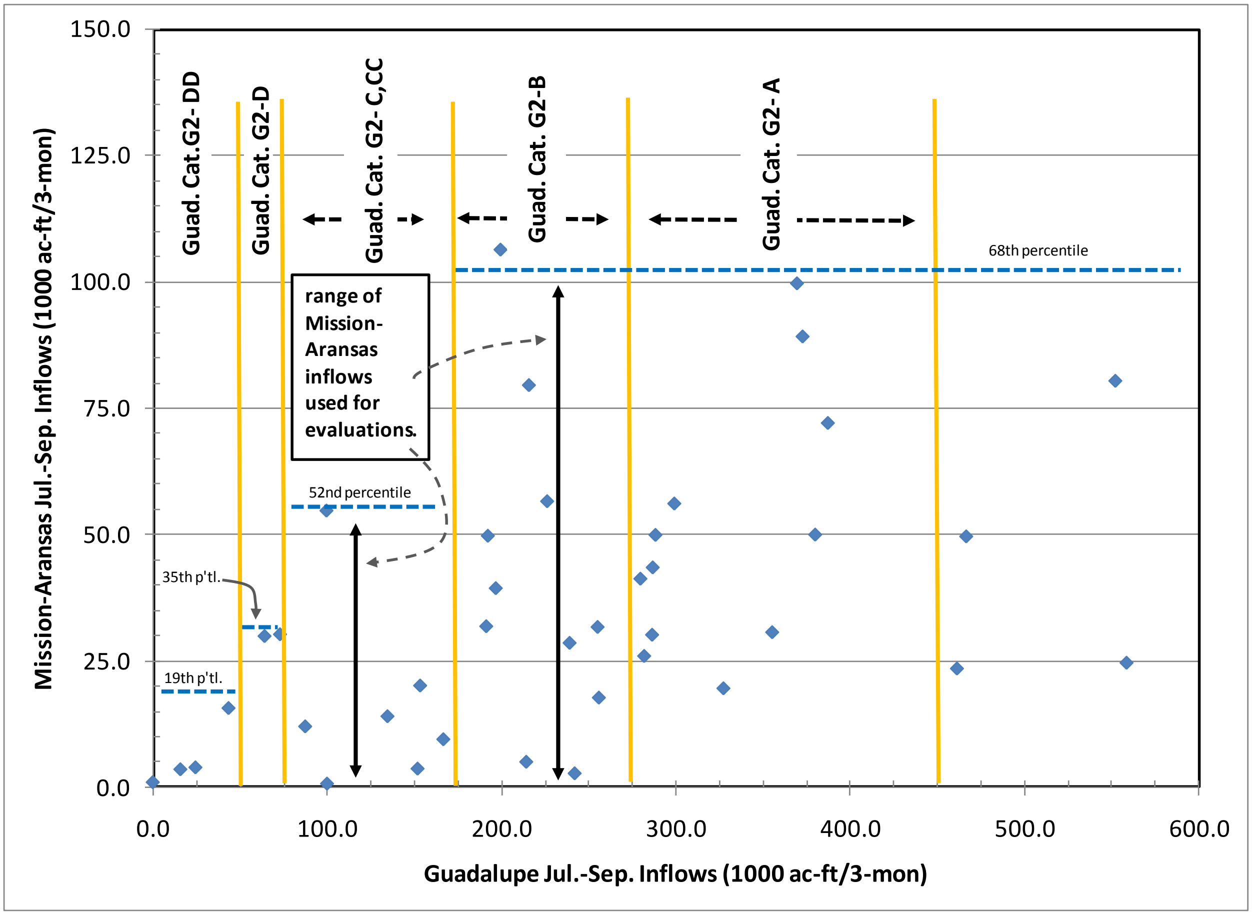


Figure 4.5-10. Inflow combinations utilized in the evaluations of oyster fixed habitats in the Mission-Aransas Estuary in Aransas Bay and Copano Bay.

4.5.2.1 Oysters, Aransas Bay

The Aransas Bay fixed habitat area was subdivided into subareas as shown in Figure 4.5-11. As before, salinity - inflow regression equations were applied at each point but in this case they were of the form previously described with both Guadalupe and Mission-Aransas inflow terms. The results of the joint inflow analyses for the Aransas Bay oyster area are summarized in Table 4.5-4. Ignoring for the moment the row with a criteria labeled “G2-A-Prime,” this analysis found that most levels of previously derived Guadalupe Estuary inflow criteria for oysters provide measurable, but lesser suitability conditions for oysters in Aransas Bay. For instance, while criteria G2-A provides 100% WUA and salinities in the range of 11-18 ppt (Table 4.5-2) in the Guadalupe Estuary oyster area, here that same level of inflow provides WUA and salinity responses of 78-100% and 18-24 ppt, respectively. This general trend carries through the range of Guadalupe Estuary criteria, with a lesser but comparable WUA response and somewhat higher salinities. This leads the GSA BBEST to conclude, with one substantial exception, that the established Guadalupe Estuary criteria are suited for protecting the Aransas Bay oyster habitat. The notable exception is that the highest level of inflow in the G2-A category would just begin to result in salinities in the favorable 10-20 ppt range for oysters (see Figure 4.4-2). Given that there is some scientific uncertainty in the shape of that curve the GSA BBEST feels that it would be beneficial to also strive for salinity toward the lower end of that 10 - 20 range occasionally.

To examine how this could be accomplished the BBEST evaluated the salinity and WUA response of a higher level of inflow from both the Mission-Aransas and Guadalupe sources. Raising the Mission-Aransas Jul.-Sept. inflows up to the 500 - 1000 thousand ac-ft range (92nd - 98th percentiles) would lower salinity into the 17-20 range as indicated. Much more effective results were obtained by raising the Guadalupe Estuary inflow to the level of 450 - 800 thousand ac-ft. for Jul.-Sept. (60th - 82nd percentiles) resulting in salinities in the range of 15-22 ppt. These higher inflows from the Guadalupe occurred 10 years in the historic record and because of their obvious benefit to the oysters in Aransas Bay, the GSA BBEST recommends that these continue to occur in the future at 75% of the historic occurrence (roughly 8 years out of 69).

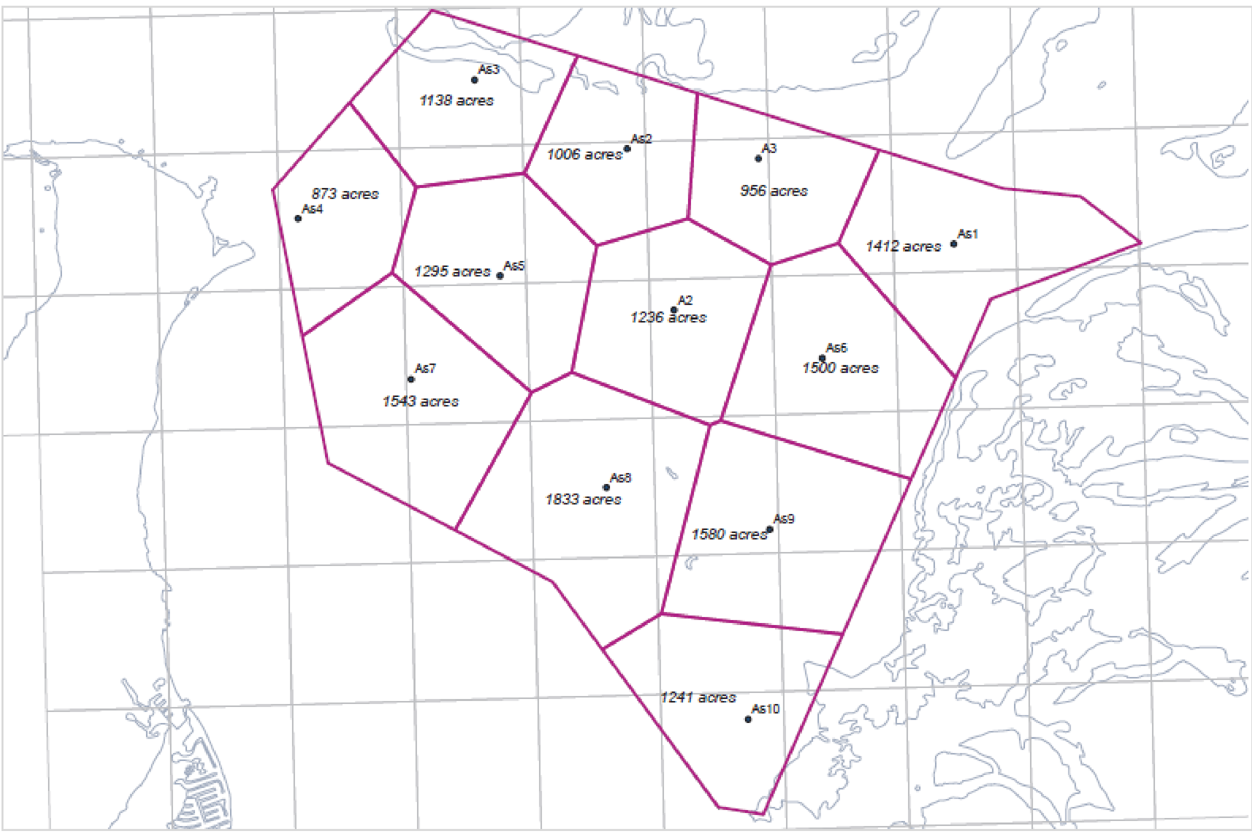


Figure 4.5-11. The division of the Aransas Bay oyster fixed habitat into subareas. (map courtesy of Lynne Hamlin, TPWD).

Table 4.5-4. Examining combinations of Guadalupe Estuary and Mission-Aransas Estuary inflows on the status of oysters in the Aransas Bay habitat area using the salinity zone approach.

Guadalupe inflow criteria [1000 ac-ft]		Mission-Aransas Jul.-Sep. inflow range [1000 ac-ft]	Salinity & Weighted Useable Area objectives in Aransas oyster area Jul.-Sep.		Co-occurrence of Guadalupe / Miss.-Aran. inflows [% yrs]	example years
Criteria level	July-Sept. inflows [1000 ac-ft]		WUA in oyster habitat	Approx. avg. salinity (ppt.)		
G2-Aprime	450-800	1- 110	94 - 100%	15 - 22	10 yrs / [14%]	'98,'92,'75
Criteria levels G2-Aprime, total historic occurrence 10 years (14%).						
Recommended occurrence in future 75% of historic (8 years/ 12%)						
MA2-Aprime	275 - 450	500 - 1000	99-100%	17 - 20	1 yr / [2%]	1983
Criteria levels MA2-Aprime, total historic occurrence 1 year (2%).						
Recommended occurrence in future 75% of historic (1 year/2%)						
G2-A	275 - 450	1- 110	78 - 100%	18 - 24	12 yrs / [18%]	'05,'95,'93
G2-B	170 - 275	1- 110	64 - 94%	21 - 27	11 yrs / [16%]	'08,'99,'88
G2-C, CC	75 - 170	1- 60	38 - 77%	24 - 32	7yrs / [10%]	'00,'82,'69
G2-D	50 - 75	1 - 35	26 - 50%	30 - 35	2yrs / [3%]	'09,'89
G2-DD	0 - 50	0 - 20	0 - 36%	33- >40	4 yrs / [4%]	'54,'56,'84

4.5.2.2 <u>Oysters, Copano Bay</u>

A similar analysis of the oysters in the fixed habitat of Copano Bay was performed. The details of this habitat are shown in Figure 4.5-12. Table 4.5-5 presents the results again in which the drivers are the inflow criteria levels of the Guadalupe Estuary oyster analyses (criteria series "G2") and coupled with similar levels of Mission-Aransas inflows. The reader is reminded of the results shown in Figure 4.5-9 that salinity levels in Copano Bay generally are about 5 ppt less saline than those of Aransas Bay (this was examined for a wide range of inflow conditions). Overall the results of this analysis found that the established inflow criteria for oysters in the Guadalupe Estuary would provide a good level of support to the oysters in Copano Bay.

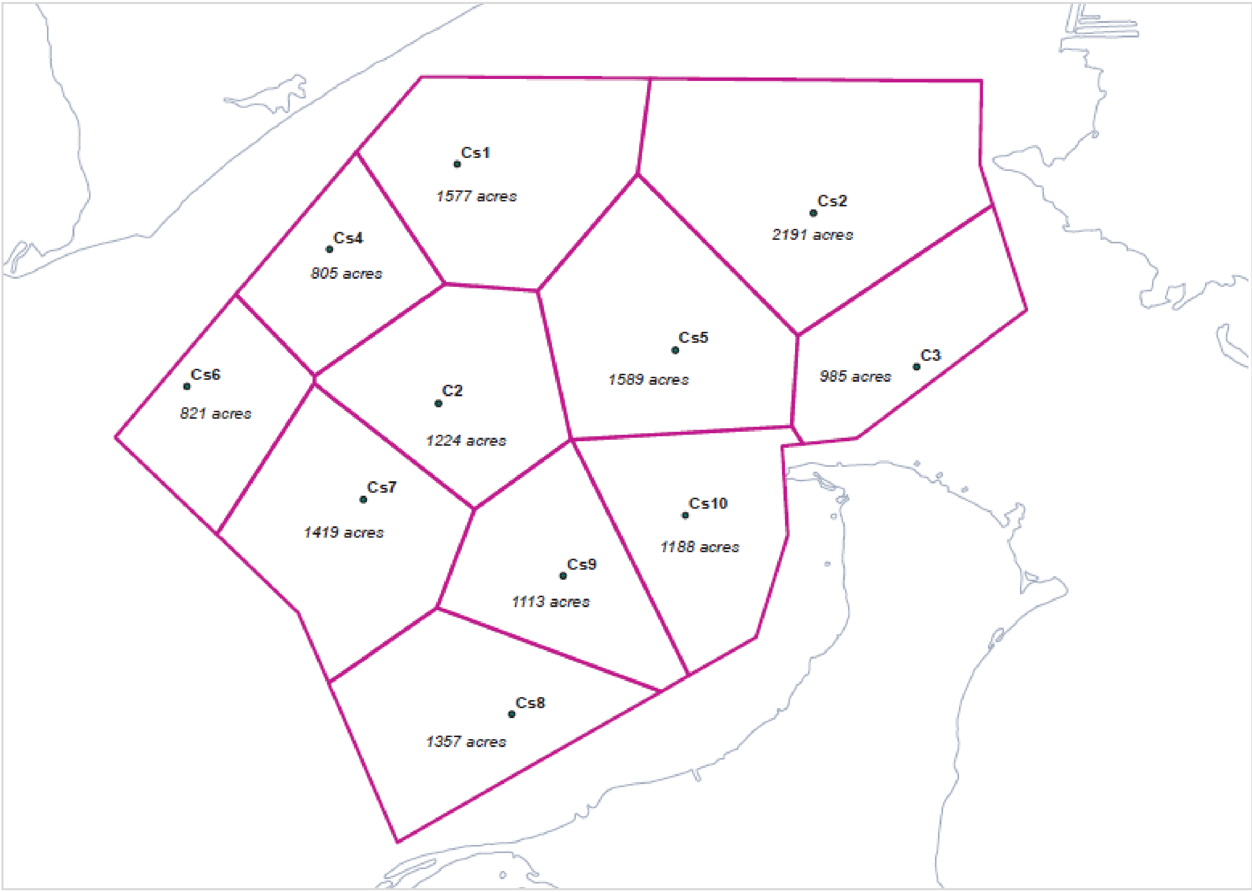


Figure 4.5-12. The division of the Copano Bay oyster fixed habitat into subareas. (map courtesy of Lynne Hamlin, TPWD).

Table 4.5-5. Examining combinations of Guadalupe Estuary and Mission-Aransas Estuary inflows on the status of oysters in the Copano Bay habitat area using the salinity zone approach.

Guadalupe criteria level		Mission-Aransas Jul.-Sep. inflow range [1000 ac-ft]	Salinity and Weighted Useable Area objectives in Copano oyster area Jul.-Sep.		Co-occurrence of Guadalupe / Miss.-Aran. inflows [% yrs]	example years
Criteria level	July-Sept. inflows [1000 ac-ft]		WUA within oyster habitat	Approx. avg. salinity (ppt.)		
G2-A	275 - 450	1- 110	95 - 100%	13 - 21	12 yrs / [18%]	'05,'95,'93
G2-B	170 - 275	1- 110	83 - 100%	16 - 23	11 yrs / [16%]	'08,'99,'88
G2-C, CC	75 - 170	1- 60	63 - 99%	18 - 27	7yrs / [10%]	'00,'82,'69
G2-D	50 - 75	1 - 35	53 - 83%	23 - 29	2yrs / [3%]	'09,'89
G2-DD	0 - 50	0 - 20	0 - 69%	26- >40	4 yrs / [4%]	'54,'56,'84

4.5.2.3 Rangia, Copano Bay

The fixed habitat for rangia in Copano Bay is detailed in Figure 4.5-13. A very similar set of analyses as described above for oysters was performed here, with the inflows set to examine the established Guadalupe Estuary rangia criteria (series "G1") in combinations with similar ranges of Mission-Aransas inflows as illustrated in Figure 4.5-14.

The results of this analysis are presented in Table 4.5-6. The GSA BBEST found that good conditions for rangia in this fixed habitat are difficult to achieve and appear to be rare overall. Most of the criteria established for rangia in the Guadalupe Estuary, in combination with a wide range of Mission-Aransas inflows, do not provide commensurate benefit here. As for Aransas Bay oysters we also evaluated the influence of higher inflows from the Guadalupe drainage and the Mission-Aransas drainage. Here we find that a higher tier of inflows from either drainage would be of benefit to the rangia in Copano Bay. Most common are the higher inflow in the range of 550 - 925 thousand ac-ft in the Mar.-May period from the Guadalupe. This level of inflow occurred 11 years in the historic record and we recommend that is continue to occur at 75% of the historic level. For more locally- derived inflows we also recommend that very high Mission-Aransas inflows in the range of 125 - 860 (the maximum to occur in the combined Mission-Aransas drainage) should continue although they are rare events.

One final note about the Copano Bay rangia area comes in light of the new field-measured data from the Mission-Aransas National Estuarine Research Reserve (NERR) station called Copano West (see Figure 4.2-3). As shown in Figure 4.5-15, the TxBlend model may have difficulty predicting salinity response to low inflow periods in this area. The discrepancy at the very high salinities, if limited to that range of salinity, would not affect the results derived for rangia in this area, but further investigation of the adequacy of the prediction at lower salinities should be pursued.

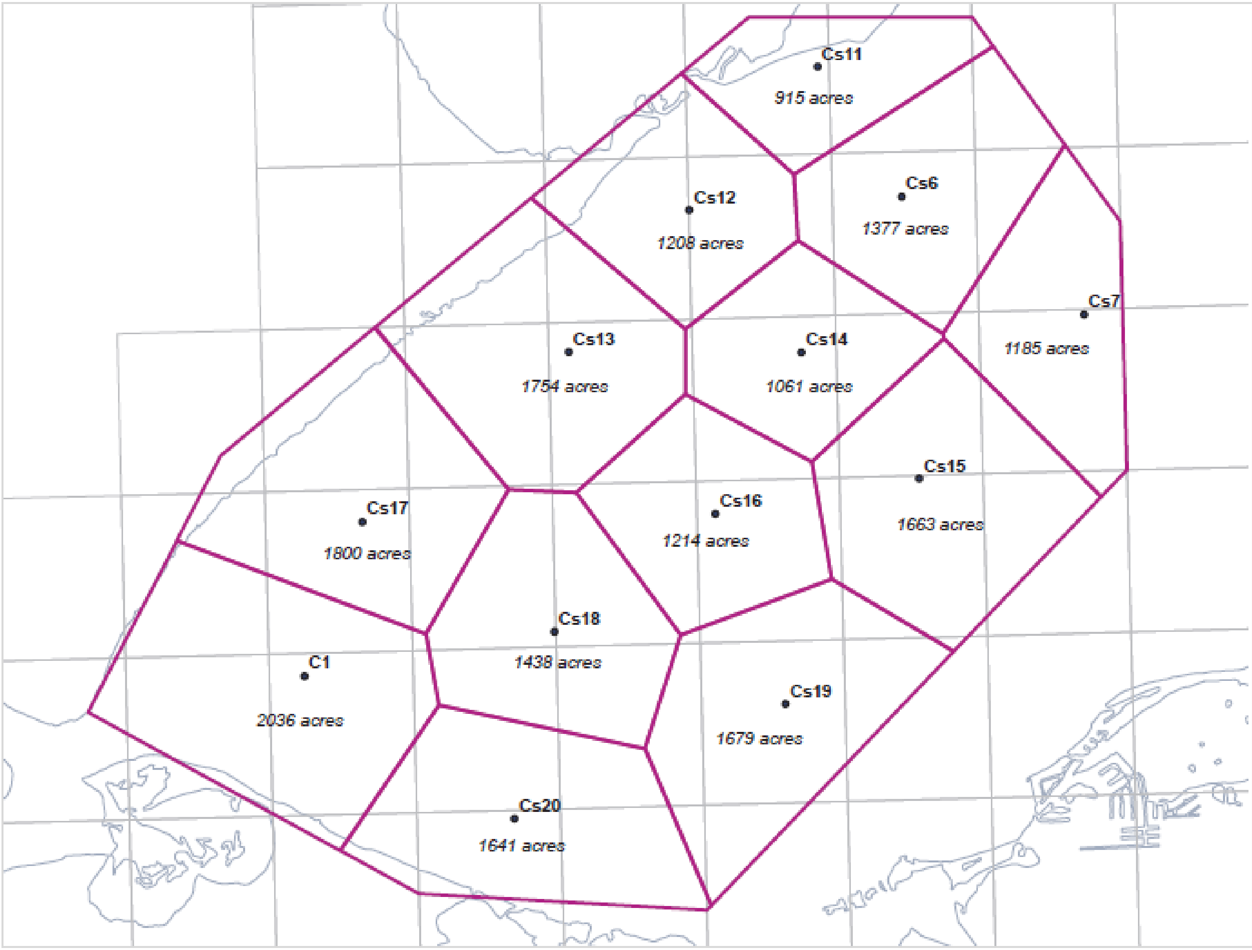


Figure 4.5-13. The division of the Copano Bay rangia fixed habitat into subareas. (map courtesy of Lynne Hamlin, TPWD).

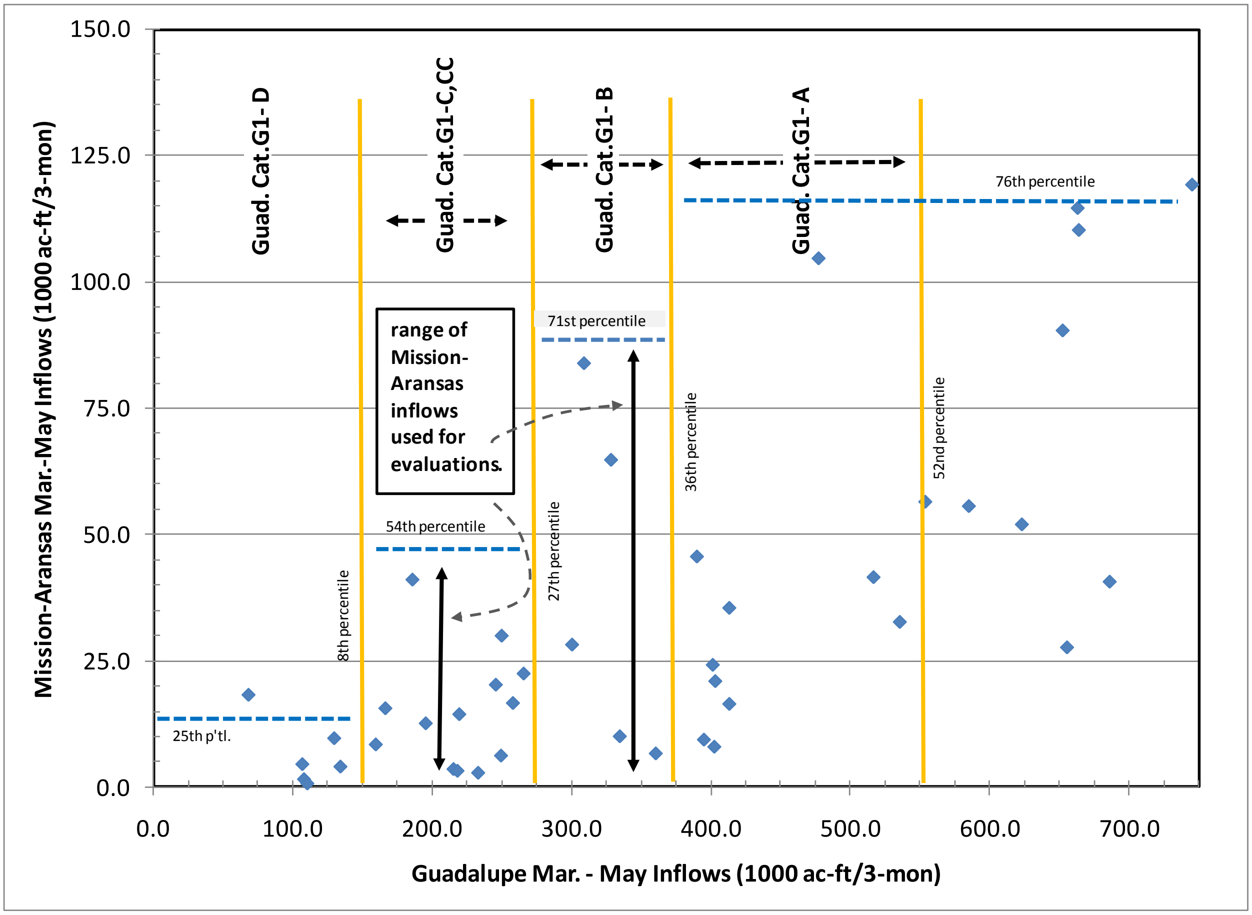


Figure 4.5-14. Inflow combinations utilized in the evaluations of rangia fixed habitats in the Mission-Aransas Estuary, Copano Bay.

Table 4.5-6. Examining combinations of Guadalupe Estuary and Mission-Aransas Estuary inflows on the status of rangia in the Copano Bay habitat area using the salinity zone approach.

Guadalupe inflow criteria		Mission-Aransas	Salinity-biology results in Copano rangia area, Mar.-May			Co-occurrence of Guadalupe / Miss.-Aran. inflows [% yrs]	example years
Criteria level	Mar.-May inflows [1000 ac-ft]	Mar.-May inflow range [1000 ac-ft]	No. mons. whole area supports reproduction	Avg. monthly area supporting reproduction	Approx. avg. salinity (ppt.)		
G1-Aprime	550 - 925	50 - 125	0 - 3	11 - 100%	7 - 11	11 yrs / [16%]	'03,'01,'94
Criteria levels G1-Aprime, total historic occurrence 11 years (16%).							
Recommended occurrence in future 75% of historic (8 years/ 12%)							
MA-1prime	375 - 550	125 - 1000	2 - 3	73 - 100%	7 - 10	1 year [1.5%]	1981
Criteria levels MA1-Aprime, total historic occurrence 1 years (1.5%).							
Recommended occurrence in future >= 1 year							
G1-A	375 - 550	0 - 125	0	0 - 73%	9.6 - 17	10 yrs / [14%]	'02,'99,'95
G1-B	275 - 375	0 - 95	0	0%	12 - 19	5 yrs / [7%]	'90,'86,'53
G1-C	150 - 275	0 - 50	0	0%	14 - 21	13 yrs / [19%]	'09,'08,'89
G1-D	0 - 150	0 - 15	0	0%	18 - >40	5 yrs / [9%]	'54,'55,'96

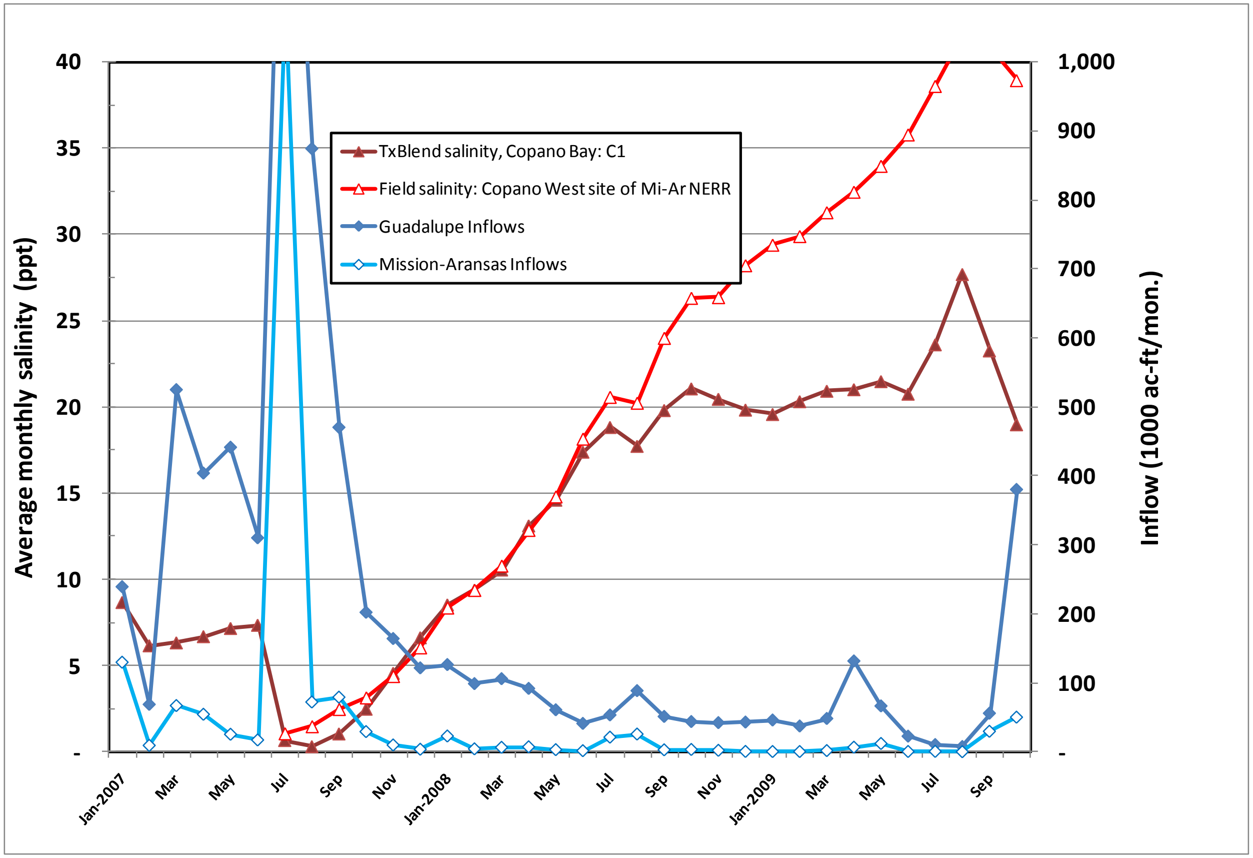


Figure 4.5-15. Illustration of the potential limited capacity of the TxBlend model to predict salinity response in the rangia fixed habitat area of the Mission-Aransas Estuary, Copano Bay.

4.5.3. Other Focal Species Analyses

4.5.3.1. White Shrimp (Motile Species) Analysis

1. White shrimp abundance in Texas Parks and Wildlife, Coastal Fisheries Database

Sampling data from the TPWD Coastal Fisheries Monitoring Program over the 28 year period of 1982 – 2009, was examined for the Guadalupe-San Antonio-Espiritu Santo Bays system, consisting of 6720 trawl and 6720 bag seine samples. These gear types collect mostly motile organisms, either nektonic or epibenthic species. Of the dominant species that comprised 95% of samples collected (16 such motile species in trawls and 21 motile species in bag seines), white shrimp (*Litopenaeus setiferus*) were identified as a major species, comprising 9% in trawl samples, 8% in bag seines, during the appropriate seasons. Ecologically, white shrimp are also known to be very important in the food webs of these bays. Consequently, based on these criteria, white shrimp, despite its motile behavior, was considered as a candidate focal species for further analyses of FWI requirements.

Based on the monthly relative abundance results (termed CPUE or catch per unit effort), white shrimp occur in San Antonio Bay only in summer and fall, between July and Dec. (see Figures 4.5-16 and 4.5-17 for trawls or seines, respectively). There was also an apparent high correlation of white shrimp CPUE with low salinity in the 0 – 12 psu range. However, as discussed earlier in Sec. 4.3, the previous data from literature references cautions that this abundance-salinity relationship may be a spurious autocorrelation and not a causal one. Therefore, we judged it was best to forego a salinity zone analysis relating FWI regimes to a "preferred" white shrimp target salinity zone of 0 – 12 psu. Instead, we designed an analysis to directly relate white shrimp relative abundance (CPUE) statistically to FWI regimes over the 1984 to 2009 period that is covered by the TPWD Monitoring Program database.

2. GIS analysis of white shrimp distribution under different inflow regimes

Because Coastal Fisheries sampling is conducted according to a geospatial grid sampling design, we decided to examine the spatial distribution of shrimp samples in the bay under different inflow years. Using GIS techniques, we first mapped the spatial distribution of shrimp samples for a number of years which varied widely in inflow regimes (see Appendix 4.5.3-1 white shrimp catch data). Four years of very low inflow during the July through September period were chosen (1984, 1988, 1996, and 2008 representing a 3-month cumulative inflow range of 40,000 – 72,000 acre-ft). Five years of moderate to high inflow during this period were chosen (1987, 1993, 2001, 2005, and 2007, representing a 3-month cumulative inflow range of 146,000 – 309,800 acre-ft). When sample distribution maps were produced, two distinct results were observed (see example maps in Figures 4.5-18,-19,-20,-21). Under the lowflow years, shrimp generally concentrated (i.e. largest sample numbers were observed) in the middle to upper portion of San Antonio Bay (Figure 4.5-18 & Figure 4.5-19 for 1988 and 1996). This also corresponded to lower salinities in the upper part of the bay, nearer the freshwater inflow from the Guadalupe River. Under higher inflow years, shrimp samples were more evenly distributed over the entire bay. Under the highest inflow years (Figure 4.5-20 & Figure 4.5-21 for 1987 and 2007), highest catches appeared to be found in the lower part of the bay. This distribution pattern led us to propose that shrimp were selecting habitat in the bay (fresher areas) in direct response to the influence of FWI.

Next, we decided to partition the San Antonio Bay system and separate the samples into upper and lower bay groups. The objective was to define a target bay zone where FWI conditions appeared favorable to shrimp and provided good habitat under the lower-flow regimes. After an initial trial using the GIWW as a boundary, we found that better separation was achieved using a boundary line higher up in middle San Antonio Bay. This actually separated Upper from Middle San Antonio Bay at the north edge of the target oyster reef zone (Fig. 4.5-22).. Based on the CF grid numbers, this line of separation was between rows 67-74 and rows 78-84. Then we calculated the average shrimp CPUE for samples in each area above and below this boundary line, that is, "upper San Antonio Bay" and "lower San Antonio Bay". In addition, since the samples in Espiritu Santo Bay contained very few shrimp (mostly CPUE values of 0) and flow generally was going southward toward Aransas Bay (based on the salinity gradient), we eliminated the Espiritu Santo samples from consideration in the "lower San Antonio Bay" calculation for the rest of the analysis.

3. Graphic analysis of white shrimp abundance related to inflow regimes

Next, we calculated the ratio of the shrimp CPUE in upper SA Bay to the total average shrimp CPUE in the entire SA Bay area for each of the 26 years. When multiplied by 100, this ratio gives the percentage of the concentration of shrimp in the upper bay area. A frequency histogram for 26 years of data in Fig.4.5-23 shows a somewhat bimodal distribution for the years. Then, the partitioning ratio of shrimp in the upper bay to total shrimp in the bay was plotted for each year against the cumulative inflow for the July through September period as shown in Fig.4.5-24, giving a curve with an R^2 of 0.405. When the antecedent flow for June was added to the cumulative 3-month flow, and re-plotted against the shrimp partitioning ratio (Fig. 4.5-25), the R^2 improved to 0.518, an indication that the 1-month antecedent June flow was contributing to the positive inflow effect. These results are consistent with the spatial observations that white shrimp tend to move into the portion of the bay that is directly influenced by the FWI.

4. Correlation between shrimp abundance and Freshwater Inflow.

In addition, we also performed a direct correlation analysis to determine the statistical relationship between cumulative June through Sept FWIs and total shrimp catch in the bay. This was evaluated 3 ways:

i. Plotting shrimp catch (total number in San Antonio Bay only) vs. 4-month combined inflow (Fig. 4.5-26)
ii. Plotting shrimp avg CPUE vs. 4-month combined inflow (Fig. not shown)
iii. Plotting shrimp median CPUE vs. 4-month combined inflow (Fig. not shown)

This direct correlation indicated that shrimp abundance over the 3-month July-Sept period was positively correlated with 4-month FWI, although the trend is again 'noisy' and non-linear. The highest R^2 was obtained for an exponential function fitted to the curves for total catch numbers, although a linear regression showed only R^2.around 0.33). Upon examination of the fitted curves (4.5-26), it appears that shrimp catch gradually declined below a 4-month total inflow value around 500,000 acre-ft. Further, out of 26 years, shrimp catch was about 50% lower approx. 8-9 years (some 30% of the yrs) when flows were lower than 250,000 ac-ft.

5. Interpretation of Inflow Requirement for White Shrimp Abundance

At this point, a definite trend is observable that FWI is providing a favorable low salinity habitat or estuarine zone for white shrimp. However it is difficult to identify a precise required inflow regime because of variation in response based on only these 26 years of samples. Our best interpretation is that over the range of low inflows (100,000 to 150,000 acre-ft) in July through Sept, very few white shrimp were caught in the bay (eg.1988, 2000, 2009). As inflows increased toward 250,000 ac-ft, catch rates steadily increased, until peaking out around 700,000 ac-ft. (eg. 2003). Above 1,000,000 ac-ft, a level reached during a number of very wet years, catch rates declined some years (1992, 1997, 2002), while in other years (eg.2004, 2007),very high numbers were present. We would argue therefore that inflows up to 600,000 to 700,000 ac-ft over this summer-fall period are quite beneficial to white shrimp. Below 250,000 ac-ft, there would appear to be a significant limiting effect on abundance, probably related to reduction in favorable habitat produced by reduced FWI.

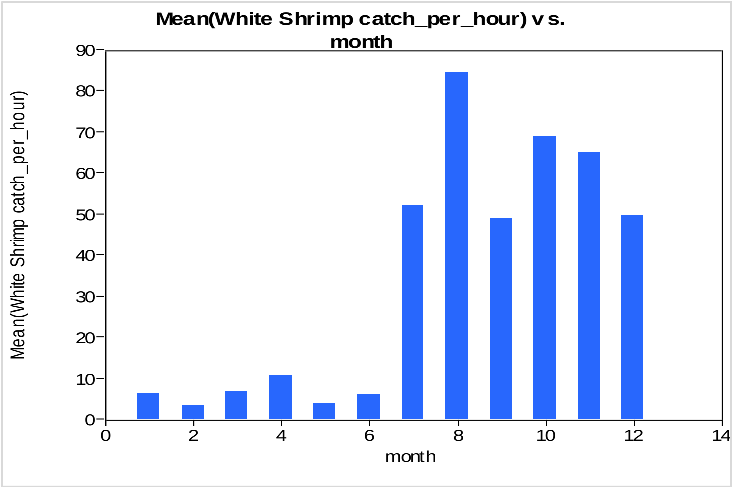


Figure 4.5-16. White Shrimp Seasonality from TPWD Trawls

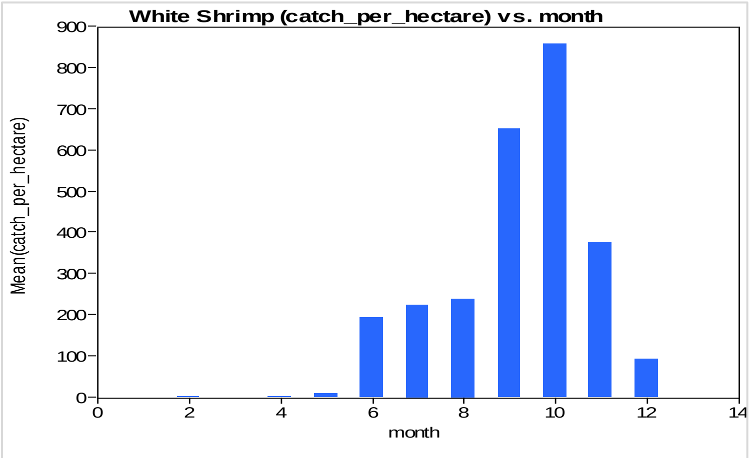


Figure 4.5-17. White Shrimp Seasonality from TPWD Bag Seines

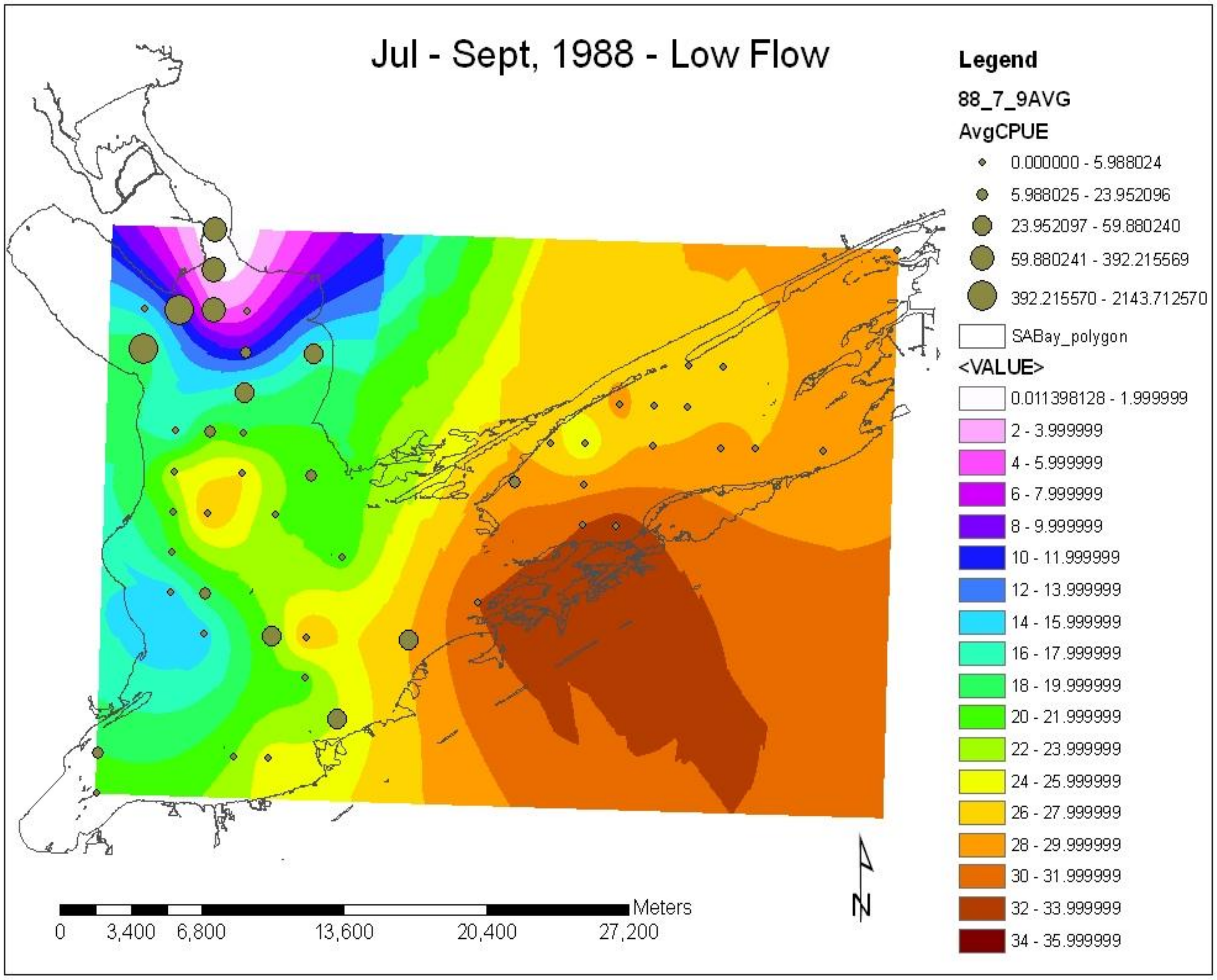


Figure 4.5-18. GIS map showing distribution of white shrimp samples and relative catch rate (as average CPUE) from TPWD Coastal Fisheries Monitoring database for July through September, 1988, in San Antonio Bay system.

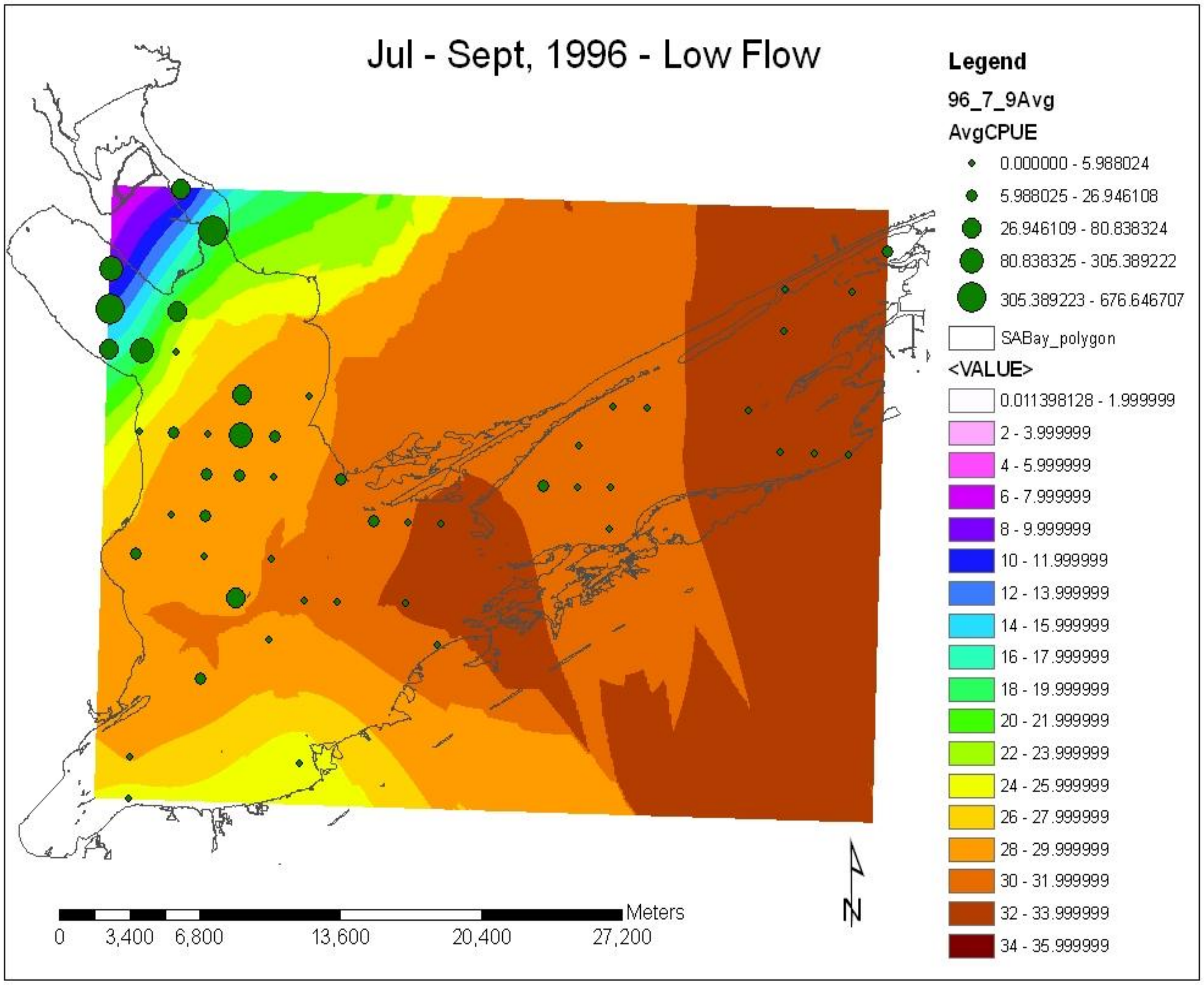


Figure 4.5-19. GIS map showing distribution of white shrimp samples and relative catch rate (as average CPUE) from TPWD Coastal Fisheries Monitoring database for July through September, 1996, in San Antonio Bay system.

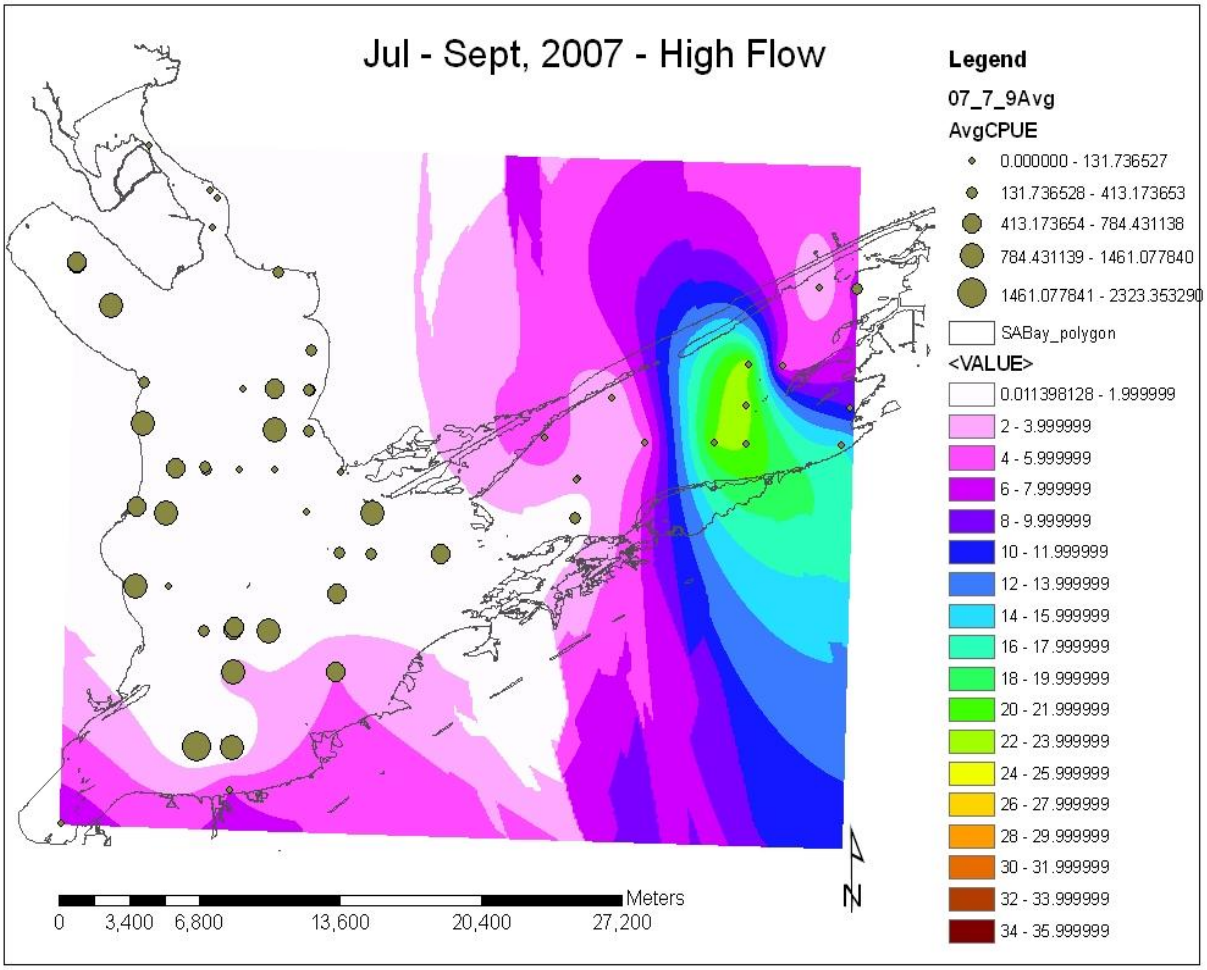


Figure 4.5-20. GIS map showing distribution of white shrimp samples and relative catch rate (as average CPUE) from TPWD Coastal Fisheries Monitoring database for July through September, 2007, in San Antonio Bay system.

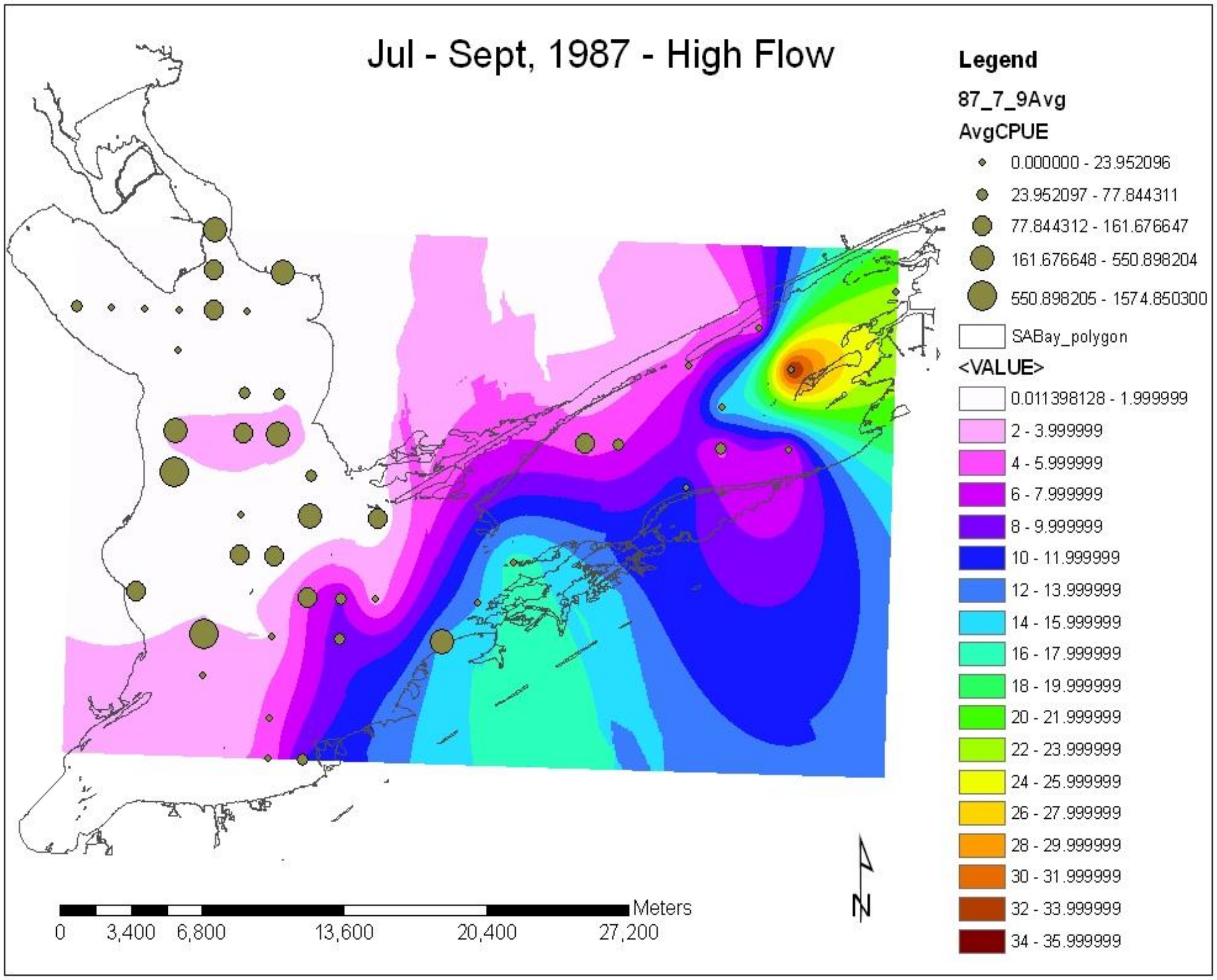


Figure. 4.5-21 GIS map showing distribution of white shrimp samples and relative catch rate (as average CPUE) from TPWD Coastal Fisheries Monitoring database for July through September, 1987, in San Antonio Bay system.

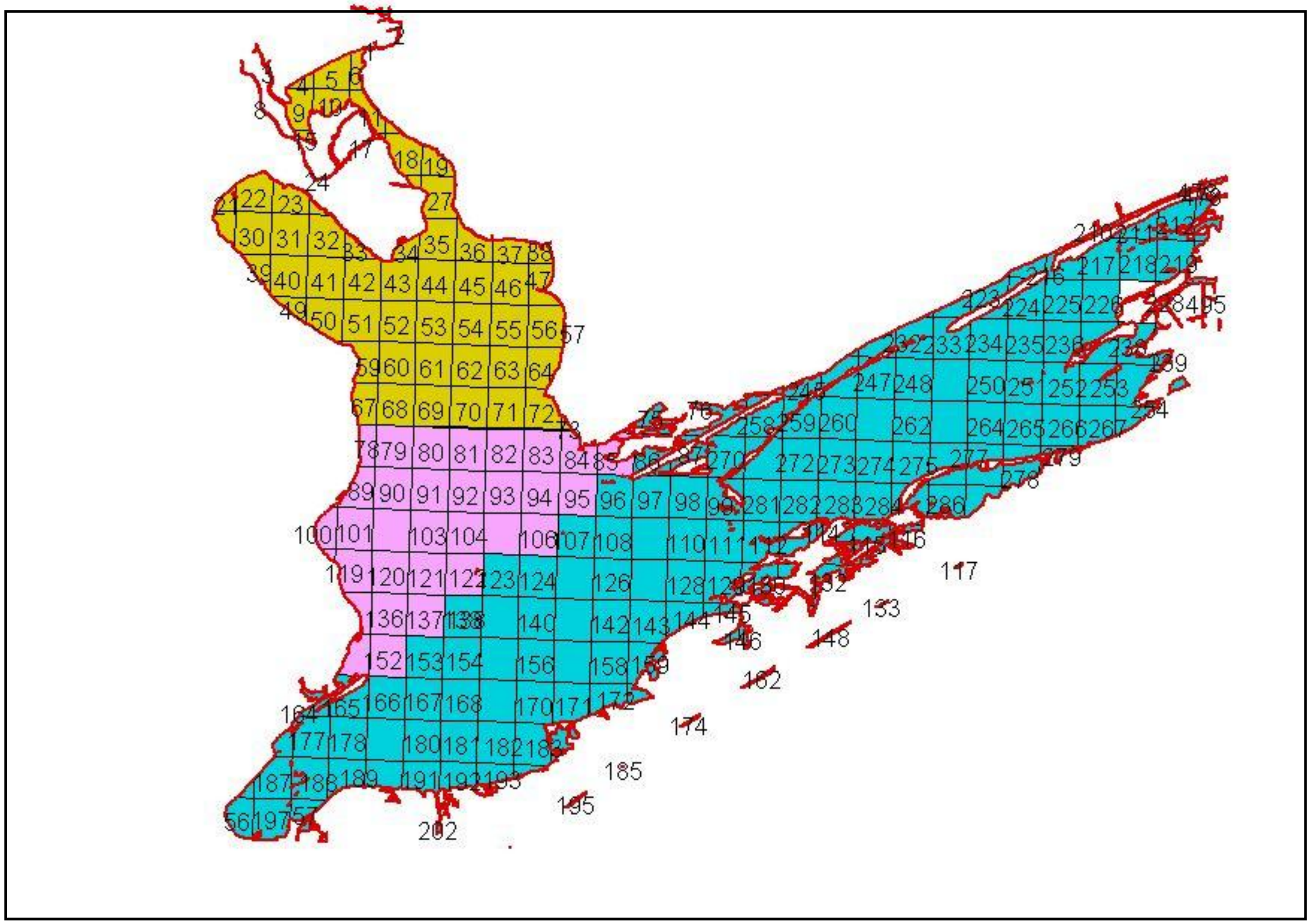


Fig. 4.5-22. TPWD Coastal Fisheries Grid showing partitioning of Upper and Lower San Antonio Bay between grids 67-72 and 78-84. Analysis was done by dropping samples from Espiritu Santo Bay and using only samples from San Antonio Bay proper.

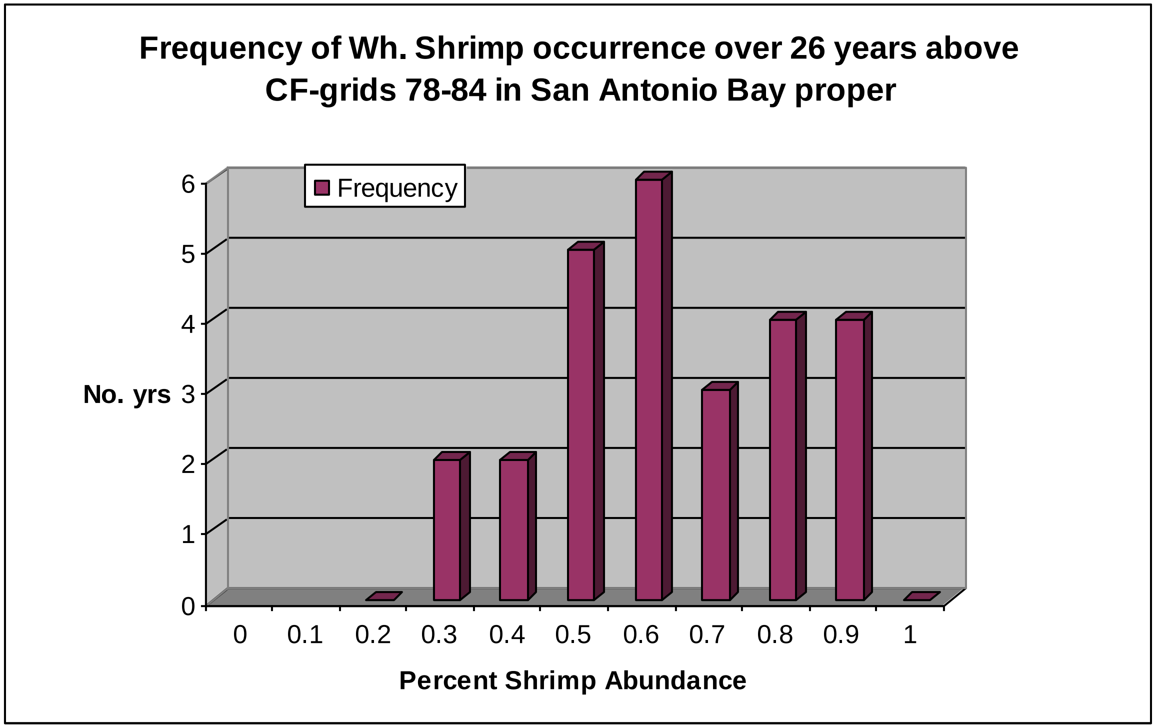


Figure 4.5-23 Frequency Histogram for Number of Years W. Shrimp Ratio of Abundance in upper San Antonio Bay proper fell into different categories between 0 and 1.0.

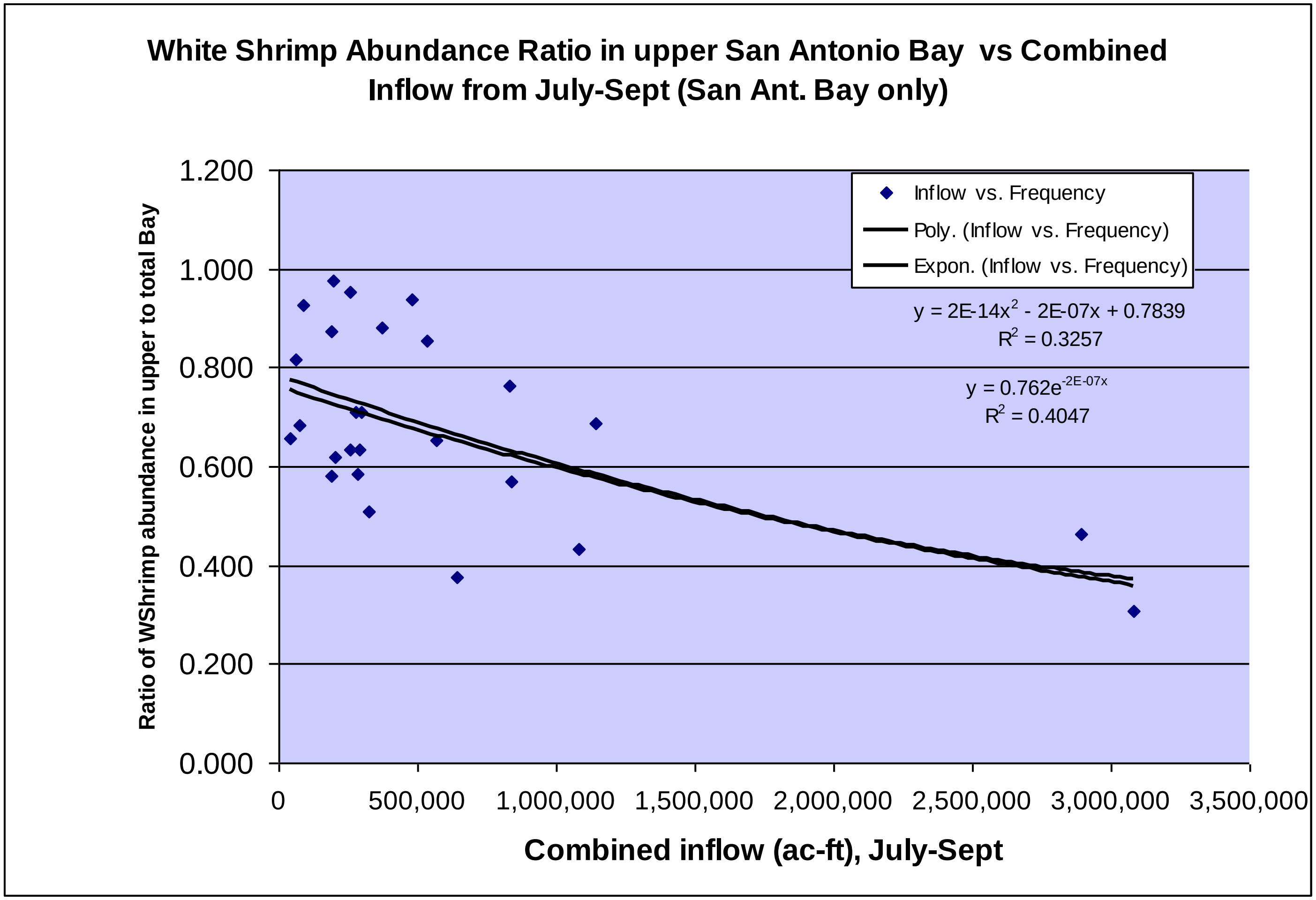


Figure 4.5-24. (July to Sept) Inflow vs. Ratio of shrimp above CF Grid Line 78-84 to Shrimp in entire bay

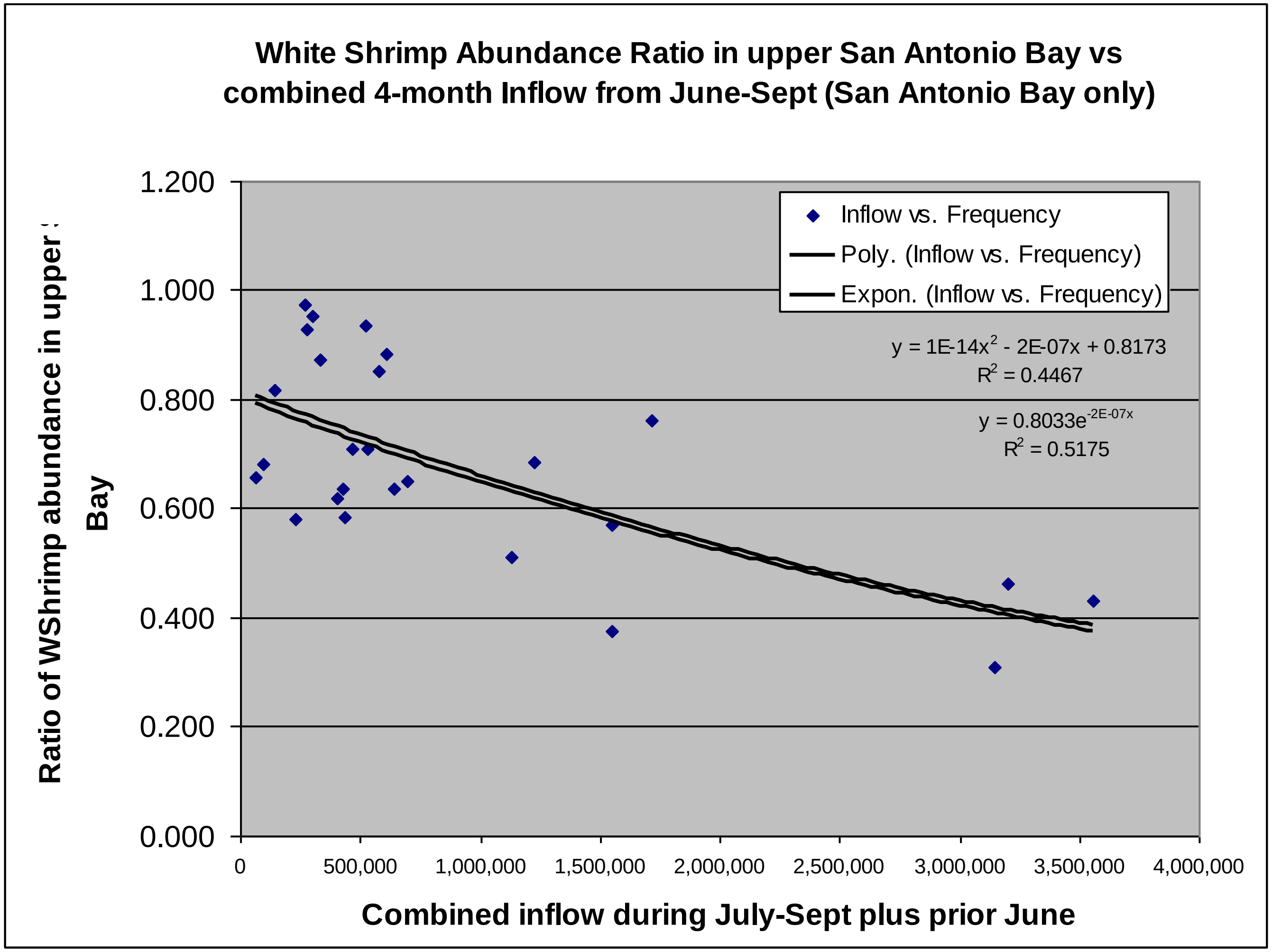


Figure 4.5-25. June + (July to Sept) Inflows vs. Ratio of shrimp above Grid Line 78-84 to shrimp in entire bay.

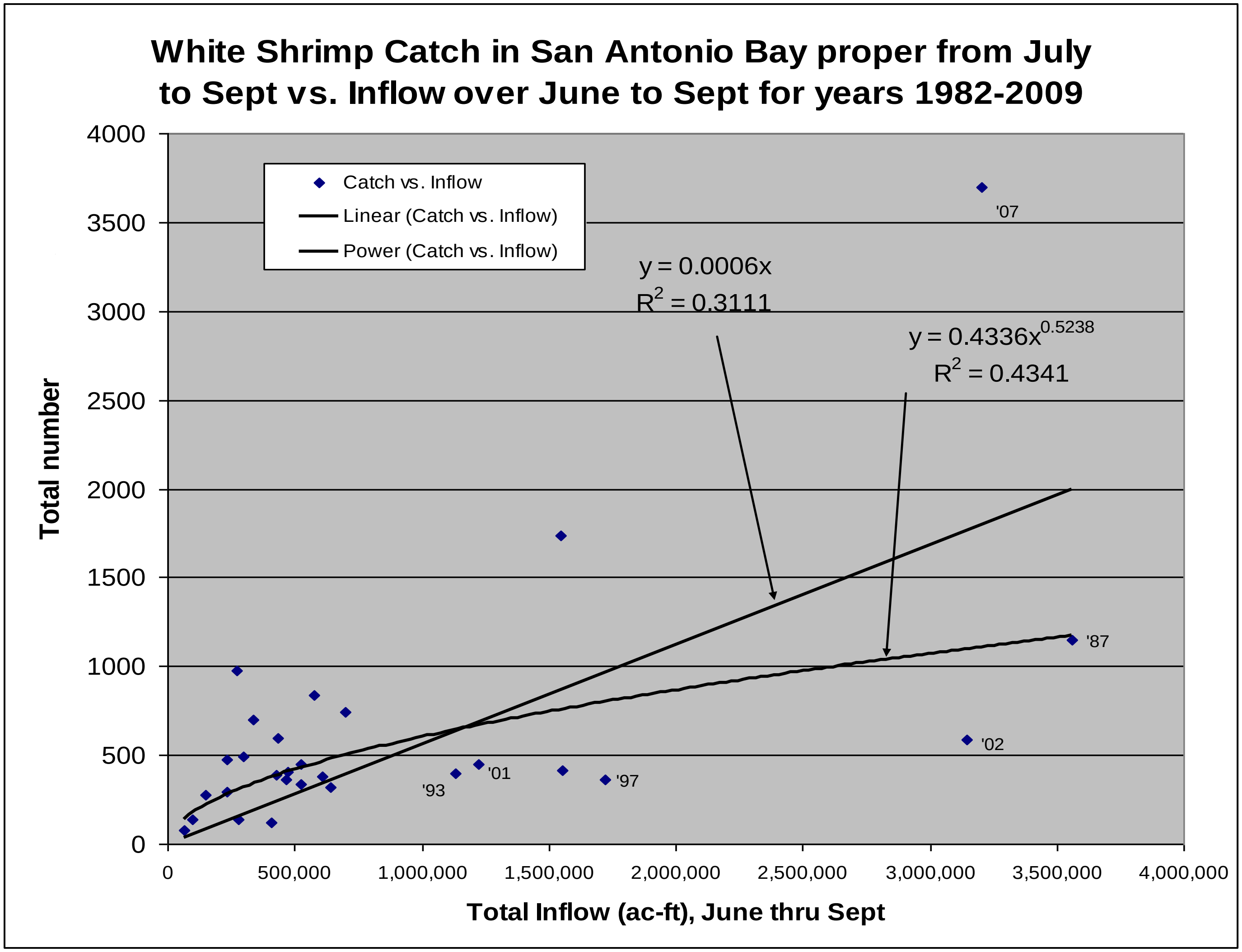


Figure 4.5-26. SHRIMP CATCH (total numbers) in San Antonio Bay, showing positive trend in response to inflows

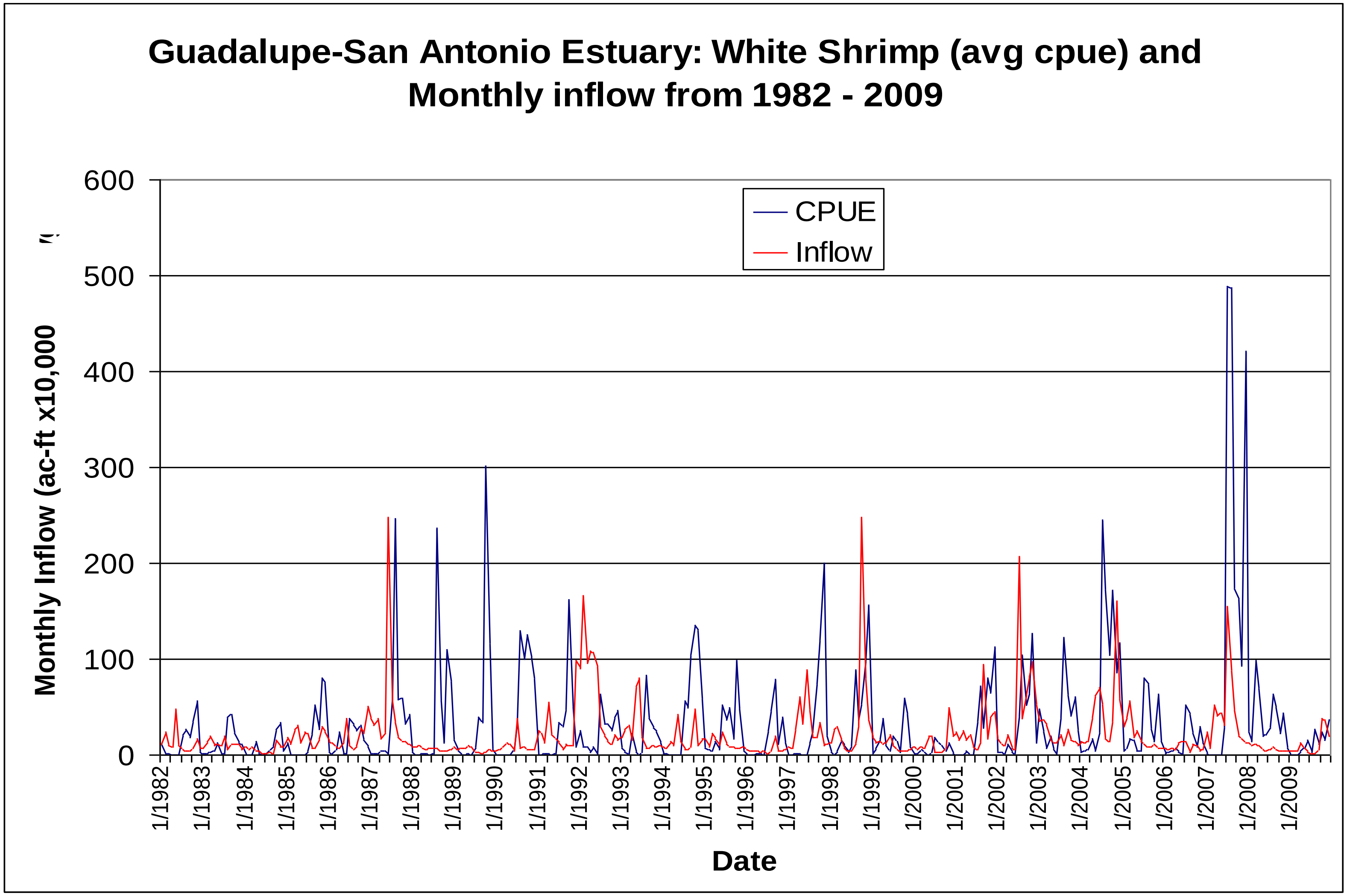


Figure 4.5-27. White Shrimp monthly trawl CPUE and Total monthly Inflow to San Antonio Bay, 1982 -- 2009

4.5.3.2. Blue Crab (Motile Species) Analysis

The overview of blue crabs in the Key Species section (Section 4.3.1.4) described the general decline in blue crab abundance in San Antonio Bay since about 1994. That decline has also been seen in most other Texas bays over that time period, suggesting the cause of the decline is not specific to San Antonio Bay. In addition, the literature reviewed in that section showed that blue crabs are not physiologically restricted by normal estuarine salinity ranges and their populations show little correlation with salinity changes.

Nevertheless, ecologically, blue crabs are known to be very important in the food webs of the bays. In particular, the SAGES study (Slack et al. 2009) showed that blue crabs constitute a major proportion of whooping crane diet when they are available. It has also been inferred that low blue crab abundance in marsh habitats around the Aransas National Wildlife Refuge, wintering home of the whooping crane, is related to whooping crane mortality (Stehn 2001) and the low crab abundance could be a result of high salinity and/or low freshwater inflow. Consequently, blue crab was deemed a candidate focal species for further "special analyses" of FWI requirements.

On 19 November 2010, the BBEST estuarine sub-committee convened a workshop on Blue Crabs held at the University of Texas Marine Science Institute (UTMSI) in Port Aransas, Texas. Technical presentation were given by Dr. Zach Darnell (Post-Doctoral Fellow, UTMSI) on the general life-history of blue crabs and Dr. Mark Fisher (TPWD Coastal Fisheries Science Director) on the status of blue crabs in the Guadalupe and Mission-Aransas Estuaries. Dr. Darnell showed data indicating that early life-stages (zoea and early stage megalope) were restricted to high salinities while later stages (settled juveniles and adults) can tolerate a wide range of salinities (except for mature females which are generally found only in higher salinities near the coast). He also presented data showing that diseases and parasites are a greater problem for blue crabs in higher salinities than in relatively low salinities. Dr. Fisher presented results of 28 years of fishery independent survey data from the TPWD seine, trawl, and gillnet surveys in the Guadalupe and Mission-Aransas Estuaries. All of these surveys, (20 per month per estuary for the seine and trawl and spring and fall surveys for gillnets) are accompanied by concurrent salinity measurements. The annual mean of the sample-site salinity measurements show a varying pattern in mean salinity over the study period with particularly high bay salinities in 1989, 1996, 2000, and 2009. Particularly low salinities were seen in 1987 and 1992, and below average salinities were seen in 1997 and over the period 2002-2005. The pattern of crab abundance, as measured by catch-per-unit-of-effort (CPUE) and using trawl catches as an example, showed relatively low catches from 1982 through 1986, a period of relatively high catches from 1987 through 1994, and rapidly declining and steadily low catch thereafter. Dr. Fisher pointed out that the patterns of CPUE in the bay system and the mean salinity of the whole bay did not match up either within a year or at and time lags. He showed that adult male blue crabs were most commonly caught within a wide salinity range of around 10 to 30 psu. Dr. Fisher also pointed out that the combination of high salinity and high water temperature can be particularly stressful for crabs and low salinity but relatively warm water temperature (a result of high river inflow) can provide a thermal refuge for crabs. He concluded that crabs are declining in abundance all along the Texas coast for unknown reasons but that, nevertheless, blue crabs have a wide salinity tolerance and the blue crabs are not a good indicator species for freshwater inflows.

In January 2011, another symposium on blue crab biology was organized by the Mission Aransas National Estuarine Reserve, headquartered at the University of Texas Marine Science Institute. This symposium was more broadly organized around addressing general blue crab biology as opposed to concentration on freshwater inflow effects. Nevertheless, much pertinent information for our purposes was included. Drs. Darnell and Fisher presented information to the attendees similar to that described above. In addition, Dr. David Eggleston, North Carolina State University, and Dr. Dan Rittschof, Duke University, presented information on blue crab biology in Mid-Atlantic estuaries. Their work has shown that blue crab populations are regulated by a complex of factors. Their study area is often characterized by potential periods of excessive freshwater inflow as opposed to the potential for extended periods of low freshwater inflow seen in our estuaries. These high inflow periods can be detrimental by displacing crabs down estuary and by causing high mortality of the immigrating megalpoe stage. On the other hand, higher salinity periods may allow crabs to move higher up the estuary to take advantage of additional suitable habitat, although Dr. Eggleston reported that a period of higher salinity did not result in higher blue crab populations. Dr. Eggleston showed data that high tides from passing tropical storms result in higher recruitment of young crab stages and subsequent high juvenile and adult crab populations, suggesting crab population may be limited by recruitment (i.e. too few very young crabs entering the estuary). Other potential limitations for crab populations, such as limited habitat for young juveniles (e.g. marshes and seagrasses) and parasites and diseases, were also discussed.

Information discussed in these two workshops provided a complex picture of factors that might influence or regulate population size of blue crabs. This conclusion is similar to the conclusion drawn by the investigators in the SAGES report (Slack et al. 2009) regarding blue crab populations in the Guadalupe/Mission Aransas estuarine system.

One component of crab biology that does seem to respond to salinity (and thus indirectly to freshwater inflow is the incidence of crab parasitism and disease. First, there is good evidence that low salinities would help rid blue crabs, especially adults, of many parasites and second, salinities above 23 psu could benefit potential parasites, thus stressing the crabs. Based on the material on parasitism and disease presented in section 4.3.1.4, the GSA BBEST developed a biological “overlay” of potential for parasitism and disease in blue crab as a function of salinity based as summarized in Fig. 4.5-28. As shown in Table 4.5-2 a Guadalupe Estuary inflow level of approximately 170 thousand ac-ft in the Jul.-Sept period, the minimum in criteria level G2-B, would lead to a salinity average in the oyster area of approximately 23 ppt. Thus the recommended criteria levels G2-B and G2-A would maintain nearly all of the Guadalupe Estuary above the GIWW at or below 23 ppt. Furthermore, the G2-A category of inflows from the Guadalupe Estuary (275-450 thousand ac-ft/3mon) would be sufficient to keep the average salinity in the Aransas Bay oyster area at 18-24 ppt, depending on the Mission-Aransas inflows (see Table 4.5-4). The G2-A prime level of inflow would further maintain areas in Mesquite Bay extending into Aransas Bay at or below 22 ppt. Thus the criteria levels G2-B and G2-A and G2-Aprime that the GSA BBEST is recommending for oysters during the summer would also be protective of blue crabs with regard to avoidance of disease and parasites. Similar inferences can be drawn with regard to the proposed spring criteria levels G1-B through G1-Aprime. These criteria would also keep salinities below 23 ppt throughout much of the Guadalupe Estuary since inflows are above 170 thousand ac-ft for these levels (although these were designed to keep salinity in some or all of the rangia habitat below 10 ppt). Also, much of the G1-C criteria bracket (that portion above 170 thousand ac-ft) would provide the same, with salinities up to 23 ppt.

In addition to these inferences related to keeping salinities at or below 23 ppt, it is clear from Figure 4.5-28, and the text in Section 4.3.1.4, that occasional periods of low to very low salinity (less that 12 ppt) appear to be beneficial to blue crabs by minimizing or eliminating parasites such as the gill barnacle and worms. Thus the higher levels of inflows that may appear 'sub-optimal' for oysters (salinity less than 10 ppt) would appear to be beneficial to blue crabs.

Another useful suite of analyses related to blue crabs was recently performed by Texas Parks and Wildlife Department (TPWD). With the abundant data of the Coastal Fisheries Resource Monitoring Program, TPWD was able to perform a probabilistic analysis of catch rates of blue crabs as a function of inflow for the 1982-2009 period. Previous attempts to derive direct linkages between these two variables have resulted in statistically weak relationships (e.g. as in TPWD 1998). Under the probabilistic approach, rather than deriving a direct causal relationship between catch rates and inflow, the goal is to relating the probability of exceeding the mean catch rate (or other measure of abundance) to observed freshwater inflow to the estuary. The full results of this recent TPWD analysis method are included in Appendix 4.3-1. The GSA BBEST executed some "overlay" type analysis of these results in which the previously-derived inflow criteria for rangia above are applied to this new blue crab approach. Figure 4.5-29 summarizes this analysis. The underlying plot of probability of catch versus inflow is from the TPWD efforts. The two principal dotted black lines indicate the probability of meeting or exceeding either the median or mean catch rate, 35.8 and 53.1 crabs per hour, respectively. As average inflow increases, the probability of meeting or exceeding either of these catch levels increases. Overlain on that backdrop are vertical lines representing the break points between the recommended criteria levels for rangia clams in the Guadalupe Estuary. For example, at the minimum inflow of the G1-A criteria, 375 thousand ac-ft in Mar.-May, the probability of meeting or exceeding the mean catch rate would be approximately 35%. The probability of meeting or exceeding the lower median catch rate would be about 75%. As is evident at the higher inflow levels of the recommended criteria suite, G1-B through G1-Aprime, the likelihood that mean catch rates of blue crabs would be met or exceeded remains in the range of 35-50% while the likelihood of exceeding the median is in the range of 75-100%. Drought level inflows below 150 thousand ac-ft would be accompanied by lower probabilities of meeting or exceeding the mean or median, about 25% and 55%, respectively.

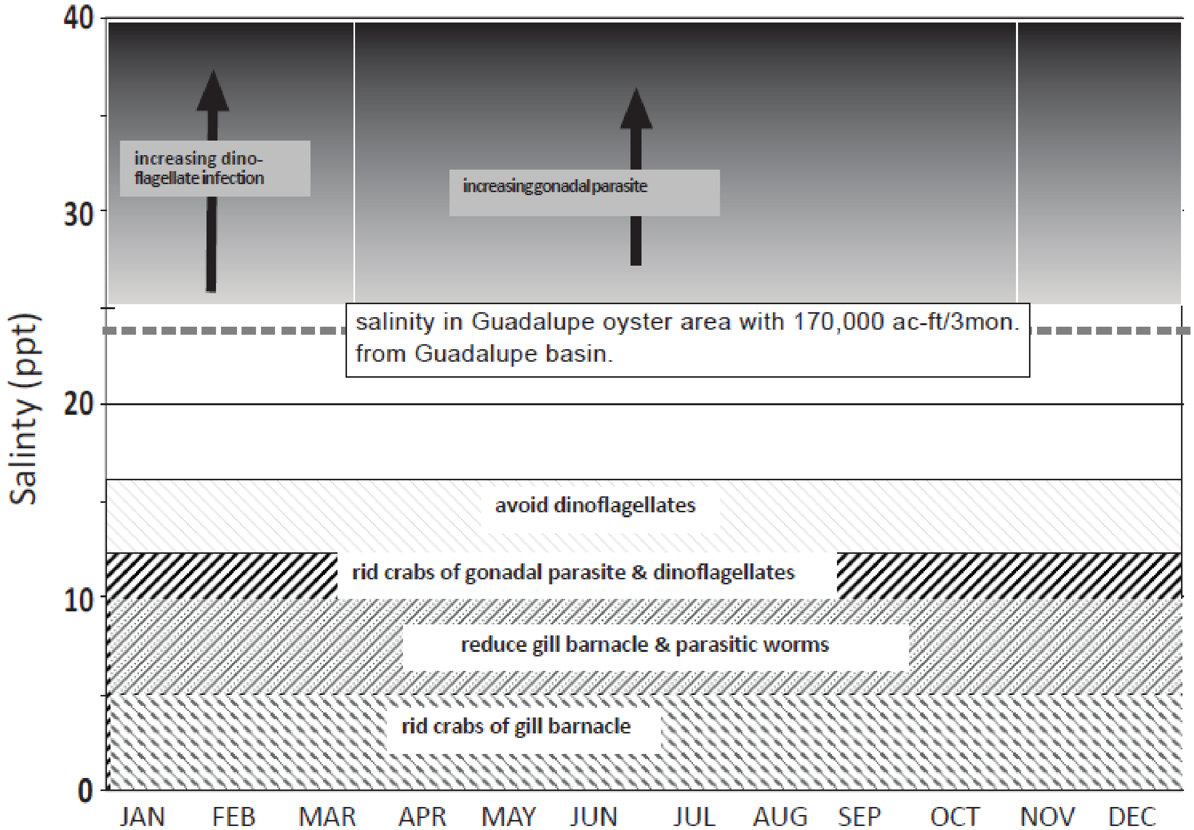


Figure 4.5-28. Summary figure developed by the GSA BBEST regarding principal disease and parasite issues for blue crabs as related to salinity. The overlay grey bar indicates the salinity that would prevail over much of the Guadalupe Estuary (above the GIWW) with an inflow of 170 thousand ac-ft in 3 months, the lower level of the G2-B criteria developed for oysters.

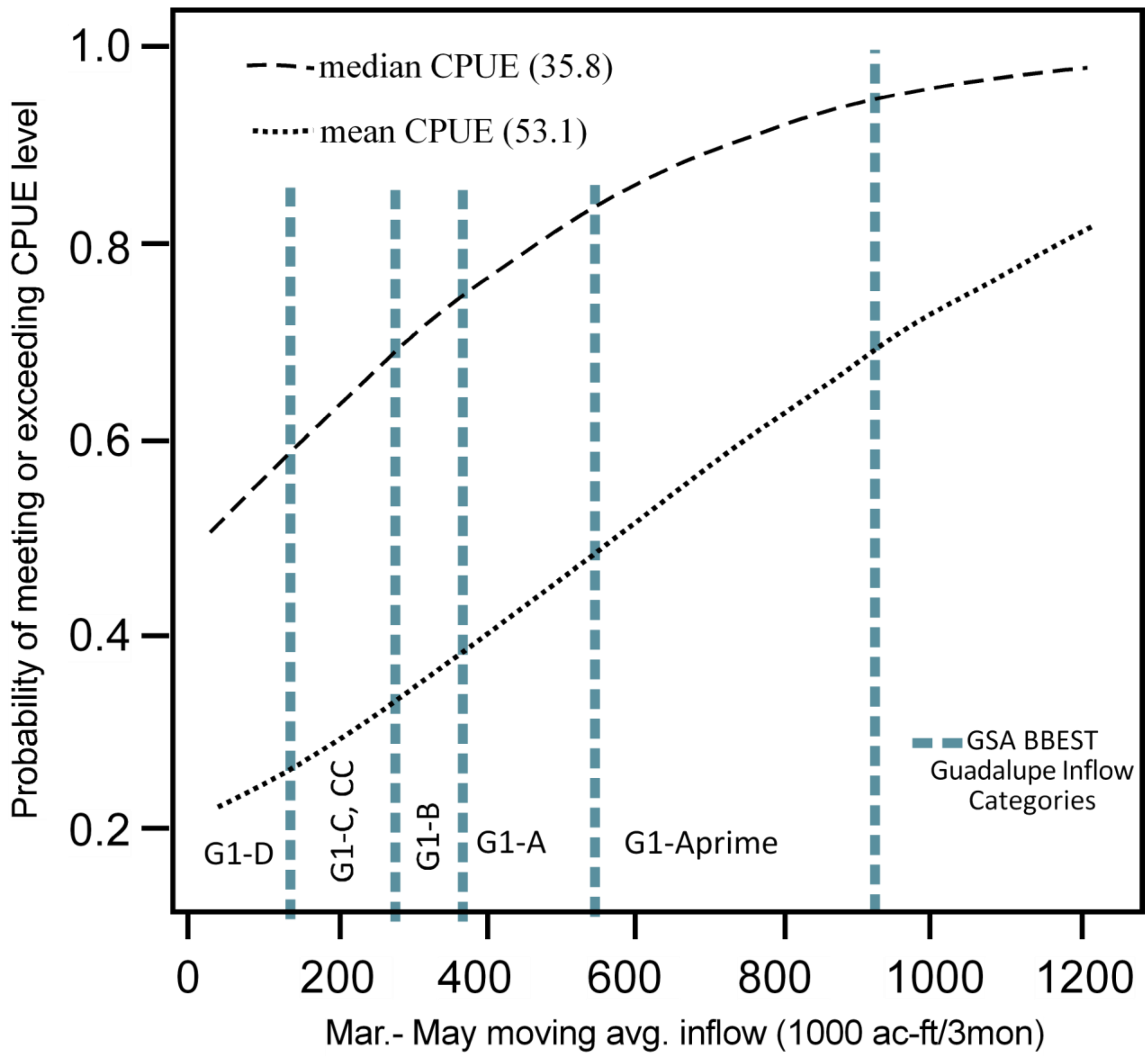


Figure 4.5-29. GSA BBEST overlay analysis using Texas Parks and Wildlife Department's probabilistic analyses of blue crab catch rates (catch per unit effort SPUE) versus running average inflow in the Mar-May period (ie. a March value includes Jan-Mar inflows). Overlain (gray bars) are the criteria ranges developed by the GSA BBEST for the rangia fixed habitat area of the Guadalupe Estuary.

Table 4.2-3. The R^2 statistic for the regression equations developed for the Guadalupe Estuary and the Mission-Aransas Estuary at various points. The Guadalupe Estuary regression equations are of the form S*= a + B1*ln(Q1:G) + B2*ln(Q2:G), while those for the Mission-Aransas Estuary are of the form S*= a + B1*ln(Q1:G) + B2*ln(Q2:G) + B3*ln(Q1:MA) + B4*ln(Q2:MA).

Guadalupe Estuary Point	R2 statistic	Mission-Aransas Estuary Point	R2 statistic
G1	0.732	M1	0.863
G2	0.787	C1	0.786
G3	0.825	C2	0.808
G4	0.835	C3	0.821
G5	0.836	C4	0.799
G6	0.856	Sc1	0.809
G7	0.87	Sc2	0.774
G8	0.859	A1	0.799
G9	0.872	A2	0.808
G10	0.868	A3	0.813

4.6. Synthesis of Biology-Based Inflow Regime Components for the Guadalupe and Mission-Aransas Estuaries

As presented above, the salinity zone analyses provided the BBEST a method to develop specific seasonal inflow recommendations based on certain life-cycle needs of rangia clams and Eastern oysters. The tables below summarize these biologic-based recommendations.

Table 4.6-1. Summary of Guadalupe Estuary recommended inflow volumes based on biologic needs of oyster and rangia. Units are thousand of acre-feet in the period indicated, either per 3 month period or per month.

Criteria level	Inflow Criteria Volumes, suite G1 for Rangia clams		Inflow Criteria Volumes, suite G2 for Eastern oysters	
	Feb.	Mar.-May	June	July-Sept.
G1-Aprime, G2-Aprime	n/a	550-925	n/a	450-800
G1-A, G2-A	n/a	375-550	n/a	275-450
G1-B, G2-B	n/a	275-375	n/a	170-275
G1-C, G2-C	≥75	150-275	≥40	75-170
G1-CC, G2-CC	0 - 75	150-275	0 - 40	75-170
G1-D, G2-D	n/a	0 - 150	n/a	50-75
G1-DD, G2-DD	n/a	n/a	n/a	0-50

Table 4.6-2. Summary of Mission-Aransas Estuary recommended inflow volumes based on biologic needs of oyster and rangia. Units are thousand of acre-feet in the period indicated, either per 3 month period or per month.

Criteria level	Inflow Criteria Volumes, set MA1 for Rangia clams		Inflow Criteria Volumes, set MA2 for Eastern oysters	
	Feb.	Mar.-May	June	July-Sept.
MA2 - Aprime	n/a	n/a	n/a	500-1000

As also derived in Section 4.5.1 each of these criteria, or combinations thereof in some cases, has a recommended attainment goal as measured over the long-term and as assessed according to recommendations in Section 6.1.7. The GSA BBEST recommends that both the magnitude of the specified inflow criteria and the respective attainment goals for each be met in order to maintain the viability of the existing habitats and populations of these focal species. The attainment goals for each derived criteria are summarized in Tables 4.6-3 and 4.6-4 for the Guadalupe Estuary and Mission-Aransas Estuary, respectively.

Table 4.6-3. Summary of attainment goals for the Guadalupe Estuary associated with the respective inflow volume recommendations in Table 4.6-1 based on biologic needs of oyster and rangia. The percentage of years refer to a long-term period, similar to that used in the criteria derivation, and as further described in Section 6.1.7.

Criteria level	Specification	Inflow Criteria Attainment, G1 suite for Rangia clams	Inflow Criteria Attainment, G2 suite for Eastern oysters
G1-Aprime, G2-Aprime	Attainment, G - Aprime	G1-Aprime at least 12% of years	G2-Aprime at least 12% of years
G1-A, G2-A	Attainment, G - A	G1-A at least 12 % of years	G2-A at least 17 % of years
G1-A&G1-B, G2-A&G2-B	Attainment, G - A & G - B combined	G1-A and G1-B combined at least 17% of years	G2-A and G2-B combined at least 30% of years
G1-C&G1-CC, G2-C&G2-CC	Attainment, G - C & G - CC combined	G1-C and G1-CC equal to or greater than 19% of years. G1-CC no more than 2/3 of total	G2-C and G2-CC equal to or greater than10% of years. G2-CC no more than 1/6 of total
G1-D	Attainment, G1- D	no more than 9% of years	n/a
G2-DD	Attainment, G2- DD	n/a	G2-D no more than 6% of years
G2-D&G2-DD	Attainment, G2-D & G2-DD combined	n/a	G2-D and G2-DD combined no more than 9% of years

Notes: the attainment goals for categories G1-C, G1-CC, G2-C,and G2-CC are contingent upon other criteria level attainment goals being met.

Table 4.6-4. Summary of attainment goals for the Mission-Aransas Estuary associated with the inflow volume recommendation in Table 4.6-2 based on biologic needs of oyster and rangia. The percentage of years refer to a long-term period, similar to that used in the criteria derivation, and as further described in Section 6.1.7.

Criteria level	Specification	Inflow Criteria Attainment, set MA1 for Rangia clams	Inflow Criteria Attainment, set MA2 for Eastern oysters
MA-Aprime	Attainment MA-Aprime	n/a	MA2-Aprime at least 2% of years

While the salinity zone analyses applied specifically to rangia clams and Eastern oyster provide the foundation for the recommended range of inflow criteria presented above, there are also reinforcing lines of evidence for these criteria from the “overlays” for blue crabs and white shrimp. As shown in Section 4.5.3.2 and the figures therein, the G1- and G2- “A” and “B” levels would appear to maintain salinities over broad areas of the estuaries within ranges that keep blue crab parasites and diseases in check. Even higher levels of inflows, such as those in the G1-Aprime and G2- Aprime level or above, while leading to ‘suboptimal’ salinities for rangia and oysters in the Guadalupe Estuary, appear to also provide benefits due to establishing low salinity areas that drive away parasites of blue crabs.

As also shown in Section 4.5.3.1 for white shrimp, spatially corroborating data was compiled which tends to support the need for the oyster inflow recommendations. Because white shrimp frequent the estuaries from July through December, the GSA BBEST compared the shrimp analysis data directly to the oyster criteria results above. When we examined white shrimp abundance over a variety of inflow years from 1984 to 2009, abundance was found to be spatially distributed in San Antonio Bay according to freshwater inflow levels, with a definite positive trend between lower salinity "habitat" in the estuary and shrimp catches. In rather dry years with 100 to 150 thousand ac-ft in July-September (similar to the G2-C criteria above), the populations were smaller than in wet years (G2-A and G2-prime), and shrimp were concentrated in the upper part of the bay closer to the freshwater input source. Despite the weak statistical significance calculated, there was a strong qualitative positive response between abundance and inflow from these low levels up to inflows in the 700 thousand ac-ft in Jul.-Sept. range. This reinforces the benefit of higher inflows, even up through the G2-prime level for white shrimp production.

5. Integration of Instream Flow and Estuary Inflow Regimes

5.1 Comparison of Initial Estuary Inflow to Instream Flow Regimes

It was of great interest to the GSA BBEST to examine the estuary inflow criteria developed thus far in Section 4 with the instream flow regimes developed in Section 3. A principal motivation for this inquiry was to ascertain if there was some gross misalignment in the criteria sets, such that, for instance, a specified estuary level could not be met with a reasonable combination of instream flow criteria.

In order to perform these comparisons, the instream flow regimes for both the Guadalupe River at Victoria and the San Antonio River at Goliad were summed. Many of the elements in the regimes, such as base flows, which are couched in instantaneous flow rate terms (i.e. cfs), were converted to a cumulative monthly volumetric equivalent to arrive at a total inflow sum to the Guadalupe Estuary. High-flow pulse components are already in a volumetric measure (ac-ft). To this sum for these two most-downstream gauges was added an estimate of accompanying inflows originating in the ungaged area below these points. For this we utilized the recent estimates of seasonal long-term ratios of ungaged inflow to gauge inflow as found in Ward (2010 and 2011, found in Appendix 5.1-1).

Figures 5.1-1 through 5.1-6 use volumetric seasonal equivalents of the instream flow criteria magnitudes, increasing from subsistence through the 3 tiers of base flow[9], then up through the 1 per 2 year high-flow pulse level, to compare to the estuary criteria derived through the salinity zone analysis approach. Discussion and key findings follow the sequence of figures.

[9] Herein referred to as “dry”, “avg.”, or “wet”, whereas in other sections the GSA BBEST uses the terminology “low”, “medium”, or “high”.

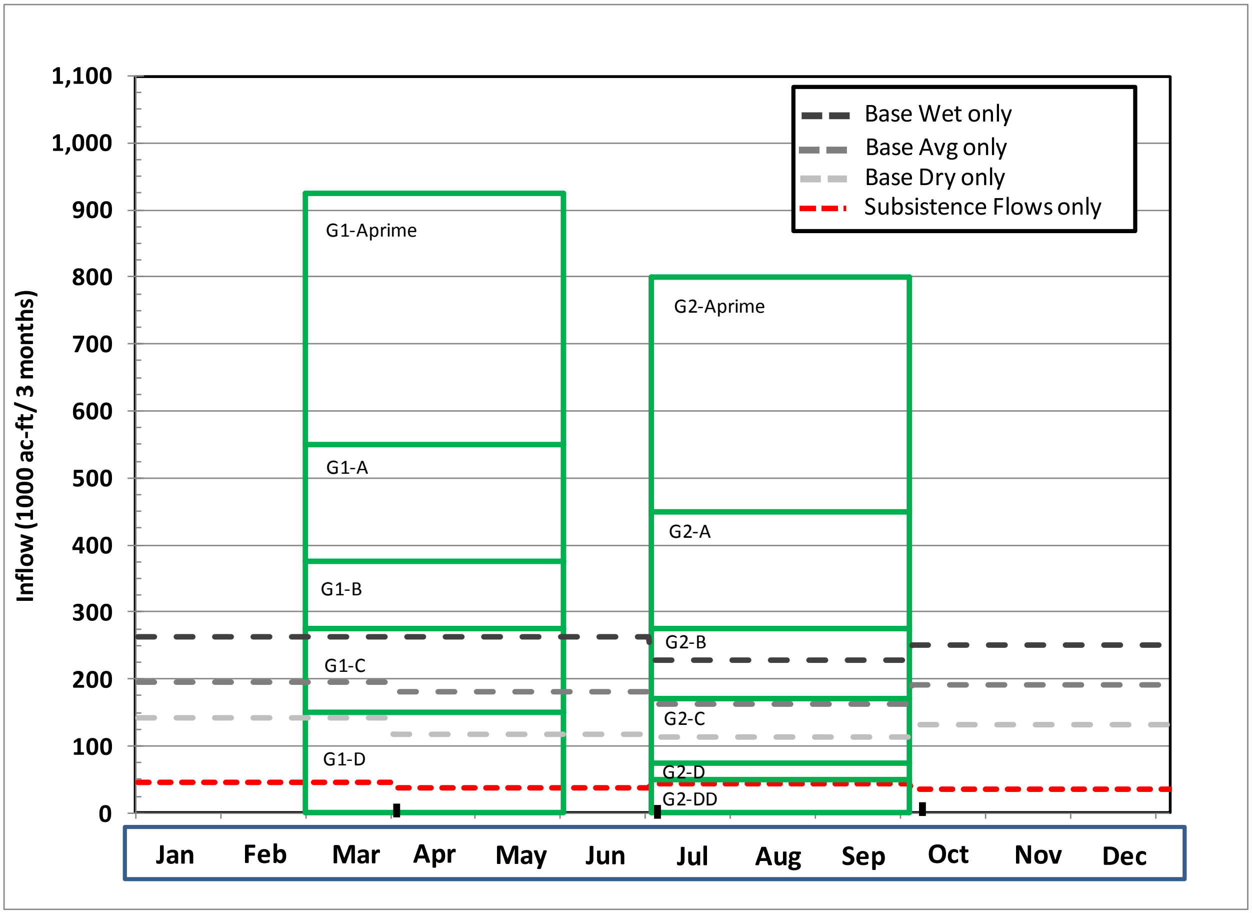


Figure 5.1-1. Comparison of the magnitudes of the estuary criteria (e.g. G1-A) derived with the salinity zone analyses to the instream criteria of the subsistence and three base flow levels with no high flow pulses. Instream criteria shown here are the sum of respective criteria for both the Guadalupe River (at Victoria) and San Antonio River (at Goliad) with a contribution for the ungaged area below gauges from long-term seasonal averages (Ward 2010, 2011).

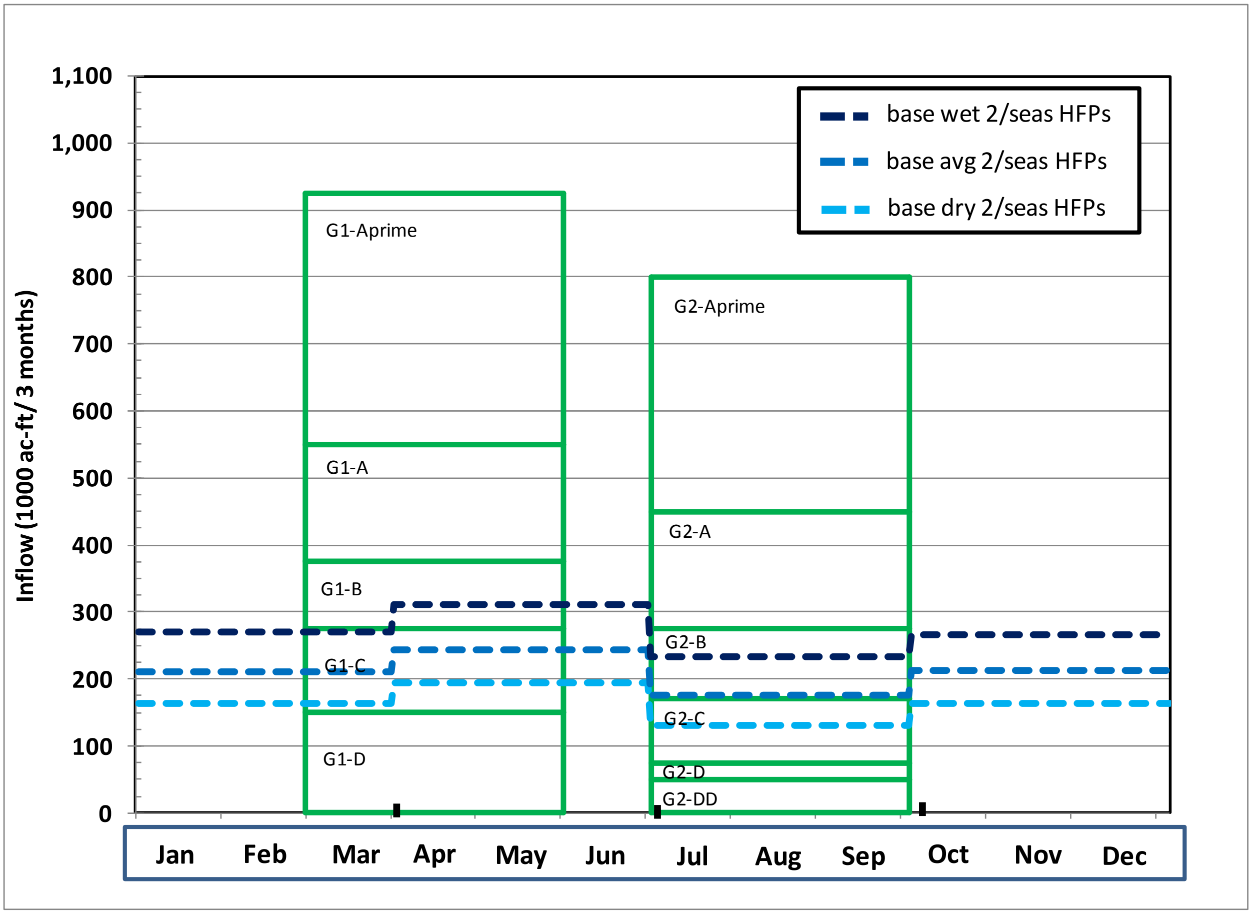


Figure 5.1-2. Comparison of the magnitudes of the estuary criteria derived with the salinity zone analyses to the instream criteria of the three base flow levels with 2 per season high flow pulses. Instream criteria shown here are the sum of respective criteria for both the Guadalupe River (at Victoria) and San Antonio River (at Goliad) with a contribution for the ungaged area below gauges from long-term seasonal averages (Ward 2010, 2011).

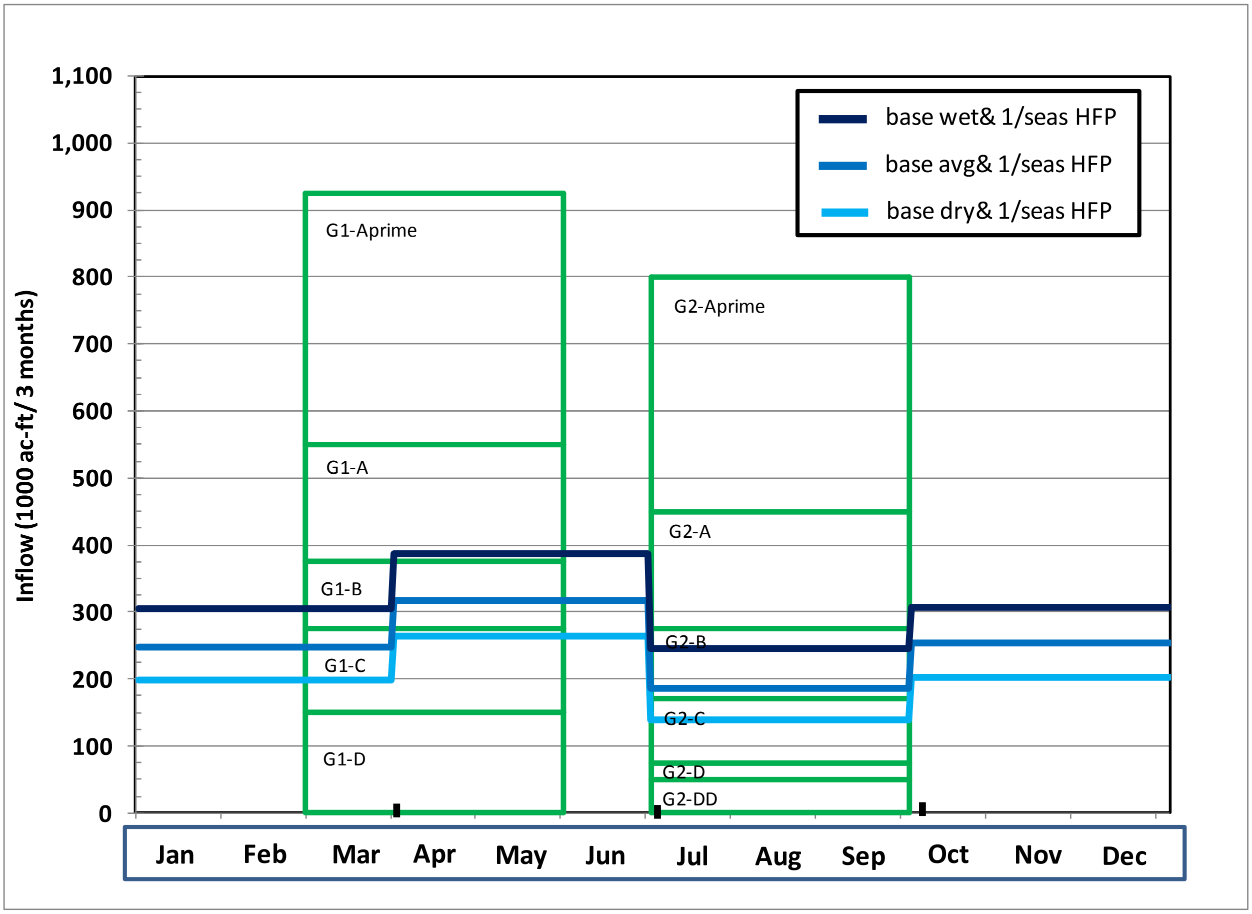


Figure 5.1-3. Comparison of the magnitudes of the estuary criteria derived with the salinity zone analyses to the instream criteria of the three base flow levels with 1 per season high flow pulses. Instream criteria shown here are the sum of respective criteria for both the Guadalupe River (at Victoria) and San Antonio River (at Goliad) with a contribution for the ungaged area below gauges from long-term seasonal averages (Ward 2010, 2011).

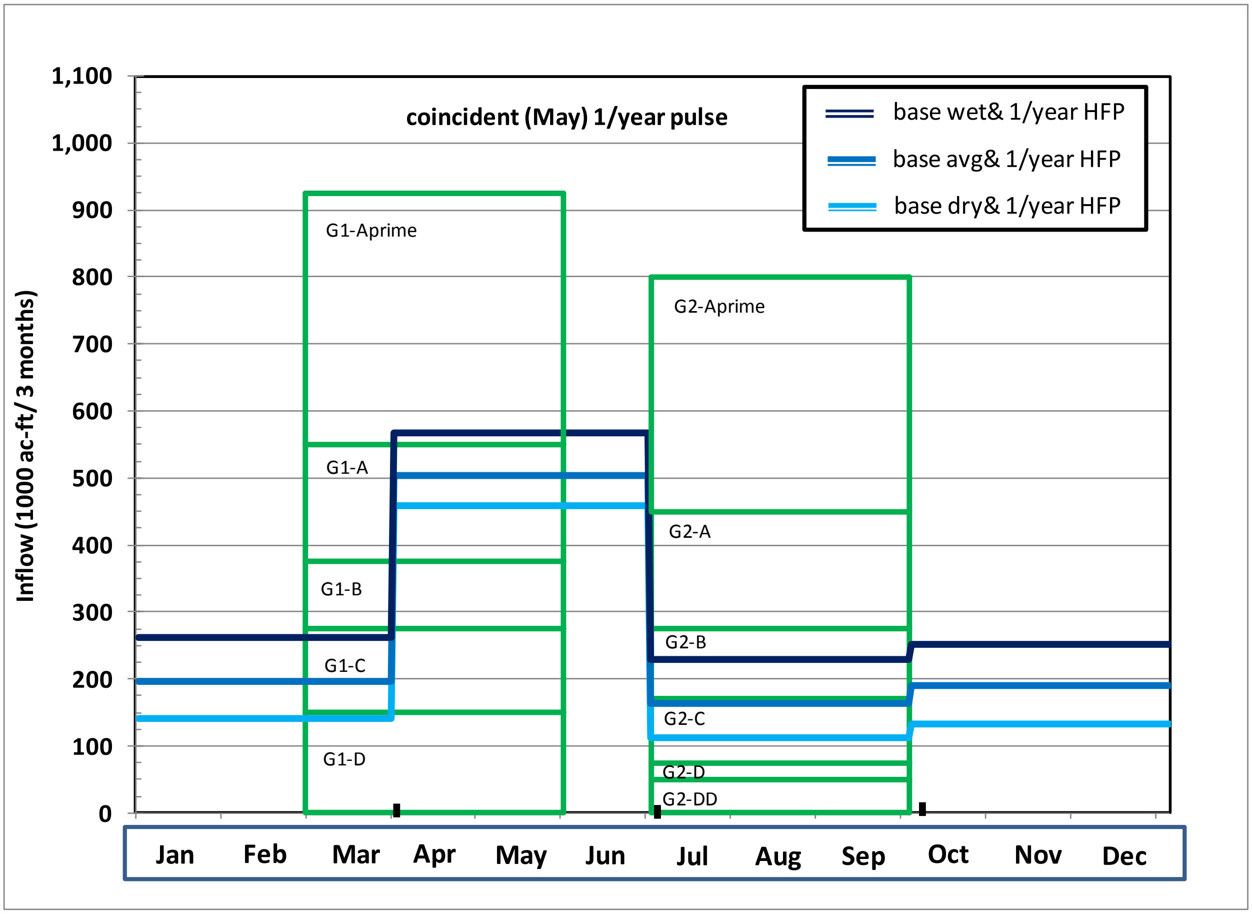


Figure 5.1-4. Comparison of the magnitudes of the estuary criteria derived with the salinity zone analyses to the instream criteria of the three base flow levels with 1 per year high flow pulses assumed to occur coincidently in May in both the San Antonio and Guadalupe river basins. Instream criteria shown here are the sum of respective criteria for both the Guadalupe River (at Victoria) and San Antonio River (at Goliad) with a contribution for the ungaged area below gauges from long-term seasonal averages (Ward 2010, 2011).

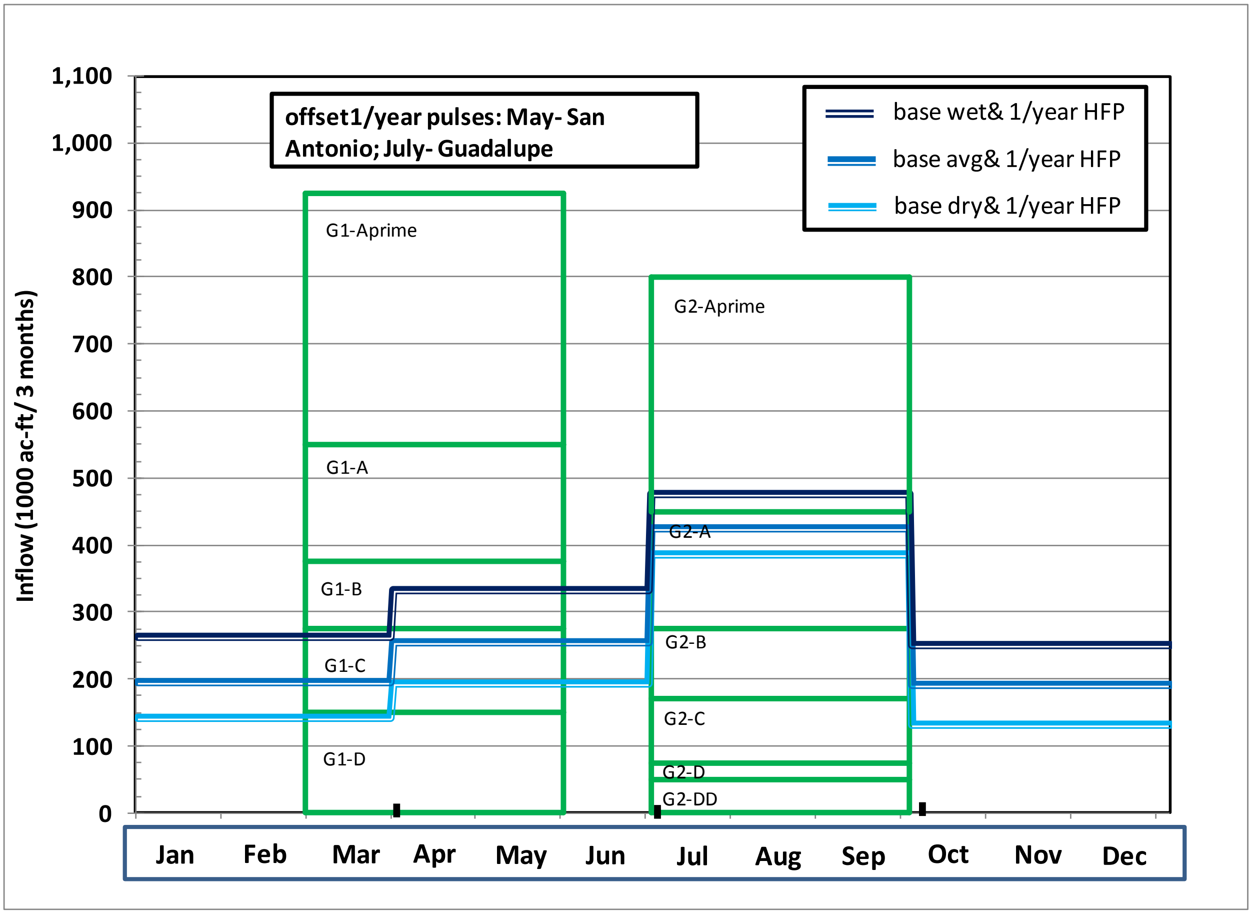


Figure 5.1-5. Comparison of the magnitudes of the estuary criteria derived with the salinity zone analyses to the instream criteria of the three base flow levels with 1 per year high flow pulses assumed to occur in May in the San Antonio basin and July in the Guadalupe river basin. Instream criteria shown here are the sum of respective criteria for both the Guadalupe River (at Victoria) and San Antonio River (at Goliad) with a contribution for the ungaged area below gauges from long-term seasonal averages (Ward 2010, 2011).

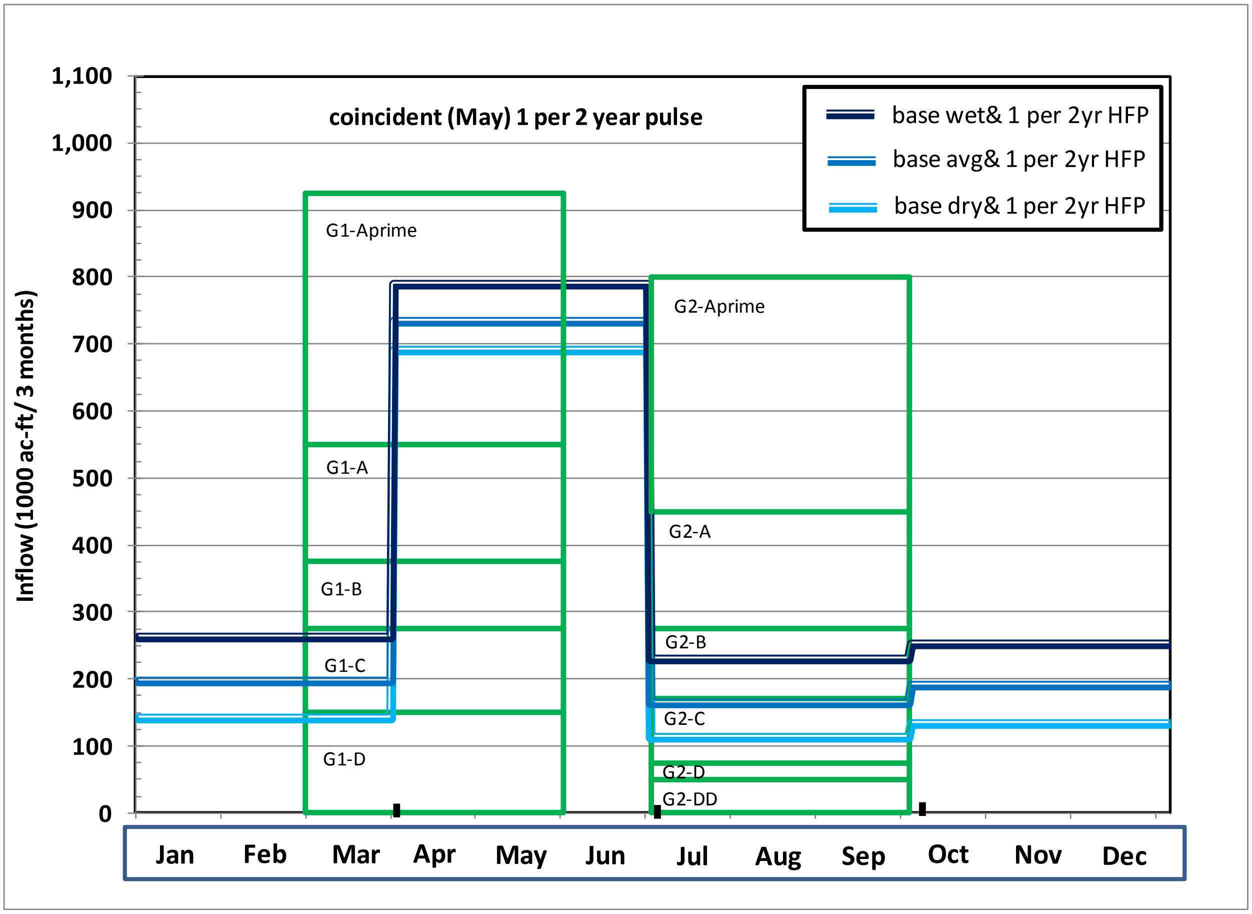


Figure 5.1-6. Comparison of the magnitudes of the estuary criteria derived with the salinity zone analyses to the instream criteria of the three base flow levels with 1 per 2 year high flow pulses assumed to occur coincidently in May in both the San Antonio and Guadalupe river basins. Instream criteria shown here are the sum of respective criteria for both the Guadalupe River (at Victoria) and San Antonio River (at Goliad) with a contribution for the ungaged area below gauges from long-term seasonal averages (Ward 2010, 2011).

It should be of little surprise perhaps that the instream subsistence level coincides in magnitude to the 'drought' estuary criteria: G1-D and G2DD. As one moves up through the inflow criteria levels, there are several key findings:

1. Instream components, "subsistence" and "base dry" up through "base average" instream flows, generally can only satisfy the C through D categories of estuary criteria for both rangia and oysters in the Guadalupe Estuary (e.g. G1-C , G2-C).
2. The highest base flow level, "wet", if occurring simultaneously in both the San Antonio and Guadalupe River basins, would be nearly sufficient to satisfy the B criteria for rangia in the spring. This simultaneous combination in the summer could satisfy G2- B category for oysters.
3. Total inflow volumes to the Guadalupe Estuary resulting from the highest level of simultaneous base flows with no high-flow pulses would not be sufficient to achieve the

B category or above for rangia in the spring. These instream flow levels could also not meet the upper levels of the B category or anything above for oysters in the summer.

4. Figures 5.1-2 and 5.1-3 indicate that the lower levels of high-flow pulses in the instream criteria (2 per season and 1 per season) if occurring simultaneously, can reach a volume sufficient to reach well into the B category for oysters and just into the A category for rangia if combined with underlying base wet flows.
5. No combination of base flows and just the two lowest tiers of high-flow pulses would be sufficient to achieve the A category of inflow criteria for oysters or much above the lowest threshold of this category for rangia (see Figure 5.1-2 and 5.1-3).
6. The above items highlight the importance of the occasional 1 per year or higher magnitude high-flow pulses within the riverine environment for supplying a volume of water on a seasonal basis sufficient to depress salinities into the more favorable A levels for rangia and oysters.
7. Achieving the G1-Aprime or G2-Aprime categories of inflow, which appear to benefit rangia and oyster, respectively, in the Mission-Aransas Estuary, requires instream high-flow pulses at the 1 per 2 year magnitude.

In summary, there are several key concepts that emerge via this comparison. First, both the instream and estuary criteria cover a broad spectrum of flow magnitudes, and furthermore, a broad spectrum of instream criteria are necessary to achieve the range of estuary criteria recommended.. Although developed through completely separate methodologies, the instream flow criteria for the Guadalupe and San Antonio rivers and the criteria levels for the Guadalupe Estuary tend to exhibit a semblance of alignment of elements across the regimes.

5.2 Nutrient Considerations – Estuarine

Coastal waters are among the most productive areas in the world, supporting approximately 20% of the total oceanic primary production (Hauxwell and Valiela 2004; Elsdon et al. 2009). High productivity in estuaries and coastal ocean areas is due to the presence of nutrients essential for survival and growth of plants and algae. Examples of vital nutrients include nitrogen, phosphorus, iron, potassium, calcium, magnesium, sulphur, silicon, and boron (Hauxwell and Valiela 2004). Nutrients can be derived from natural events, e.g., upwelling, storm events, and litter fall, as well as from human activities, e.g., sewage outfalls, leaching from cleared land, fertilizer runoff, and industrial and agricultural effluents (Carpenter et al. 1998; Elsdon et al. 2009; Quigg et al. 2009). Variation in nutrient concentrations can greatly affect the growth of phytoplankton, macroalgae, mangroves, salt marsh vegetation, and seagrasses (Howarth et al. 2000; Hauxwell and Valiela 2004).

The most important nutrients for primary production in coastal waters are nitrogen and phosphorus (Hauxwell and Valiela 2004). Nitrogen is typically the limiting nutrient in coastal waters thereby restricting primary production (Gardner et al. 2006). Sources of nitrogen include atmospheric deposition, decomposition of organic matter, fertilizer application (e.g., lawns, turf, agriculture), and wastewater (Carpenter et al. 1998; Bowen and Valiela 2001). In low-flow systems with low nutrient levels, an increase in nitrogen can cause a rapid increase in production usually resulting in algal blooms (Valiela et al. 1997; Carpenter et al. 1998; Bowen and Valiela 2001; Quigg et al. 2009).

The most common form of N in the environment is dinitrogen gas (N_2); the atmosphere is 78% N_2. However, N_2 is only biologically available to a small group of organisms capable of the energy-intensive process of N fixation (Vitousek et al. 2002). A milestone in our ability to sustain increased human population was the development of the Haber-Bosch process developed by Fritz Haber and Carl Bosch in 1910, which allows for the industrial fixation of atmospheric N_2. Due to increased food and energy needs of our growing population, we have moved from a time where all N was fixed biologically in the natural world to a time where industrial N production equaled that of the natural world, to the present where we now fix more than double the N of all natural sources combined (Vitousek et al. 1997). The Haber-Bosch process currently produces enough nitrogenous fertilizer each year to sustain one-third of the Earth's population (Tilman 2002).

Human activities that have altered the N cycle by tripling the pool of biologically available N are a result of not only industrial fertilizer production via the Haber-Bosch process, but also via fossil fuel combustion, increased cultivation of N-fixing crops, and mobilization of N through activities such as land clearing, biomass burning, and drainage of wetlands (Vitousek et al. 1997). Increased accumulation of biologically available N in the environment has resulted in an 'N cascade', where each atom of N can move through the atmosphere, terrestrial, and aquatic ecosystems with multiple effects along that path (Galloway et al. 2003). In particular, increased N delivery to coastal marine ecosystems leads to problems including a loss of biodiversity, increased occurrence of harmful algal blooms, increased turbidity and subsequent loss of seagrass beds and their communities, and hypoxic zones that result from decomposition of excessive algal blooms (National Research Council 2000, Rabalais 2002). Increased eutrophication of coastal marine ecosystems fundamentally changes the structure and function of the system, moving from diverse, productive ecosystems to highly turbid and sometimes hypoxic ecosystems (Figure 5.2-1). Coaxing a eutrophic ecosystem back towards its previous state is a difficult task; therefore active monitoring for signs of eutrophication is critical.

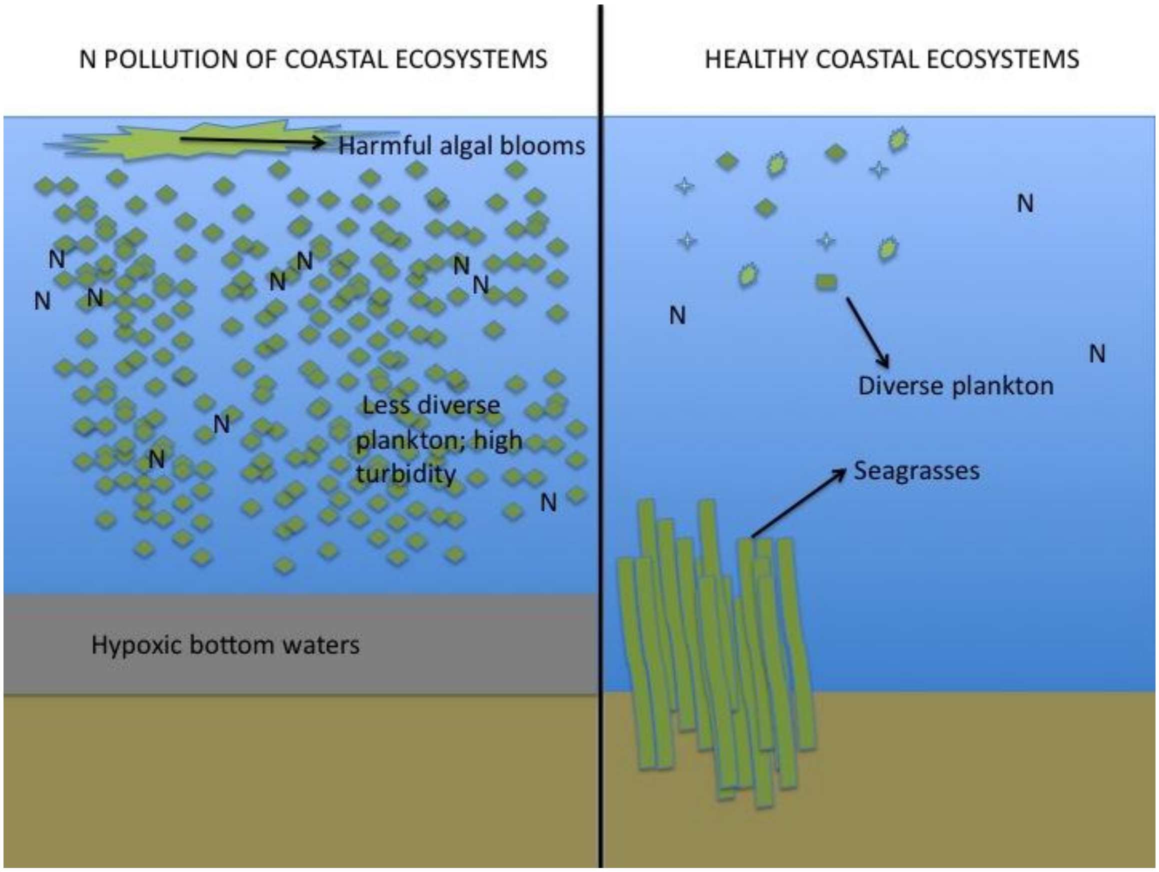


Figure 5.2-1. Illustration of a eutrophic coastal ecosystem in comparison to a healthy coastal ecosystem.

N pollution is 'one of the greatest consequences of human-accelerated global change on the coastal oceans of the world' (Howarth and Marino 2006). It is estimated that two-thirds of the nation's coastal waters are degraded by N pollution and subsequent eutrophication, and models project that N export to coastal ecosystems will continue to rise (Seitzinger et al. 2002). Although coastal eutrophication is not currently a problem in San Antonio or Aransas-Copano Bays, it is important to monitor the ecosystem for early signs of eutrophication as San Antonio and the surrounding areas continue to grow.

Alternatively, it is important to consider the implications of too little N export to coastal ecosystems. Riverine export of N to coastal ecosystems is the major source of N to these ecosystems. If diversion of river water from the estuaries or prolonged periods of drought fails to deliver enough N to support the production of the coastal ecosystem, biodiversity and productivity of the coastal ecosystem would decrease in response. Reduction in freshwater inflows not only raise salinities in coastal ecosystems, but also reduce the total input of N and other nutrients to support plant growth at the base of the food web.

As mentioned above, most N is in the form of N_2 gas. Once N is 'fixed', either biologically or by humans industrially, it is available to plants and bacteria (Figure 5.2-2). Organic nitrogen and the various inorganic forms of nitrogen, such as nitrate (NO_3^-) and ammonium (NH_4^+), can be cycled through living organisms many times. For example, in a coastal ecosystem a single molecule of NH_4^+ could be taken up by phytoplankton, then as the phytoplankton dies and sinks to the sediment the N could be released during decomposition and used by bacteria, buried in the sediment, or exported to the ocean. Alternatively the N could be transported up the food chain as phytoplankton and bacteria and then consumed by small marine organisms and eventually by fish. The only way to 'close the loop' and return reactive N back to N_2 gas is through the process of denitrification. This vignette of the fate of one molecule of NH_4^+ illustrates that measuring concentrations of a nutrient such as N do not provide the whole story; the concentration of nitrogen could remain low and steady, masking a dynamic story of nitrogen cycling. However, measuring concentrations of nutrients in both rivers and bays is an important first step towards monitoring nutrients in coastal ecosystems.

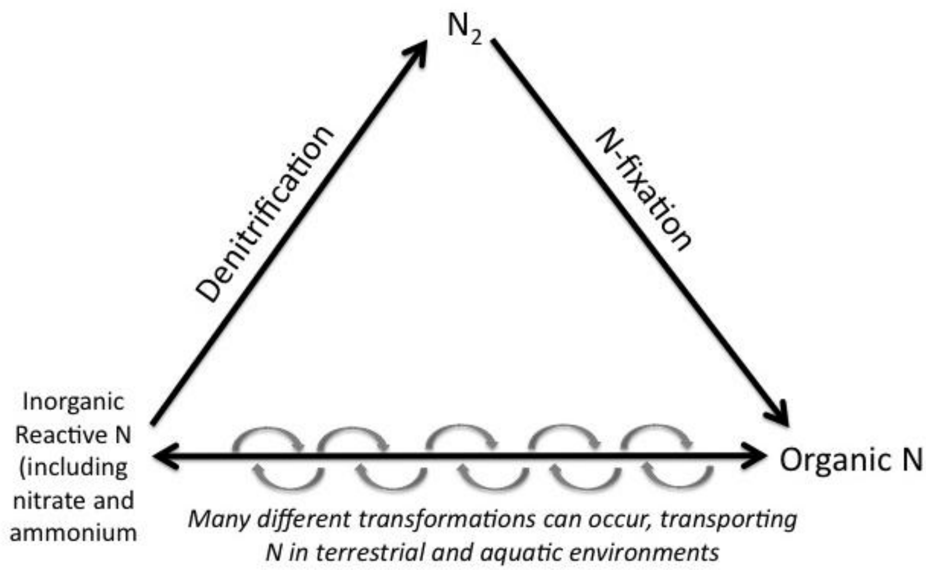


Figure 5.2-2.

5.2.1 Nitrogen Cycling in Coastal Ecosystems

There have been a number of detailed studies on N cycling in coastal ecosystems, and a number of factors are important in determining the fate of N in coastal ecosystems. Conditions such as temperature, salinity, organic carbon availability, oxygen availability, and sediment sulfide concentrations can all play a role in determining whether N is denitrified and removed from the aquatic system or remains as reactive N in the coastal ecosystem (Gardner et al. 2006, Gardner and McCarthy 2009). For example, high temperatures coupled with high salinity and organic C availability can result in N remaining in the system as NH_4^+ instead of being denitrified (Gardner and McCarthy 2009). These results have implications not only for annual cycles, with perhaps less N loss occurring during the summer, but also for broader climate change issues.

The balance between N fixation and denitrification is also an important factor for determining how much N is available in an ecosystem (Figure 5.2-2). While at times N fixation exceeds denitrification or vice-versa, N fixation and denitrification tend to balance where both processes have been simultaneously measured in the Coastal Bend region of Texas (Gardner et al. 2006). This balance can be important for maintaining N availability when riverine N inputs are low (An et al. 2001). In summary, detailed study of N transformations in coastal ecosystems contribute a deeper understanding of the controls on ecosystem production and could provide early cues of potential eutrophication problems in an ecosystem.

5.2.2 Land Use/Land Cover

Agriculture, urban, and industrial land uses can have dramatic impacts on estuarine environments (Bowen and Valiela 2001; Martinez et al. 2007; Elsdon et al. 2009). Analysis of the world's coastal ecosystems revealed 18% of all lands within 100 km of the coast are considered altered, either by urbanization or agriculture (Martinez et al. 2007). Nutrient pollution caused by changing land use/land cover (LULC) patterns is a priority water quality issue in most coastal ecosystems, including the Mission-Aransas Estuary. Changes in LULC can cause an increase in the amount of land-derived nitrogen to estuaries which can alter biogeochemistry and food webs (Bowen and Valiela 2001). In addition to nutrients, changes in LULC also affect the export of water, organic matter, and sediment.

Generalizations on how different LULC cover influences coastal waters can be difficult to make due to variability of many factors. Each estuary is unique and has specific characteristics in LULC, runoff, and biological and physical processes that may not allow comparisons among rural and urban categories (Elsdon et al. 2009). The Mission-Aransas NERR watersheds have different LULC characteristics (Figure 5.2-3, Table 5.2-1). A large percent of the Aransas River watershed (drains 639.7 km^2) contains cultivated cropland, while the highest percent of land cover in the Mission River watershed (drains 1787.1 km^2) is shrub land.

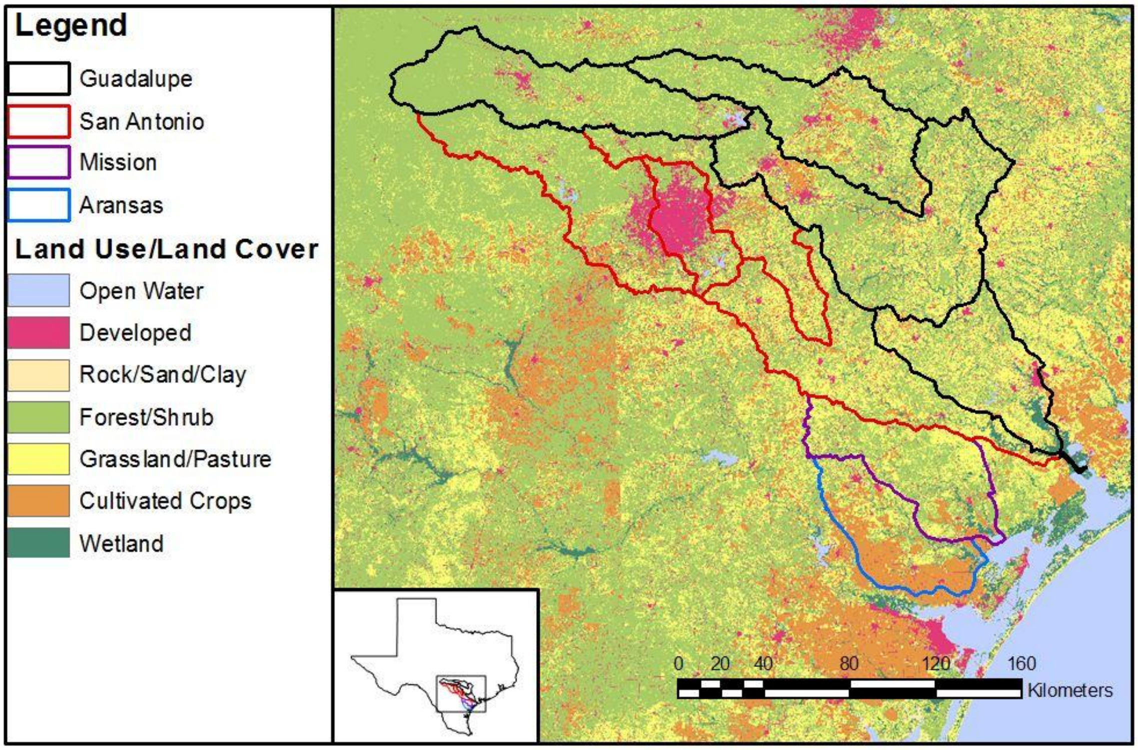


Figure 5.2-3. Land use/cover map of the Guadalupe, San Antonio, Mission and Aransas watersheds.

Table 5.2-1. Land use/land cover characteristics of the Mission and Aransas watersheds. Data provided by NOAA (Mooney 2009).

Land Use Land Cover Category	Aransas River Watershed %	Mission River Watershed %
Developed	3.20	1.24
Cultivated	44.65	6.30
Pasture/Grassland	22.63	36.45
Forest	3.35	8.55
Scrub/Shrub	22.09	42.60
Wetlands	3.26	3.68
Shore/Bare land	0.24	0.37
Water	0.58	0.80

5.2.3 Nutrient and organic matter export from the San Antonio and Guadalupe river watersheds to San Antonio Bay

Variations in freshwater inflows to San Antonio Bay are accompanied by variations in river water nutrient and organic matter concentrations. In the case of nitrate, concentrations are relatively high in the San Antonio and Guadalupe rivers during base flow conditions, but decrease strongly during high flow conditions (Figure 5.2-4). This pattern is consistent with a dilution of wastewater sources of nitrogen during rain events. Higher maximum nitrate concentrations in the San Antonio River reflect higher human population densities (i.e. people per square kilometer) in the San Antonio River watershed as compared to the Guadalupe River watershed. In contrast with the patterns observed for nitrate, concentrations of dissolved organic nitrogen (DON) increase from base flow to high flow (Figure 5.2-5). This pattern is consistent with extraction and flushing of DON from organic-rich soils during rain events.

Nutrient concentrations given in Figures 5.2-4 and 5.2-5 are expressed in terms of runoff and normalized to the watershed area to allow comparisons among watersheds of different sizes. The same data are given in Figures 5.2-6 and 5.2-7 but are expressed in terms of discharge (ac-ft/day) to provide a direct comparison to other components of river flow at each location.

Nutrient loading to San Antonio Bay from the San Antonio and Guadalupe rivers is a function of how much water is flowing into the bay as well as the nutrient concentrations in the river water. A positive relationship between river discharge and nutrient concentration (as demonstrated for DON) focuses loading during storm events, whereas a negative relationship between river discharge and nutrient concentration (as demonstrated for nitrate) results in a more even distribution of loading between base flow and storm flow. These differences are demonstrated in Figure 5.2-8, where daily estimates of nitrate and DON fluxes over the 2000-2009 period are shown. While nitrate fluxes vary substantially over time, they are much more evenly distributed throughout the year as compared to the DON fluxes. Indeed the vast majority of DON export from the Guadalupe and San Antonio river watersheds occurs during a few major rain/runoff events each year. On an annual basis, nitrate fluxes greatly exceed DON fluxes from the San Antonio River, whereas nitrate and DON fluxes from the Guadalupe River are more evenly balanced (Table 5.2-2).

In addition to values for nitrate and DON, Table 5.2-1 provides annual export estimates for several other important solutes in the San Antonio and Guadalupe Rivers that influence biological productivity in coastal waters. Ammonium export is far lower than Nitrate and DON export for both rivers, but it is still a significant nitrogen source to San Antonio Bay. The San Antonio and Guadalupe rivers also export a substantial amount of phosphate. While both nitrogen and phosphorus are essential for productivity in the bay, ratios of dissolved inorganic nitrogen (nitrate + ammonium) to phosphate inputs are lower than the Redfield N:P ratio of ~16:1 that is typically required for optimum growth by primary producers in marine systems (Valiela 1995). Dissolved inorganic N:P contributions are approximately 9:1 and 5:1 from the San Antonio and Guadalupe rivers respectively. Thus, river inputs are pre-conditioned to foster nitrogen limitation of biological production in the bay. Decomposition of river-supplied DON may provide an additional source of inorganic nitrogen that supports primary production in the bay through recycling. Inputs of dissolved organic carbon (DOC) may also support a substantial amount of secondary production in the bay. However, the extent that organic matter inputs via rivers influence production in coastal waters depends strongly on the quality of the inputs. The proportion of organic matter inputs that can be broken down through photo-oxidation and biological processing in San Antonio Bay is yet to be determined.

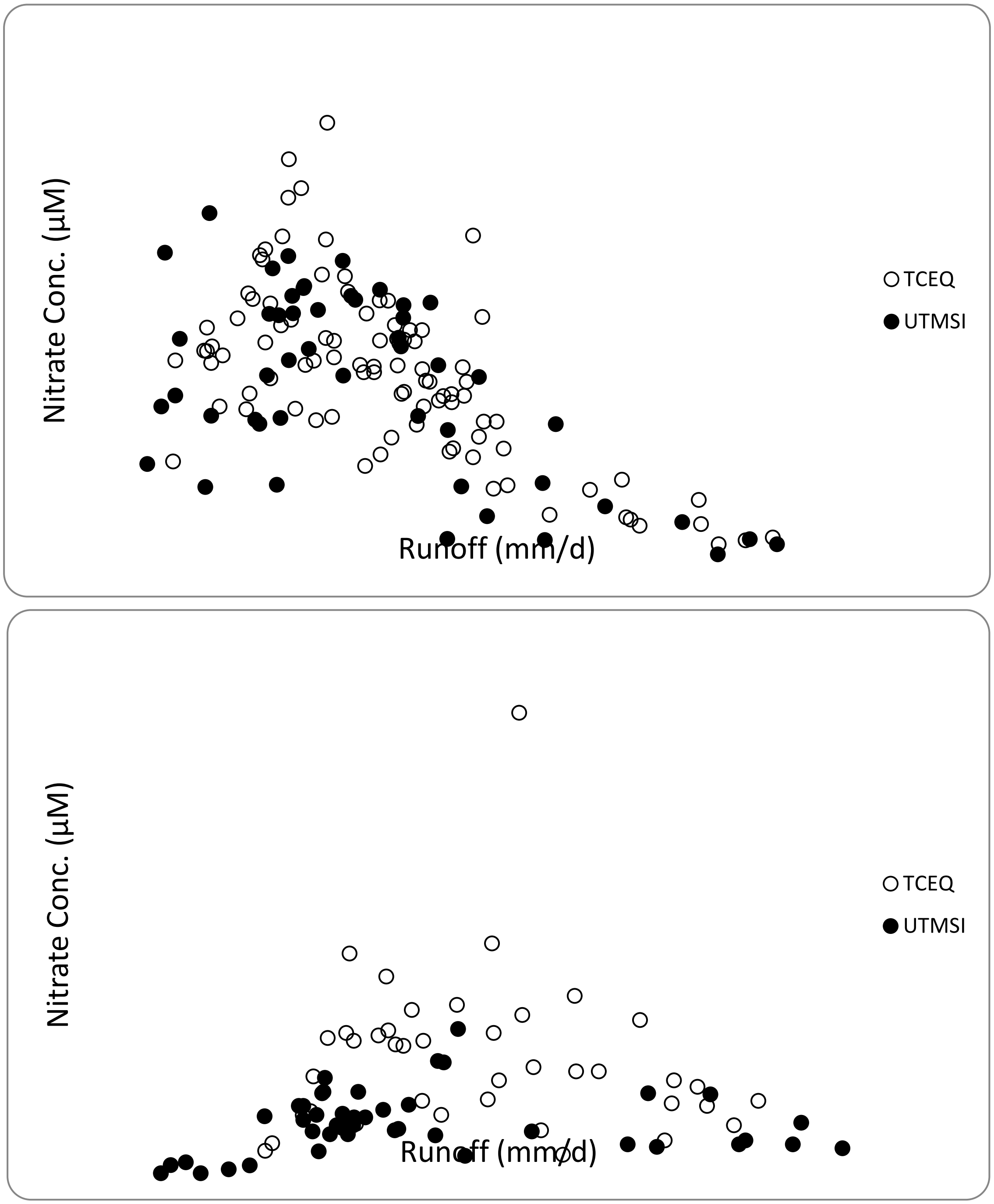


Figure 5.2-4. Variability in nitrate concentrations in the San Antonio (top panel) and Guadalupe (bottom panel) rivers as a function of runoff. Data are from the San Antonio River at Goliad and the Guadalupe River at Victoria. Runoff is calculated as river discharge (USGS) divided by watershed area. Concentrations are from TCEQ (2000-2009) and McClelland lab at UTMSI (2008-2009). For conversion to English units, 10 mm is approximately 0.4 inches.

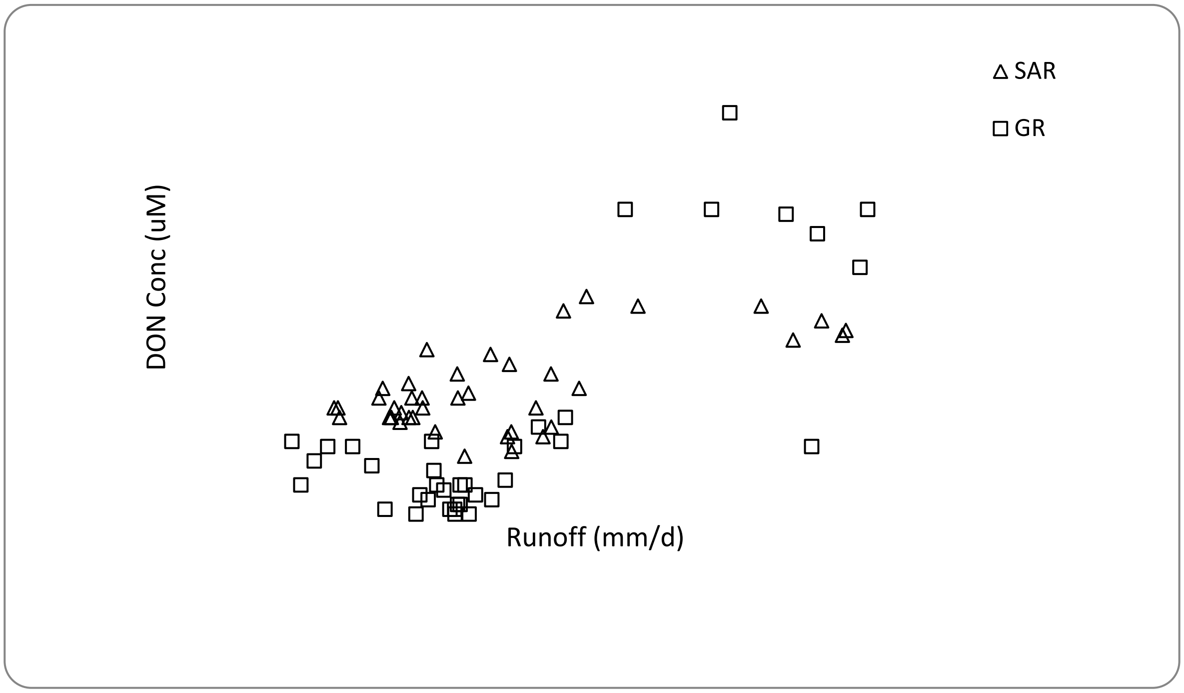


Figure 5.2-5. Variability in dissolved organic nitrogen (DON) concentrations in the San Antonio (SAR) and Guadalupe (GR) rivers as a function of runoff. Data are from the San Antonio River at Goliad and the Guadalupe River at Victoria. Runoff is calculated as river discharge (USGS) divided by watershed area. Concentrations are from McClelland lab at UTMSI (2008-2009). For conversion to English units, 10 mm is approximately 0.4 inches.

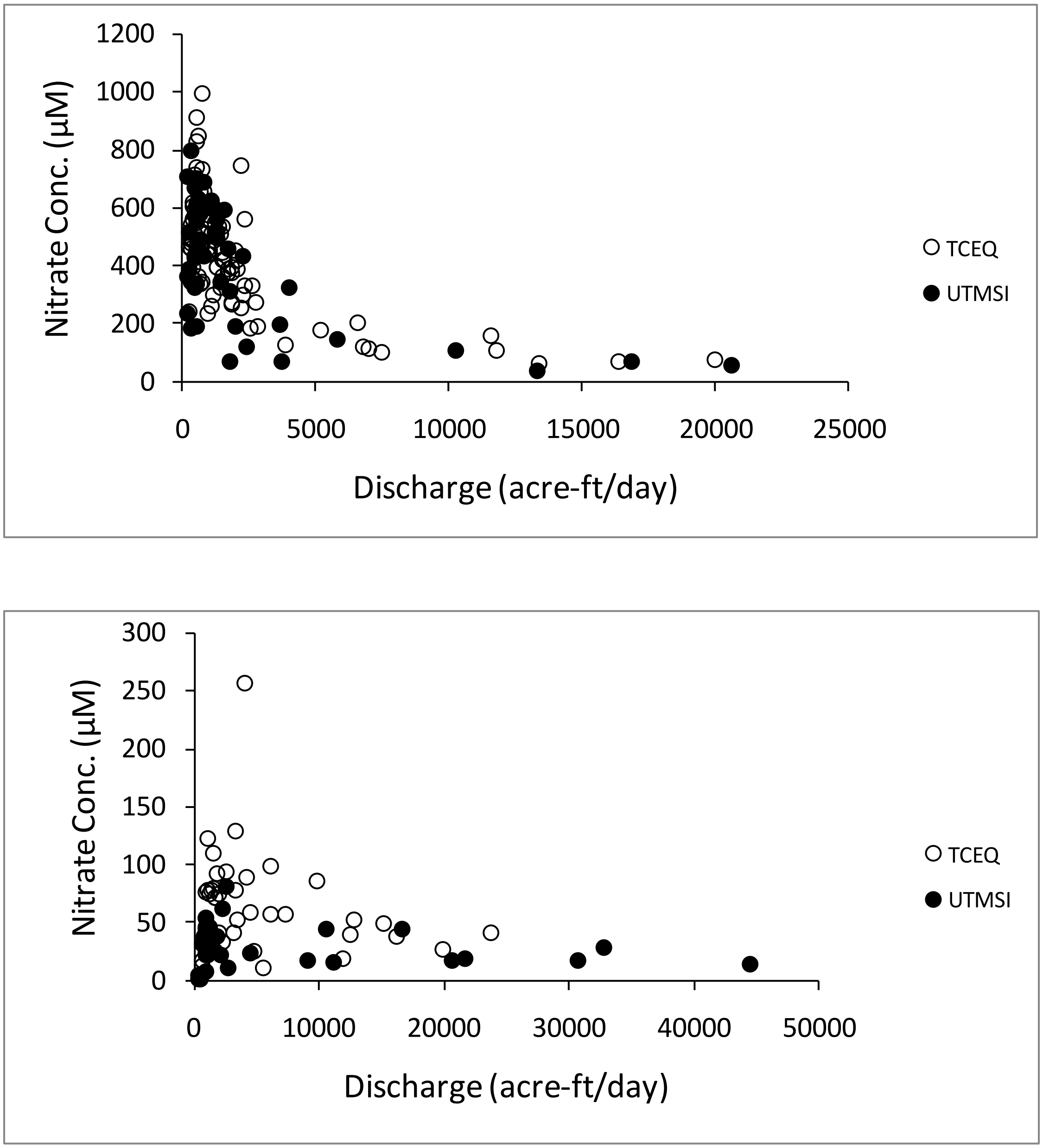
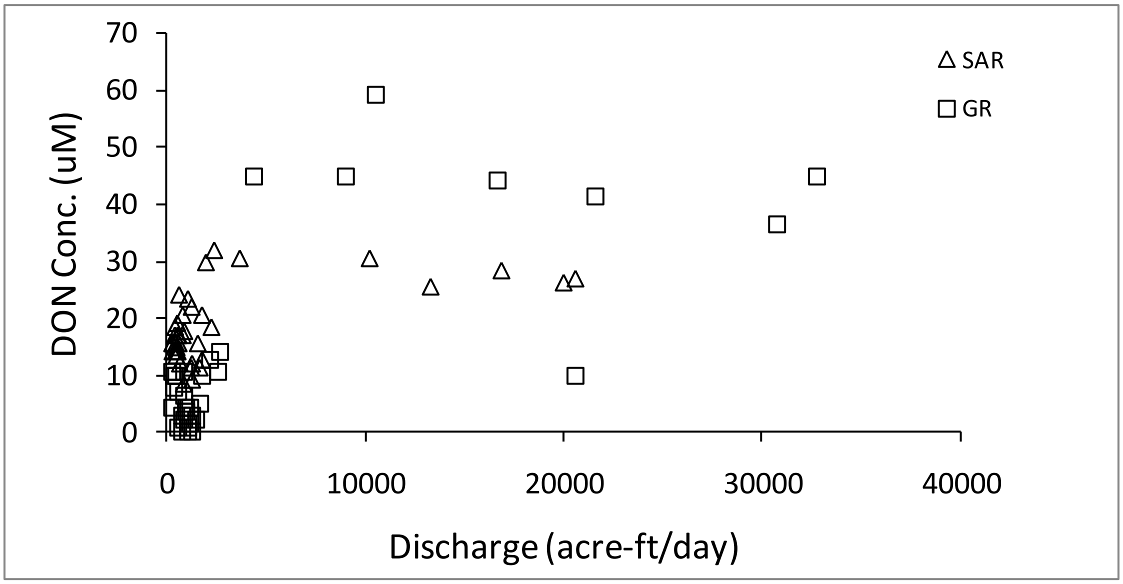


Figure 5.2-6. Variability in nitrate concentrations in the San Antonio (top panel) and Guadalupe (bottom panel) rivers as a function river discharge. Data are from the San Antonio River at Goliad and the Guadalupe River at Victoria. Runoff is calculated as river discharge (USGS) divided by watershed area. Concentrations are from TCEQ (2000-2009) and McClelland lab at UTMSI (2008-2009).



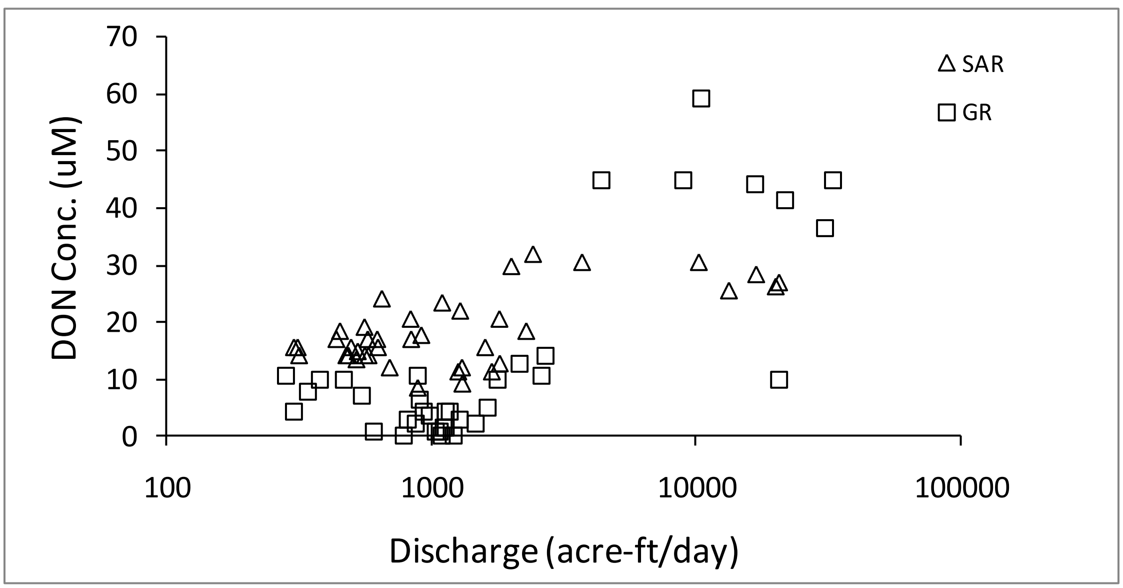


Figure 5.2-7. Variability in dissolved organic nitrogen (DON) concentrations in the San Antonio (SAR) and Guadalupe (GR) rivers as a function of runoff. Data are from the San Antonio River at Goliad and the Guadalupe River at Victoria. Runoff is calculated as river discharge (USGS) divided by watershed area. Concentrations are from McClelland lab at UTMSI (2008-2009)

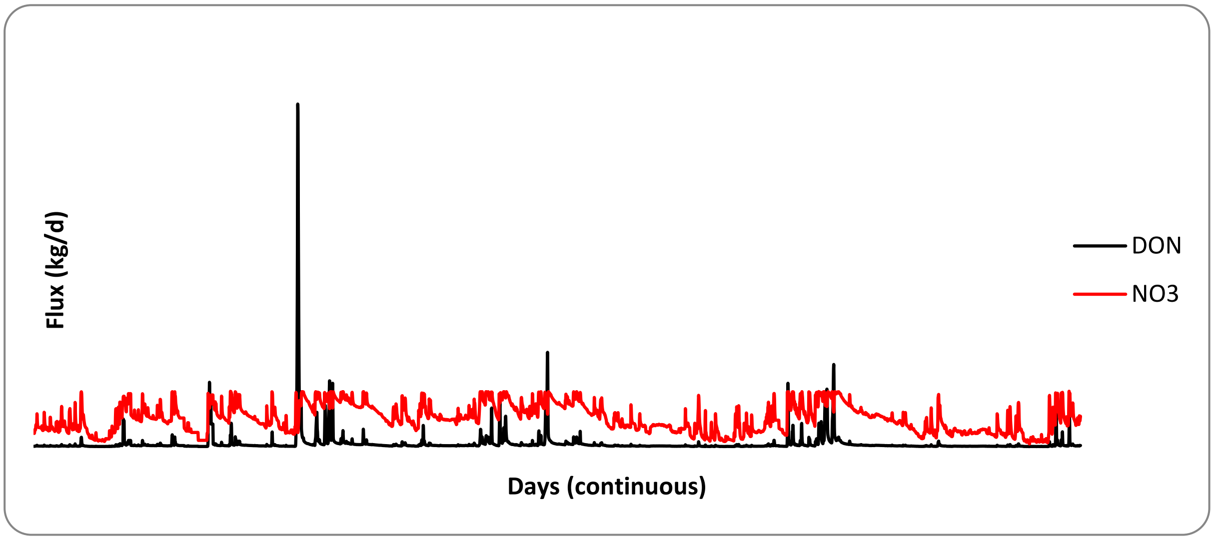


Figure 5.2-8. Daily nitrate and DON export from the San Antonio River over the 2000-2009 time period. Flux values (kg/d) were calculated using the USGS Load Estimator (LOADEST) program (Runkel et al., 2004). Provided with paired measurements of discharge and concentration for calibration, LOADEST uses regression relationships to calculate daily export values. River discharge data from the USGS was used in combination with the data presented in Figures 5.2-3 and 5.2-4 to calibrate and run LOADEST. Analysis performed by R. Mills (UTMSI). For conversion to English units, 20000 kg is approximately 44,000 pounds.

Table 5.2-2 Nutrient and organic matter export from the San Antonio and Guadalupe river watersheds. Values are average annual export ± one standard deviation for the 2000-2009 time period calculated by summing LOADEST output over yearly intervals. Estimates provided by McClelland lab at UTMSI. For conversion to English units, 1000 kg is approximately 2200 pounds.

	San Antonio River (10^3 kg/y ± 1 stdev)	Guadalupe River (10^3 kg/y ± 1 stdev)
Nitrate	3507 ± 1018	1229 ± 689
Ammonium	75 ± 64	162 ± 137
Dissolved organic nitrogen	394 ± 353	948 ± 926
Phosphate	403 ± 148	278 ± 274
Dissolved organic carbon	4721 ± 3890	11794 ± 12524

5.2.4 Estuarine Monitoring within the Mission-Aransas National Estuarine Research Reserve

The NERR operates a System-Wide Monitoring Program (SWMP), a nationally-coordinated and standardized program that is carried out at all NERRs. The program measures water quality parameters (e.g., salinity, temperature, dissolved oxygen, turbidity, pH and water level), weather, and a suite of nutrients. Nutrient samples are taken on a monthly basis at five permanent stations and monthly diel samples at one station. Analyses for ammonium, nitrate, nitrite (or nitrate+nitrite), orthophosphate and chlorophyll *a* are conducted on-site at Reserve facilities.

In the Reserve, adequate supplies of fresh water carrying nutrients and sediments to coastal wetland habitats is essential for the health and productivity of several commercial fisheries. Silicate, phosphate and chlorophyll *a* concentrations decrease along the estuarine gradient from the rivers to the Gulf of Mexico (Figure 5.2-9). Nitrogen and ammonium concentrations are low and variable in concentrations often below detection limits. Nitrogen is the primary limiting nutrient in Texas estuaries and is supplied to the Reserve by the Aransas and Mission rivers (24%) and precipitation (28%). The final nutrient concentration is determined by estuarine processes, e.g., uptake by primary producers, geochemical trappings within sediments, regeneration by biological communities, and benthic-pelagic coupling (Tunnell et al., 1996).

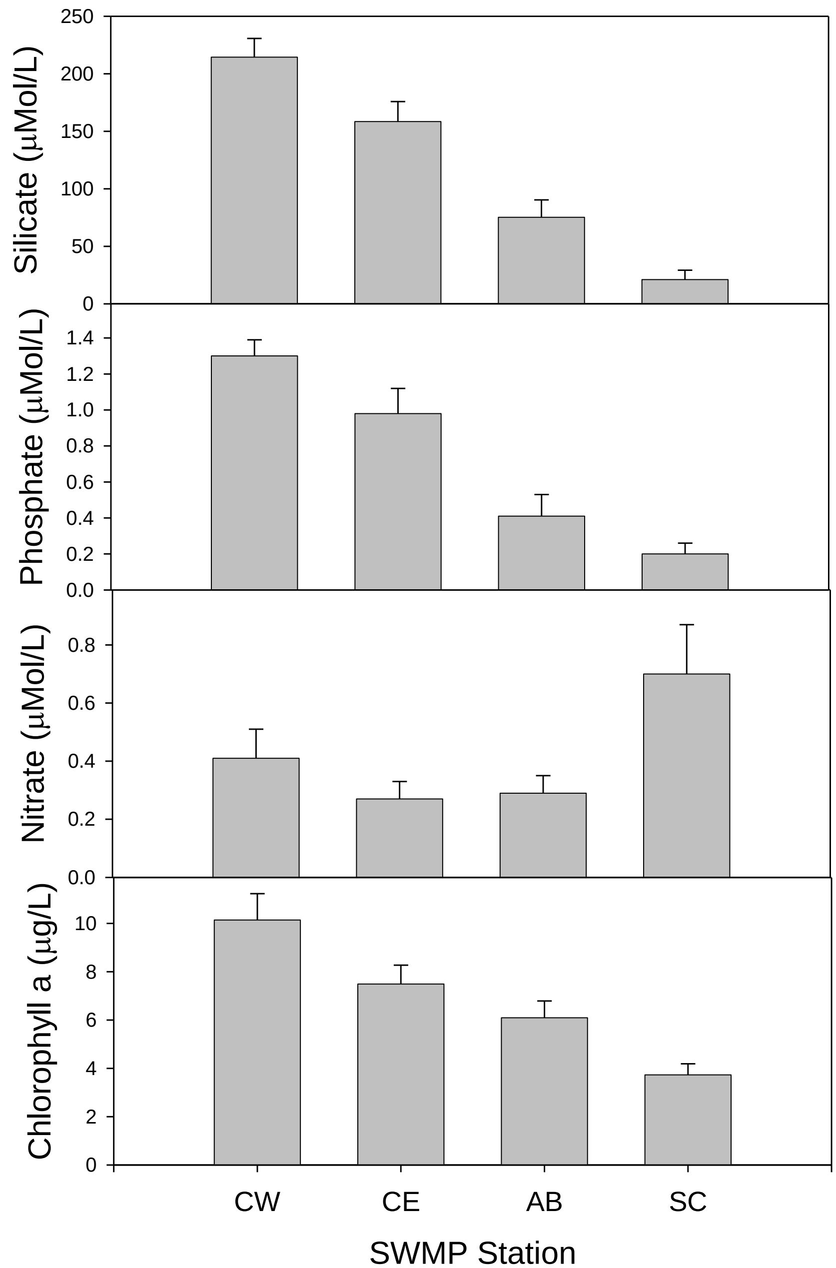


Figure 5.2-9. Nutrient concentrations and phytoplankton biomass along an estuarine gradient in the Mission-Aransas NERR. Mean values from summer 2007 through summer 2010. Error bars represent standard error. CW=Copano Bay west, CE=Copano Bay east, AB=Aransas Bay SC=UTMSI pier.

Nitrogen inputs in arid coastal regions are usually limited; however, it has been suggested that nitrogen cycling rates in Texas coastal waters are comparable to rates observed in hypereutrophic ecosystems (Gardner et al. 2006). High nitrogen cycling rates are facilitated by ammonium production from sediments, nitrogen fixation, and denitrification. These processes provide critical supply and removal mechanisms for available nitrogen in South Texas estuaries. Further, during the frequent periods of drought riverine nutrient inputs are low due to low flows (Gardner et al. 2006).

A study in the Mission-Aransas Estuary in 2007 and 2008 focused on monthly and storm event monitoring and emphasizes the importance of peak flow events to the nitrogen load to this system (Mooney and McClelland, unpublished data). In South Texas a few storm events each year provide a disproportionate amount of annual freshwater inputs to the estuaries. In 2007, a series of major storms occurred in the Mission and Aransas watersheds. In Copano Bay, the salinity dropped from 12 to nearly 0 psu within a few days (Mission-Aransas NERR data). Following these storms, nitrate and ammonium concentrations were elevated in Copano Bay for a short time, but inorganic P concentrations remained elevated for many months (Figure 5.2-10). This data provides additional evidence that this system, like many estuaries, is N limited. The elevated P concentrations left a signature of the riverine inputs that could be followed for months after the flood, unlike the N that was taken up by phytoplankton almost immediately. It is also important to monitor P concentrations in the face of potential eutrophication; as increasing amounts of N are added to the estuary, high concentrations of P could enable larger algal blooms.

In addition, this study of storm events ended during a period of drought and opened some interesting questions about N availability. Increased N cycling that result in retained N in the system has been measured during drought conditions in Corpus Christi Bay, a nearby estuary (Gardner et al. 2006). In Copano Bay, increased NH_4^+ concentrations were measured during June to November 2008 when salinities were 25 – 30 psu (Figure 5.2-10c). Perhaps during droughts phytoplankton production in Copano Bay is also supported by increased N cycling rather than N inputs from the rivers. Although riverine inputs of N are critical, management of N in estuaries also requires knowledge of processes occurring within the estuary.

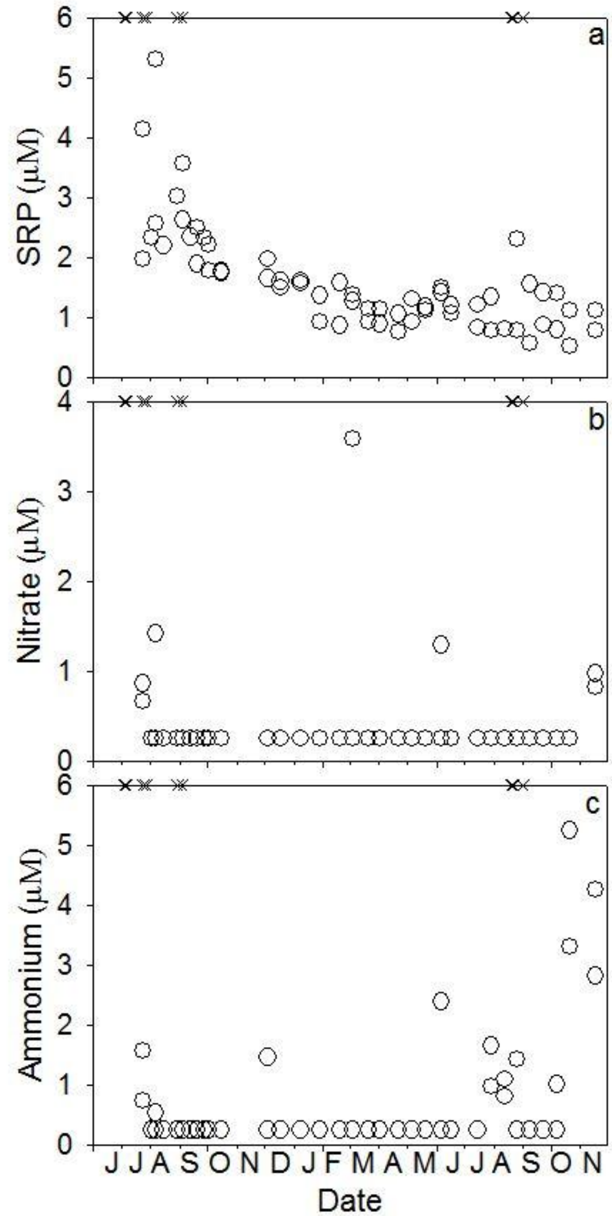


Figure 5.2-10. Inorganic P (SRP), nitrate, and ammonium concentrations in Copano Bay from June 2007 to November 2008. Storms are marked by an x at the top of each graph.

The importance of riverine nutrient inputs is even more pronounced in areas like South Texas, where the rivers are characterized by low base flows with few large episodic events per year. Nitrogen cycling in systems like South Texas may prove to be increasingly important during drought periods. While measuring concentrations of nutrients, organic matter, and Chlorophyll a are important for understanding the system, our knowledge of the ecosystem is greatly enhanced when coupled with information about river export and N cycling.

A Nitrogen loading analysis was performed by David Brock (Longley 1994, TWDB/TPWD 1998) for the State's Guadalupe Estuary Bay and Estuary Freshwater Inflow study. From an analysis of nitrogen budgets, he was able to relate the total N budget for this system to FWI in a wet year and dry year. This work established a minimum inflow requirement of 286,000 ac-ft/yr to provide the N input needed to balance losses from the Estuary such as export to the Gulf, denitrification, sediment burial, and fisheries harvest and emigration. This flow value, listed as an official nutrient constraint from the State's FWI analysis, is actually based on modern (post-development) water quality conditions, reflecting anthropogenic N loadings from the Guadalupe-San Antonio River drainages. Upon further analysis, Brock (2001) determined that modern flow-weighted nitrogen loading is 2.33 mg/l of total N, as compared to “pre-modern” levels on the order of 0.9 mg/l N. When this reduced loading rate and refinements in calculating the N budget (especially for denitrification) were made, a nutrient constraint reflecting the natural, pre-modern levels of N loading to the Guadalupe Estuary would require some 860,000 ac-ft of combined inflow per year.

5.3 Sediment Considerations

5.3.1 Sediment Loading to Guadalupe Bay.

The role of freshwater inflows in supplying sediments to estuaries has been recognized as critical to maintaining elevations of the shallow water habitats and wetlands, particularly in upper parts of the estuary. Geographically, the entire Guadalupe Delta extends from Green Lake above Mission Lake, through Mission Lake, and down into the old, lower lobes below the South fork of the Guadalupe River (see Fig. 4.1–1). Historically, sediment has been transported by the Guadalupe River and discharged to Guadalupe Bay through this delta system where it is required to offset a 0.25m (*ca* 8 in) rise in sea level since 1935 or 8 mm/yr (Longley 1994).

As noted previously (Sec. 4.3.3), Traylor Cut was opened into Mission Lake in 1935, and this effectively allowed 50-65% of the normal Guadalupe River flow to be diverted into the Lake. The attendant increase in sedimentation has caused the depth of Mission Lake to decrease some 60% (ca 0.6 m or 2 ft) over the 60 years to 1986. At the same time, the lower Delta below the S. Fork has been sinking and eroding from compactional subsidence due to the decreased sediment loading from decreased river flows through the S. fork of the river (White and Calnan 1990). Thus, the lower Delta is in a dying phase. As modeling studies by the TDWR (1980) have also determined, the upper Delta above Mission Lake is inundated by high tides and river overbanking about 5 – 7 times per year. These studies have concluded that sediment compactional subsidence is no longer occurring here in this upper part since it is some 2000 years older than the lower Delta. In effect, sediment deposition from Guadalupe River flooding appears sufficient to currently maintain this upper Delta portion.

Because of these geographic differences in Delta sedimentation processes, the TWDB performed a sediment loading analysis and calculated the amount of sediment input needed to account for the filling-in of Mission lake between 1935 and 1986 (Longley and Malstaff 1994). Their analysis treated Mission Lake as the main natural hydrologic unit of the Delta, and the receptacle for the bulk of the sediment from Guadalupe River flows. Measured values of gaged flow and sediment load collected by TWDB and USGS over the period from 1935 to 1986 were used. From the change in volume and depth over the 50 years, Mission Lake total sediment loading was calculated to be 815,800 m^3/yr (661 ac-ft/yr). As this rate of total sedimentation reflects excess deposition (i.e. subdelta accretion and progradation), they also calculated the minimal amount of sediment loading needed from Guadalupe River flow to offset relative sea-level rise (subsidence) in Mission Lake, which was determined to be 162,667 m^3 /yr (132 ac-ft/yr). Converting this sediment volume into FWI volume gave an minimal annual gaged inflow requirement of 355,235 ac-ft/yr to just maintain the bathymetry of Mission Lake and the Traylor Cut subdelta. Since on average, about 80.85% of the combined inflow to Guadalupe Estuary comes from gaged flow, this minimal gaged flow needed to deposit the required amount of sediment translates into 439,375 ac-ft/yr of combined inflow.

If one considers that this inflow is for sediment loading only into Mission Lake, then the inflow needed for other areas of the lower Delta that may not be subsiding (such as immediately adjacent to the N. and S. forks) would be still higher.

5.3.2 Sediment Loading Related to Instream Pulse Flows

Instream processes must be sufficient to maintain the upstream source of sediments carried down into the Guadalupe Delta. Sediment loadings to the estuary would be implicitly protected through the geomorphic overlay efforts undertaken by the GSA BBEST, in which maintenance of the annual water yield and effective discharge are maintained within 10% of the estimated values based on the selected hydrologic period of record. As described in Sec. 3.6, overbank flows on the order of 1 per 2 or more years are often required to effectively transport large amounts of sediments and other particulate matter from the lower watershed (Smith and Ward 2004). In addition, regular sediment transport provided from stream flow through the coastal plain is also important to maintaining river deltas and tidal channels in the tidal marshes and subtidal environments (Naiman and Décamps 1997).

5.4 Effects on Initial Freshwater Inflow and Instream Flow Regimes

In Section 5.1, the criteria developed to maintain riverine sound ecological environments, covering a broad range of stream conditions, are compared to those derived for the estuaries. There is broad alignment of the two independently-derived suites of criteria, and it appears that instream flow components are capable of meeting the estuary inflow levels recommended. The comparisons also highlighted the fact that there are four months, October-January, in which the GSA BBEST did not derive an estuary criteria using the salinity zone approach. The GSA BBEST was unable to identify any particular habitat or species that exhibits specific salinity preferences or time-sensitive biological needs during that portion of the year. However, this is not equivalent to a GSA BBEST conclusion that no inflows are necessary during this time frame. For instance, the best-available information on blue crab disease and parasite prevalence as a function of salinity (see Figure 4.5-28) does not eliminate any particular time of year from consideration.

One approach to filling in "missing months" is to simply pro-rate and distribute the criteria derived for months with more definitive biological or salinity needs to other months based on long-term inflow ratios (e.g., as in MBHE, 2008 for Matagorda Bay). Another approach, applied during drought conditions, is to adopt a 'refugium' approach in which a limited area of the estuary is chosen and inflows derived to just maintain an adequate salinity range in that area. This approach has been used for Matagorda Bay (LCRA, et al. 1997).

Other lines of evidence regarding nutrient and sediment inputs, as related to inflow magnitudes, point to the benefits of higher inflow levels, regardless of the time of year during which such inputs are received. As shown in Section 5.2, nutrient delivery to the Guadalupe Estuary, especially dissolved organic nitrogen, is concentrated during a few major rainfall/runoff events each year. The delivery of nutrients from sources carried by tributary rivers appears to be vital to support the primary productivity (phytoplankton and plant growth) in the bays.

Consideration of the information briefly summarized above leads to the conclusion that a range of inflows is necessary during all months of the year to sustain sound estuarine ecosystems. Examples provided in Section 5.1 demonstrate that the instream flow regime recommendations, including all components thereof, are capable of delivering sufficient volumes of freshwater to satisfy the established estuary criteria. Hence, the GSA BBEST recommends that instream flow regime recommendations, appropriately adjusted for streamflow contributions below the most downstream regime recommendation location(s), be applied as freshwater inflow criteria for the estuaries during the months of October through January, which are not explicitly addressed by the Eastern oyster and Rangia clam analyses. The GSA BBEST recognizes that application of instream flow regime recommendations as estuarine inflow criteria during these months will very likely be sufficient to maintain a sound ecological environment in the estuaries.

6. Environmental Flow Regime Recommendations

The environmental flow regime recommendations of the GSA BBEST for the Guadalupe – San Antonio River Basin, the San Antonio – Nueces Coastal Basin, and the associated bays and estuaries are summarized in the following pages. The environmental flow regime recommendations of the GSA BBEST include not only schedules of flow quantities, but also descriptions of how these flow quantities are to be applied in the context of environmental flow standards. It is the general expectation of the GSA BBEST that the TCEQ will consider direct translation of seasonal subsistence, base, and pulse flow values within recommended instream flow regimes into environmental flow standards and, ultimately, consider such values as potential permit conditions applicable to new surface water appropriations. Permit conditions may be defined as a set of rules specifying when impoundment or diversion of streamflow is authorized under a specific water rights permit. Similarly, it is the expectation of the GSA BBEST that the TCEQ will consider direct translation of seasonal ranges of freshwater inflows and associated attainment goals into environmental flow standards and, ultimately, apply such standards in the evaluation of applications for new surface water appropriations. With these expectations, the GSA BBEST perceives that it is important to explicitly address application of our environmental flow regime recommendations in order to have reasonable certainty that such recommendations will support a sound ecological environment.

The following subsections of this report focus on presentation of the recommended environmental flow regimes (Section 6.1), comparison of these regimes to flow restrictions in existing water rights and prior estuarine inflow recommendations of the state (Section 6.2), and example applications of our environmental flow regime recommendations (Section 6.3).

6.1 Environmental Flow Regime Summaries

The recommended environmental flow regimes for 15 stream locations throughout the Guadalupe – San Antonio River Basin are summarized in Tables 6.1-1 through 6.1-15 in upstream to downstream order (see Figure 3.1-1). The recommended environmental flow regime for one instream location in the San Antonio – Nueces Coastal Basin is summarized in Table 6.1-16. Further information regarding instream flow regime components is included in Sections 6.1.1 through 6.1.4 and recommendations regarding hydrologic conditions are included in Section 6.1.5. Examples of application of instream flow regimes are included in Section 6.3. Recommended environmental flow regimes for the Guadalupe and Mission-Aransas Estuaries are found in Section 6.1.6 and summarized in Tables 6.1-17 and 6.1-18, respectively. Further information regarding estuarine inflow regime components is included in Section 6.1.7.

Table 6.1-1. – Environmental Flow Regime Recommendation, Guadalupe River at Comfort

Overbank Flows	Qp: 15,900 cfs with Average Frequency 1 per 5 years Regressed Volume is 100,000 Duration Bound is 97			
	Qp: 7,420 cfs with Average Frequency 1 per 2 years Regressed Volume is 72,400 Duration Bound is 69			
High Flow Pulses	Qp: 4,020 cfs with Average Frequency 1 per year Regressed Volume is 37,400 Duration Bound is 53			
	Qp: 350 cfs with Average Frequency 1 per season Regressed Volume is 3,390 Duration Bound is 20	Qp: 1,190 cfs with Average Frequency 1 per season Regressed Volume is 8,950 Duration Bound is 26	Qp: 570 cfs with Average Frequency 1 per season Regressed Volume is 4,110 Duration Bound is 19	Qp: 500 cfs with Average Frequency 1 per season Regressed Volume is 4,060 Duration Bound is 24
	Qp: 140 cfs with Average Frequency 2 per season Regressed Volume is 1,030 Duration Bound is 11	Qp: 400 cfs with Average Frequency 2 per season Regressed Volume is 2,980 Duration Bound is 17	Qp: 160 cfs with Average Frequency 2 per season Regressed Volume is 1,130 Duration Bound is 12	Qp: 160 cfs with Average Frequency 2 per season Regressed Volume is 1,110 Duration Bound is 13
Base Flows (cfs)	110	100	75	110
	77	69	50	77
	54	35	25	48
Subsistence Flows (cfs)	10	5.2	2.0	2.7
	Jan, Feb, Mar	Apr, May, Jun	Jul, Aug, Sep	Oct, Nov, Dec
	Winter	Spring	Summer	Fall

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

Notes:

1. Period of Record used : 1/1/1940 to 12/31/2009.
2. Volumes are in acre-feet and durations are in days.

Table 6.1-2. – Environmental Flow Regime Recommendation, Guadalupe River near Spring Branch

	Winter (Jan, Feb, Mar)	Spring (Apr, May, Jun)	Summer (Jul, Aug, Sep)	Fall (Oct, Nov, Dec)
High Flow Pulses	Qp: 23,700 cfs with Average Frequency 1 per 5 years Regressed Volume is 242,000 Duration Bound is 82			
	Qp: 11,300 cfs with Average Frequency 1 per 2 years Regressed Volume is 109,000 Duration Bound is 60			
	Qp: 5,720 cfs with Average Frequency 1 per year Regressed Volume is 51,900 Duration Bound is 45			
	Qp: 570 cfs with Average Frequency 1 per season Regressed Volume is 5,150 Duration Bound is 19	Qp: 2,310 cfs with Average Frequency 1 per season Regressed Volume is 17,500 Duration Bound is 26	Qp: 870 cfs with Average Frequency 1 per season Regressed Volume is 5,970 Duration Bound is 19	Qp: 1,000 cfs with Average Frequency 1 per season Regressed Volume is 8,060 Duration Bound is 23
	Qp: 210 cfs with Average Frequency 2 per season Regressed Volume is 1,520 Duration Bound is 11	Qp: 870 cfs with Average Frequency 2 per season Regressed Volume is 6,500 Duration Bound is 19	Qp: 240 cfs with Average Frequency 2 per season Regressed Volume is 1,520 Duration Bound is 11	Qp: 230 cfs with Average Frequency 2 per season Regressed Volume is 1,660 Duration Bound is 12
Base Flows (cfs)	160	160	110	150
	100	91	64	100
	70	44	36	57
Subsistence Flows (cfs)	13	6.6	4.6	6.6

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

Notes:

1. Period of Record used : 1/1/1923 to 12/31/2009.
2. Volumes are in acre-feet and durations are in days.

Table 6.1-3. – Environmental Flow Regime Recommendation, Blanco River at Wimberley

	Winter (Jan, Feb, Mar)	Spring (Apr, May, Jun)	Summer (Jul, Aug, Sep)	Fall (Oct, Nov, Dec)
High Flow Pulses	Qp: 8,310 cfs with Average Frequency 1 per 5 years Regressed Volume is 82,000 Duration Bound is 74			
	Qp: 4,640 cfs with Average Frequency 1 per 2 years Regressed Volume is 43,100 Duration Bound is 58			
	Qp: 2,820 cfs with Average Frequency 1 per year Regressed Volume is 24,900 Duration Bound is 47			
	Qp: 380 cfs with Average Frequency 1 per season Regressed Volume is 3,840 Duration Bound is 28	Qp: 960 cfs with Average Frequency 1 per season Regressed Volume is 6,540 Duration Bound is 26	Qp: 190 cfs with Average Frequency 1 per season Regressed Volume is 1,130 Duration Bound is 13	Qp: 440 cfs with Average Frequency 1 per season Regressed Volume is 3,220 Duration Bound is 21
	Qp: 54 cfs with Average Frequency 2 per season Regressed Volume is 360 Duration Bound is 10	Qp: 360 cfs with Average Frequency 2 per season Regressed Volume is 2,370 Duration Bound is 18	Qp: 74 cfs with Average Frequency 2 per season Regressed Volume is 410 Duration Bound is 9	Qp: 82 cfs with Average Frequency 2 per season Regressed Volume is 500 Duration Bound is 10
Base Flows (cfs)	52	64	56	54
	34	40	36	36
	20	18	18	18
Subsistence Flows (cfs)	7.9	6.7	7.6	7.1

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

Notes:
1. Period of Record used : 1/1/1929 to 12/31/2009.
2. Volumes are in acre-feet and durations are in days.

Table 6.1-4. – Environmental Flow Regime Recommendation, San Marcos River at Luling

Overbank Flows	Qp: 17,900 cfs with Average Frequency 1 per 5 years Regressed Volume is 208,000 Duration Bound is 78			
	Qp: 10,600 cfs with Average Frequency 1 per 2 years Regressed Volume is 110,000 Duration Bound is 57			
	Qp: 6,120 cfs with Average Frequency 1 per year Regressed Volume is 56,400 Duration Bound is 41			
High Flow Pulses	Qp: 1,330 cfs with Average Frequency 1 per season Regressed Volume is 11,400 Duration Bound is 23	Qp: 2,740 cfs with Average Frequency 1 per season Regressed Volume is 18,400 Duration Bound is 21	Qp: 500 cfs with Average Frequency 1 per season Regressed Volume is 2,670 Duration Bound is 9	Qp: 1,710 cfs with Average Frequency 1 per season Regressed Volume is 11,200 Duration Bound is 18
	Qp: 340 cfs with Average Frequency 2 per season Regressed Volume is 1,800 Duration Bound is 8	Qp: 1,140 cfs with Average Frequency 2 per season Regressed Volume is 6,800 Duration Bound is 14	Qp: 240 cfs with Average Frequency 2 per season Regressed Volume is 1,090 Duration Bound is 6	Qp: 540 cfs with Average Frequency 2 per season Regressed Volume is 2,740 Duration Bound is 9
Base Flows (cfs)	210	220	220	200
	160	160	170	170
	120	110	110	120
Subsistence Flows (cfs)	78	75	73	77
	Jan Feb Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec
	Winter	Spring	Summer	Fall

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

Notes:

1. Period of Record used : 1/1/1940 to 12/31/2009.
2. Volumes are in acre-feet and durations are in days.

Table 6.1-5. – Environmental Flow Regime Recommendation, Plum Creek near Luling

	Winter (Jan, Feb, Mar)	Spring (Apr, May, Jun)	Summer (Jul, Aug, Sep)	Fall (Oct, Nov, Dec)
Overbank Flows	Qp: 10,800 cfs with Average Frequency 1 per 5 years Regressed Volume is 43,100 Duration Bound is 32			
Overbank Flows	Qp: 7,280 cfs with Average Frequency 1 per 2 years Regressed Volume is 29,700 Duration Bound is 29			
High Flow Pulses	Qp: 4,550 cfs with Average Frequency 1 per year Regressed Volume is 19,000 Duration Bound is 26			
High Flow Pulses	Qp: 1,470 cfs with Average Frequency 1 per season Regressed Volume is 6,870 Duration Bound is 23	Qp: 2,100 cfs with Average Frequency 1 per season Regressed Volume is 8,860 Duration Bound is 21	Qp: 230 cfs with Average Frequency 1 per season Regressed Volume is 1,080 Duration Bound is 15	Qp: 750 cfs with Average Frequency 1 per season Regressed Volume is 3,280 Duration Bound is 17
High Flow Pulses	Qp: 350 cfs with Average Frequency 2 per season Regressed Volume is 1,800 Duration Bound is 17	Qp: 720 cfs with Average Frequency 2 per season Regressed Volume is 3,300 Duration Bound is 17	Qp: 48 cfs with Average Frequency 2 per season Regressed Volume is 230 Duration Bound is 10	Qp: 150 cfs with Average Frequency 2 per season Regressed Volume is 720 Duration Bound is 13
Base Flows (cfs) – High	12	10	5.0	8.3
Base Flows (cfs) – Medium	8.4	5.6	2.5	5.2
Base Flows (cfs) – Low	4.6	2.6	1.6	2.5
Subsistence Flows (cfs)	1.0	1.0	1.0	1.0

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

Notes:

1. Period of Record used : 1/1/1931 to 12/31/2001.
2. Volumes are in acre-feet and durations are in days.

Table 6.1-6. – Environmental Flow Regime Recommendation, Guadalupe River at Gonzales

	Jan / Feb / Mar — Winter	Apr / May / Jun — Spring	Jul / Aug / Sep — Summer	Oct / Nov / Dec — Fall
Overbank Flows	Qp: 36,700 cfs with Average Frequency 1 per 5 years Regressed Volume is 492,000 Duration Bound is 70			
Overbank Flows	Qp: 24,400 cfs with Average Frequency 1 per 2 years Regressed Volume is 306,000 Duration Bound is 57			
Overbank Flows	Qp: 14,300 cfs with Average Frequency 1 per year Regressed Volume is 165,000 Duration Bound is 43			
High Flow Pulses	Qp: 4,140 cfs with Average Frequency 1 per season Regressed Volume is 48,300 Duration Bound is 29	Qp: 6,590 cfs with Average Frequency 1 per season Regressed Volume is 58,400 Duration Bound is 24	Qp: 1,760 cfs with Average Frequency 1 per season Regressed Volume is 14,800 Duration Bound is 14	Qp: 4,330 cfs with Average Frequency 1 per season Regressed Volume is 41,200 Duration Bound is 23
High Flow Pulses	Qp: 1,150 cfs with Average Frequency 2 per season Regressed Volume is 9,640 Duration Bound is 13	Qp: 3,250 cfs with Average Frequency 2 per season Regressed Volume is 26,900 Duration Bound is 17	Qp: 950 cfs with Average Frequency 2 per season Regressed Volume is 7,060 Duration Bound is 10	Qp: 1,410 cfs with Average Frequency 2 per season Regressed Volume is 11,400 Duration Bound is 13
Base Flows (cfs) — High	860	870	800	810
Base Flows (cfs) — Medium	690	650	650	690
Base Flows (cfs) — Low	540	440	440	510
Subsistence Flows (cfs)	210	210	210	180

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

Notes:

1. Period of Record used : 1/1/1940 to 12/31/2009.
2. Volumes are in acre-feet and durations are in days.

Table 6.1-7. – Environmental Flow Regime Recommendation, Sandies Creek near Westhoff

	Winter (Jan, Feb, Mar)	Spring (Apr, May, Jun)	Summer (Jul, Aug, Sep)	Fall (Oct, Nov, Dec)
Overbank Flows	Qp: 14,300 cfs with Average Frequency 1 per 5 years Regressed Volume is 86,700 Duration Bound is 39			
Overbank Flows	Qp: 6,240 cfs with Average Frequency 1 per 2 years Regressed Volume is 38,000 Duration Bound is 32			
Overbank Flows	Qp: 4,020 cfs with Average Frequency 1 per year Regressed Volume is 24,500 Duration Bound is 29			
High Flow Pulses	Qp: 770 cfs with Average Frequency 1 per season Regressed Volume is 4,840 Duration Bound is 21	Qp: 1,670 cfs with Average Frequency 1 per season Regressed Volume is 10,100 Duration Bound is 24	Qp: 250 cfs with Average Frequency 1 per season Regressed Volume is 1,430 Duration Bound is 16	Qp: 570 cfs with Average Frequency 1 per season Regressed Volume is 3,650 Duration Bound is 18
High Flow Pulses	Qp: 300 cfs with Average Frequency 2 per season Regressed Volume is 1,880 Duration Bound is 16	Qp: 440 cfs with Average Frequency 2 per season Regressed Volume is 2,710 Duration Bound is 18	Qp: 59 cfs with Average Frequency 2 per season Regressed Volume is 330 Duration Bound is 11	Qp: 150 cfs with Average Frequency 2 per season Regressed Volume is 960 Duration Bound is 14
Base Flows (cfs) – High	12	9.0	3.8	9.4
Base Flows (cfs) – Medium	9.9	6.0	2.7	5.9
Base Flows (cfs) – Low	6.3	3.1	1.8	3.2
Subsistence Flows (cfs)	1.0	1.0	1.0	1.0

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

Notes:
1. Period of Record used : 1/1/1965 to 12/31/2009.
2. Volumes are in acre-feet and durations are in days.

Table 6.1-8. – Environmental Flow Regime Recommendation, Guadalupe River at Cuero

	Winter (Jan, Feb, Mar)	Spring (Apr, May, Jun)	Summer (Jul, Aug, Sep)	Fall (Oct, Nov, Dec)
Overbank Flows	Qp: 45,400 cfs with Average Frequency 1 per 5 years Regressed Volume is 869,000 Duration Bound is 91			
Overbank Flows	Qp: 24,700 cfs with Average Frequency 1 per 2 years Regressed Volume is 406,000 Duration Bound is 64			
Overbank Flows	Qp: 16,600 cfs with Average Frequency 1 per year Regressed Volume is 247,000 Duration Bound is 50			
High Flow Pulses	Qp: 4,610 cfs with Average Frequency 1 per season Regressed Volume is 55,300 Duration Bound is 26	Qp: 8,870 cfs with Average Frequency 1 per season Regressed Volume is 110,000 Duration Bound is 32	Qp: 2,110 cfs with Average Frequency 1 per season Regressed Volume is 19,300 Duration Bound is 17	Qp: 5,200 cfs with Average Frequency 1 per season Regressed Volume is 54,700 Duration Bound is 23
High Flow Pulses	Qp: 1,610 cfs with Average Frequency 2 per season Regressed Volume is 14,100 Duration Bound is 13	Qp: 3,370 cfs with Average Frequency 2 per season Regressed Volume is 31,800 Duration Bound is 18	Qp: 1,050 cfs with Average Frequency 2 per season Regressed Volume is 8,300 Duration Bound is 12	Qp: 1,730 cfs with Average Frequency 2 per season Regressed Volume is 14,100 Duration Bound is 13
Base Flows (cfs) – High	980	940	800	870
Base Flows (cfs) – Medium	760	680	600	670
Base Flows (cfs) – Low	550	410	390	480
Subsistence Flows (cfs)	130	120	130	86

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

Notes:

1. Period of Record used : 1/1/1936 to 12/31/2009.
2. Volumes are in acre-feet and durations are in days.

Table 6.1-9. – Environmental Flow Regime Recommendation, Guadalupe River at Victoria

	Winter (Jan, Feb, Mar)	Spring (Apr, May, Jun)	Summer (Jul, Aug, Sep)	Fall (Oct, Nov, Dec)
Overbank Flows	Qp: 48,000 cfs with Average Frequency 1 per 5 years Regressed Volume is 971,000 Duration Bound is 96			
Overbank Flows	Qp: 25,500 cfs with Average Frequency 1 per 2 years Regressed Volume is 438,000 Duration Bound is 66			
Overbank Flows	Qp: 16,700 cfs with Average Frequency 1 per year Regressed Volume is 257,000 Duration Bound is 51			
High Flow Pulses	Qp: 4,620 cfs with Average Frequency 1 per season Regressed Volume is 56,100 Duration Bound is 26	Qp: 9,020* cfs with Average Frequency 1 per season Regressed Volume is 119,000 Duration Bound is 34	Qp: 2,060 cfs with Average Frequency 1 per season Regressed Volume is 19,200 Duration Bound is 16	Qp: 5,370 cfs with Average Frequency 1 per season Regressed Volume is 57,800 Duration Bound is 23
High Flow Pulses	Qp: 1,690 cfs with Average Frequency 2 per season Regressed Volume is 14,400 Duration Bound is 13	Qp: 3,300 cfs with Average Frequency 2 per season Regressed Volume is 33,000 Duration Bound is 18	Qp: 1,040 cfs with Average Frequency 2 per season Regressed Volume is 8,570 Duration Bound is 11	Qp: 1,880 cfs with Average Frequency 2 per season Regressed Volume is 15,600 Duration Bound is 13
Base Flows (cfs) – High	1,050	1,020	870	940
Base Flows (cfs) – Medium	800	710	630	720
Base Flows (cfs) – Low	580	450	420	510
Subsistence Flows (cfs)	160	130	150	110

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

Notes:
1. Period of Record used : 1/1/1935 to 12/31/2009.
2. Volumes are in acre-feet and durations are in days.
3. * value is estimated to be overbank.

Table 6.1-10. – Environmental Flow Regime Recommendation, Medina River at Bandera

	Jan–Mar (Winter)	Apr–Jun (Spring)	Jul–Sep (Summer)	Oct–Dec (Fall)
Overbank Flows	Qp: 6,920 cfs with Average Frequency 1 per 5 years Regressed Volume is 50,000 Duration Bound is 83			
Overbank Flows	Qp: 3,470 cfs with Average Frequency 1 per 2 years Regressed Volume is 34,500 Duration Bound is 63			
High Flow Pulses	Qp: 1,890 cfs with Average Frequency 1 per year Regressed Volume is 18,000 Duration Bound is 50			
High Flow Pulses	Qp: 110 cfs with Average Frequency 1 per season Regressed Volume is 960 Duration Bound is 17	Qp: 480 cfs with Average Frequency 1 per season Regressed Volume is 4,190 Duration Bound is 28	Qp: 340 cfs with Average Frequency 1 per season Regressed Volume is 2,310 Duration Bound is 21	Qp: 220 cfs with Average Frequency 1 per season Regressed Volume is 1,930 Duration Bound is 24
High Flow Pulses	Qp: 53 cfs with Average Frequency 2 per season Regressed Volume is 400 Duration Bound is 12	Qp: 110 cfs with Average Frequency 2 per season Regressed Volume is 900 Duration Bound is 17	Qp: 94 cfs with Average Frequency 2 per season Regressed Volume is 670 Duration Bound is 14	Qp: 68 cfs with Average Frequency 2 per season Regressed Volume is 500 Duration Bound is 14
Base Flows (cfs) – High	54	48	41	49
Base Flows (cfs) – Medium	32	22	16	33
Base Flows (cfs) – Low	17	9.8	6.2	16
Subsistence Flows (cfs)	1.1	1.0	1.2	1.0

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

Notes:
1. Period of Record used : 1/1/1941 to 12/31/2009.
2. Volumes are in acre-feet and durations are in days.

Table 6.1-11. – Environmental Flow Regime Recommendation, Medina River at San Antonio

	Winter (Jan, Feb, Mar)	Spring (Apr, May, Jun)	Summer (Jul, Aug, Sep)	Fall (Oct, Nov, Dec)
Overbank Flows	Qp: 9,940 cfs with Average Frequency 1 per 5 years Regressed Volume is 123,000 Duration Bound is 107			
Overbank Flows	Qp: 6,020 cfs with Average Frequency 1 per 2 years Regressed Volume is 69,300 Duration Bound is 83			
High Flow Pulses	Qp: 2,920 cfs with Average Frequency 1 per year Regressed Volume is 30,400 Duration Bound is 58			
High Flow Pulses	Qp: 350 cfs with Average Frequency 1 per season Regressed Volume is 3,570 Duration Bound is 27	Qp: 1,000 cfs with Average Frequency 1 per season Regressed Volume is 7,950 Duration Bound is 27	Qp: 440 cfs with Average Frequency 1 per season Regressed Volume is 3,050 Duration Bound is 21	Qp: 450 cfs with Average Frequency 1 per season Regressed Volume is 3,890 Duration Bound is 28
High Flow Pulses	Qp: 120 cfs with Average Frequency 2 per season Regressed Volume is 970 Duration Bound is 15	Qp: 380 cfs with Average Frequency 2 per season Regressed Volume is 2,680 Duration Bound is 17	Qp: 140 cfs with Average Frequency 2 per season Regressed Volume is 860 Duration Bound is 12	Qp: 130 cfs with Average Frequency 2 per season Regressed Volume is 930 Duration Bound is 14
Base Flows (cfs) – High	71	77	72	74
Base Flows (cfs) – Medium	53	62	57	60
Base Flows (cfs) – Low	20	37	33	27
Subsistence Flows (cfs)	7.9	7.6	7.0	7.4

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

Notes:
1. Period of Record used : 1/1/1940 to 12/31/2009.
2. Volumes are in acre-feet and durations are in days.

Table 6.1-12. – Environmental Flow Regime Recommendation, San Antonio River near Elmendorf

	Winter (Jan, Feb, Mar)	Spring (Apr, May, Jun)	Summer (Jul, Aug, Sep)	Fall (Oct, Nov, Dec)
Overbank Flows	Qp: 12,200 cfs with Average Frequency 1 per 5 years Regressed Volume is 123,000 Duration Bound is 52			
High Flow Pulses	Qp: 5,640 cfs with Average Frequency 1 per 2 years Regressed Volume is 49,400 Duration Bound is 34			
High Flow Pulses	Qp: 3,310 cfs with Average Frequency 1 per year Regressed Volume is 26,400 Duration Bound is 25			
High Flow Pulses	Qp: 830 cfs with Average Frequency 1 per season Regressed Volume is 6,210 Duration Bound is 14	Qp: 1,560 cfs with Average Frequency 1 per season Regressed Volume is 10,700 Duration Bound is 16	Qp: 1,110 cfs with Average Frequency 1 per season Regressed Volume is 6,460 Duration Bound is 12	Qp: 1,010 cfs with Average Frequency 1 per season Regressed Volume is 6,570 Duration Bound is 13
High Flow Pulses	Qp: 440 cfs with Average Frequency 2 per season Regressed Volume is 2,940 Duration Bound is 10	Qp: 820 cfs with Average Frequency 2 per season Regressed Volume is 5,060 Duration Bound is 11	Qp: 540 cfs with Average Frequency 2 per season Regressed Volume is 2,870 Duration Bound is 9	Qp: 480 cfs with Average Frequency 2 per season Regressed Volume is 2,630 Duration Bound is 8
Base Flows (cfs) – High	210	200	170	190
Base Flows (cfs) – Medium	150	150	130	150
Base Flows (cfs) – Low	110	99	88	97
Subsistence Flows (cfs)	61	50	49	56

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

Notes:
1. Period of Record used : 1/1/1934 to 12/31/1969.
2. Volumes are in acre-feet and durations are in days.

Table 6.1-13. – Environmental Flow Regime Recommendation, San Antonio River near Falls City

	Winter (Jan, Feb, Mar)	Spring (Apr, May, Jun)	Summer (Jul, Aug, Sep)	Fall (Oct, Nov, Dec)
Overbank Flows	Qp: 10,600 cfs with Average Frequency 1 per 5 years Regressed Volume is 110,000 Duration Bound is 57			
Overbank Flows	Qp: 6,000 cfs with Average Frequency 1 per 2 years Regressed Volume is 56,500 Duration Bound is 41			
High Flow Pulses	Qp: 3,160 cfs with Average Frequency 1 per year Regressed Volume is 26,600 Duration Bound is 29			
High Flow Pulses	Qp: 830 cfs with Average Frequency 1 per season Regressed Volume is 6,330 Duration Bound is 16	Qp: 1,670 cfs with Average Frequency 1 per season Regressed Volume is 12,300 Duration Bound is 19	Qp: 1,030 cfs with Average Frequency 1 per season Regressed Volume is 6,440 Duration Bound is 14	Qp: 850 cfs with Average Frequency 1 per season Regressed Volume is 5,690 Duration Bound is 14
High Flow Pulses	Qp: 420 cfs with Average Frequency 2 per season Regressed Volume is 2,740 Duration Bound is 10	Qp: 840 cfs with Average Frequency 2 per season Regressed Volume is 5,630 Duration Bound is 13	Qp: 470 cfs with Average Frequency 2 per season Regressed Volume is 2,650 Duration Bound is 10	Qp: 440 cfs with Average Frequency 2 per season Regressed Volume is 2,520 Duration Bound is 9
Base Flows (cfs) – High	200	200	170	190
Base Flows (cfs) – Medium	140	140	110	120
Base Flows (cfs) – Low	110	95	85	92
Subsistence Flows (cfs)	60	52	52	58

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

Notes:
1. Period of Record used : 1/1/1926 to 12/31/1969.
2. Volumes are in acre-feet and durations are in days.

Table 6.1-14. – Environmental Flow Regime Recommendation, Cibolo Creek near Falls City

	Winter (Jan, Feb, Mar)	Spring (Apr, May, Jun)	Summer (Jul, Aug, Sep)	Fall (Oct, Nov, Dec)
Overbank Flows	Qp: 13,500 cfs with Average Frequency 1 per 5 years Regressed Volume is 62,800 Duration Bound is 42			
Overbank Flows	Qp: 7,220 cfs with Average Frequency 1 per 2 years Regressed Volume is 34,200 Duration Bound is 35			
Overbank Flows	Qp: 5,160 cfs with Average Frequency 1 per year Regressed Volume is 24,700 Duration Bound is 32			
High Flow Pulses	Qp: 570 cfs with Average Frequency 1 per season Regressed Volume is 3,200 Duration Bound is 20	Qp: 2,280* cfs with Average Frequency 1 per season Regressed Volume is 10,400 Duration Bound is 21	Qp: 390 cfs with Average Frequency 1 per season Regressed Volume is 1,990 Duration Bound is 15	Qp: 1,000* cfs with Average Frequency 1 per season Regressed Volume is 5,000 Duration Bound is 22
High Flow Pulses	Qp: 140 cfs with Average Frequency 2 per season Regressed Volume is 820 Duration Bound is 13	Qp: 670 cfs with Average Frequency 2 per season Regressed Volume is 3,230 Duration Bound is 16	Qp: 110 cfs with Average Frequency 2 per season Regressed Volume is 580 Duration Bound is 10	Qp: 190 cfs with Average Frequency 2 per season Regressed Volume is 1,000 Duration Bound is 13
Base Flows (cfs) — High	29	27	22	27
Base Flows (cfs) — Medium	23	19	15	20
Base Flows (cfs) — Low	17	13	11	13
Subsistence Flows (cfs)	6.0	4.9	5.0	6.5

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

Notes:
1. Period of Record used : 1/1/1931 to 12/31/2009.
2. Volumes are in acre-feet and durations are in days.
3. * values are estimated to be overbank.

Table 6.1-15. – Environmental Flow Regime Recommendation, San Antonio River at Goliad

	Winter	Spring	Summer	Fall
	Jan, Feb, Mar	Apr, May, Jun	Jul, Aug, Sep	Oct, Nov, Dec
Overbank Flows	Qp: 23,600 cfs with Average Frequency 1 per 5 years Regressed Volume is 273,000 Duration Bound is 69			
Overbank Flows	Qp: 10,600 cfs with Average Frequency 1 per 2 years Regressed Volume is 107,000 Duration Bound is 45			
Overbank Flows	Qp: 7,680 cfs with Average Frequency 1 per year Regressed Volume is 73,500 Duration Bound is 38			
High Flow Pulses	Qp: 1,520 cfs with Average Frequency 1 per season Regressed Volume is 12,800 Duration Bound is 19	Qp: 3,540 cfs with Average Frequency 1 per season Regressed Volume is 30,000 Duration Bound is 24	Qp: 1,640 cfs with Average Frequency 1 per season Regressed Volume is 11,200 Duration Bound is 16	Qp: 2,320 cfs with Average Frequency 1 per season Regressed Volume is 17,600 Duration Bound is 19
High Flow Pulses	Qp: 550 cfs with Average Frequency 2 per season Regressed Volume is 3,940 Duration Bound is 11	Qp: 1,570 cfs with Average Frequency 2 per season Regressed Volume is 11,300 Duration Bound is 16	Qp: 750 cfs with Average Frequency 2 per season Regressed Volume is 4,450 Duration Bound is 10	Qp: 780 cfs with Average Frequency 2 per season Regressed Volume is 5,070 Duration Bound is 11
Base Flows (cfs) – High	290	280	220	270
Base Flows (cfs) – Medium	200	180	150	200
Base Flows (cfs) – Low	140	130	120	130
Subsistence Flows (cfs)	76	60	54	66

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

Notes:
1. Period of Record used : 1/1/1940 to 12/31/1969.
2. Volumes are in acre-feet and durations are in days.

Table 6.1-16. – Environmental Flow Regime Recommendation, Mission River at Refugio

	Winter (Jan, Feb, Mar)	Spring (Apr, May, Jun)	Summer (Jul, Aug, Sep)	Fall (Oct, Nov, Dec)
Overbank Flows	Qp: 11,500 cfs with Average Frequency 1 per 5 years Regressed Volume is 66,200 Duration Bound is 44			
Overbank Flows	Qp: 6,830 cfs with Average Frequency 1 per 2 years Regressed Volume is 38,400 Duration Bound is 36			
Overbank Flows	Qp: 4,160 cfs with Average Frequency 1 per year Regressed Volume is 22,800 Duration Bound is 30			
High Flow Pulses	Qp: 450 cfs with Average Frequency 1 per season Regressed Volume is 2,340 Duration Bound is 15	Qp: 1,560 cfs with Average Frequency 1 per season Regressed Volume is 7,910 Duration Bound is 18	Qp: 420 cfs with Average Frequency 1 per season Regressed Volume is 2,010 Duration Bound is 12	Qp: 410 cfs with Average Frequency 1 per season Regressed Volume is 2,090 Duration Bound is 14
High Flow Pulses	Qp: 60 cfs with Average Frequency 2 per season Regressed Volume is 310 Duration Bound is 8	Qp: 320 cfs with Average Frequency 2 per season Regressed Volume is 1,440 Duration Bound is 10	Qp: 57 cfs with Average Frequency 2 per season Regressed Volume is 240 Duration Bound is 6	Qp: 45 cfs with Average Frequency 2 per season Regressed Volume is 200 Duration Bound is 6
Base Flows (cfs) – High	15	14	12	15
Base Flows (cfs) – Medium	8.6	8.3	7.0	7.8
Base Flows (cfs) – Low	4.7	4.5	3.8	4.5
Subsistence Flows (cfs)	1.0	1.3	1.0	1.3

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

Notes:
1. Period of Record used : 1/1/1940 to 12/31/2009.
2. Volumes are in acre-feet and durations are in days.

6.1.1 Subsistence Flows

Available hydrologic, biological, geomorphologic, and water quality data and professional judgment suggest that recommended subsistence flows will provide aquatic habitat, longitudinal connectivity, dissolved oxygen, and temperature sufficient to ensure survival of aquatic species for transient periods. Frequent violations of stream standards for dissolved oxygen and temperature have not occurred and would not be expected to occur at the statistically-derived subsistence flow values. Active data collection and monitoring under subsistence flow conditions is recommended to more quantitatively assess the potential effects of extended periods of subsistence flows on aquatic species.

It is the consensus of the GSA BBEST that translation of seasonal subsistence flows into environmental flow standards and permit conditions should not result in more frequent occurrence of flows less than the recommended seasonal subsistence values as a result of the issuance of new surface water appropriations or amendments. Recognizing ecological risks associated with potential increases in the frequency of occurrence of flows near the seasonal subsistence level, the GSA BBEST further recommends that 50% of the difference between inflow[10] and the seasonal subsistence flow be passed when inflows are between the specified seasonal base and subsistence values under dry hydrologic conditions.

6.1.2 Base Flows

Available hydrologic, biological, geomorphologic, and water quality data and professional judgment suggest that recommended base flows will provide variable flow conditions, suitable and diverse aquatic habitat, longitudinal connectivity, soil moisture, and water quality sufficient to sustain aquatic species for extended periods. Results of habitat modeling for both the SB2/LSAR and GSA guild sets at two locations on the San Antonio River (Elmendorf and Goliad) and two locations on the Guadalupe River (Gonzales and Victoria) indicate that the statistically-derived base flows will maintain suitable habitat for all of the habitat guilds considered. Frequent violations of stream standards for dissolved oxygen and temperature have not occurred and would not be expected to occur at the statistically-derived base flow values.

It is the understanding of the GSA BBEST that translation of seasonal base flows into environmental flow standards and permit conditions may result in more frequent occurrence of flows less than or equal to the recommended seasonal base values as a result of the issuance of new surface water appropriations or amendments. The GSA BBEST finds this to be an acceptable ecological risk based on consideration of figures showing percentages of maximum habitat versus discharge for habitat guilds included in Section 3.3.

6.1.3 High Flow Pulses

Available hydrologic, biological, geomorphologic, and riparian vegetation data and professional judgment suggest that recommended pulses will provide high in-channel flows of varying durations, recruitment events for organisms, lateral connectivity, channel and substrate

[10] Inflow, in this context, means incoming flow to a riverine point of diversion or impoundment and should not be confused with freshwater inflow to bays and estuaries.

maintenance, limitation of riparian vegetation encroachment, and in-channel water quality restoration after prolonged low flow periods as necessary for long-term support of a sound ecological environment. These recommended pulses generally include peak daily average flow rates and cumulative volumes and durations for high flow pulses with frequencies (and increasing magnitudes) of two per season, one per season, one per year, one per two years, and one per five years. Depending on location, some of these high flow pulses may be more accurately described as overbank flows.

It is the understanding of the GSA BBEST that translation of pulse flows of specified frequencies into environmental flow standards and permit conditions may result in less frequent occurrence of high flow pulses as a result of the issuance of new surface water appropriations or amendments. In order to provide greater certainty that the ecological functions of high flow pulses will be maintained, the GSA BBEST recommends five levels of pulse flow events based on the HEFR analysis. The five levels of pulse flow events were categorized as seasonal or annual frequency events. Because the high pulse flows are episodic events, the GSA BBEST adopted criteria that are to be used in conjunction with the HEFR generated high pulse flow recommendations. The adopted criteria describe the qualifications for meeting a high pulse flow event and the criteria for allowing higher-level pulse flow events to satisfy the yet unmet annual or seasonal pulse flow events that exist at lower pulse flow or overbank levels.

A qualifying flow pulse or overbank event begins when flow exceeds the prescribed threshold flow magnitude. It continues (which means flows are passed up to that flow magnitude) until the prescribed volume is passed. If the prescribed volume is not met by the associated prescribed duration (calculated as the upper confidence bound of the duration regression in HEFR), the event is considered as being met. If during a qualifying event at one magnitude, flows increase to a magnitude that triggers a new threshold event, the flow magnitude, volume, and duration of the higher qualifying flow pulse controls the flow regime, and the first event is initially ignored. In this case, the higher flow events are considered to satisfy lower flow events in the same season (e.g., an overbank event satisfies a one-per-season event and one two-per-season event).

6.1.4 Overbank Flows

Available hydrologic, biological, geomorphologic, and riparian vegetation data and professional judgment suggest that recommended overbank flows will provide high flows exceeding channel capacity, life phase cues for organisms, riparian vegetation diversity maintenance, conditions conducive to seedling development, floodplain connectivity, lateral channel movement, floodplain maintenance, recharge of floodplain water tables, flushing of organic material into the channel, nutrient deposition in the floodplain, and restoration of water quality in isolated floodplain water bodies as necessary for long-term support of a sound ecological environment. These recommended overbank flow rates and cumulative volumes and durations for episodic events occur with typical frequencies of one per year, one per two years, and one per five years.

6.1.5 Definition of Hydrologic Condition (Wet/Average/Dry)

The GSA BBEST recommends that seasonal hydrologic condition at any specific location be defined on the basis of the 12-month cumulative antecedent flow volumes near that location with the understanding that these volumes will be selected such that dry, average, and wet conditions will apply 25%, 50%, and 25% of the time, respectively. Use of 12-month cumulative flow volumes will provide adequate recognition of the persistence of drought and avoid more complex antecedent seasonal computations associated with shorter durations. It is recommended that the applicable hydrologic condition for the entire season be defined on the basis of an assessment of hydrologic condition at the beginning of the first day of the season, thereby recognizing practical operations. Furthermore, the GSA BBEST recommends that hydrologic conditions be applicable only at times when inflows are less than the peak flow associated with the recommended two-per-season high flow pulse. As will become apparent in the illustrative example application of our environmental flow regime recommendation in Section 6.3, compliance with high flow pulse and overbank flow recommendations is not intended to be subject to hydrologic conditions.

6.1.6. Estuarine Inflow Regime Summaries

The freshwater inflow regime recommendations of the GSA BBEST for the Guadalupe and Mission-Aransas Estuaries are summarized in Tables 6.1-17 and 6.1-18. Table 6.1-17 gives the magnitudes of recommended inflow criteria, represented as volumes of freshwater inflow during the February through May and June through September periods associated with the environmental flow analyses of Rangia clams and Eastern oysters, respectively. The attainment goals for each element of the regime recommendations are specified in Table 6.1-18.

Table 6.1-17. Summary of recommended inflow volumes for the Guadalupe and Mission-Aransas Estuaries. Units are thousands of ac-ft in the period indicated, either per 3 month period or per month.

Guadalupe Estuary Criteria - Volumes				
Criteria level	Inflow Criteria Volumes, suite G1 for Rangia clams		Inflow Criteria Volumes, suite G2 for Eastern oysters	
	Feb. (1000 ac-ft/mon)	Mar.-May (1000 ac-ft/3mon)	June (1000 ac-ft/mon)	July-Sept. (1000 ac-ft/3mon)
G1-Aprime, G2-Aprime	n/a	550-925	n/a	450-800
G1-A, G2-A	n/a	375-550	n/a	275-450
G1-B, G2-B	n/a	275-375	n/a	170-275
G1-C, G2-C	≥75	150-275	≥40	75-170
G1-CC, G2-CC	0 - 75	150-275	0 - 40	75-170
G1-D, G2-D	n/a	0 - 150	n/a	50-75
G1-DD, G2-DD	n/a	n/a	n/a	0-50
Mission-Aransas Estuary Criteria - Volumes				
Criteria level	Inflow Criteria Volumes, set MA1 for Rangia clams		Inflow Criteria Volumes, set MA2 for Eastern oysters	
	Feb.	Mar.-May	June	July-Sept.
MA2 - Aprime	n/a	n/a	n/a	500-1000

Table 6.1-18. Summary of attainment goals for the respective inflow volume recommendations in Table 6.1-17. The percentages of years refer to a long-term period, similar to that used in the criteria derivation, and as further described in Section 6.1.7.

Guadalupe Estuary Criteria -Attainment Recommendations			
Criteria level	Specification	Inflow Criteria Attainment, G1 suite for Rangia clams	Inflow Criteria Attainment, G2 suite for Eastern oysters
G1-Aprime, G2-Aprime	Attainment, G - Aprime	G1-Aprime at least 12% of years	G2-Aprime at least 12% of years
G1-A, G2-A	Attainment, G - A	G1-A at least 12 % of years	G2-A at least 17 % of years
G1-A&G1-B, G2-A&G2-B	Attainment, G - A & G - B combined	G1-A and G1-B combined at least 17% of years	G2-A and G2-B combined at least 30% of years
G1-C&G1-CC, G2-C&G2-CC	Attainment, G - C & G - CC combined	G1-C and G1-CC equal to or greater than 19% of years. G1-CC no more than 2/3 of total	G2-C and G2-CC equal to or greater than10% of years. G2-CC no more than 1/6 of total
G1-D	Attainment, G1- D	no more than 9% of years	n/a
G2-DD	Attainment, G2- DD	n/a	G2-D no more than 6% of years
G2-D&G2-DD	Attainment, G2-D & G2-DD combined	n/a	G2-D and G2-DD combined no more than 9% of years
Mission-Aransas Estuary Criteria -Attainment Recommendations			
Criteria level	Specification	Inflow Criteria Attainment, set MA1 for Rangia clams	Inflow Criteria Attainment, set MA2 for Eastern oysters
MA-Aprime	Attainment MA-Aprime	n/a	MA2-Aprime at least 2% of years

Note: The attainment goals for categories G1-C, G1-CC, G2-C, and G2-CC, which allow for an increase in the frequency of occurrence of these magnitudes of inflows, are contingent upon other criteria level attainment goals being met.

6.1.7. Attainment Goals for Estuarine Inflow Recommendations

Compliance with the recommended inflow criteria and associated attainment goals for the Guadalupe and Mission-Aransas Estuaries, as detailed in Table 6.1-18, is expected to be evaluated with modeling approaches. Such modeling approaches are expected to include applications of the Guadalupe – San Antonio River Basin and San Antonio – Nueces Coastal Basin Water Availability Models (WAMs) that:

1) predict comprehensive total inflow quantities to the estuarine systems, including contributions from ungaged coastal drainages and corrections for diversions and return flows below the most downstream gaging stations; and
2) use a long-term period of record (65+ years) with an underlying variable climate and hydrologic regime similar to, or the same as, that used in the derivation of the GSA BBEST recommendations.

For compliance with the estuarine inflow regime recommendations, simulated freshwater inflows in the long-term evaluation should meet each specific inflow criterion (e.g., G2-A, G1-CC) at the stated magnitude and attainment frequencies in Tables 6.1-17 and 6.1-18.

6.2 Comparisons to Water Rights Permits

During the last 25 years, water rights in Texas have typically been issued with special conditions specifying one or more streamflow rates that must be exceeded before the water right owner may impound or divert state water. These special conditions or environmental flow restrictions have been derived by scientific methods, precedent, negotiations, and various combinations thereof. General comparisons of GSA BBEST flow regime recommendations, which are based on best available science, to the flow restrictions found in existing water rights in selected portions of the Guadalupe and San Antonio River Basins are presented in the following paragraphs.

In the Guadalupe River Basin, major water rights on the Guadalupe River that include environmental flow restrictions and are located near GSA BBEST flow regime recommendation locations include Certificate of Adjudication Number (CA#) 18-2074 held by GBRA and Permit Number (P#) 5466 held by the City of Victoria. P#5466 includes some diversion restrictions associated with monthly "normal" flows (353-1,260 cfs) and averaging about 580 cfs. These "normal" flows are generally comparable to the low and medium base flows (420-800 cfs) in the regime recommended by the GSA BBEST. P#5466 also includes monthly "low" flows (150-300 cfs) below which no diversions are authorized. Subsistence flows specified by the GSA BBEST for the Guadalupe River at Victoria range from 110 cfs to 160 cfs. GBRA's CA#18-2074, which is associated with Canyon Reservoir, includes monthly flows for the Guadalupe River at Gonzales (500-700 cfs) below which certain flow restrictions may affect inflows passed through Canyon Reservoir. These flows are comparable to the low and medium base flows (440-690 cfs) in the regime recommended by the GSA BBEST.

In addition, many water rights on the San Marcos River near Luling include flow restrictions of 110-135 cfs during the months of May through August. These are comparable to the spring and summer low base flow (110 cfs) in the regime recommended by the GSA BBEST.

In the San Antonio River Basin, many water rights permits on the San Antonio River have environmental flow restrictions that do not vary and are applicable throughout the year. Near Elmendorf, flow restrictions precluding diversions when flows are less than 100-163 cfs are included in several permits. These are comparable to the low and medium base flows (88-150 cfs) in the regime recommended by the GSA BBEST. Similarly, flow restrictions precluding diversions when San Antonio River flows are less than 100-197 cfs are included in numerous permits near Falls City. These are comparable to the full range of base flows (85-200 cfs) in the regime recommended by the GSA BBEST.

6.3 Comparison of GSA BBEST Estuary Recommendations to Texas State Methodology

The Texas Bays & Estuary Program used the Estuarine Mathematical Programming Model (TxEMP), a non-linear optimization model in conjunction with the hydrodynamic circulation model (TxBlend), to evaluate Freshwater Inflows (FWI) needed to maintain normal salinity gradients and fisheries harvests in Texas bays and estuaries (Longley, ed., 1994, Powell et al. 2002). TxEMP is an example of a "resource-based" multi-objective management model which determines target inflows to estuaries. The primary resource objective is to evaluate statistical relationships between historical FWI hydrology and commercial fisheries production, and the secondary objective is maintenance of salinity conditions within set inflow bounds. These are two TxEMP model objective functions which together determine inflows that achieve fishery production based on historical commercial fishery harvest data, [11] and maintain the historical salinity and hydrology conditions found in each specific estuary. The model was designed to be run with both functions operating together using a combination of constraints, probabilistic uncertainty, and weighting factors.

The TxEMP model finds monthly "beneficial inflow" quantities that support historical levels of characteristic estuarine resources in each bay system (primarily target fisheries species). Following is a brief summary of the pertinent model information:

a) TxEMP objective functions use a deterministic approach to optimize salinity with inflows, and fisheries harvest with inflows.
b) TxEMP constrains Inflow to Historical Flow Regimes (the tenth to 50th percentile range).
c) TxEMP constrains Fishery Harvest to certain salinity ranges, based on historical hydrology and salinity relationships. Fishery harvests for selected target species are also constrained to a maximum amount, 80% of the mean annual historical harvest, and to certain ratios of abundance existing between target species.
d) TxEMP produces a monthly distribution of flows which sum to an annual total, and two cases, MinQ and MaxH, are considered target flows.
e) MinQ describes the TxEMP solution for optimized salinity conditions without maximal harvest, while MaxH describes the solution for optimized (i.e., maximum) fishery harvest within pre-set salinity/hydrology ranges.
f) MinQ-sal describes a TxEMP solution that maintains salinity within the limits of the monthly inflow bounds and no maintenance of fishery harvest (i.e., no input or constraints from harvest equations). This is a fairly recent flow target which has not been extensively examined for the Guadalupe Estuary.

MinQ and MaxH target flows are computed inflows in the range where bay salinities are maintained on a monthly basis according to pre-set historical hydrology bounds. For the Guadalupe Estuary, MinQ was computed as 1.02 million ac-ft per year, while MaxH was computed as 1.15 million ac-ft per year (TWDB and TPWD, 1998). These are mid-range inflows which do not apply to low-inflow or drought conditions. MinQ-sal, derived through application of the State Methodology, was estimated at 662.9 thousand ac-ft per year for this system, and

[11] In later applications, the TPWD Coastal Monitoring sampling data for "catch" (abundance measure) was used.

was considered to be a low-inflow value, but still adequate for reasonable bay production. All of the TxEMP annual results are divided into monthly inflows based on the salinity and inflow bounds set from historical hydrology data (Table 6.3-1). For the Guadalupe Estuary, both MinQ and MaxH show moderate inflow levels in January and February; elevated inflows in May and June resulting from springtime pulses; and lower inflow levels during the remaining months. Because hydrology input data for the TxEMP model are constrained by pre-set, historical hydrology records to the individual monthly medians or 50th percentile monthly flows, MinQ and MaxH flows for Guadalupe Estuary fall in the historical hydrology record between the 26th and 35th frequency percentiles, respectively. Since flow solutions higher than the historical monthly medians are not allowed by model constraints, MaxH solutions by definition can only be equal to or less than the historical monthly median flows. Any need for higher flows in certain months to achieve higher fishery harvest cannot be directly evaluated from the model results.

While the TxEMP model predicts individual monthly inflow targets, estuarine biologists now recognize that seasonal inflow pulses are more beneficial and critical for biota than strictly-defined monthly inflows. The timing, frequency, duration, and magnitude of inflow pulses must be considered (Estevez 2002, SAC 2009). Any number of Texas estuarine species (brown shrimp, blue crab, croaker, flounder) reach their peak juvenile-young adult abundance during the late winter through early summer period (March through June) as measured in TPWD trawl and bag seine samples by the Coastal Fisheries Monitoring Program (TPWD Reports 1996, 1998, 2001, 2002). Oyster production is most affected in the summer months when disease and parasites cause the most stress. Thus, recognition of the impact of seasonal, rather than monthly or bi-monthly, inflows on estuarine productivity by the GSA BBEST represents a significant departure from the state methodology.

Because TxEMP derives a monthly distribution of inflows, it is somewhat difficult to directly compare them to the combined seasonal flow targets recommended by the GSA BBEST. A very simplistic approach is to compare the cumulative monthly TxEMP flows for a season (e.g., March through May or July through September) to the corresponding seasonal inflow recommendations from the GSA BBEST analyses which targeted Rangia or oysters, respectively. For cumulative March through May inflows beneficial to Rangia, summing the monthly TxEMP results totals about 291,000 ac-ft for MinQ and 327,400 ac-ft for MaxH. Similarly, for cumulative July-September inflows beneficial to oysters, this would total about 174,000 ac-ft for MinQ, and 229,400 ac-ft for MaxH. Hence, TxEMP summed MinQ values for March through May (291 thousand ac-ft or kac-ft) would correspond roughly to the lower end of the G1-B range for Rangia (275-375 kac-ft). Similarly, TxEMP summed MinQ values for July through September (174 kac-ft) would correspond to the low end of the of the G2-B criteria (170-275 kac-ft) for oysters.

Another basis for comparison is to fill in the “missing months” of the GSA BBEST estuary criteria levels with reasonable elements of the instream criteria, a topic discussed in Section 5.4. Thus, Table 6.3-2 provides some further comparisons of the GSA BBEST approach using this approximation. As is evident in this table, some combinations of the GSA BBEST-derived criteria can total to levels higher than the state methodology results. However, one should not overlook a fundamental element of the GSA BBEST criteria, namely, the associated attainment goals for each of the various criteria levels. Taken together, the various magnitudes and attainment frequency goals comprise a 'regime' of inflows. For instance, the upper level criteria G1-Aprime and G2-Aprime are recommended to occur at frequencies of about 12% of years each. Although this represents a 25% decline from the historical (1941-2009) frequency of occurrence of these inflow volumes within the respective seasonal windows, the GSA BBEST recognizes that the recommended combinations of inflow volume and frequency of occurrence, together, will likely maintain a sound ecological environment.

Table 6.3-1. Monthly flow targets computed by TxEMP model for Guadalupe Estuary (from TWDB and TPWD, 1998) (Flow units are ac-ft per month).

Month	Min Q	Max H
January	111,200	111,200
February	124,200	124,200
March	52,400	52,400
April	52,400	52,400
May	186,000	222,600
June	136,000	162,700
July	60,800	88,600
August	60,800	88,300
September	52,400	52,400
October	52,400	52,400
November	73,800	73,800
December	66,200	66,200
Total Annual	1,028,800	1,147,400

Table 6.3-2. Comparison of State's TxEMP model results to GSA BBEST-derived estuary criteria complemented with instream values for "missing months" (all in units of thousand ac-ft per month)

	TxEMP-Derived Inflows			GSA BBEST Guadalupe Estuary Criteria[1] / Instream Combinations				
Month	MinQ-Sal	MinQ	MaxH	G1-A prime, G2-A prime w. Instream Base Wet and 1/seas HFP	G1-A, G2-A w. Instream Base Wet and 1/seas HFP	G1-B, G2-B w. Instream Base Avg. and 2/seas HFP	G1-C, G2-C w. Instream Base Dry. and no HFP	G1-D, G2-D w. Instream Subsistence
Jan	52.4	111.2	111.2	101.7	101.7	70.4	47.1	15.4
Feb	52.4	124.2	124.2	101.7	101.7	70.4	47.1	15.4
Mar	52.4	52.4	52.4	245.8	154.2	108.3	70.8	25
Apr	52.4	52.4	52.4	245.8	154.2	108.3	70.8	25
May	61.0	186.1	222.6	245.8	154.2	108.3	70.8	25
Jun	60.9	136.0	162.7	128.7	128.7	81.5	39.1	12.8
Jul	60.9	60.9	88.6	208.3	120.8	74.2	40.8	20.8
Aug	60.9	60.9	88.3	208.3	120.8	74.2	40.8	20.8
Sep	52.4	52.4	52.4	208.3	120.8	74.2	40.8	20.8
Oct	52.4	52.4	52.4	102.5	102.5	71.2	44.2	12.2
Nov	52.4	73.8	73.8	102.5	102.5	71.2	44.2	12.2
Dec	52.4	66.2	66.2	102.5	102.5	71.2	44.2	12.2
Totals	662.9	1,028.9	1,147.4	2,001.9	1,464.6	983.4	600.7	217.6
approximate attainment goals (% of years)[2]	not specified	not specified	not specified	12% G1-Aprime; 12% G2-Aprime	12% G1-A, 17% G2-A	G1-A &B combined 17%; G2-A & B combined 30%	G1-C &CC at least 19%; G2-C&CC at least 10%	G1-D no more than 9%; G2-D no more than 6%

Note : 1) shaded cells indicate criteria from salinity zone analyses for rangia and oysters; 2) full details on attainment in Sections 4.6, 6.1.6, and 6.1.7.

6.4 Example Applications of Flow Regime Recommendations

An important consideration of the GSA BBEST in providing its instream environmental flow regime recommendations in the form of Tables 6.1-1 through 6.1-16 is its understanding of how such regimes might be applied to new surface water appropriations. Hence, our understanding of potential flow regime application is summarized in the following illustrative example of a theoretical diversion or impoundment project on the San Antonio River at Goliad. Guiding principles for flow regime application are summarized in Table 6.4-1 and the following sub-sections by flow regime component, moving from low- to high-flow situations with recognition of situations when hydrologic conditions are to be considered. References to Table 6.4-1 in the following sub-sections are made by line number in the table.

6.4.1 Subsistence Flows

1) If inflow is less than the seasonal subsistence value, then all inflow must be passed and none impounded or diverted (Line 1). Hydrologic conditions are not a factor.

6.4.2 Base Flows

1) Hydrologic conditions as defined in Section 6.1.5 are applicable when inflow is less than the two-per-season peak flow or all pulse recommendations have been satisfied.
2) Under dry hydrologic conditions, if inflow is less than the seasonal base value and greater than the seasonal subsistence value, then 50% of the difference between inflow and the seasonal subsistence value must be passed, and the balance may be impounded or diverted to the extent available, subject to senior water rights (Line 2).
3) Under average and wet hydrologic conditions, if inflow is less than the seasonal base value, then all inflow must be passed and none impounded or diverted (Lines 9 and 12).
4) If inflow is less than the two-per-season peak value and greater than the seasonal base value for the current hydrologic condition, then that seasonal base value must be passed, and the balance may be impounded or diverted to the extent available, subject to senior water rights (Lines 3, 10, and 13).

6.4.3 High Flow Pulses

1) If inflow is greater than a specified peak value and less than the next greatest specified peak value, and all applicable pulse recommendations have not been satisfied, then all inflow up to the lower of the two peak values must be passed until either the recommended volume or duration has passed, and the balance of inflow may be impounded or diverted to the extent available, subject to senior water rights (Lines 4a, 5a, 6a, 7a, 8a, 11, and 14).
2) If inflow is greater than the two-per-season peak value and all applicable pulse recommendations except one remaining two-per-season event have been satisfied, then all inflow up to the two-per-season peak value must be passed until either the recommended volume or duration has passed, and the balance of inflow may be impounded or diverted to the extent available, subject to senior water rights (Lines 5b, 6b, 7b, and 8b).

3) If all applicable pulse recommendations have been satisfied and inflow is greater than the seasonal base value for the current hydrologic condition, then that seasonal base value must be passed, and the balance may be impounded or diverted to the extent available, subject to senior water rights (Lines 4b, 5c, 6c, 7c, and 8c).
4) Pulse events are initiated upon occurrence of specified peak flow, counted in the season or year in which they begin, and assumed to continue into the following season or year as necessary to meet specified volumes or durations.
5) One large pulse counts as one pulse in each of the smaller categories subject to reset at season or return period end.
6) Each return period (i.e., three-month season, one-year, two-years, or five-years) is independent of the preceding and subsequent return period with respect to high flow pulse attainment frequency.

6.4.4 General Considerations

Under all hydrologic conditions, the GSA BBEST recommends that flows passed for senior water rights count towards satisfaction of any specified subsistence, base, and pulse flow rates and volumes.

6.4.5 Example Flow Regime Applications and Verification

To the extent that the Guadalupe – San Antonio River Basin, San Antonio – Nueces Coastal Basin, and the Guadalupe and Mission-Aransas Estuaries have exhibited characteristics of sound ecological environments throughout the last century, the GSA BBEST is cognizant of, and in full agreement with, the observation in SAC guidance documentation that any recommendations based on historical flow parameters (and their historical frequencies of occurrence) logically might be considered to represent flow quantities greater than, perhaps substantially greater than, the minimums needed to continue to support a sound ecological environment as available water resources are being developed. In point of fact, the GSA BBEST recognizes that some lesser quantities of flow and/or lesser frequencies of occurrence may also be fully adequate. For example, fluvial sediment transport overlay analyses by TWDB staff acting at the request of the GSA BBEST have demonstrated that flows based on full use of all authorized water rights (as compared to historical uses and uses representative of present conditions) are more than adequate to avoid undesirable channel degradation.

Attainment frequency guidelines may be defined as the recommended frequencies of occurrence of various flow components expressed as a percentage of time that specified flow magnitudes are expected to be equaled or exceeded during specified seasonal or annual time periods with existing and proposed water use activities fully operational. In the context of an environmental flow regime or standard, attainment frequency guidelines can be applicable to base, pulse, and/or overbank flows; however, the need to achieve minimum subsistence flows generally applies all of the time to the extent upstream flows are available. As recommended by the GSA BBEST, an attainment frequency approach is applied to our estuary criteria.

Instream Flow Regime Application Example
San Antonio River @ Goliad

Line #	Season	Hydrologic Condition	Incoming Streamflow (cfs)	550 cfs 2/Season Pulse Count	1,520 cfs 1/Season Pulse Count	7,680 cfs 1/Year Pulse Count	10,600 cfs 1/2Years Pulse Count	23,600 cfs 1/5Years Pulse Count	Passing Streamflow (cfs)	Impound or Divert (cfs)	Line Notes
1	Winter	Dry	70						70	0	Pass all inflow.
2	Winter	Dry	116						96	20	Pass seasonal Subsistence flow (76 cfs) plus 50% of the difference between Inflow and seasonal Subsistence flow.
3	Winter	Dry	300						140	160	Pass Dry Base flow (140 cfs).
4a	Winter	n/a	600	0 or 1					550	50	2/Season Pulse applies. Pass inflow up to 550 cfs until 3,940 acft or 11 days have passed. Add 1 to 2/Season pulse count.
4b	Winter	Dry	600	2					140	460	2/Season Pulses met. No larger pulses engaged. Pass Dry Base flow (140 cfs).
5a	Winter	n/a	1,600	0, 1, or 2	0				1,520	80	1/Season Pulse applies. Pass inflow up to 1,520 cfs until 12,800 acft or 19 days have passed. Add 1 to 1/season & smaller pulse count.
5b	Winter	n/a	1,600	1	1				550	1,050	2/Season Pulse applies. Pass inflow up to 550 cfs until 3,940 acft or 11 days have passed. Add 1 to 2/Season pulse count.
5c	Winter	Dry	1,600	2	1				140	1,460	2/Season and 1/Season Pulses met. No larger pulses engaged. Pass Dry Base flow (140 cfs).
6a	Winter	n/a	7,700	0, 1, or 2	0 or 1	0			7,680	20	1/Year Pulse applies. Pass inflow up to 7,680 cfs until 73,500 acft or 38 days have passed. Add 1 to 1/Year & smaller pulse counts.
6b	Winter	n/a	7,700	1	1	1			550	7,150	2/Season Pulse applies. Pass inflow up to 550 cfs until 3,940 acft or 11 days have passed. Add 1 to 2/Season pulse count.
6c	Winter	Dry	7,700	2	1	1			140	7,560	2/Season, 1/Season, & 1/Year Pulses met. No larger pulses engaged. Pass Dry Base flow (140 cfs).
7a	Winter	n/a	11,000	0, 1, or 2	0 or 1	0 or 1	0		10,600	400	1/2Year Pulse applies. Pass inflow up to 10,600 cfs until 107,000 acft or 45 days have passed. Add 1 to 1/2Year & smaller pulse counts.
7b	Winter	n/a	11,000	1	1	1	1		550	10,450	2/Season Pulse applies. Pass inflow up to 550 cfs until 3,940 acft or 11 days have passed. Add 1 to 2/Season pulse count.
7c	Winter	Dry	11,000	2	1	1	1		140	10,860	2/Season, 1/Season, 1/Year, & 1/2Year Pulses met. No larger pulses engaged. Pass Dry Base flow (140 cfs).
8a	Winter	n/a	24,000	0, 1, or 2	0 or 1	0 or 1	0 or 1	0	23,600	400	1/5Year Pulse applies. Pass inflow up to 23,600 cfs until 273,000 acft or 69 days have passed. Add 1 to 1/5Year & smaller pulse counts.
8b	Winter	n/a	24,000	1	1	1	1	1	550	23,450	2/Season Pulse applies. Pass inflow up to 550 cfs until 3,940 acft or 11 days have passed. Add 1 to 2/Season pulse count.
8c	Winter	Dry	24,000	2	1	1	1	1	140	23,860	2/Season, 1/Season, 1/Year, 1/2Year, & 1/5Year Pulses met. Pass Dry Base flow (140 cfs).
9	Winter	Average	116						116	0	Pass all inflow.
10	Winter	Average	300						200	100	Pass Average Base flow (200 cfs).
11	Winter	n/a	600	0 or 1					550	50	2/Season Pulse applies. Pass inflow up to 550 cfs until 3,940 acft or 11 days have passed. Add 1 to 2/Season pulse count.
		>>>>>>>>	**Application of high flow pulse recommendations is independent of hydrologic conditions. See Lines 5a through 8c above noting that the minimum of Average Base flow or inflow must be passed.**								
12	Winter	Wet	116						116	0	Pass all inflow.
13	Winter	Wet	300						290	10	Pass Wet Base flow (290 cfs).
14	Winter	n/a	600	0 or 1					550	50	2/Season Pulse applies. Pass inflow up to 550 cfs until 3,940 acft or 11 days have passed. Add 1 to 2/Season pulse count.
		>>>>>>>>	**Application of high flow pulse recommendations is independent of hydrologic conditions. See Lines 5a through 8c above noting that the minimum of Wet Base flow or inflow must be passed.**								

General Notes
1) Flows passed for senior water rights count towards satisfaction of specified subsistence, base, and pulse flow rates and volumes.
2) The applicable hydrologic condition for the entire season is defined on the basis of assessment of hydrologic condition at the beginning of the first day of the season thereby recognizing both drought persistence and practical operations.
3) Hydrologic conditions only apply when inflow is less than the 2/Season peak flow or all pulse recommendations have been satisfied.
4) One large pulse counts as one pulse in each of the smaller categories subject to reset at season or return period end. Return periods are rounded down to calendar year end.
5) Each return period (i.e., 3-month season, 1-year, 2-years, or 5-years) is independent of the preceding and subsequent return period with respect to high flow pulse attainment frequency.
6) Large pulse events (i.e., 1/Year, 1/2Year, & 1/5Year) are classified as Overbank events at most flow regime recommendation locations selected by the GSA BBEST.
7) Pulse events are initiated upon occurrence of specified peak flow, counted in the season or year in which they begin, and assumed to continue into the following season or year as necessary to meet specified volumes or durations.
8) Pulse criteria are not engaged in shaded cells because incoming streamflow does not exceed the prescribed threshold flow magnitude.

Table 6.4-1. Instream Flow Regime Application Example: San Antonio River at Goliad

Some have suggested that it is appropriate to consider the effects of flow regime application under an "infinite infrastructure" scenario. This infinite infrastructure scenario assumes that, once a particular set of environmental flow requirements has been implemented, the only flow remaining in a stream or passing into an estuarine system is the environmental flow prescription itself. In other words, all other streamflow would be fully consumed by existing or proposed water supply projects. The occurrence of such flow conditions has been demonstrated to be highly impracticable and essentially impossible, either with full use of existing water rights or with new project development. Hence, the GSA BBEST has considered finite, but very large scale, example infrastructure projects including a major reservoir on the San Antonio River at Goliad and a major run-of-river diversion from the Guadalupe River at Cuero. With the exception of seawater desalination, no surface water projects even approaching the scale of these examples are recommended for implementation within the next 50 years in the approved 2011 South Central Texas Regional Water Plan (South Central Texas Regional Water Planning Group, 2010). Kennedy Resource Company (KRC) performed hydrologic time series analyses of these example infrastructure projects and developed flow frequency curves representative of scenarios ranging from natural to "infinite infrastructure." The KRC report is included as Appendix 6.4-1.

It is important to recognize that both realistic operations of water supply systems and the prior appropriation water rights system play very important roles in the maintenance and reliable occurrence of flows under dry hydrologic conditions, to the extent such flows are naturally available. Clearly, the delivery of reliable water supplies from large reservoir projects to downstream points of diversion contributes to the maintenance of flow, and any applicable instream criteria, in the intervening stream segment. Under dry hydrologic conditions, such water deliveries may exceed seasonal subsistence and approach seasonal base flows within a recommended flow regime. The prior appropriation system also functions to ensure the occurrence of instream flows upstream of a major reservoir or run-of-river water right, particularly the critical maintenance of such flows in the range between subsistence and base under dry hydrologic conditions. As major reservoirs are not full and run-of-river rights may not be fully satisfied under dry hydrologic conditions, junior water rights and future applicants for surface water appropriation located upstream would be required to pass inflows for downstream water rights. The GSA BBEST feels that it is imperative that TCEQ recognize the contributions of downstream water deliveries and inflow passage to honor downstream water rights towards maintenance of recommended flow regimes supportive of a sound ecological environment.

As a quantitative example to illustrate the translation of a flow regime recommendation into environmental flow standards and permit conditions and demonstrate the potential effects on instream flows and their frequency of occurrence, the GSA BBEST has considered construction and long-term operation of the previously proposed Goliad Reservoir. It is noted that this reservoir project is not recommended to meet projected needs for additional water supply in the current State Water Plan and that its construction would occur, if ever, well beyond the 50-year state water planning horizon. For the purposes of this illustrative example, however, it is assumed that this reservoir would be located at the reference gage location on the San Antonio River at Goliad, have a conservation storage capacity of 707,615 ac-ft, and be operated with direct diversions of the firm yield subject to application of the recommended flow regime (Table 6.1-15) in the form of permit conditions described herein. The assumed simulation period is 1934 through 1989 and seasonal hydrologic conditions are defined by a 12-month moving average of flow with triggers defined such that dry, average, and wet hydrologic conditions would occur 25%, 50%, and 25% of the time.

Figure 6.4-1 shows historical and regulated frequencies of streamflow passing the San Antonio River at the Goliad reference gage location. For perspective, Figure 6.4-1 also shows regulated streamflow frequencies assuming "infinite infrastructure" with only flows specified in the recommended flow regime remaining unconsumed. This flow frequency curve is identified in Figure 6.4-1 as the "Minimum Flow Protected by Recommendation." Flow frequency curves similar to those in Figure 6.4-1 were originally developed by KRC (Appendix 6.4-1) with both the Reservoir Example and the Minimum Flow Protected by Recommendation results being based on an initial draft flow regime proposal including only two tiers of high flow pulses. Sediment transport analyses performed by the TWDB at the request of the GSA BBEST as part of the geomorphology overlay provided technical support for including five tiers of high flow pulses in the GSA BBEST flow regime recommendations.

Key observations upon review of Figure 6.4-1 include the following:

1) Leveling of the regulated streamflow frequency curves is apparent at specified flow values (potential permit conditions) within the recommended flow regime.
2) Flows at the seasonal subsistence levels (less than 76 cfs) occur only slightly more frequently than they did historically (because upstream water rights are included at full authorized consumptive use amounts) and much less frequently than the Minimum Flow Protected by Recommendation curve suggests. Ecological significance of this change may be assessed, in part, by review of water quality monitoring data (Table 3.4-2 and Appendix 3.4) and curves relating percentage of maximum habitat and streamflow by habitat guild (Figure 3.3-12)
3) Flows within the range of seasonal base levels (between 120 cfs and 290 cfs) occur much more frequently than they did historically. Ecological significance of this change may be assessed, in part, by review of curves relating percentage of maximum habitat and streamflow by habitat guild (Figure 3.3-12).
4) Flows within the range of seasonal pulse and overbank levels (greater than 550 cfs) occur much less frequently than they did historically, but much more frequently than the Minimum Flow Protected by Recommendation curve suggests. Ecological significance of this change may be assessed, in part, by review of sediment yield and effective discharge computations (Table 3.5-7) and consideration of riparian functions (Figure 3.6-15).
5) Streamflow frequency information, as presented in Figure 6.4-1 and considered in the context of relevant information in this report, may be particularly useful to GSA BBASC as it considers many factors in preparing its recommendations on environmental flow standards and strategies. For example, the reductions in seasonal pulse and overbank flows associated with existing water rights and the simulated operations of a large new reservoir at Goliad result in simulated 50% reductions in annual sediment yield, even with operations of the example project being subject to the environmental flow regime recommendations of the GSA BBEST. Approximately 12% of the overall reduction is attributable to the effects of full water rights use by others, reduced Edwards Aquifer springflow, and current effluent discharges. The GSA BBEST recognizes that a reduction in annual sediment yield greater than about 10% from that which occurred historically at

this location might not adequately maintain the channel shape and, therefore, the aquatic habitats necessary to provide for a sound ecological environment. As shown in Table 3.5-7, only a small reservoir (less than about 100,000 ac-ft in capacity) at this location might limit flow changes sufficiently to retain a stable channel in dynamic equilibrium.

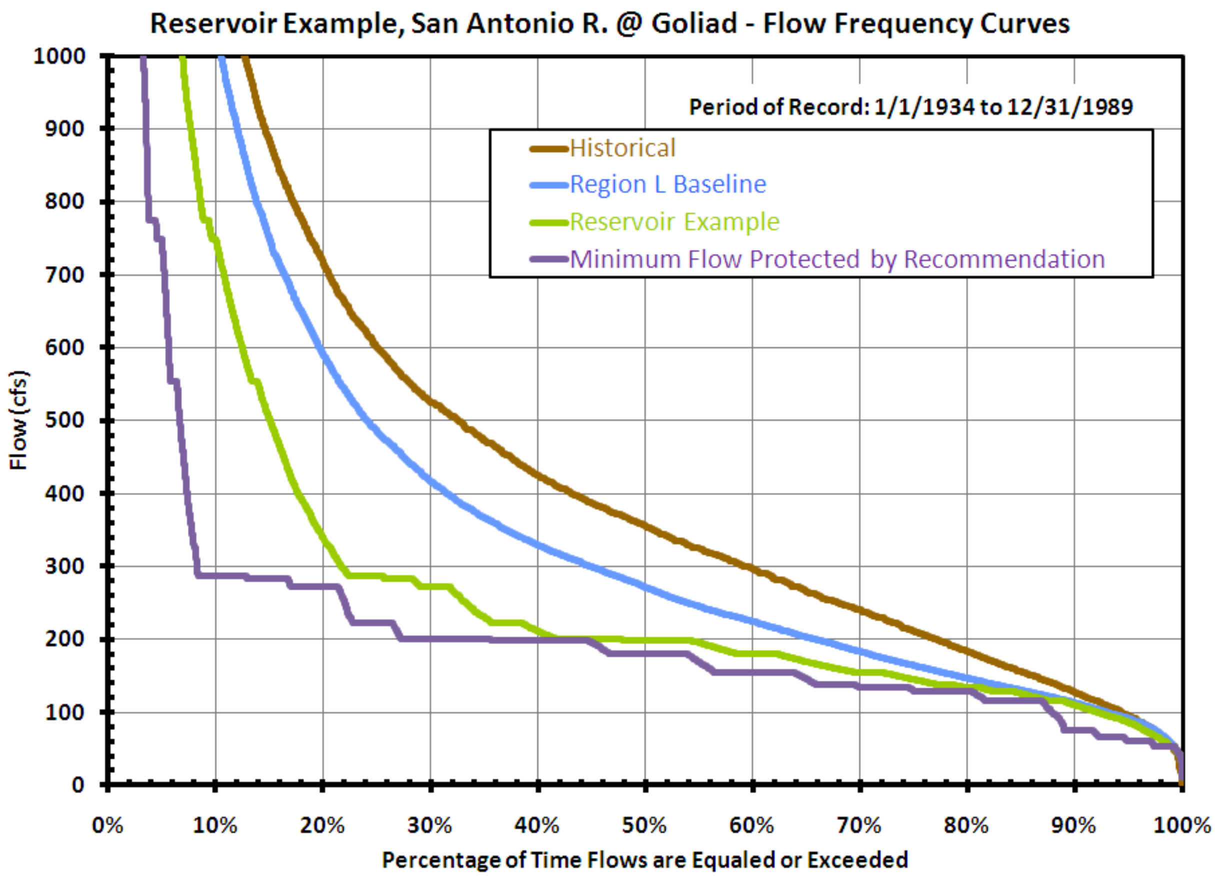


Figure 6.4-1 – San Antonio River at Goliad Flow Frequency Curves

As a second quantitative example to illustrate the translation of a flow regime recommendation into environmental flow standards and permit conditions, and demonstrate the potential effects on instream flows and their frequency of occurrence, the GSA BBEST has considered construction and long-term operation of a large-scale run-of-river diversion with off-channel storage similar to the historically proposed Cuero II project (Kretzschmar et al., 2008). It is noted that this reservoir project is not recommended to meet projected needs for additional water supply in the current State Water Plan and that its construction would occur, if ever, well beyond the 50-year state water planning horizon. For the purposes of this illustrative example, however, it is assumed that facilities capable of diverting 3,000 cfs would be located at the reference gage location on the Guadalupe River at Cuero, and operated subject to application of the recommended flow regime (Table 6.1-8) in the form of permit conditions described herein. In this example, water diverted from the Guadalupe River would be delivered to a large off-channel reservoir having a conservation storage capacity of 583,975 ac-ft on an as-needed basis, subject to diversion of the project firm yield from the off-channel reservoir. As in the previous example, the assumed simulation period is 1934 through 1989, and seasonal hydrologic conditions are defined by a 12-month moving average of flow, with triggers defined such that dry, average, and wet hydrologic conditions would occur 25%, 50%, and 25% of the time. Figure 6.4-2 shows historical and regulated frequencies of streamflow passing the Guadalupe River at Cuero reference gage location including the Minimum Flow Protected by Recommendation.

Key observations upon review of Figure 6.4-2 include the following:

1) Leveling of the regulated streamflow frequency curves is apparent at specified flow values (potential permit conditions) within the recommended flow regime.
2) Flows at the seasonal subsistence levels (less than 130 cfs) occur only slightly more frequently than they did historically (because upstream water rights are included at full authorized consumptive use amounts) and much less frequently than the Minimum Flow Protected by Recommendation curve suggests. Ecological significance of this change may be assessed, in part, by review of water quality monitoring data (Table 3.4-2 and Appendix 3.4) and curves relating percentage of maximum habitat and streamflow by habitat guild (Figures 3.3-14 and 3.3-15).
3) Flows within the range of seasonal base levels (between 390 cfs and 980 cfs) occur more frequently than they did historically. Ecological significance of this change may be assessed, in part, by review of curves relating percentage of maximum habitat and streamflow by habitat guild (Figures 3.3-14 and 3.3-15).
4) Flows within the range of seasonal pulse and overbank levels (greater than 1,050 cfs) occur less frequently than they did historically, but much more frequently than the Minimum Flow Protected by Recommendation curve suggests. Ecological significance of this change may be assessed, in part, by review of sediment yield and effective discharge computations (Table 3.5-7) and consideration of riparian functions (Figure 3.6-15).
5) Streamflow frequency information, as presented in Figure 6.4-2 and considered in the context of relevant information in this report, may be particularly useful to GSA BBASC as it considers many factors in preparing its recommendations on environmental flow standards and strategies. For example, the reductions in seasonal pulse and overbank flows associated with the simulated operations of existing water rights and a large new run-of-river diversion at Cuero result in simulated 14% reductions in annual sediment yield with such operations being subject to the environmental flow regime

recommendations of the GSA BBEST. Approximately one half of the overall reduction is attributable to the net effects of full water rights use by others, reduced Edwards Aquifer springflow, and current effluent discharges. The GSA BBEST recognizes that a reduction in annual sediment yield greater than about 10% from that which occurred historically at this location might not adequately maintain the channel shape and, therefore, the aquatic habitats necessary to provide for a sound ecological environment. Lacking significant storage on the river like the Reservoir Example at Goliad, operations of this Run-of-River Example under the GSA BBEST flow regime recommendation might limit flow changes sufficiently to retain a stable channel in dynamic equilibrium, thereby posing significantly less ecological risk with respect to geomorphology and riparian vegetation.

The GSA BBEST understands that consideration of two examples of potential flow regime application does not address all potential ecological concerns at all locations throughout the Guadalupe – San Antonio River Basin and in the Guadalupe Estuary. These examples are, however, clearly indicative that flow regime application in accordance with recommendations presented herein will likely support a sound ecological environment at these locations even though frequencies of attainment for various flows will be less than observed historically. Additional assessment of the attainment of the recommended estuary criteria in accordance with Tables 6.1.17 and 6.1.18 would be necessary to accompany these instream location evaluations.

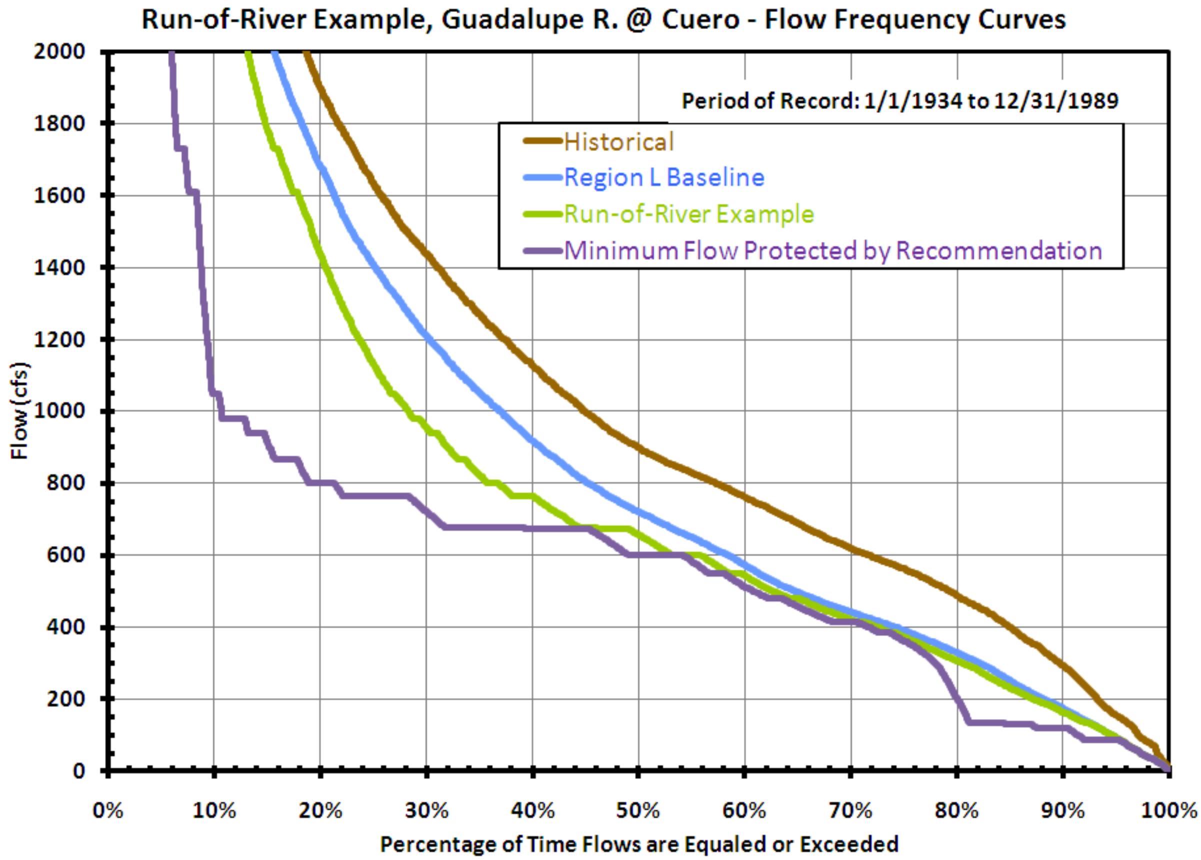


Figure 6.4-2 – Guadalupe River at Cuero Flow Frequency Curves

7. Adaptive Management

Adaptive management is an essential component of the SB3 process and work plan development for each bay and basin area. In this section, GSA BBEST members provide initial recommendations of types of monitoring, studies, and activities that will provide necessary information and data for periodic reviews of the environmental flow analyses, regime recommendations, standards, and strategies. The intended outcome of the completion of specified research and monitoring stated within the work plan includes providing more confidence in established environmental flow recommendations, supplying new information (filling gaps), and assisting in making new recommendations when necessary using adaptive management. To achieve the adaptive management process, the first step is identifying what studies are necessary, followed by securing funding and resources to implement the research and monitoring. The final step will involve developing a mechanism that will support any changes required in the standards and/or implementation (SAC 2010). The development of this recommendations report was based upon best available science and professional judgment that could be acquired, analyzed, and interpreted in a compressed 12-month timeframe. The purposes of this section are to recognize uncertainties associated with the flow regime recommendations, to identify gaps in existing knowledge, and to recommend monitoring protocols for future evaluation and adjustments to the flow regime recommendations. The following research priorities, data collection, and monitoring recommendations are broadly categorized by subject matter and provided for consideration by the GSA BBASC in preparation of its work plan.

7.1 Research Priorities, Data Collection, and Monitoring Recommendations

7.1.1 Instream Flows

7.1.1.1 Hydrology and Water Quality

- SARA and GBRA annually enter into a cooperative funding agreements with the USGS to support multi-purpose water quality and stream flow monitoring programs. The programs support the annual operation and maintenance of stream flow gauges, water quality gauges, and special studies within the San Antonio and Guadalupe River watersheds. It is recommended that cooperative funding agreements and monitoring programs be continued into the future.

- Per Senate Bill 818 and under contract with the TCEQ, SARA, and GBRA administer and execute the CRP Monitoring for their respective basins. The program has been in place since 1991 and is designed to monitor general water quality, compile a long term comprehensive data base, detect trends, identify pollutant sources and aid in water quality planning. The CRP is funded by fees charged to wastewater dischargers by the TCEQ. It is recommended that the CRP be continued.

- In order to augment the CRP monitoring and data base, SARA and GBRA conduct a supplemental stream monitoring programs. These programs includes long-term monitoring of established sites to identify areas of concern and intensive surveys that focus on identifying potential sources contributing to elevated bacteria levels.

- The San Antonio and Guadalupe River Basin Monitoring Network was developed by the TCEQ in cooperation with SARA, GBRA and other local government entities to provide near-real time monitoring of water quality data enabling users to identify, manage and minimize pollutants. This network was established for monitoring water quality concerns due to: point and non-point source pollution carried in storm water runoff, point source discharges, sewer overflows, accidental toxic spills, growth and development of industrial complexes, urbanization and other impacts to the environment. The main objective is to monitor normal conditions of the receiving streams and collect data to document long-term trends in the water quality. The goal is to develop a Real Time Monitoring (RTM) system that traces the continuity of water quality from ground water through spring emergences, through the Metropolitan areas, and includes tributaries that contribute flow towards San Antonio Bay. It is recommended that the RTM system be expanded to include sites in the lower basins, the Guadalupe Estuary and San Antonio Bay.

- In addition to water quality and bacterial monitoring SARA and GBRA conduct biological monitoring with routine fish and benthic macro invertebrate collections. The fish community data collected by SARA and GBRA proved to be invaluable during the in stream flow analysis conducted by the GSA BBEST, it is recommended that biological monitoring in the San Antonio and Guadalupe River basins continue and that similar biological monitoring be expanded to include the Guadalupe estuary and San Antonio Bay .

7.1.1.2 Multi-disciplinary Approaches

- The San Antonio River Basin Instream Flows Project was implemented under SB2 Texas In stream Flows Program (TIFP). SARA is working with the TCEQ, TWDB and the TPWD to conduct engineering and scientific studies in the LSAR Basin to determine the stream flow regimes necessary to support a sound ecological environment. A multi-discipline approach has been taken with participating agency staff, consultants and universities conducting biological (both aquatic and riparian), water quality, geomorphological, hydrological and hydraulics studies. Once the studies are complete, study participants along with stakeholders will evaluate the results of the studies. The relationships between flow and ecosystem function, including biological, chemical and physical processes, will be used to generate flow recommendations. It is recommended that the results and recommendations derived from the Lower San Antonio Instream Flows Project and the TIFP be integrated with the adaptive management plans to be developed for the Guadalupe and San Antonio River systems. The multidiscipline approach to data collections applied by the TIFP should be adopted by the CRP and the SARA and GBRA monitoring programs. A similar instream flows project should also be conducted for the Lower Guadalupe River Basin with an accelerated timeline for completion.

- The Edwards Aquifer Recovery Implementation Program (EARIP) is a collaborative, consensus-based stakeholder process in Texas. Many stakeholders are working to develop a plan to protect the federally-listed species potentially affected by the management of the Edwards Aquifer and other activities. The goals of the plan include contributing to the recovery of these species. In May 2007, the Texas Legislature directed the EAA and certain other state and municipal water agencies to participate in the EARIP and to prepare a FWS-approved plan by 2012 for managing the Aquifer to preserve the listed species at Comal and San Marcos Springs. The Legislature directed that the plan must include recommendations regarding withdrawal adjustments during critical periods that ensure that federally-listed species associated with the Edwards Aquifer will be protected. It is recommended that the results and recommendations derived from the EARIP be integrated with the adaptive management plans to be developed for the Guadalupe and San Antonio River systems.

- Many environmental protection, water management, ecosystem monitoring, conservation / preservation, pollution protection / abatement, and academic research efforts, projects and programs are currently ongoing or being planned within the Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission, Copano, Aransas, and San Antonio Bays. The participants include the USGS, NOAA, TCEQ, TPWD, TWDB, SARA, GBRA, University of Texas (UT), University of Texas Marine Science Institute (UTMSI), Texas A&M University (TAMU), Texas A&M University-Corpus Christi (TAMUCC), Texas State University (TxST), Edwards Aquifer Authority (EAA), FWS, Texas State Soil and Water Conservation Board (TSSWCB), and many other local, municipal and nonprofit organizations. It is recommended that a forum be developed where the participants engaged in any facet of environmental flow management, monitoring or research can collaborate and or partner so that future efforts can be integrated into a comprehensive effort.

7.1.1.3 Biology Overlay

The Instream Flow subcommittee used a limited number of overlays to evaluate the adequacy of subsistence, base, pulse and overbank flow recommendations. In most instances, overlays were based on existing data or new information that could be gathered in less than 1 year (i.e., rapid assessments). Although we used best available information, the Instream Flow subcommittee recognizes limitations of the following aspects of biotic, water quality, and fluvial geomorphology overlays:

- Using fishes and their associated habitats as surrogates for all aquatic fauna and flora—We are confident that aquatic fauna, flora, and habitats are protected by the instream flow recommendations based on the fish habitat guild approach. However, we recognize that aquatic macrophytes, algal communities, platyhelminths, mollusks, annelids, crustaceans, aquatic insects, amphibians, and birds might have life histories dependent upon specific elements of the hydrograph and not assessed as a biological overlay. Even various life history parameters of fishes (i.e., larval drift, dispersion) were not specifically included in the biological overlay. In general, there is a paucity of biotic information available throughout the basin, and additional research is needed to provide greater understanding on the interactions among species occurrences, abundances, habitat associations and instream flow components. Without this greater understanding, modification of the BBEST flow recommendations will increase the uncertainty of biotic responses.

- Although water quality and temperature evaluations were made based on a detailed and exhaustive evaluation of available monitoring data, we recognize that detailed modeling studies at each quantification site are necessary to evaluate the ability to assess flow dependent changes in water quality and temperature for flows significantly lower than our recommendations.

- Active water quality data collection and fish sampling under subsistence flow conditions is recommended to more quantitatively assess the potential effects of extended periods of subsistence flows on aquatic species.

- The geomorphic overlay relied on the principal of maintaining the annual sediment yield and effective discharge within 10 percent of the historical values based on the preponderance of evidence within the published scientific literature. We recognize, however, that these types of estimates have an inherent degree of uncertainty due to scatter in the data and even choice of the sediment transport equation utilized. Additional studies on maintenance of the natural fluvial geomorphology (i.e., channel stability/mobility, channel width and depth, meander wavelength, gravel bar formation) would be beneficial to evaluate, test, and inform the current instream flow recommendations.

- At least two biomonitoring frameworks are considered acceptable by regulatory agencies for the use in monitoring changes in the riverine flora and fauna. The Regionalized Index of Biotic Integrity (IBI) (Karr, 1981; Linam et al. 2002) is available and currently used for monitoring of the fish community in several Texas rivers and a generalized IBI is used to monitor macroinvertebrates. The Biological Condition Gradient (BCG) (Davies and Jackson 2006) is a more comprehensive approach to biological monitoring with the benefits of explicitly defining a "sound ecological environment," which is useful for restoration purposes. With some effort, the BCG can be developed for various reaches of streams and rivers within the Guadalupe – San Antonio River Basin with information currently available. As a more sensitive model of biological changes associated with modified flow regimes or some other anthropogenic disturbance, the Instream Flow subcommittee highly recommends the use of BCG to validate flow regimes recommendations made by GSA BBEST and the validation process should begin simultaneously with the adoption of the flow regime.

- The sediment transport analyses used by the GSA BBEST at three sites clearly indicate the importance of sediment transport to channel stability and maintenance, and ultimately the ability to maintain a sound ecological environment. We recommend that monitoring of river reaches in terms of basic channel geometry, aquatic habitat distributions, and riparian community structure and distribution be incorporated into the adaptive management monitoring plans.

7.1.1.4 Geomorphology Overlay

The purpose of monitoring is to evaluate and document responses to the implemented environmental flow regime. Documentation of the responses to the environmental flow regime will allow the BBASC and the BBEST the opportunity to determine effectiveness of the environmental flow regime, refine the regime to better meet objectives, and evaluate the procedures used to develop the regime. The purpose of the Geomorphology Overlay is to insure that environmental flow regimes protect the natural stability or dynamic stability of channels in the Guadalupe-San Antonio Basin. Stream stability is often defined as the ability of a stream to pass the water, sediment and large woody debris delivered by the watershed such that, over time, the channel dimension, pattern, and profile are maintained and the stream system neither aggrades nor degrades. Thus, a stream that laterally migrates, but maintains its bankfull width and width/depth ratio, is considered to exhibit natural stability even though the river is considered to be an "active" or "dynamic" system. See Table 7.1-1 at end of section.

- To perform the analysis necessary for adaptive management of the environmental flow regime, the USGS and other agencies that collect discharge and stage at numerous gaging stations within the basin must continue to collect stream gaging and hydrology data. Collection of sediment data (such as total suspended sediment concentration, suspended bed material load, bedload, and bed material gradations) should also be added at select gaging stations in the basin. While it is cost prohibitive to collect sediment data near all of the gaging stations in the basin, 5 to 8 stations should be selected for a sediment data collection program. In order to allow comparison to historical data, stations where sediment data has been collected in the past should be priority sites for the sediment data collection program.

- Channel response monitoring should be directed toward determining if channel stability has changed as a result of the implementation of the environmental flow regime in the basin. Monitoring should include surveying at selected sites which would be permanently monumented and resurveyed at a prescribed time interval. For example, resurveying a specific site annually during the winter (when sight obstruction by vegetation is minimized) is one way to collect data that may, over time, allow development of an understanding of the scour-fill cycle of the stream. Data collected at each site should allow for analysis of changes in cross-sectional and thalweg shape, berm formation, bank failure, and vegetation changes. Photo documentation should be part of the data set. The site should be a minimum of one meander wavelength in length and cross sections should be taken along the entire length of the site at an interval of 5 to 10 channel widths apart. Bed material samples should be taken at each cross-section, one sample at channel thalweg and one sample on each side of channel at the mid-point between the thalweg and water's edge. Consideration should be given to focused monitoring of changes in characteristics of channel geomorphology and riparian vegetation on "paired" river segments above and below new reservoir or large-scale diversion projects permitted under the new environmental flow standards.

- Streambank stability depends on hydraulic parameters related to flow conditions and the characteristics of bank materials. All channels should be visually monitored on a periodic basis to determine reaches that are experiencing severe bank stability problems. In addition to overall visual monitoring, some sites where aggradation is occurring and some sites where bank caving is occurring should be selected for detailed monitoring. At the selected sites, surveys of closely spaced cross sections should be made semiannually to document changes. After sufficient data have been collected, numerical models to predict bank stability and/or bank failures for the sites should be developed. If their results can be validated by the monitoring data, these models will be a valuable tool for predicting the consequences to streambank stability associated with modifications of the environmental flow regime.

7.1.1.5 Riparian Vegetation Overlay

- SB2 TIFP Monitoring Protocol implements a comprehensive, standardized data collection process within the riparian corridor. Recommendations include extending the program to include all USGS gage stations as well as stream reaches above and below a permit location. Establishment of a data portal for access to monitoring protocols and data would allow data sharing and expansion of monitoring sites throughout the watershed.

- A thorough understanding of riparian community regeneration and diversity is not known for these basins. Data collected through the TIFP on woody vegetation density and basal area provides a dataset that can be assessed to determine current community structure and successional dynamics across the floodplain. Data should be analyzed and correlated to fine-resolution multi-spectral imagery to develop high-detail riparian community maps and datasets. These data can be used to relate to potential changes in the riparian community in relation to flow regime alterations.

- The hydrologic connectivity between the channel, floodplain, and terrace features is not well understood. Groundwater monitoring stations should be established at key USGS gaging stations to relate groundwater discharge and recharge at various flow regimes. These data can be related to geomorphologic and surface water monitoring data for a better understanding of basin function and determination of sound ecological environment conditions

- No information was available to assess the linkage among instream fish communities that periodically utilize floodplain environments (e.g., oxbow lakes) following overbank flows in the lower portion of the basins. A monitoring study to address this knowledge gap should be established with a particular emphasis on key species.

7.1.2 Freshwater Inflows to Bays and Estuaries

7.1.2.1 <u>Hydrology and Salinity</u>

An extensive body of scientific literature from the past 40 years has clearly recognized the importance of freshwater inflows as a critical component of maintaining the ecological integrity of bay and estuaries in Texas.

Policy decisions must depend on the latest analytical procedures and methodologies:

Hydrology updates
Sediment loading
Hydrodynamic and conservative transport models
Inflow-salinity regressions
Nutrient balance
Effects of salinity and inflow on zooplankton
Effects of salinity and inflow on benthic organisms and processes
Effects of inflow on primary production (phytoplankton, submerged and emergent vegetation)
Fishery response equations and harvest-inflow analyses
Areal distribution of wetlands and other habitats
Inventory of secondary and tertiary resource consumers by area
Abundance of major secondary and tertiary resource consumers

Both field sampling techniques and sophistication of modeling approaches have been refined over time and a number of modeling tools currently exist to aid in the adaptive management process:

TxBlend Texas Hydrodynamic and Conservative Transport Model
TxEMP—Texas Estuary Mathematical Programming
HEFR— Hydrologic Environmental Flow Regime
TIFP—Texas Instream Flows Program
WAM—Water Availability Modeling
ELMR—Estuarine Living Marine Resources, provides estuarine spatial and temporal distribution, and relative abundance information on marine species

Freshwater inflows into the bays are essential to mix with Gulf waters entering from the passes and create salinity gradients across the estuary. These gradients drive coastal marsh and submergent aquatic vegetation composition and dominance in relation to elevation and bathymetry gradients. Sediments and nutrients transported from the river system to the estuary reduce erosion in coastal environments and drive nutrient cycling, respectively. A quantitative relationship among geomorphic, hydrologic, and biological components of the estuarine communities has not been developed.

- Continue efforts to update and improve the hydrodynamic and salinity model TxBlend including additional targeted salinity monitoring tailored to low inflows and geographic areas identified as areas of weakness.

- Establish a salinity-monitoring station specifically in mid-Guadalupe Bay (well-above San Antonio Bay proper) for implementation phase modeling analyses.

- A salinity data collection and monitoring program should be established in marsh areas proximate to San Antonio, Mission, Copano, and Aransas bays in order to more accurately define relationships between bay salinity at presently monitored locations and salinity in critical marsh habitats.

- Sediment discharge loads carried by freshwater inflows should be calculated in relation to flow regimes to determine the contribution these sediments provide to erosion and accretion rates in coastal environments.

- The TCEQ should establish approved records of historical surface water diversions and return flows that occurred below the following streamflow gaging stations: Guadalupe River at Victoria (USGS# 08176500), San Antonio River at Goliad (USGS# 08188500), and Coleto Creek near Victoria (USGS# 08177500). The TWDB should then formally update their estimates of historical freshwater inflow to the Guadalupe Estuary accounting for such approved records of historical surface water diversions and return flows.

7.1.2.2 <u>Key Bay Species/Habitat and Responses to Salinity</u>

Freshwater inflows which maintain natural salinity gradients and bay habitats are critical for sustaining historical estuarine fisheries populations. Most species require special estuarine nursery conditions for postlarval/juvenile stages. Many non-commercial species are also required to support food webs culminated by higher trophic-level species. Additional information is necessary to further understand the responses of key estuarine species to changes in salinity within the San Antonio, Copano, Aransas bay systems.

- Implement investigation of the location-specific reproductive requirements of rangia clams.

- Implement investigation of the location-specific requirements of eastern oysters with regard to avoiding the “dermo” parasite.

- Develop a better assessment of the distribution and abundance patterns of rangia in the Guadalupe and Mission-Aransas Estuaries via appropriate sampling design and field equipment.

- Implement concurrent salinity and water level monitoring in marsh wetland areas and adjacent open bay waters to establish linkages and conceptual models of interrelationships between these two components.

- Modeling analyses between water levels in the Guadalupe River, tides, and salinity of overlying Guadalupe Delta flood waters should be performed. This would allow development of a specific Delta inundation – salinity model for correlating inundation of Guadalupe Delta with riverine FWI events.

- Continue studies of habitat conditions vs. salinity requirements of key faunal species (e.g. blue crabs, white shrimp) in order to better understand their life cycles. In turn this would allow for development of more quantitative models describing their requirements for freshwater inflow.

- Identify and monitor key salinity-sensitive plant species in upper estuary and delta for use as focal species in future FWI studies.

- Develop basin-wide, multi-parameter Habitat Suitability Models for eastern oysters as well as for blue crabs and white shrimp .

7.1.2.3 Nutrient Considerations

Projections of population growth in coastal regions of the U.S. show continued growth in these regions, including the Texas Coastal Bend (U.S. Department of Commerce and NOAA). Additionally, it is well-established that increased urbanization of coastal regions results in increased nitrogen (N) and phosphorus (P) export to the coastal waterways, resulting in serious degradation of estuarine ecosystems (Seitzinger et al. 2002; Howarth and Marino 2006). In light of this, we believe it would be very beneficial to monitor both rivers and estuaries for N concentrations and to determine nutrient load to these systems. In summary:

- Measurement of total nitrogen (TN) and dissolved inorganic N (DIN, including nitrate and ammonium) would be recommended. If possible, including measurements of organic nitrogen and phosphorus would also provide important information.

- These samples should be taken at regular, frequent intervals, including measurements during peak flows following storms and at base flow during droughts.

- Using flow data from the rivers calculate N flux to the estuaries.

- Technology to enable accurate, easy measurement of nutrients is developing rapidly. There are nutrient sensors (comparable to those used to measure dissolved oxygen or temperature) that are becoming more readily available. There are also nutrient monitors, or ‘mini labs’ that can be deployed for in situ measurement of nutrient concentrations using standard EPA methods.

Table 7.1-1. Monitoring strategies for the riparian corridors that include spatial dimensions and temporal scales of stability of channel features and factors that influence stability, as well as environmental factors that influence the stream habitat at each spatial scale (modified from Gregory et al. 1991)

.Feature	Spatial Dimensions (Channel widths)	Time Scale of Stability (yr)	Factors Related to Stability	Factors Related to Stream Habitat	Stream Influences	Monitoring	Citation Example
Particle Composition	$10^{-3} – 10^{-2}$	10^{0}	Shear Stress, Bed	High-flow events	Vegetation Community	See Geomorphology Monitoring Recommendations	
Subunit Composition	10^{-1}	10^{0}	Shear Stress, Bed composition, Organic Debris	Local hydraulic features	Pool, Riffle, rapids, or cascades; eddies, side channels, and backwaters (Gregory et al. 1991)	See Geomorphology Monitoring Recommendations	
Channel Unit	10^{0}	$10^{1} – 10^{2}$	Hydraulics, Bed Composition, Organic Debris	Water-surface slope, width:depth ratio of channel, and extent of turbulent, high-velocity flow	Pool, Riffle, etc. from flow redistribution; Riparian Community Type (Gregory et al. 1991)	Texas Instream Flows Program (TIFP) Monitoring Protocol	Woody Species regeneration and Single-Stemmed Species, and (Winward 2000)
Reach	$10^{1} – 10^{2}$	$10^{3} – 10^{4}$	Basin-wide Aggradation/Degradation, Local Base-level Control	Geomorphic Features	Fluvial development of Geomorphic surfaces, Floodplain width (Gregory et al. 1991), and Riparian Community Type	See Geomorphology Monitoring Recommendations;	Hyperspectral and Aerial Photography (Richards et al. 1996)
Section (Watershed?)	$10^{3} – 10^{4}$	10^{4} - 10^{5}	Tectonic and/or Sea Level Change, Climate	Geomorphology, substrate, stream gradient, water flow features, and vegetation patterns	Riparian Complex; Human influences	Full width of the Riparian Area across portion of valley; Prominent Community types (6-12) and Special features; Soils	Vegetation Cross-Section Composition, Proportion Transitional Types, and Greenline Composition (Winward 2000)
Network (Basin)	10^{5}	10^{6+}	Geology	Geology, Catchment Area, Mean Slope, and Std. Dev. of Elevation	Hydrology and Sediment Inputs to Stream Channel; Physical Habitats	Vegetative Cover; Heterogeneity (Fragmentation) of Land-use Data; Bankfull Width and Depth	Hyperspectral and Aerial Photography (Richards et al. 1996)

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