


Environmental Flows Recommendations Report

Final Submission to the Environmental Flows Advisory Group, Nueces River and Corpus Christi and Baffin Bays Basin and Bay Area Stakeholders Committee, and Texas Commission on Environmental Quality

Nueces River and Corpus Christi and Baffin Bays
Basin and Bay Expert Science Team

October 2011


Nueces River and Corpus Christi and Baffin Bays
Basin & Bay Expert Science Team

October 28, 2011

The Honorable Troy Fraser, Co-Presiding Officer
Environmental Flows Advisory Group

The Honorable Allan Ritter, Co-Presiding Officer
Environmental Flows Advisory Group

Mark Vickery, P.G., Executive Director
Texas Commission on Environmental Quality

Con Mims, Chair
Nueces River and Corpus Christi and Baffin Bays
Basin & Bay Area Stakeholder Committee

Dear Chairman Fraser, Chairman Ritter, Mr. Vickery, and Mr. Mims:

Pursuant to its charge under Senate Bill 3 of the 80th Texas Legislature, the Nueces River and Corpus Christi and Baffin Bays Basin & Bay Expert Science Team (Nueces BBEST) hereby submits its Environmental Flows Recommendations Report for your consideration.

Respectfully Submitted,

Sam Vaugh, P.E., Chair

Rocky Freund, Vice-Chair

Tom Arsuffi, Ph.D.

David Buzan

Ken Dunton, Ph.D.

Ben Hodges, Ph.D.

David Hoeinghaus, Ph.D.

Ryan Smith

Lonnie Stewart

Greg Stunz, Ph.D.

Jace Tunnell

Lance Williams, Ph.D.

Nueces BBEST Acknowledgements

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- City of Corpus Christi – Gus Gonzalez and Norm Kuenstler
- Nueces River Authority – Sky Jones-Lewey
- Trungale Engineering & Science – Joe Trungale
- Texas State University – Thom Hardy and Tim Bonner
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- The Bledsoe Family
- The Dooley Family
- The Hixon Family

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Common Abbreviations

acft	acre-feet
acft/yr	acre-feet per year
cfs	cubic feet per second
BBASC	Basin and Bay Area Stakeholders Committee
BBEST	Basin and Bay Expert Science Team
BOR	U.S. Bureau of Reclamation
CCEFN	Consensus Criteria for Environmental Flow Needs
CCM	Comparative Cross-Section Methodology
CCR/LCC	Choke Canyon Reservoir / Lake Corpus Christi
EAA	Edwards Aquifer Authority
EFAG	Environmental Flows Advisory Group
FRAT	Flow Regime Application Tool
ft	feet
ft-msl	feet mean sea level
FWI	Freshwater Inflow
HEFR	Hydrology-based Environmental Flow Regime
IHA	Indicators of Hydrologic Alteration
kacft	thousand acre-feet
kacft/yr	thousand acre-feet per year
NRA	Nueces River Authority
NWS	National Weather Service
NWF	National Wildlife Federation
PHABSIM	Physical Habitat Simulation
Q95	Daily average flow rate exceeded 95 percent of the time
SAC	Science Advisory Committee
SB2	Senate Bill 2
SB3	Senate Bill 3
SCTRWP	South Central Texas Regional Water Plan
TCEQ	Texas Commission on Environmental Quality
TIFP	Texas Instream Flow Program
TMDL	Total Maximum Daily Load
TPWD	Texas Parks and Wildlife Department
TWDB	Texas Water Development Board
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WAM	Water Availability Model
WUA	Weighted Usable Area

Section 1. Preamble

1.1 Senate Bill 3 Environmental Flows Process

Senate Bill 3 (SB3) of the 80th 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** (see Section 1.1.4), 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 Nueces River and Corpus Christi and Baffin Bays Basin and Bay Expert Science Team (Nueces BBEST) and is timely submitted in the midst of the SB3 environmental flows process to serve as a useful technical resource.

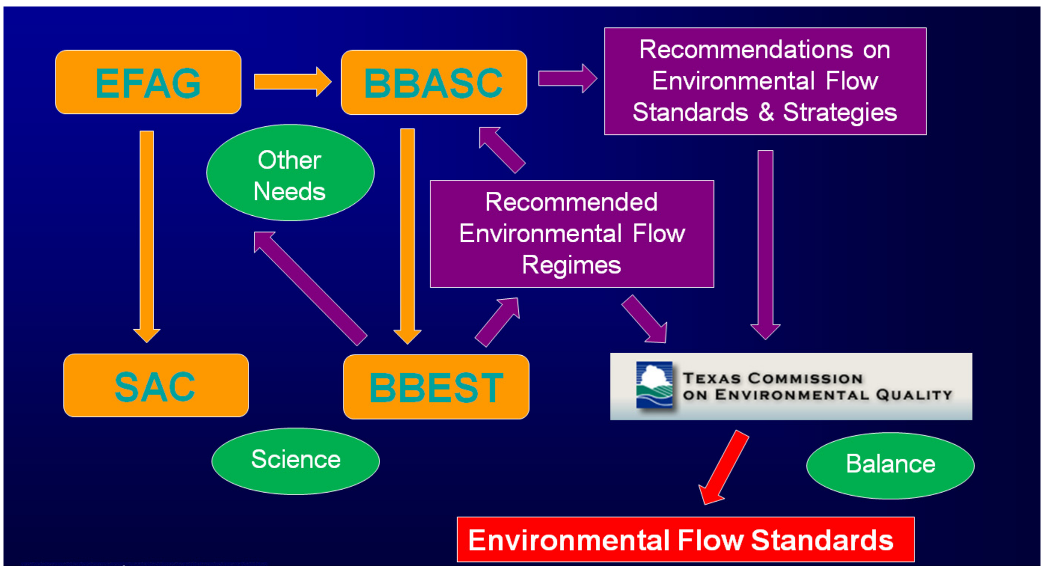


Figure 1.1.1. SB3 Environmental Flow Process.

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 Nueces 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 Nueces BBASC is comprised of 36 members, many of whom also serve on the Nueces Estuary Advisory Council (NEAC) created in 1992. On April 21, 2010, the Nueces BBASC acted to appoint 12 scientists as members of the Nueces BBEST. Information regarding the Nueces 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.

1.2 Nueces River and Corpus Christi and Baffin Bay Basin and Bay Expert Science Team (Nueces BBEST)

1.2.1 Membership

The Nueces BBEST is comprised of 12 members appointed by the Nueces BBASC. Due to scheduling conflicts and other commitments, one original member chose to withdraw in March 2011 and was subsequently replaced by the Nueces BBASC. Active membership of the Nueces BBEST is summarized below along with administrative and subcommittee assignments.

Sam Vaugh	– Chair, Hydrology Subcommittee Lead
Rocky Freund	– Vice-Chair, Instream and Hydrology Subcommittees
Dave Buzan	– Instream Subcommittee Lead, Estuary Subcommittee
Greg Stunz	– Estuary Subcommittee Lead
Tom Arsuffi	– Instream Subcommittee
Ken Dunton	– Estuary Subcommittee
Ben Hodges	– Estuary and Hydrology Subcommittees
David Hoeinghaus	– Instream and Hydrology Subcommittees
Ryan Smith	– Instream and Hydrology Subcommittees
Lonnie Stewart	– Instream and Hydrology Subcommittees
Jace Tunnell	– Estuary Subcommittee
Lance Williams	– Instream Subcommittee

1.2.2 Nueces 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.*

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

Since its first meeting on June 21, 2010, the Nueces BBEST has worked with diligence and determination to accomplish the tasks with which it is charged. As a result of quarterly and monthly meetings of the full Nueces BBEST, focused subcommittee meetings, and the individual and collective efforts of BBEST members, we believe that we have met our initial charge. Agendas and minutes of the Nueces BBEST meetings are included as Appendix 1.2.1. It is acknowledged with great appreciation that our efforts were very ably supported and significantly enhanced by dedicated personnel from the TWDB, TPWD, TCEQ, Nueces River Authority (NRA), City of Corpus Christi, Trungale Engineering & Science, Texas River Systems Institute (TRSI), Harte Research Institute for Gulf of Mexico Studies, and a number of other organizations.

1.3 Sound Ecological Environment

SB3 defines an environmental flow regime as:

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

According to Science Advisory Committee (SAC) guidance (SAC 2009a), a sound ecological environment:

- 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.

A "sound environment" is defined many ways. All definitions involve different interpretations of language and intent. In the BBEST's analysis, an acceptably sound ecological environment is where the flow regime maintains important physical, chemical, and biological characteristics of a water body as well as the native species dependent on these characteristics. An unhealthy environment is where human modifications of the flow regime have reduced or eliminated important physical, chemical, or biological features, and significantly altered or reduced native biological community structure.

Flow regimes developed by the BBEST should support an acceptably sound ecological environment including important physical, chemical, and biological characteristics that presently exist or have existed in the past. Flow regimes described by the BBEST are not intended to produce pristine conditions that may have existed before human development. Nor are they intended to produce ecological conditions that have never occurred in a water body. The BBEST agrees that the sound ecological environment for a water body depends on its geographic location within the watershed and its historical conditions.

Streams in the Nueces River basin have changed in a variety of ways over the past 100 years. The causes of those changes have been natural and man-made. Precipitation patterns have caused extended drought periods and high flow periods at various times. Man-made changes have included construction of reservoirs, water diversions, return flows, groundwater development, land use practices, livestock grazing, and brush proliferation. Man-made changes have also included the introduction of invasive species like common carp, Asian clam, and giant cane (*Arundo donax*). Although the effects of these changes on aquatic ecosystems vary between water bodies, it is reasonable to say that all water bodies selected for analysis by the BBEST have been modified to some degree by man's activities.

The BBEST reached consensus on the above definition of "sound ecological environment" as well as the soundness of current riverine, riparian, and estuarine environments assessed in this report. The BBEST also reached consensus on the components (i.e. subsistence, base, pulses, and overbank flows) of environmental flow regimes that will maintain a sound ecological environment in these basins.

Compared to Texas streams east of the Nueces River basin, relatively few analyses of the ecological health of Nueces basin streams have been conducted. Although there have been modifications to many of these streams, a review of available biological, physical, and chemical data indicates that Nueces basin streams maintain acceptable sound environments. Four locations have experienced substantial hydrological modifications: the Nueces River at Three Rivers and Mathis because of upstream reservoirs, and Oso and San Fernando Creek because of wastewater discharges. Additional sampling and analysis will be particularly helpful at these sites to better understand relationships between flow and health of their environments.

After an extensive review and analysis of comprehensive data sets that exists for the Nueces Estuary system, the BBEST reached consensus that the Nueces Bay and Delta region is an unsound ecological environment. This conclusion was based on the substantial alterations in freshwater reaching the bay and delta which have led to a failure to sustain a healthy complement of native species and its associated beneficial physical processes (see Section 2.8 and Section 4). In particular, the reduction of inflow caused:

- Loss/alteration of key habitat features and natural flow regimes required by indicator species (*Spartina alterniflora*, benthic infauna, oysters, *Rangia*, blue crabs, and Atlantic croaker); and
- Nutrient elemental cycling and sediment loading to be compromised.

A modification of flow regime will be required to rebuild these species and processes to sound levels. In this report, the BBEST members reached consensus on freshwater inflow recommendations (see Section 4 and Section 6) intended to restore the Nueces Bay and delta to a sound state by increasing the frequency of attainment of specified seasonal inflows.

The BBEST finds that other water bodies and systems in the Nueces Estuary (i.e. Corpus Christi Bay, Baffin Bay and Laguna Madre Systems, Oso Creek and Bay System) are considered sound ecological environments in terms of naturally and currently available habitat and species diversity. All bays and systems of the Nueces Estuary are discussed in more detail below as well as an historical account (Section 2.8). The BBEST also reached consensus and cautioned that all of these areas are generally characterized by very limited natural water supply, and any modifications (i.e. reduction) to the current flow regime would raise serious concern as to whether a sound ecological environment could be maintained.

1.3.1 Streams of the Nueces River Basin

Edwards Plateau Streams

Edwards Plateau streams addressed here include the West Nueces River at Brackettville, Nueces River at Laguna, Frio River at Concan, Dry Frio River at Reagan Wells, upper Sabinal River, Hondo Creek, and Seco Creek. These streams are characterized by spring flows, clear water, and relatively few point source wastewater discharges and water diversions. Water quality assessments indicate that oxygen levels, pH, chloride, and sulfate levels are typically adequate for a healthy aquatic community.

South Texas Brush Country Streams

South Texas Brush Country streams for which environmental flow regimes are described include the Nueces River at Uvalde, Cotulla, Tilden, Three Rivers, and Mathis. On the Frio River, sites include the Frio River at Derby and Tilden. Environmental flow regimes were also described for the Atascosa River, lower Sabinal River, and San Miguel Creek. A unique stream is the Leona River below Uvalde where an environmental flow regime was developed for springs flowing into the river. In contrast to the Edwards Plateau streams, South Texas Brush Country streams are more turbid and a greater proportion experience extended periods of no flow. The arid conditions these streams are exposed to may increase their vulnerability to changes in flow regime.

Flow regimes for the Nueces River at Mathis and at Three Rivers are greatly influenced by upstream reservoir operations. Flow regimes at these two sites differ substantially from the natural flow variability typical of streams which are not downstream of major reservoirs operated for water supply. High pulse flows and floods are reduced in magnitude, frequency, and duration when compared to a stream with natural flow variability. In addition, low flows tend to be at higher levels than in the past. Although their flow regimes have been modified, these streams are considered acceptably sound environments because modifications have continued to allow flows within the range of recommended base flows and some lower pulse flows, and the BBEST recognizes there are not likely to be significant modifications of the flow regimes in the near future. Determination of environmental health for the two sites immediately downstream of reservoirs should not be interpreted as an indication that similar flow modifications at other sites would support sound environments. The BBEST believes flow variability provided by its environmental flow regime recommendations is critical to maintaining sound environments at the other sites.

Coastal Streams

Two small coastal streams, Oso Creek and San Fernando Creek, were assessed. Both of these streams have relatively small watersheds in an arid region. Perennial flows in these streams appear to be maintained by point source wastewater discharges. Portions of the watersheds have been substantially modified by agricultural development and, in the case of Oso Creek, by recent urban development. In both cases, information suggests these streams were probably intermittent prior to human development. Because these streams provide aquatic habitat more persistently than they did before in portions of their reaches, they are considered to maintain acceptable sound environments.

1.3.2 Nueces Estuary

Nueces Bay and Delta

Within the Nueces Estuary system, the Nueces Bay/Delta region is the most affected by freshwater availability and has experienced substantial alteration in freshwater inflow (see Section 2.8 for detailed description). The Nueces River currently flows along the southern edge of the Nueces Delta complex and empties directly into Nueces Bay away from the delta. The Nueces River flow is controlled by the Choke Canyon Reservoir / Lake Corpus Christi (CCR/LCC) System, and delivers water supplies to the City of Corpus Christi, San Patricio County Municipal Water District, Nueces County WCID#1, and others. Because of these water demands, the lower reaches of the Nueces River system and delta have been subjected to extensive management and alternations (for reviews and case studies, see Bureau of Reclamation, 2000; Montagna, et al., 2009; and Section 2.8 in this report). These alterations have dramatically altered the flow regime, ecology, and physical characteristics of the region (**Figure 1.3.1**). For example, the Nueces Bay is often a reverse estuary where salinity is higher in the delta than in the bay and more saline in the bay than in the Gulf of Mexico.

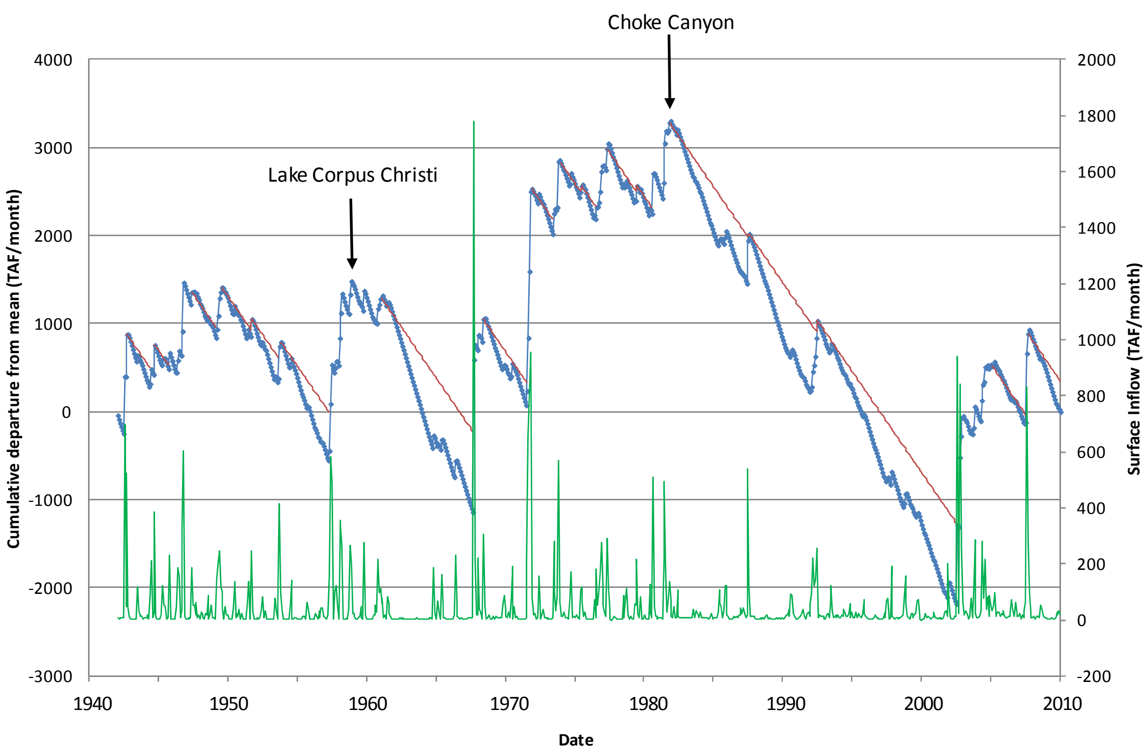


Figure 1.3.1. Surface inflow (green line) and cumulative inflow departure from the mean (blue line) over time. Lake Corpus Christi dam was constructed in 1958 and Choke Canyon dam was constructed in 1982.

The two primary alterations affecting the freshwater inflow regime for Nueces Bay and Delta were: 1) dam construction, with the CCR/LCC System controlling 98 percent of flow in the Nueces River Basin (Montagna, et al., 2009); and 2) major modification and channelization that redirected flow away from the delta to the lower bay near Corpus Christi Bay (Bureau of Reclamation, 2000). Previous analysis summarized in **Table 1.3.1** attributed a ~55 percent reduction in flow to Nueces Bay and ~99 percent reduction to the delta to these alterations. Review of estimated naturalized flows (WAM) suggests about two-thirds of the reduction of Nueces

Bay inflow and about half the reduction in Nueces Delta inflow was caused by drought. Regardless, dam construction and channelization contributed to decreased freshwater inflow to the delta and bay that resulted in increased salinities. Montagna (2009) showed that, during 1976-1982, the average salinity was below 26 one hundred percent of the time; while during 1983-2002, salinities were below 26 only five percent of the time.

Table 1.3.1. A summary of mean annual flow of the Nueces River into the Nueces Estuary (1940-1996) and upper Nueces Delta (1940-1999). Time periods in both studies were based upon the construction dates of large reservoirs in the watershed. Source: Bureau of Reclamation 2000.

Time Period	Mean Annual River Flow into Nueces Estuary (acft)	Percent Change from Period 1	Mean Annual River Flow into Upper Nueces Delta (acft)	Percent Change from Period 1
1940 - 1957	619,000	—	127,997	—
1958 - 1982	614,000	-0.8%	77,989	-39.1%
1983 - 1996(9)	279,000	-54.9%	537	-99.6%

The reduced overall freshwater inflows and nearly eliminated overbanking events as a result of drought and reservoir construction have led to the current unsound condition of Nueces Bay and Delta. The frequent high salinities inhibit sustainable oyster production at levels supporting commercial harvest and compromise vegetation communities. In addition, the loss of sediment supply exacerbates an eroding delta, with some 6 to 10 acres per year being lost (for detailed information see Section 2.8). In general, there is a loss of the salinity gradient that influences the zonation of communities found in an ecologically sound estuary. An ecologically sound Nueces Bay would function differently from the present condition. Following our base flow recommendations (see Section 4 and Section 6) and having at least one overbanking event per year into the Nueces Delta would restore the area to a sound state. Under these conditions, the delta and river mouth would have sediment shoaling during flood events, creating new habitat. Additionally, the salinities in Nueces Bay/Delta would not exceed 18 for most of the year (especially during fall), allowing plant and animal communities not only to persist at sustainable population levels, but to colonize new areas.

Corpus Christi Bay

Corpus Christi Bay is the primary bay within the Nueces Estuary, and was designated as an estuary of national significance by the U.S. Environmental Protection Agency (USEPA) in 1992. The bay has a total open water surface area of 167 square miles, and a direct connection to the Gulf of Mexico via the Aransas Pass and Packery Channel for tidal exchange. A dominant feature affecting the salinity regime and effects of freshwater inflow to the bay is a deep ship channel that runs the entire length of the bay. This channel facilitates the exchange of Gulf water creating marine conditions in the bay. These influxes of marine waters from the Gulf restrict any significant impact of freshwater inflow from the Nueces River in reducing salinities in Corpus Christi Bay (see Section 4 for details). The BBEST consensus is that this is a sound ecological environment based on strong scientific data that freshwater has little direct impact on Corpus Christi Bay, including relatively limited reduction in salinity, even from large-scale floods.

Baffin Bay and Laguna Madre Systems

Baffin Bay and Laguna Madre systems are surrounded by very little urban development and industrialization. The substantial source of freshwater originates from runoff from various watersheds into Baffin Bay. These "negative" estuaries have several ephemeral streams, including San Fernando, Santa Gertrudis, and Los Olmos Creeks, that flow into the bay primarily during rain events. Because of the semi-arid, subtropical climate, there is scarce freshwater inflow and extensive evaporation. Thus, the bay has a relatively high salinity often reaching 75 in its northern reaches. The consensus of the BBEST, in terms of naturally and currently available water, is that these systems are considered sound ecological environments.

Oso Creek and Bay System

Oso Bay is an enclosed, shallow water body filled by Oso Creek. The bay also receives water from the Upper Laguna Madre via the American Electric Power plant that intakes and releases saltwater as a coolant. The water from the Upper Laguna Madre passes through the power plant, into cooling ponds, and then into the lower reach of Oso Creek before entering Oso Bay. The surface water within Oso Creek is important ecologically for providing habitat for many plant and animal species, and provides an influential role in water purification and storm protection. The consensus of the BBEST, under the current supply of available water, is that these systems are considered sound ecological environments.

1.4 Introduction to Environmental Flows Recommendations Report

The Environmental Flows Recommendations Report of the Nueces 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 Nueces River Basin, the Nueces – Rio Grande Coastal Basin, and the associated bay systems. Environmental flow analyses performed by the Nueces 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 Nueces BBEST are provided in Section 6. Finally, research, data collection, and monitoring activities identified as priorities by the Nueces BBEST for adaptive management are summarized in Section 7.

Readers simply seeking the environmental flow regime recommendations of the Nueces 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.

Section 2. Overview of Watersheds and Bays

2.1 Nueces River Basin

The Nueces River Basin covers approximately 17,000 square miles, encompassing all or part of 23 counties in South-Central Texas, and includes a highly complex environment of ground water and surface water interactions. Other rivers within the basin include the Frio, Leona, Sabinal, and Atascosa Rivers (**Figure 2.1.1**). The basin is bordered by the Colorado, Guadalupe, and San Antonio River Basins to the north, the San Antonio – Nueces Coastal Basin to the southeast, the Nueces – Rio Grande Coastal Basin to the south, and the Rio Grande River basin to the south and southwest. Throughout the basin, the rivers are used for water supply and recreational purposes.

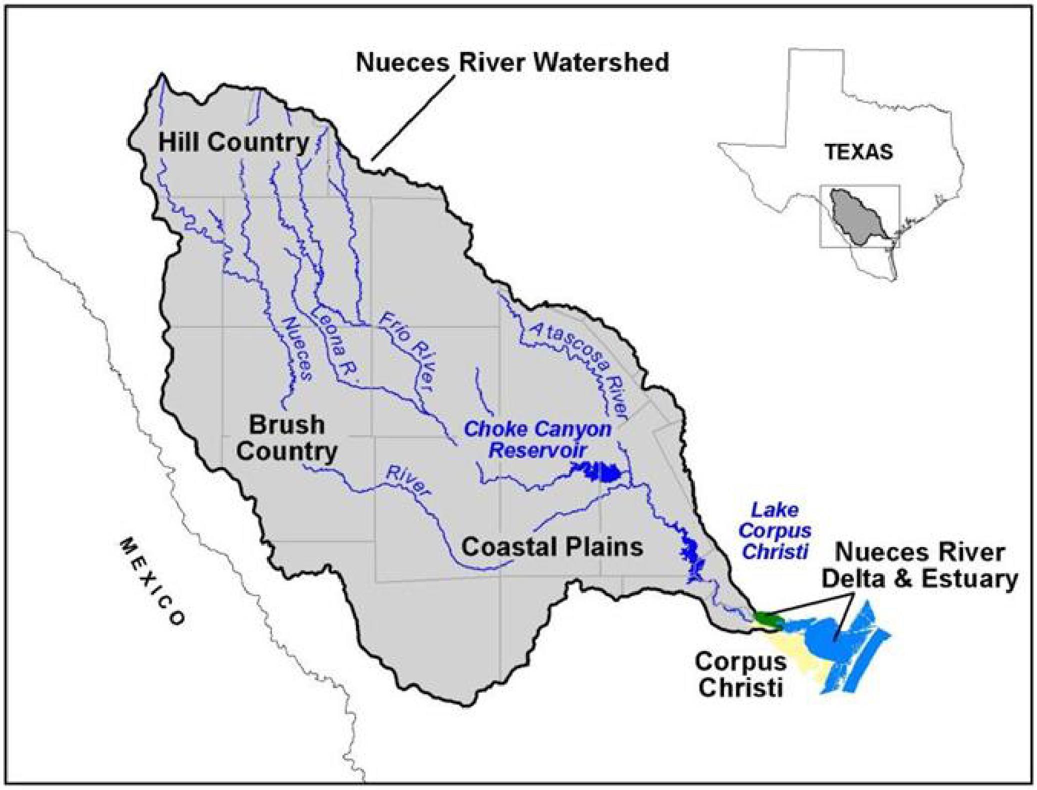


Figure 2.1.1. Location of the Nueces River Basin.

Streams throughout the basin cross three major aquifer recharge zones and two lesser aquifer recharge zones. The most significant of these is the Edwards Aquifer recharge zone, where an average of 334,000 acre-feet per year (acft/yr) entered the aquifer during the 1934-1996 historical period. Other major aquifer outcrops, according to the Texas Water Development Board, include the Carrizo-Wilcox and the Gulf Coast-Goliad Sand. These recharge zones significantly affect channel loss rates and delivery of water from upstream to downstream locations.

The Hill Country is characterized by spring fed, perennially flowing streams that drain from the Edwards Plateau (**Figure 2.1.2**). These streams typically lose their baseflow to the Edwards Aquifer recharge zone. Leona Springs, which receives a significant portion of its flow from the Edwards Aquifer, is the only major spring located in the Nueces River Basin downstream of the Edwards Aquifer recharge zone. Scrub brush and rangeland dominate the landscape downstream of the Edwards Aquifer, and even the major streams typically have reduced flow or periods of no flow once they are out of the Hill Country and downstream of the Edwards Aquifer recharge zone.

Figure 2.1.2. Nueces River.

The Nueces River Basin ecosystems include the Edwards Plateau or Hill Country, the South Texas Brush Country, and the Gulf Coast Prairies and Marshes. Because the basin is located along many migratory flyways, birds comprise a major portion of the wildlife population of the area. The area offers birds unique nesting and forage resources including coastal prairies, wetlands, and riverine ecosystems. The state-listed endangered brown pelican uses the Coastal Bend's natural resources year-round. The basin is also home to other state and federally listed endangered and threatened species. Common types of wildlife found in the area include white-tailed deer, raccoons, ringtails, gray foxes, coyotes, beaver, bobcats, and several species of skunks. Wintering songbirds such as robins and cedar waxwings may also be found.

River delta and estuary systems depend on freshwater inflows for maintaining habitats and productivity. Freshwater inflows provide a mixing gradient that establishes a range of salinity as well as nutrients that are important for productivity of estuarine systems. Also, freshwater inflows deposit sediments, which help maintain the deltas and barrier islands that protect the bays and marshes. Without freshwater inflows many plant and animal species could not survive.

2.1.1 Ecoregions

Land use in the Nueces River Basin is predominately related to agriculture, with approximately 10 percent classified as cropland, 6 percent pastureland, and 84 percent rangeland with only a small fraction for urban area. There are primarily three natural eco-regions that make up the Nueces River Basin, namely the Edwards Plateau (Hill Country), the South Texas Plains (South Texas Brush Country), and the Gulf Coast Prairies and Marshes (Coastal Plains). One common trait among each of these regions is the ongoing problem of non-native species that are replacing the native grasslands. Invasive species have been a problem for hundreds of years since European settlers first moved into this area.

The Edwards Plateau area includes the northern portions of Uvalde, Medina, and Bandera Counties. This limestone-based area of the Edwards Plateau is characterized by spring fed, perennially flowing streams that originate in its interior and flow across the Edwards Aquifer recharge zone, which bounds it on the south and east. This area is also characterized by the occurrence of numerous ephemeral streams that are important conduits of storm runoff and contribute to the recharge of the Edwards Aquifer. The soils are shallow, ranging from sands to clays, and are calcareous in reaction. This area is predominately rangeland, with cultivation confined to the deeper soils.

Parts of Uvalde, Zavala, Dimmit, Medina, Frio, LaSalle, Atascosa, Wilson, and Karnes Counties lie in the South Texas Plains area, which is characterized by subtropical dryland vegetation consisting of small trees, shrubs, cacti, and grasses. Early settlers of this area called this the "Wild Horse" or "Mustang" Desert. Principal plants are honey mesquite (*Prosopis glandulosa*), live oak (*Quercus virginiana*), post oak, several members of the cactus family (Cactaceae), blackbrush acacia (*Acacia rigidula*), guajillo (*Acacia berlandieri*), huisache (*Acacia smallii*), and others that often grow very densely.

The Gulf Prairies and Marshes area includes all or parts of San Patricio, Nueces, Jim Wells, Duval, and Live Oak Counties. There are two subunits: 1) the marsh and salt grasses immediately at tidewater and a little farther inland; and 2) a strip of bluestems and tall grasses, with some gramas in the western part. Many of these grasses make excellent grazing. Oaks (*Quercus spp.*), elm, and other hardwoods grow to some extent, especially along streams, and the area has some post oak and brushy extensions along its borders. Much of the Gulf Prairies is fertile farmland.

2.1.2 Climate and Precipitation

Average annual rainfall in the semi-arid basin ranges from approximately 21 inches in the west to approximately 32 inches in the east. Rainfall in the basin is highly variable in magnitude and frequency, as most significant rainfall originates from localized convective thunderstorms or from tropical storms and hurricanes covering wider areas. The sporadic nature of rainfall in the basin results in short periods of high flows in the streams and rivers, followed by long periods of low or zero flows, except in the Hill Country above the Edwards Aquifer recharge zone, where moderate to high base flows are the normal condition.

The area has a mild climate that ranges from sub-humid to semi-arid. Long, hot summers, warm falls, and short mild, winters characterize the Coastal Plain, while temperatures are somewhat lower in the Hill Country. The mean annual temperature is approximately 70°F (Fahrenheit), decreasing from about 73°F in the southern part of the Coastal Bend area to about 67°F at the northern end of the basin. Periods of extreme heat occur during the summer, but they are moderated by Gulf breezes, especially at night. High temperatures (°F) in the summer average in the 90's and often into the 100's, and low temperatures in the winter average in the 50's. Mild temperatures normally prevail during the winter months, but subfreezing weather does occasionally occur as a result of cold fronts pushing down from the north. The average number of frost-free days ranges from 310 in the southern part of the basin to 230 in the northern end. Prevailing winds are typically from the east to southeast, except in the winter when they periodically shift to the north.

2.1.3 Geology and Physiography

Topography varies from steep slopes in the Hill Country upstream of the Edwards Aquifer recharge zone to generally flat as the streams and rivers traverse the Brush Country and Coastal Plains approaching the Gulf of Mexico. The steep slopes and characteristically thin soils of the Hill Country result in this area producing the greatest runoff per unit rainfall in the basin. In the Hill Country portion of the basin upstream of the Edwards Aquifer recharge zone, an annual average of about 13 percent of precipitation appears as runoff or gaged streamflow with the other 87 percent being lost predominately to evapotranspiration. This differs from the lower basin where flat, sandy soils reduce average annual runoff volumes to between 2 and 5 percent of average annual precipitation. The remaining water in this part of the basin is lost to evapotranspiration, aquifer recharge, and channel losses. Overall, about 3 percent of the average annual basin-wide precipitation appears as runoff flowing into Lake Corpus Christi in the lower basin, with the other 97 percent being lost to evapotranspiration, channel losses, and aquifer recharge.

2.1.4 Aquifers

The Edwards Aquifer, together with the karst geology of its recharge zone and the major perennial springs, constitutes a unique set of habitats where significant concentration of isolated, endemic species occur. The porous to cavernous formation making up the Edwards and associated limestones constitute the Edwards

Aquifer, the groundwater source that presently supplies the City of San Antonio, numerous other cities, several military installations, and maintains spring habitats critical for several endemic, endangered species. The Edwards Aquifer is the only important aquifer habitat in Texas in which vertebrate species live and it supports a surprisingly diverse ecosystem.

There are three parts to the aquifer, drainage area, recharge zone, and artesian zone (**Figure 2.1.3**). The drainage area is comprised of the area north and west of the aquifer in the Texas Hill Country, primarily in the Nueces River Basin. Covering approximately 4,400 square miles, this area serves as the collection area for precipitation and channeling water in the form of runoff through many streams that lie on older, less permeable formations, delivering the water to the recharge zone. Geologically the recharge zone is known as the Balcones Fault Zone, and consists of exposed, porous Edwards Limestone on the surface that serves as a conduit that funnels the water underground into the artesian zone. The recharge enters the aquifer from streams flowing across the outcrop which contains fractures, sinkholes, and caves. Once the water is underground it flows into the part of the aquifer referred to as the artesian zone. The Edwards Aquifer has a tremendous capacity for moving and storing water via its many intricate interconnecting spaces ranging in size from small pores to large caverns. This zone is located between two impermeable layers, which confines the water and in some instances allows the water to flow to the surface through faults discharging as springs, or through artesian wells. All water discharged from the aquifer is from wells or springs, and approximately half of all discharge is through the springs associated with the aquifer system.

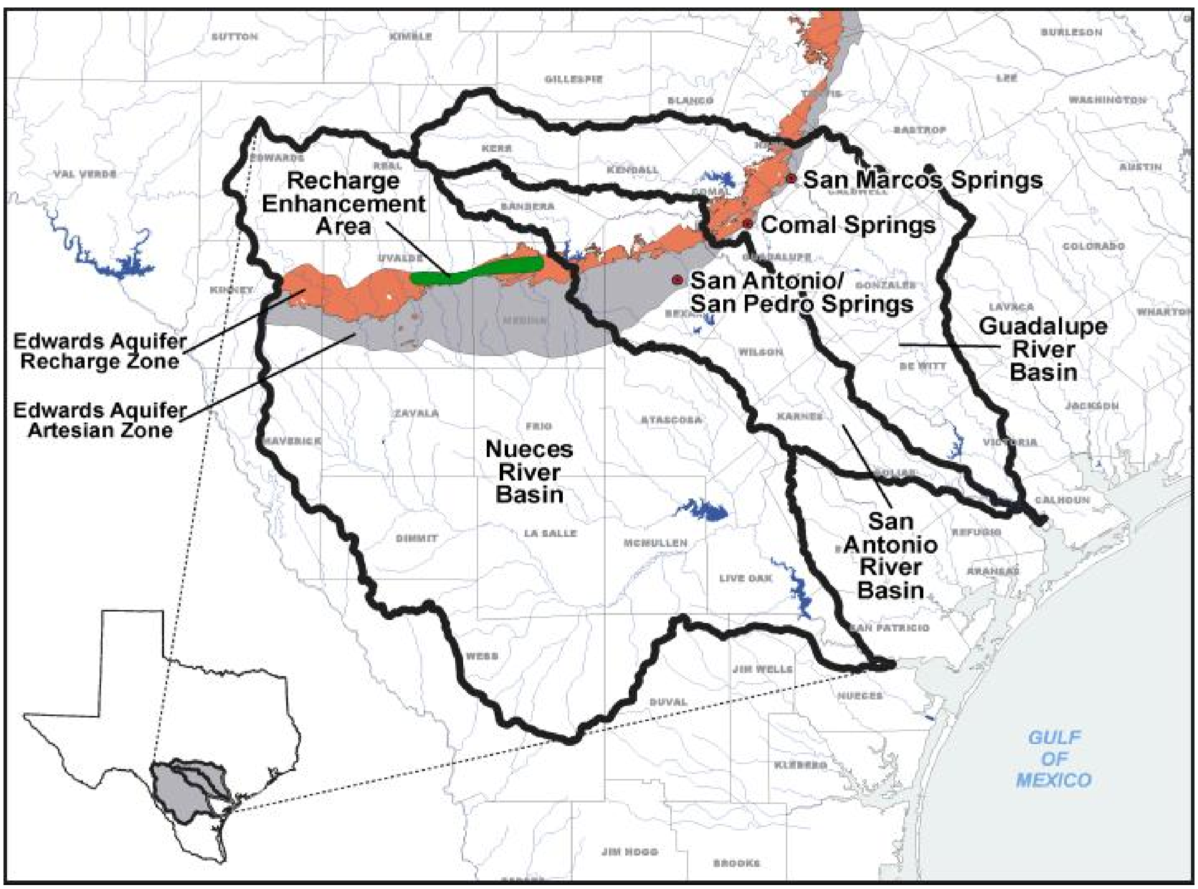


Figure 2.1.3. Edwards Aquifer Location and Components.

A significant federal interest has been established through several court actions relating to the Edwards Aquifer with respect to protection of minimum spring flows and species at Comal and San Marcos Springs. These court actions resulted in the U.S. Fish and Wildlife Service establishing minimum flow limits necessary to protect the endangered species that rely upon flows from these springs. The Edwards Aquifer Authority (EAA) is the state agency responsible for regulating pumpage from the Edwards Aquifer.

By the end of 2012, the EAA is required to implement and enforce water management procedures to ensure that continuous minimum spring flows at Comal Springs and San Marcos Springs are maintained to protect endangered and threatened species to the extent required by federal law. In an effort to develop a long-term plan that would balance continued water use and development with the recovery of listed species, the Edwards Aquifer Recovery Implementation Program (EARIP) was initiated in early 2007 as a means for bringing together all interested stakeholders to develop a management plan for the conservation and recovery of the listed species while allowing continued water use and development. Management strategies, including voluntary irrigation suspension, municipal conservation, supplemental leases of Edwards rights coupled aquifer storage and recovery (ASR) in the Carrizo formation, and modified critical period reductions, will significantly assist the EAA in accomplishing these goals by contributing to higher water levels in the aquifer during severe drought, which will enhance the reliability of spring flows and the quantities of supply available for withdrawal from the Edwards Aquifer.

Ecosystems that have experienced reduced flows because of aquifer pumpage include the Comal and San Marcos springs, the spring runs located just downstream of certain springs, the San Marcos and Guadalupe Rivers, and the Guadalupe Estuary. A portion of the recharge that occurs in the Nueces River Basin emerges as springflows in these neighboring basins, providing higher streamflows that benefit terrestrial and aquatic species that inhabit these ecosystems. A total of eight plant, amphibian, insect, and fish species are federally listed as endangered in the Edwards Aquifer system, and one is listed as threatened. The eight endangered species of the Edwards Aquifer spring systems include the Texas Blind Salamander, San Marcos Salamander, Fountain Darter, San Marcos Gambusia, Texas Wild Rice, Comal Springs Riffle Beetle, Comal Springs Dryopid Beetle, and the Peck's Cave Amphipod.

Not only do the higher flows mentioned above contribute to the health of the species and the ecosystem in general, but also reduce the likelihood that the springs would go dry. Recharge to the Edwards Aquifer in the Nueces River Basin also contributes to the flow of Leona Springs located in Uvalde County. Leona Springs form the headwaters of the Leona River, which contributes to the flow into Choke Canyon Reservoir.

2.1.5 Choke Canyon Reservoir/Lake Corpus Christi System - Agreed Order

The City of Corpus Christi operates a reservoir system that encompasses two large reservoirs in the Nueces Basin for water supply: Choke Canyon Reservoir (**Figure 2.1.4**), permitted in 1976 and built in 1982, (on the Frio River upstream of Three Rivers) with an authorized storage capacity of 695,271 acft and Lake Corpus Christi which was last expanded in 1958 (on the Nueces River near Mathis) with an authorized storage capacity of 257,260 acft. Combined system storage capacity is close to 1 million acft. The City of Corpus Christi operates Choke Canyon Reservoir (CCR) and Lake Corpus Christi (LCC) as a system in order to supply water to municipal and industrial customers within its regional service area. The majority of the water supplied by these reservoirs is released from Lake Corpus Christi and diverted downstream above the saltwater barrier dam near Calallen (**Figure 2.1.5**). The next largest reservoir operated for water supply in the basin is the Upper Nueces Reservoir, owned by the Zavala-Dimmit Counties Water Improvement District No. 1, with a permitted capacity of 4,010 acft. Water diverted from this reservoir is used primarily for irrigation purposes.

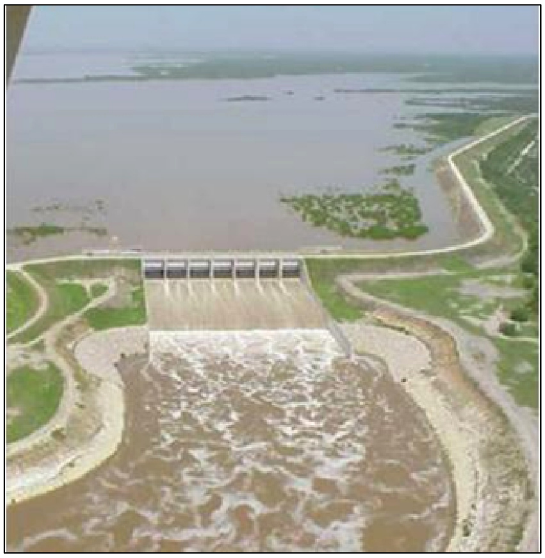


Figure 2.1.4. Choke Canyon Reservoir Dam. **Figure 2.1.5.** Calallen Saltwater Barrier and Diversion Dam.

The reservoir system, including the two major reservoirs, is owned and operated by the City of Corpus Christi to meet municipal and industrial water demands. The city operates the Choke Canyon Reservoir/Lake Corpus Christi (CCR/LCC) System in compliance with a Texas Commission on Environmental Quality (TCEQ) Agreed Order. The Agreed Order, last amended April 17, 2001, established an operating procedure pertaining to Special Condition 5.B., Certificate of Adjudication No. 21-3214 (the water right for Choke Canyon Reservoir), held by the City of Corpus Christi, the Nueces River Authority (NRA), and the City of Three Rivers. This order specifies monthly inflow targets for the Nueces Bay that must be met by allowing reservoir inflows to pass through the reservoirs to Nueces Bay and its delta based on total system storage of the reservoirs. The annual amount has monthly targets that were developed by the Texas Water Development Board (TWDB) and the Texas Parks and Wildlife Department (TPWD) to maximize the biological benefit to the species that inhabit the estuary.

To address concerns about the health of the Nueces Estuary, the Nueces Estuary Advisory Council (NEAC), chaired by the TCEQ, was formed in 1990 to establish operational guidelines for the CCR/LCC System and desired monthly freshwater inflows to the Nueces Estuary (in accordance with Special Condition 5.B. of Certificate of Adjudication No. 21-3214). These operational guidelines were first summarized in the 1992 Interim Order regarding freshwater inflow operations of the CCR/LCC System requiring the City of Corpus Christi to pass inflow up to 151,000 acft/yr, with 97,000 acft/yr specifically targeted for Nueces Bay to be measured at the Calallen Dam. This TCEQ Order has been amended several times over the last eighteen years and the current operating order was established April 17, 2001 (the 2001 Agreed Order) (Montagna, et al., 2009).

The 2001 Agreed Order established a monthly schedule of desired freshwater inflows to Nueces Bay to be satisfied by reservoir spills, return flows, runoff below Lake Corpus Christi, and/or pass-throughs of system inflows. In simplest terms, the amount of water that flows into the reservoir system, up to a target amount, must be “passed through” to the bays and estuaries. Inflow above the target amount, which varies based on month, volume of water in the reservoir system (**Table 2.1.1**), and salinity levels in Nueces Bay, can be captured for future use. The maximum required pass-through amount for any given year is 138,000 acft. When the reservoir system is at least 70 percent full, the annual Nueces Bay inflow target is 138,000 acft/yr. Under the current 2001 Agreed Order, pass-throughs can be reduced based on inflow banking, low monthly salinity in the upper Nueces Bay, and implementation of drought contingency measures tied to CCR/LCC System storage. For example, when reservoir system capacity is below 70 percent, but above 40 percent, the annual Nueces Bay inflow target is 97,000 acft/yr. If system storage drops below 40 percent, but is above 30 percent, the City automatically enacts drought contingency measures and the pass-through requirements drop to 1,200 acft/month (the monthly median inflow to Lake Corpus Christi during the drought of record). If the system storage drops below 30 percent, the City automatically enacts more stringent drought contingency measures and pass-throughs from the reservoir system are suspended.

Table 2.1.1. 2001 Agreed Order established monthly "pass-through" targets for freshwater inflows to the Nueces Estuary.

2001 Agreed Order Pass-Through Targets (acft)				
Month	**Capacity ≥ 70%**	**40% ≤ Capacity < 70%**	**30% ≤ Capacity < 40%**	**Capacity < 30%**
Jan	2,500	2,500	1,200	0
Feb	2,500	2,500	1,200	0
Mar	3,500	3,500	1,200	0
Apr	3,500	3,500	1,200	0
May	25,500	23,500	1,200	0
June	25,500	23,000	1,200	0
July	6,500	4,500	1,200	0
Aug	6,500	5,000	1,200	0
Sept	28,500	11,500	1,200	0
Oct	20,000	9,000	1,200	0
Nov	9,000	4,000	1,200	0
Dec	4,500	4,500	1,200	0

The drought of the 1950s is considered the "drought of record" for the State of Texas. **Figure 2.1.6** shows that, for the Nueces River Basin, three droughts that have occurred since the 1950s were actually more severe in terms of reservoir inflows.

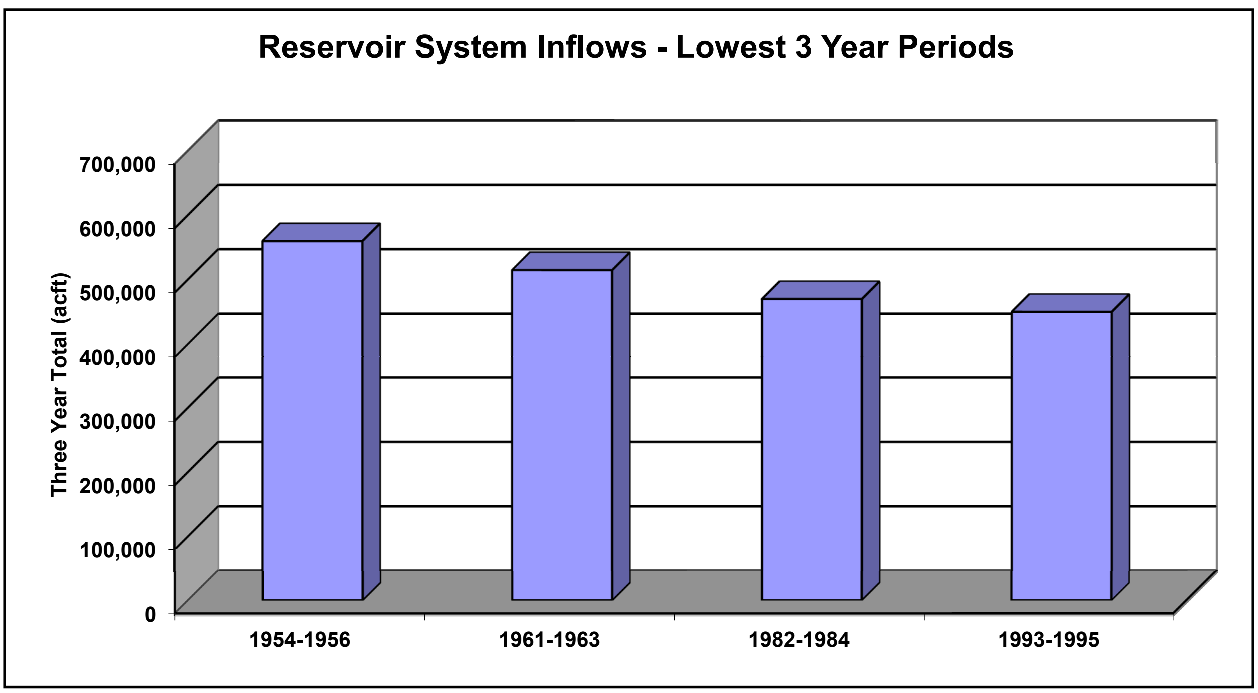


Figure 2.1.6. Reservoir system inflows for the last four major droughts of 3-year duration (HDR, 2000).

2.1.6 Additional Water Sources

The Mary Rhodes Pipeline was constructed by the City of Corpus Christi and NRA in 1997 and 1998. This pipeline brings a minimum of 41,840 acft/yr of water from Lake Texana, located in the distant Lavaca River Basin, and delivers it directly to the O.N. Stevens Water Treatment Plant thereby reducing demand on the CCR/LCC System. This new water supply project has created additional opportunities for enhanced freshwater inflows to Nueces Bay and its delta.

2.2 Nueces - Rio Grande Coastal Basin

The Nueces – Rio Grande Coastal Basin covers approximately 10,400 square miles, encompassing all or part of 12 counties in South Texas (**Figure 2.2.1**). The basin is bordered by the Nueces River Basin and the San Antonio – Nueces Coastal Basin to the north, bays, estuaries, and the Gulf of Mexico to the east, and the Rio Grande River Basin to the south and southwest. The inland area of the basin is dominated by large ranches, including the King Ranch. State-operated recreational areas are primarily along the coast and include Mustang Island State Park, Port Isabel Light House State Historic Park in Port Isabel, and the Padre Island National Seashore.

Senate Bill 3 includes a portion of the Nueces – Rio Grande Coastal Basin within the BBEST's charge. Therefore, a section of the report includes descriptions of Oso Creek and San Fernando Creek.

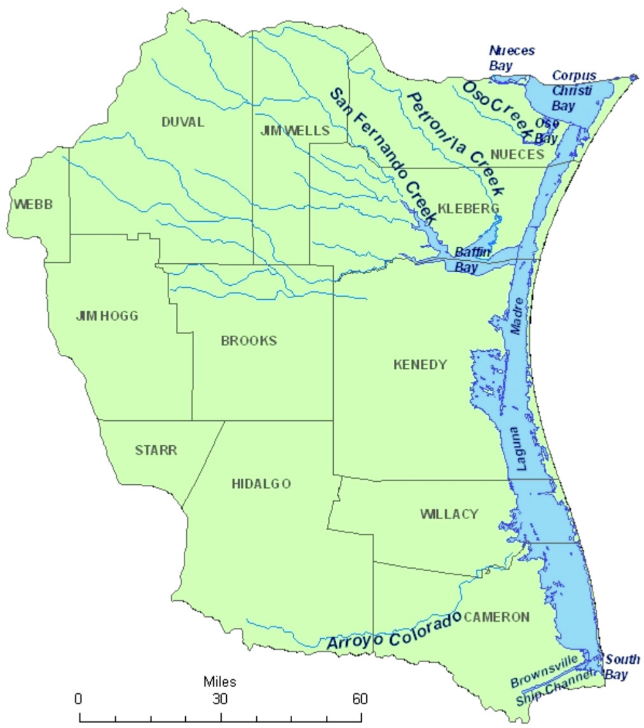


Figure 2.2.1. Location of the Nueces – Rio Grande Coastal Basin.

2.2.1 Oso Creek Watershed

The Oso Creek watershed is located entirely in Nueces County and drains approximately 165,000 acres. The area is relatively flat, ranging from about 15 feet above sea level at its confluence with Oso Bay to about 65 feet above sea level in the upland areas. The creek and its tributaries drain into Oso Bay which in turn drains into Corpus Christi Bay. The upper portion of the Oso Creek watershed includes a substantial amount of cropland, whereas the lower portion meanders through the southern edge of the city of Corpus Christi. The primary crops are grain sorghum, cotton and small amounts of corn. Improved pastureland can be found scattered throughout the watershed.

Mean annual precipitation for the area averages 29 inches per year. Mean annual evaporation rates average from 35.4 to 45.3 inches per year, but may range as high as 59 inches per year during drought. Typically, the area experiences net annual moisture losses of approximately 12.2 inches per year. Tropical storms and hurricanes arising in the Gulf of Mexico may deliver larger quantities of rainfall during late summer and early fall on an irregular basis. The area is classified as semi-arid based on these higher than average annual moisture deficits caused by evaporation and sub-tropical hot, humid summers and mild, cool winters. Summer high temperatures typically average 92°F, while the winter lows average 47°F.

Southeasterly prevailing winds are characteristic of the Texas Gulf coast for most of the year. Winds average 11.9 mph and serve as a primary source of atmospheric moisture. Strong northerly frontal passages are common in winter and may result in below freezing temperatures and extreme low tides for several days. Tides are primarily diurnal with average amplitude of 4 inches. Astronomical tidal fluctuations typically range from 0 to 23.6 inches, with wind direction and velocity being the primary controlling factors influencing the duration of inundation and tidal range within the area.

According to TPWD, the entire watershed including Oso Creek and Oso Bay is 47.3 percent upland, 3.3 percent wetlands, 0.9 percent transitional lands, and 48.4 percent water and submerged land. Of the uplands, urban development accounts for 14.8 percent, crop and pastureland 69.2 percent, prairie 4.5 percent, and shrub/forested land 10.7 percent. Much of the stormwater and runoff from these areas directly enters Oso Creek and Oso Bay.

Oso Creek flows 29.5 miles from a point 3 miles upstream of SH 44 west of Corpus Christi to the confluence with Oso Bay in Nueces County. The southeastern end of the creek flows through highly developed areas of Corpus Christi. The northwestern end is primarily rural, but development is rapidly encroaching. The creek is highly influenced by waste water treatment facility (WWTF) effluent which consists of the majority of the flow throughout most of the year.

2.2.2 San Fernando Creek Watershed

San Fernando Creek is formed by the confluence of Chiltipin and San Diego Creeks one mile northeast of Alice in central Jim Wells County and runs southeast for 44 miles, forming the Kleberg-Nueces County line, to its mouth on Cayo del Grullo, seven miles southeast of Kingsville in east central Kleberg County. The creek is intermittent in its upper reaches. It traverses flat to rolling terrain with local escarpments, surfaced by sandy and clay loams and dark clays that support brush, grasses, cacti, and mesquite. Blue-green algal mats and crustaceans grow in the creek's lowest reaches.

2.3 Corpus Christi Bay

The Corpus Christi Bay area was designated as an estuary of national significance by the U.S. Environmental Protection Agency (USEPA) in 1992. The Corpus Christi Bay system — of which Nueces Bay is a part — comprises over 124,700 acres along the central Texas coast (**Figure 2.3.1**). Corpus Christi Bay is a shallow (~10.5 feet), almost enclosed bay with a level bottom. It has a total open water surface area of 167 square miles and is microtidal (normal tidal fluctuation is less than 6 feet), which makes it sensitive to meteorological forcing. Average monthly wind speeds range from 10 to 17 mph. Mean precipitation of around 29 inches per year is exceeded by mean evaporation of 59 inches per year. Precipitation is bimodal, with peaks in the spring and fall. Mean summer and winter air temperatures are 92°F and 47°F, respectively. Prevailing winds are southeasterly to south-southeasterly throughout most of the year, with strong northerly frontal systems occurring intermittently throughout the winter.

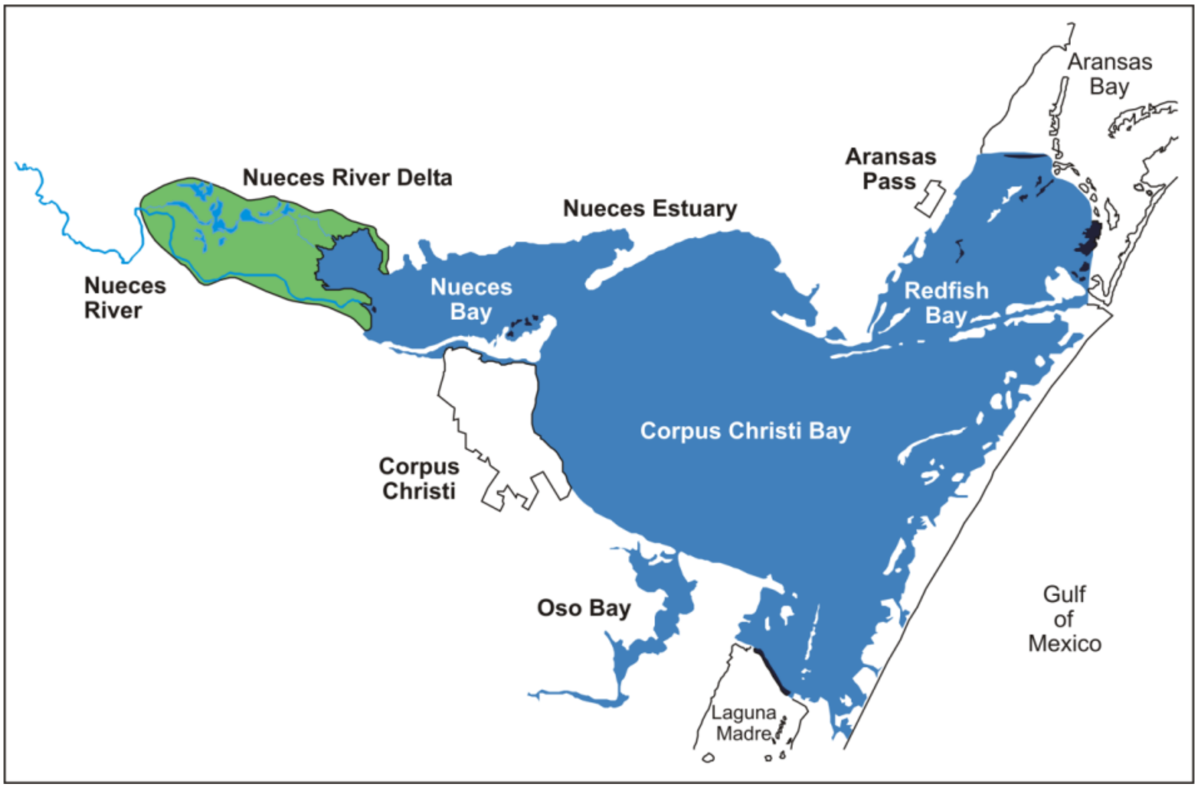


Figure 2.3.1. Location of Corpus Christi Bay, Nueces Bay, and Nueces River Delta.

The mouth of the Nueces River empties into Nueces Bay north of Corpus Christi at the San Patricio county line. Most of Nueces Bay is located in the San Antonio-Nueces coastal basin, but a small portion lies in the Nueces-Rio Grande coastal basin. The Corpus Christi Bay system exchanges water with the Gulf of Mexico through a direct connection at the Aransas Pass. A dominant feature affecting the salinity regime and effects of freshwater inflow to the bay is a deep ship channel that runs the entire length of the bay. This channel facilitates the exchange of bay waters with the Gulf, creating marine conditions in the bay. This large amount of Gulf water exchange allows these marine conditions to persist even during high flow events to the estuary. The limited effect freshwater inflow has on reducing salinity in the Corpus Christi and associated bays is the primary reason this BBEST has chosen to focus its effort on Nueces Bay.

In 2010, the estimated population of the Corpus Christi, Texas metropolitan statistical area (MSA) was just over 413,000, of whom more than 305,000 live in Corpus Christi. Several industrial plants and refineries are located near or adjacent to Nueces Bay. The Corpus Christi Ship Channel stretches from the Port Aransas Jetties to the Inner Harbor of Corpus Christi, and was completed in 1926 to allow ships and their cargo access to the mainland Port of Corpus Christi. The ship channel is 45 feet deep and has changed the water movement and natural circulation patterns within the ~10.5 feet shallow bay (Ward and Armstrong, 1997).

Freshwater that enters the Corpus Christi Bay system is a combination of water that originates in the adjacent contributing watersheds and water that originates in the large regional watershed of the Nueces River (greater Nueces River Basin) upstream of the adjacent contributing watersheds. In the watersheds of the Nueces and Corpus Christi Bay system, which have by far the largest net difference between return and diversion flows, diversions exceed return flows. Consumption of water by municipal and industrial users in the greater Corpus Christi area and agricultural users in rural areas reduces freshwater inflow to the Nueces and Corpus Christi Bay system by about 14 percent from what it would be without return and diversion flows. For the Nueces and Corpus Christi Bay system, an approximately 11 percent increase in runoff due to increased urban area since predevelopment (about 12,000 acft/yr) has been documented (Asquith, et al., 1997).

2.4 Nueces Bay and Delta

Nueces Bay is a secondary bay of the Corpus Christi Bay system. The Corpus Christi Bay system, combined with Nueces Bay, has a surface area of 200 square miles. It is a shallow, well-mixed, wind driven bay located in a semi-arid zone. Salinity may vary from near fresh (< 2) during heavy flood events to hypersaline (> 45) during prolonged periods of low inflow. Mean annual salinity is reported as 25. Tides are primarily diurnal with amplitude averaging on the order of 4 inches. Tidal range is controlled primarily by wind.

The Nueces River currently flows along the southern edge of the Nueces delta complex and empties directly into Nueces Bay away from the delta. A normal estuary is regularly inundated with salt water from tides and freshwater from river inflows. These freshwater inflows are important in maintaining the critical balance of salinity needed in the estuary for a healthy environment. Specifically, the freshwater facilitates nutrient exchange and buffers bay salinity. However, with the combined effects of the enlargement of Lake Corpus Christi in 1958, the construction of the Choke Canyon Reservoir in 1982, and with each drought cycle producing less inflows, freshwater inflows to the delta have been greatly reduced. This activity has reduced the number and volume of flood events that reach the Nueces Estuary and provide this critical habitat with fresh water. The combined reservoir operations and drought have decreased river flow into Nueces Bay and the delta (Bureau of Reclamation, 2000). Review of estimated naturalized flows (WAM) suggests about two-thirds of the reduction of Nueces Bay inflow and about half the reduction in Nueces Delta inflow was caused by drought. The average number of flood events per year has been reduced from 2.3 before the construction of the reservoirs to only 0.8 since the completion of Choke Canyon Reservoir (Asquith, et al., 1997).

As the freshwater inflows diminish, the estuary's function as a healthy productive biological ecosystem has been significantly reduced. Consequently, this has led to a hypersaline, or "reverse estuary" condition where salinity values in the delta are generally higher than that of the bay or ocean. Many species can tolerate these harsher environmental conditions, but the prolonged periods of salinity-induced stress leads to lower biological productivity as well as less species diversity. In an attempt to solve this issue the City of Corpus Christi, under instruction from the 2001 Agreed Order, installed a 2-mile-long pipeline and pump station (completed in 2008) to divert up to the first 3,000 acft of pass-throughs from above the saltwater barrier dam directly into the upper Rincon Bayou that winds down through the Nueces River Delta (Montagna, et al., 2009).

The Nueces River Delta is composed of a complex array of channels, pools, marshes and tidal flats and is one of the most extensive marsh ecosystems on the Texas Gulf Coast and an integral part of the Nueces Estuary (**Figure 2.4.1**). The delta provides a critical transitional environment used by marine and estuarine species at important stages of their life cycle (Longley, 1994). The Nueces Delta is approximately 20,000 acres in size and home to numerous fowl, aquatic, estuarine, and wildlife species. Some of these species include sea ox-eye daisy, glasswort, saltwort, seablite, coastal dropseed, several migratory bird species, and many other plant and animal species. Many commercial fishing species that are routinely harvested from the Nueces Estuary use the delta as breeding and/or feeding grounds. These species include red drum, black drum, brown shrimp, white shrimp, blue crab, Atlantic flounder, and speckled trout.

There has been a long history of natural and anthropogenic changes that have occurred in the Nueces Delta, but the most recent in terms of water management came in the last two decades. From December 1994 until September 1999, the U.S. Bureau of Reclamation did a demonstration project in the Nueces Delta in order to restore regular inundation to the upper part of the delta. The two main parts of the project were overflow channels (one at the Nueces River, and the other at Rincon Bayou in the interior of the delta) allowing for more river water to flow directly into the delta. The study showed that even small amounts of inflows into targeted areas were biologically important. At the conclusion of their study, the temporary easements called for the overflow channels to be refilled.

In 2001, the City of Corpus Christi and the Nueces River Authority presented the NEAC with a proposal for the Rincon Bayou Diversion project and their proposed amendments to the 1995 Agreed Order. Main parts of this proposal included either obtaining easements or purchasing land necessary to re-open the Nueces River Overflow Channel, construct and operate a pipeline to deliver up to 3,000 acft/month directly into the upper part of the delta, and implement an ongoing monitoring program to determine that these projects "do no harm".

Figure 2.4.1. Aerial view of the Nueces River Delta.

In exchange for the Rincon Bayou Diversion Project, the City proposed to amend the 1995 Agreed Order to make some of the drought contingency measures "voluntary" when reservoir capacity fell below 50 percent, providing for greater flexibility for the City to implement its Drought Management Plan. This eliminated much of the political pressure on the City Council when it came to their Drought Plan (Tolan, 2011).

The Agreed Order was amended in April 2001, changing Section 2 that deals with drought relief and the responsibilities of the permit holders. The amendment also puts forth the steps the City must take:

- Acquire the land to make the Nueces River Overflow Channel permanent;
- Construct and operate a conveyance facility for up to 3,000 acft/month;
- Implement an on-going monitoring and assessment plan;
- Construction necessary must be accomplished by Dec 31, 2002; and
- In the event the City fails to timely complete the work, the provisions of the Agreed Order of April 1995 shall be reinstated and become operative despite this amendment, unless the Executive Director grants a modification after considering the recommendations of the NEAC.

The Nueces Overflow Channel was re-opened in October 2001 allowing for more frequent water fluctuations into the Nueces Delta, mostly during flooding events. Because the overflow channel can deliver water to the delta only during floods, the Rincon Pipeline was built to deliver freshwater to the Nueces Delta. The Calallen Pool is upriver behind the salt water dam (at Calallen), and separates the tidal portion of the river from fresh water. The salt water dam overflows only during rain events or required pass-throughs. The pipeline was planned to pass-through the first 3,000 acft/month from Calallen Pool to Rincon Bayou each month that pass-through was required. The pipeline was supposed to be complete by 2004, but there were years of delays because of difficulty obtaining necessary easements and poor weather (Montagna, 2009). Construction of the pipeline was finally complete in 2008, and has operated five pass-through events as of May 2011.

2.5 Oso Bay

Oso Bay is a secondary bay that is an enclosed, shallow body of water situated along the southern shore of Corpus Christi Bay, with a surface area of approximately 7 square miles. Oso Bay receives freshwater inflows from Oso Creek and exchanges water only with Corpus Christi Bay (Fisher, 1996). Generally characterized as a soft sediment estuarine area, temperature and wind exert a strong influence on Oso Bay. The entire bay is subject to tidal exchange, and significant portions are alternately exposed and submerged, depending on wind velocity and direction. Typically, average depth in Oso Bay is <3.0 feet. The majority of all tidal exchange occurs through a pass located on the east side of Ward Island; with minimal exchange occurring through the small pass located to the west. The bay exchanges saltwater with Corpus Christi Bay and receives fresh water from Oso Creek, a stream whose flow is dominated by discharges subject to permit. Ecologically, Oso Bay provides habitat for many plants and animals, and plays an influential role in water purification and storm protection.

Clays and sands dominate Oso Bay sediments, with areas high in organic material found near the City of Corpus Christi Oso WWTF (Armstrong, 1987). Bowman and Jennings (1992) stated that rough shell hash constituted a major bottom component present near the mouth of the bay as it empties into Corpus Christi Bay, but was not present elsewhere. Seagrass beds, mostly comprised of *Halodule wrightii*, cover numerous areas of the bay bottom. Emergent vegetation, and a well-defined wetland area, is located adjacent to the Oso WWTF outfall in the Blind Oso.

Under normal climatic conditions, the entire flow in Oso Creek is effluent dominated. Fisher (1996) states documented water quality problems may relate to the permitted 565 million gallons per day (MGD) that could be discharged to Oso Creek and Oso Bay from these permitted wastewater facilities. The stream originates as treated effluent from the city of Robstown WWTF (3.0 MGD). This flow moves downstream, combining with effluents from several minor domestic WWTF outfalls: Roloff Evangelistic Enterprises, Inc. (0.02 MGD) and Texas A&M Extension Service (0.025 MGD). Approximately 15 miles downstream from the Robstown WWTF, effluent from the City of Corpus Christi Greenwood WWTF (6.0 MGD) enters Oso Creek. Additional freshwater originates from the inputs of three adjacent golf courses, storm water, agricultural, and urban runoff.

A cooling water discharge from the Topaz Ltd.'s Barney Davis Electric Generating Station (CP&L-BD) (540 MGD) combines with Oso Creek at the upper end of Oso Bay. Hypersaline water, drawn from the Upper Laguna Madre, passes through the plant heat-exchange system and discharges into baffled thermal equalization ponds before entering Oso Bay. This discharge remains the most significant hydrological factor in the Oso Bay/Oso Creek system, resulting in a net positive outflow into Corpus Christi Bay (Watson, 1991). Near the mouth of Oso Bay, the Oso WWTF (16.2 MGD) discharges domestic wastewater effluent into the Oso Bay system. Although freshwater comprises only a small percentage of the total discharge it is ecologically important within the system.

In addition to diverted storm water runoff, discharges of oil field brines routinely entered Oso Creek and associated tributaries from 1939 until 1973. Spent drilling muds were often disposed of into Oso Creek and along its banks. These practices altered soil structure, enhanced erosional processes, increased sedimentation rates, and resulted in negative stream impacts along the length of the creek leading to Oso Bay. Bowman and Jennings (1992) stated that the widely fluctuating historical flow pattern in the Oso Creek and Oso Bay system results from the influence of infrequent, yet, large-scale rain events associated with the hurricane season. These events, interspersed with minor to severe drought conditions tend to skew the annual flow data for the system.

Oso Bay continues to provide productive nursery habitat for commercially important species, such as white and brown shrimp (*Litopenaeus setiferus* and *Farfantepenaeus aztecus*), blue crabs (*Callinectes sapidus*), and assorted finfish species.

The northwest portion of the bay between Ward Island and Ennis Joslin Road is known as the Blind Oso. It is extremely shallow and has a soft muddy bottom and wetland areas. Local area stakeholders indicate that the Blind Oso is not used for contact recreation, but is used extensively by waterfowl since it provides high quality habitat for waterfowl and shorebirds.

2.6 Upper Laguna Madre

The Laguna Madre runs along the Texas coast from Corpus Christi Bay in Nueces County to the Brownsville Ship Channel in Cameron County. The only development is in the very northern and very southern ends: Corpus Christi and Port Isabel, respectively. Padre Island National Seashore encompasses most of the barrier island to the east. The land to the west is occupied predominantly by large ranches such as the King Ranch. The Laguna is connected to Corpus Christi Bay and there are two channels through the island at Port Mansfield and Port Isabel, which are both in the lower Laguna Madre outside of the Nueces BBEST focus area.

The Laguna Madre is a long shallow hypersaline bay along the western coast of the Gulf of Mexico in Nueces, Kenedy, Kleberg, Willacy, and Cameron counties. It is separated by the roughly 20-mile-long Saltillo Flats land bridge into Upper and Lower bays. The two are joined by the Gulf Intracoastal Waterway, which has been dredged through the bay. Cumulatively, Laguna Madre is approximately 130 miles long, the length of Padre Island. Since the Upper Laguna Madre from the southern end of Baffin Bay in Kenedy County to Corpus Christi Bay in Nueces County is the portion of the Laguna Madre in the geographic charge of the BBEST, this section will focus on it.

The Upper Laguna Madre is one of the most unspoiled ecosystems in Texas with Padre Island National Seashore protecting the western shoreline and King Ranch protecting the eastern shoreline. The bay is shallow and narrow, averaging only 3.6 feet in depth and 4 miles to 6 miles in width. The depth is only 0.7 foot to 1.1 feet in most areas. The exception is the Gulf Intracoastal Waterway which is dredged to 12-feet-deep and138-feet-wide. It runs the bay's length and joins the upper and lower stretches. The Upper Laguna Madre has an average salinity that is above the seawater average of 35. Because of the high salinity, it holds the distinction as one of only six hypersaline bays in the world. The reasons for its hypersalinity include shallowness, the lack of a significant river source, dry climate, high evaporation, and the isolation from other bodies of water. A key characteristic of this estuary is that evaporation greatly exceeds inflow by factors of two to three times and this is one of the primary reasons for the hypersaline structure. Its salinity was even greater before the Gulf Intracoastal Waterway was dredged, which allowed water exchange between the Lower and Upper Laguna Madre. However, even with the Gulf Intracoastal Waterway very little water exchange occurs (Tunnell and Judd, 2002).

Rainwater from tropical storms and hurricanes is the only significant fresh water the bay receives. Overall, the local climate conditions have a greater effect on the overall salinity structure of the Upper Laguna Madre system than do the direct freshwater inflows effect at typical levels. While the Upper Laguna Madre does receive some freshwater inflow amounts, these inflows have little effect on any estuary-wide salinity structure (Tolan, et al., 2004).

Despite the high salinities, the Upper Laguna Madre remains one of the most productive bay systems in Texas for finfish and this productivity can be ultimately linked to the seagrass-based food web characteristic of this unique system. The seagrasses of Laguna Madre account for 80 percent of all seagrass found off the Texas Coast and provide habitat for fish, shrimp and crab, which also feed the bird populations.

2.7 Baffin Bay

Baffin Bay projects inland from the Upper Laguna Madre forming part of the eastern boundary between Kenedy and Kleberg counties. Baffin Bay is a small embayment located on the western edge of the Upper Laguna Madre and it is often considered a part of this larger system. Baffin Bay has also been called Lago de la Santisima Trinidad and Salt Lagoon (Handbook of Texas Online, 2002). Similar to the Laguna Madre, Baffin Bay receives minimal riverine input.

However, intermittent creeks drain into the secondary bays of Baffin Bay during periods of rainfall: Petronila Creek flows to Alazan Bay, San Fernando Creek flows to Cayo del Grullo, and Los Olmos Creek flows to Laguna Salada. Based on a study by Orlando, et al. (1993), direct precipitation contributes 65 percent of the total fresh water discharge to the estuary. Exchange with the Gulf of Mexico is through Corpus Christi Bay to the north. Because of the scarce freshwater inflow and extensive evaporation, which is promoted by shallow water and warm climate, the bay has a relatively high water salinity reaching 75 in its northern part. With limited freshwater inflow, evaporation far exceeds precipitation, resulting in a hypersaline estuary. During prolonged droughts the salinity level can spike to over 100 (average seawater level is 35). Between 1946 and 1948 and in 1968, the salinity level in the bay exceeded 100 killing many of the fish in the area. More than any other bay in Texas, Baffin Bay lives in a fragile balance facing high salinity cycles when inflow ceases and summer and winter temperatures become extreme.

The climate has been described as semi-arid, sub-humid or subtropical, with an extreme varying precipitation. Tropical storms and hurricanes are common, and they strongly alter the climate and hydrology of the region.

About 8.1 square miles of the bottom of the bay is covered in seagrass; most other parts are dominated by shoal grass (*Halodule wrightii*) with occasional rocky outcrops. Scattered parts of the bay, mostly near the mouth, contain the relict serpulid worm reefs, which are composed of the remains of serpulid tube worms. Although some tube worm species still inhabit the bay area and the reefs, they bring no significant contribution to the reef structure. Most reefs are circular or ellipsoid structures between 26 to 131 feet in diameter and 1.5 to 6.6 feet in height above the sediment. Their total area is about 6 square miles, but it is gradually reducing due to erosion (Hardegree, 1997).

The lands around the bay are flat and dominated by grasslands and oak savanna which are used for agriculture and cattle farming. Common tree and plant species include southern live oak (Q*uercus virginiana*), prickly pear (*Opuntia spp.*), lime prickly-ash (*Zanthoxylum fagara*), greenbriar (*Smilax spp.*), sunflowers (*Helianthus spp.*), tanglehead (*Heteropogon contortus*), crinkleawn (*Trachypogon spicatus*), gulfdune paspalum (*Paspalum monostachyum*), fringed signalgrass (*Urochloa ciliatissima*), shrubby oxalis (*Oxalis frutescens angustifolia*), dayflower (*Commelina spp.*), Texas lantana (*Lantana urticoides*), Texas bullnettle (*Cnidoscolus texanus*), silverleaf nightshade (*Solanum elaeagnifolium*), crotons (*Croton spp.*), and Lindheimer tephrosia (*Tephrosia lindheimeri*).

2.8 History of the Nueces Estuary

The Nueces Estuary is composed of three major systems: Nueces Bay; Corpus Christi Bay; and the Nueces Delta. The Nueces River and associated catchment drains 4.3 million hectares (10.6 million acres) of a semi-arid, subtropical region of south Texas directly into Nueces Bay, a secondary bay in the Nueces Estuary (**Figure 2.8.1** and **Figure 2.8.2**). Nueces Bay is linked to the Gulf of Mexico by Corpus Christi Bay, the estuary's primary bay. Northwest of Nueces Bay is the Nueces Delta, which incorporates Rincon Bayou, on the northside of the Nueces River, and the delta proper, at the mouth of the Nueces River. The Nueces Delta exchanges tidal waters with Nueces Bay and receives freshwater from direct precipitation and overbanking from Nueces River flooding events.

Historically the Nueces Estuary was a "typical" estuarine environment, consisting of freshwater at one end and marine on the other with a salinity gradient in between that supported two significant indicator species, *Rangia cuneata* (Atlantic rangia) and *Crassostrea virginica* (eastern oyster). The basis for this conclusion comes from historical accounts of a freshwater swamp in this area, the abundant *Rangia* midden mounds found in the Nueces Delta today, in addition to the historical literature describing very large harvestable oyster population that all would have required lower salinity conditions to have occurred and persisted.

Currently Nueces Bay often has high salinities, and the Nueces Delta has become a reverse estuary where low salinity water enters the delta from the bay as opposed to fresh water entering the delta from a river source. Harvestable oyster populations have dramatically declined, and *Rangia* is largely missing. This has led to degraded conditions in both the Nueces Delta and Nueces Bay. Evidence shows that most changes to the Nueces Estuary occurred within the 20th century, so this is the period of focus for this account of the natural history of the Nueces Estuary. The report is followed by a list of materials reviewed (Appendix 2.8.1) and a timeline of events (Appendix 2.8.2).

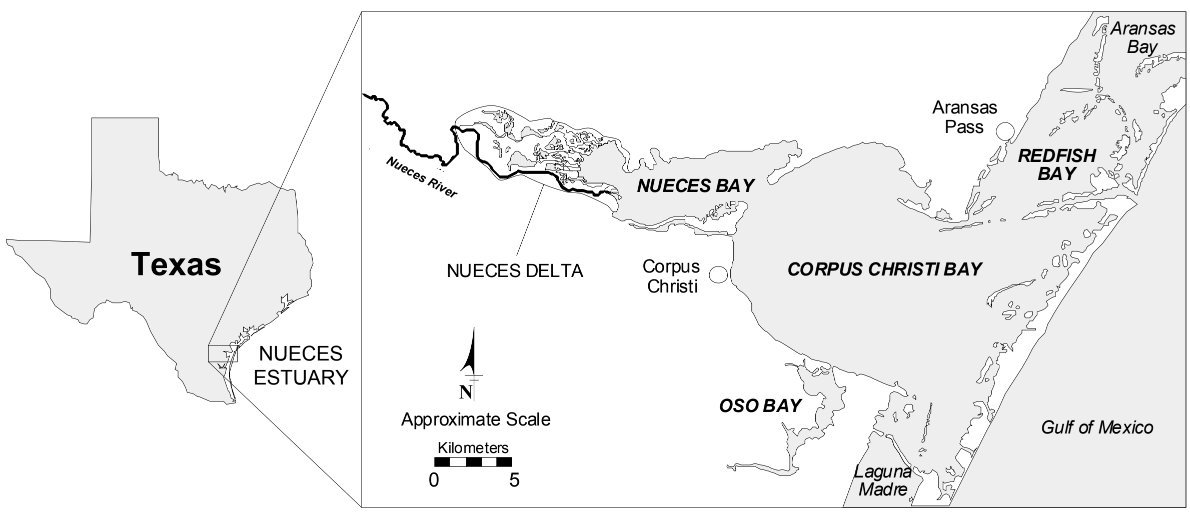


Figure 2.8.1. Location map of the Nueces Estuary in relation to Texas.

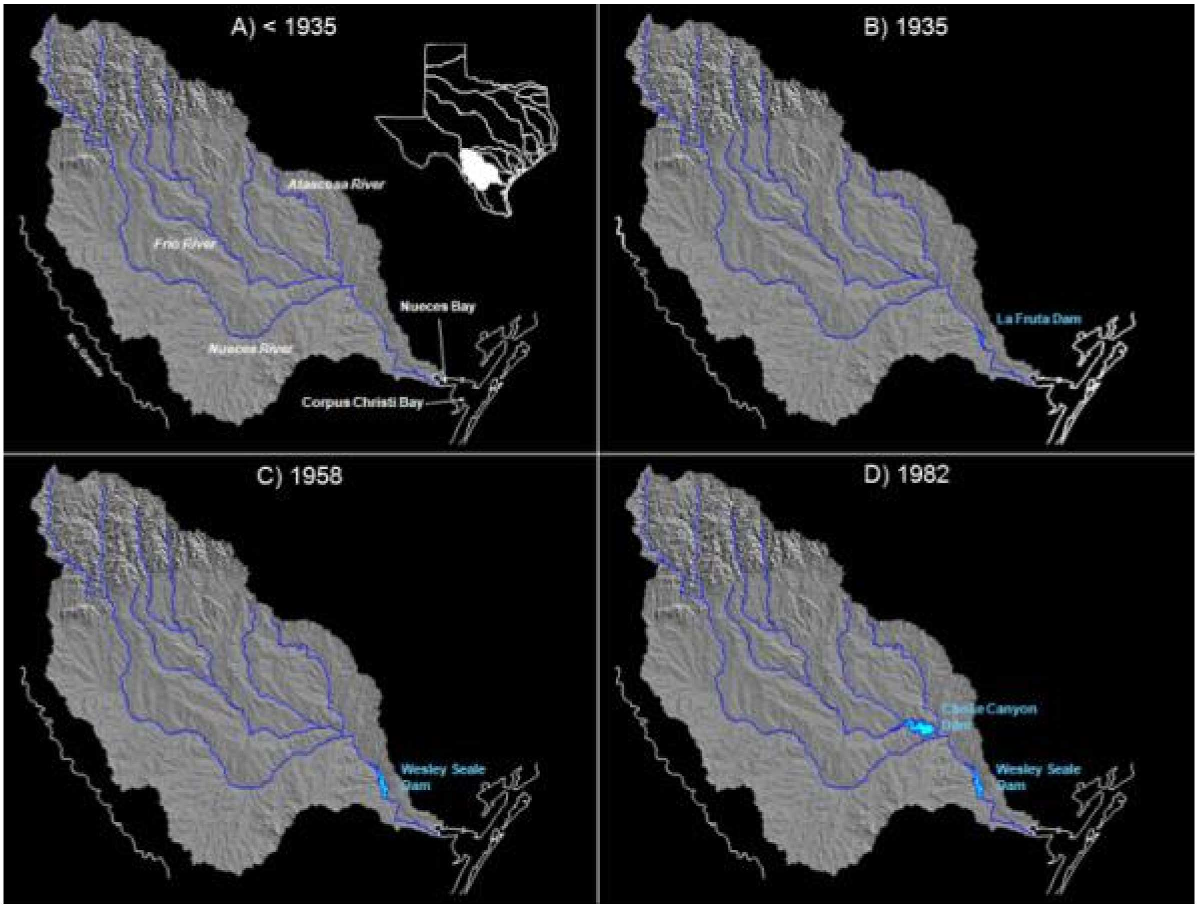


Figure 2.8.2. The history of major dams in the Nueces Basin. Source: Bureau of Reclamation (2000).

2.8.1 Pre-20th Century

Here we outline changes to the Nueces Estuary within the 20th century; however, there is some information available on earlier times. Based on the salinity range of the organisms found near the northern Nueces Bay shoreline (White's Point), salinity regimes in Nueces Bay have ranged from 5-10 to above 15 between 1500 and 7000 years before present (Ricklis and Cox, 1998). Humans have inhabited the area surrounding the Nueces Estuary since at least 5600 before present when Native American tribes inhabited the area (Ricklis and Cox, 1998). There is evidence that these Native Americans, including Karankawan Indians, fished areas of the Nueces Estuary and utilized *Rangia* and eastern oyster as a source of food and a source of material to make tools.

As portrayed by Peirce (1894) of 1877 conditions, the lower Nueces Delta, where the Nueces River drained into Nueces Bay was described as being a large recently accreted mud flat, several miles in extent, fit for only alligators and mud-snakes. The area immediately above the lower Delta was heavily forested and entwined with 'thousands of snags and water soaked logs', indicating a history of immense floods that occurred in the lower floodplain of the Nueces River watershed (BOR, 2000). The upper Nueces Delta in 1877 was a boggy area filled with pools of low-salinity brackish water. Confirmation of historical low salinities (0.5-5) that occurred in the area is also indicated by the current presence of *Rangia* middens in the Delta, the remains of foraging activities of Native American who inhabited the area up until the early 19th century. *Rangia* is only present in other Texas estuaries where mean salinities are less than 12 (Montagna and Kalke, 1995) but need salinities less than 10 for larval survival (Hopkins, et al., 1973; LaSalle and Cruz, 1985). By 1888, oysters from the Nueces Estuary were being harvested in large quantities and shipped to Mexico and other parts of the U.S. (Anon, 1888; Merriman, 1888; Woods, 1939). Some private oyster beds were located on the reefs between Nueces and Corpus Christi Bays and oysters originating from Mesquite and Aransas Bays were used to seed the same private beds (Woods, 1939). The quantity of oysters harvested was enough that heavily loaded wagons exported oysters daily (Merriman, 1888).

Major water impoundments and removal of water from the Nueces River were largely absent in the 19th century, although water for municipal and agriculture uses within the Nueces River catchment occurred, including in the upstream Hill Country. In 1852, it was documented that teamsters (people driving teams of draft animals) drove daily to the lower Nueces River to haul freshwater to Corpus Christi (CCCT, 1852). By 1887, concern for a water supply for Corpus Christi was brought to the attention of the Corpus Christi City Council (Anon, 1958). One irrigated farm in Montell, Uvalde County contained a 2.5-mile-long 2- to 7-foot depth ditch (Casa Blanca ditch) for irrigation purposes.

2.8.2 20th Century

<u>Hydrology</u>

Some of the impacts to freshwater inflows into the Lower Nueces River, Delta, and Bay occurred during the early 1900s with the construction of the saltwater barrier dam (actually first built in 1898) along the Nueces River (Cunningham, 1998), and the two Railroads being built across the Nueces Delta, which blocked additional flow across the landscape. By 1910, numerous small dams were located along the Nueces River, although none substantial enough to withstand any major floods (**Figure 2.8.3**).

By 1913, the water supply for Corpus Christi was obtained from the small reservoir formed by the installation of the saltwater dam 10.5 miles upstream of the Nueces River mouth (Riche, 1913). The combined active pumps between 10.5 and 17 miles of the Nueces River mouth exceeded the entire flow of the river in seasons of extended drought. In 1913, sharp fluctuations in river stage were still common with as many as nine floods (including flash floods) occurring per month, some up to 8 feet above normal levels.

Figure 2.8.3. A small dam on the Nueces River circa 1900. Source: Taylor (1904).

In 1926, construction of the initial La Fruta Dam began, which is the first major dam in the Nueces River catchment (Anon, 1958; Figure 2.8.2). This earth embankment near Mathis was designed to impound 50,000 acft (61.6×10^6 m^3) of water. Construction of the dam was officially completed in January 1930 (Cunningham, 1998). The initial La Fruta Dam partially collapsed in November 1930 and was finished for the second and last time on July 1934. During 1929-1930 when filling of the reservoir behind the La Fruta dam began, Corpus Christi Bay was usually hypersaline (saltier than the Gulf of Mexico) and salinities in the northeast corner of Nueces Bay rose to 23 (Burr, 1930).

In June-July 1935, large flooding events in the Nueces River and other local tributaries turned Nueces Bay into effectively a freshwater lake for six weeks and consequently killed much of the oyster population within the bay (TGFOC, 1935). Around 1935, it was possible for the brines that occurred in the shallow Nueces Bay to be displaced by freshwater within a few hours after abnormally high flood stages on the Nueces River.

Construction of the Wesley Seale Dam, a new larger dam immediately downstream of the La Fruta Dam, began in 1955 in response to recent droughts and a growing demand for municipal water (Figure 2.8.2; Cunningham, 1998). The Wesley Seale Dam was designed to store 302,000 acft of water. Lake Corpus Christi, the resulting lake formed, covered up and hence nullified the La Fruta Dam.

Further demand for freshwater culminated in the creation of the Choke Canyon Dam on the Frio River, a tributary of the Nueces River. Construction began in 1978 and was finished in 1982 with a maximum capacity of 695,000 acft of water. Choke Canyon Reservoir filled and spilled for the first time in 1987.

The two major reservoirs in the Nueces Estuary catchment have provided flood control and municipal water supplies but have greatly reduced inflow to the estuary (Asquith, et al., 1997; BOR, 2000). Direct water losses from evaporation and consumptive uses have caused considerable changes in inflow, especially the reduced frequency of high-flow events in the Nueces River (Ward and Armstrong, 1997). The changes in inflow balance (the total inflows minus diversions and evaporation) to the Nueces Estuary are obvious when observing the three periods of dam presence; La Fruta Dam (1935 to 1957), Wesley Seale Dam (1958 to 1982), and Choke Canyon Dam (1983 onwards) (**Figure 2.8.4** and **Figure 2.8.5**).

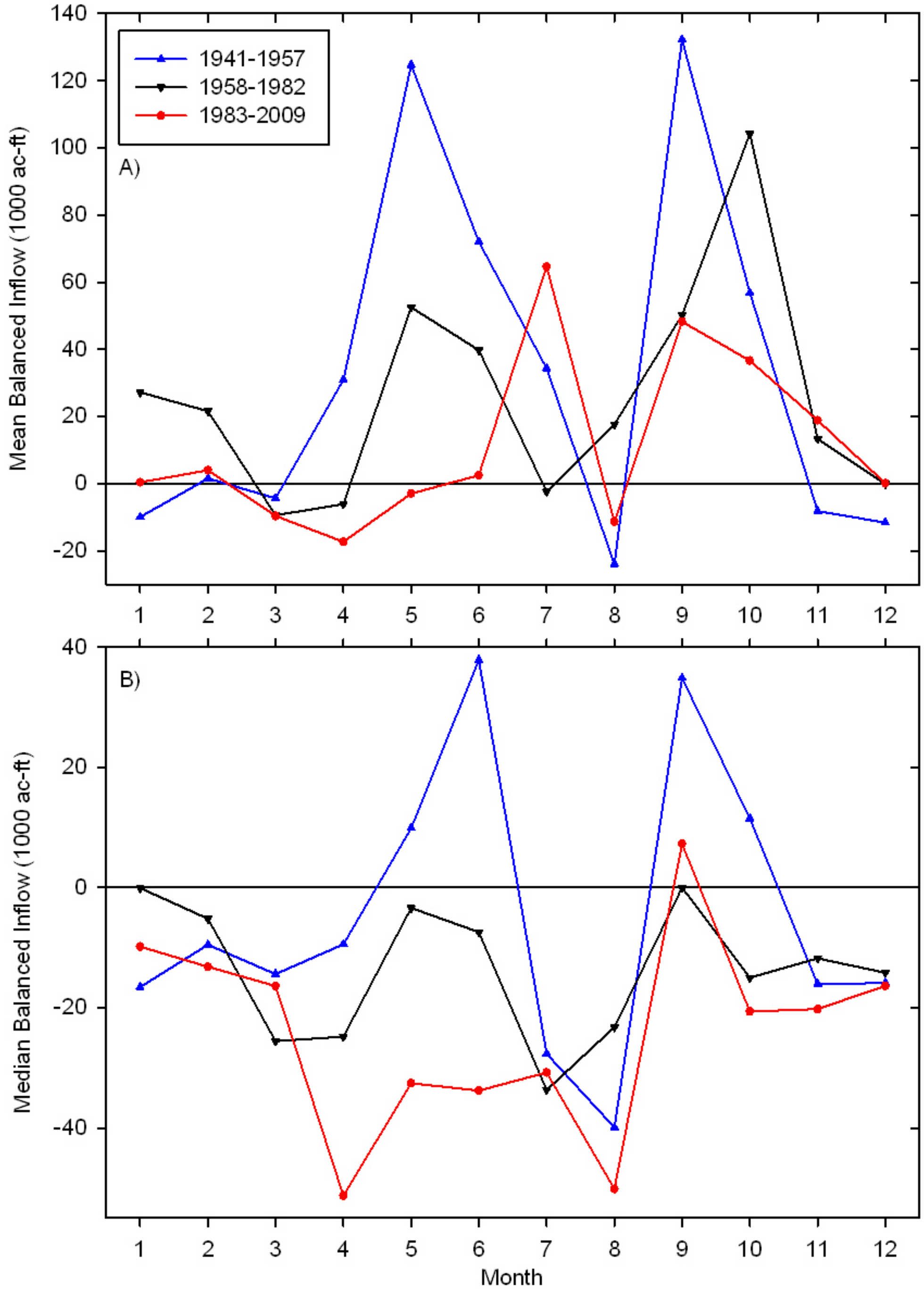


Figure 2.8.4. Inflow balance (i.e. total inflows minus diversions and evaporation) for Nueces Estuary by month. A) Mean and B) median inflow balance. Data source: TWDB.

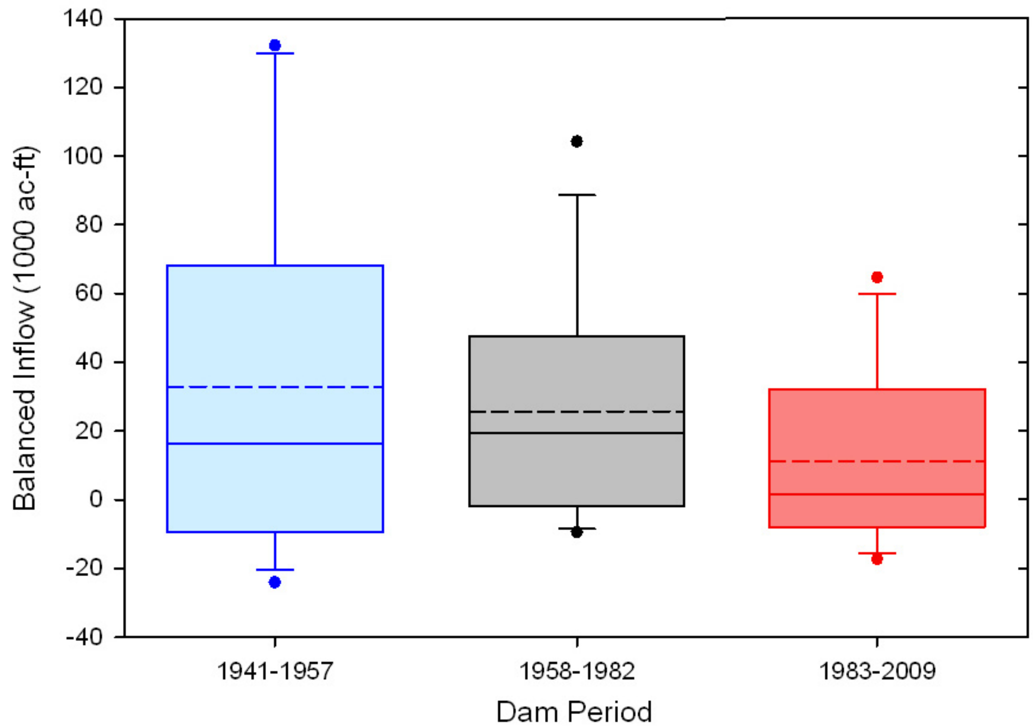


Figure 2.8.5. Box and whisker plot of mean monthly inflow balance for each time period. Dashed line = mean monthly flow, dot = outlier.

When La Fruta Dam (1934 to 1957) was the only major dam in the catchment, there were two peaks of monthly inflow balance in May/June and September/October (Figure 2.8.4, data analyzed 1941 to 1957). Median balanced inflows were negative outside these months during the La Fruta Dam period. Mean monthly inflows were reduced during the Wesley Seale Dam period (1958 to 1982) but two peaks still occurred in May/June and September/October. Median monthly inflow balance however, was almost all negative in the period after construction of the Wesley Seale Dam and before Choke Canyon. The timing and scale of peak inflows has changed in the most recent period, the Choke Canyon period. The May/June peak of inflow balance is now occurring in July; however, the September peak remains the same. Median inflow balance remains almost negative for almost all months in the most recent period. Mean monthly balanced inflows have decreased throughout the period of analysis (Figure 2.8.5). Remarkably, the mean inflow balance during the first period was greater than that of the other periods even though the first period was largely in drought and the latter two periods had higher mean annual precipitation (BOR, 2000). This indicates the reservoirs have reduced inflows dramatically. The variability of inflows have also decreased over time, which is expected because reservoirs are operated to reduce flooding by storing large flows and not allowing them to run in the river.

Reduced inflows have caused salinity increases of 0.05 yr^{-1} in Corpus Christi Bay and 0.25 yr-1 in Nueces Bay from the 1950s to the 1990s (Ward and Armstrong, 1997).

<u>Oysters</u>

Major anthropogenic alterations of the Nueces Estuary include excavation of shipping channels, alterations of the Nueces River channel, oyster shell mining, barrier construction and artificial inlet construction. The primary alteration affecting salinity is the reduction in freshwater inflow, from dominantly anthropogenic causes. Changes in salinity consequently can change the locations and abundance of species that occur in all estuaries, including the Nueces Estuary. Eastern oysters are a very notable example of a salinity sensitive species that has significantly decreased in abundance in the Nueces Estuary, specifically Nueces Bay.

The historic extent of oysters can be determined by photographic evidence (**Figure 2.8.6**) and fishing harvest (**Figure 2.8.7**). Quantification of the oyster harvest landed at Corpus Christi began in the 1920s and continued into the 1940s (TGFOC, 1932-1950). In the 1929 fiscal year (September 1928 to August 1929), 4008 barrels of oysters were landed at Corpus Christi, approximately 6 percent of the Texas total (Figure 2.8.7). Most of the Corpus Christi landings were from Nueces Bay. Although the oyster volume units reported changed in 1936, it is obvious that Corpus Christi oyster landings still made a sizeable contribution to the total Texas oyster harvest until 1941 when individual landings at ports stopped being reported. Relative to the total Texas oyster harvest, the Corpus Christi harvest peaked at 23 percent in 1939 fiscal year in the period from 1929 to 1941. Currently, there is no commercial oyster fishery in Nueces Bay, nor has there been for several decades.

Figure 2.8.6. Photos showing the oyster industry of Corpus Christi (Kilgore Picture Postcard Collection). Top: Lone Star Fish & Oyster Co., 1929. Bottom: Shelling oysters, 1925.

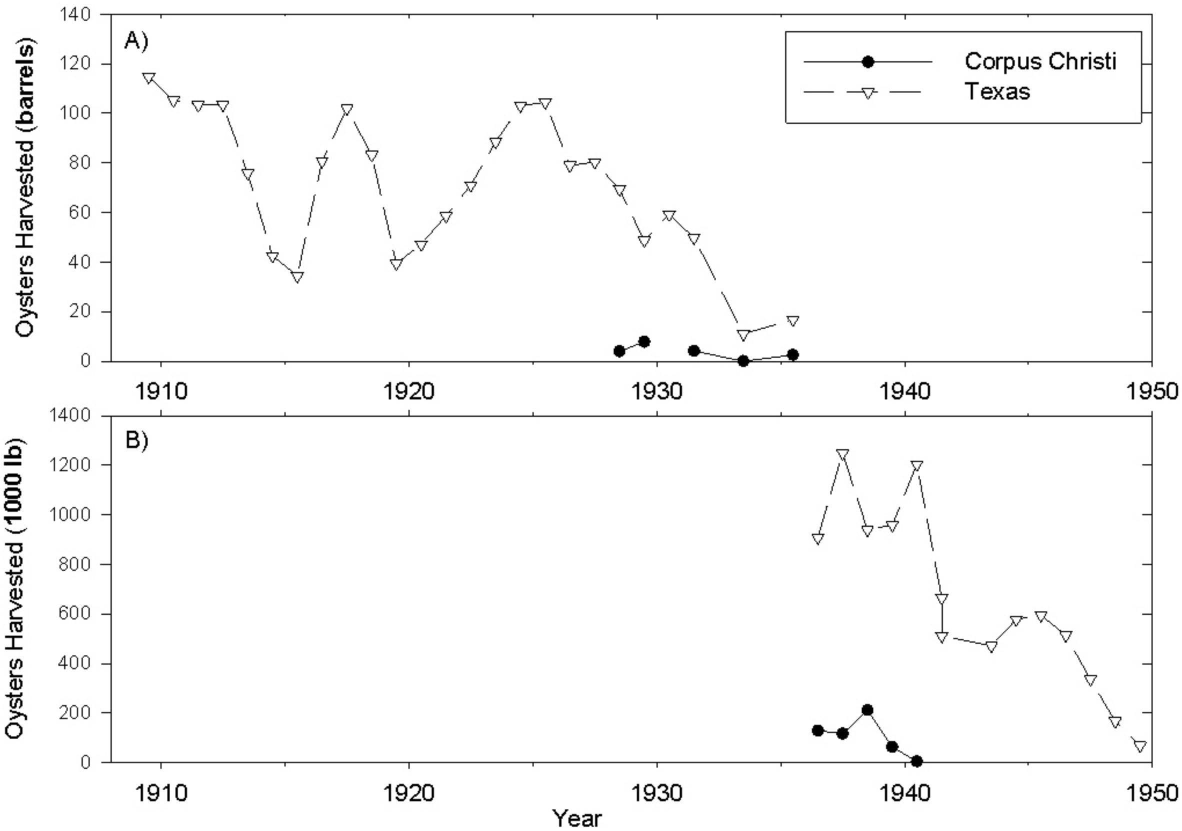


Figure 2.8.7. Oyster Harvest for Corpus Christi and total for Texas. A) recorded in barrels and B) recorded in pounds. Data from Texas Game, Fish and Oyster Commission (1932-1950). Note: Actual barrel capacity is unknown.

In addition to oyster removal and depletion due to increasing salinities, habitat has also been altered by dead shell removal/dredging. Oyster shell removal for roads and construction materials (termed mudshell) occurred from the early 1900s until 1974 (**Figure 2.8.8**; Withers, 2010). In 1934, the Columbia-Southern Chemical Corporation began operations, dredging 160,000 tons of oyster shell per year from the bays around Corpus Christi (Wise, unknown date), with the shell being used for chemical processes. By the mid 1930s, dredging for the shell substrate supplanted actual oyster harvest. Approximately 1200 to 1300 cubic yards of oyster shell were mined from Nueces Bay each year between 1958 and 1963 (10 percent of Texas total; Doran, 1965). Shell dredging operations took advantage of dry periods when live reefs would temporarily die back allowing legal shell removal from these oyster producing reefs. The shell removal was largely unregulated and undocumented, but some records show that during one year (1958) a conservative estimate of 1.175 million cubic yards were removed (Ward, 1997). Eventually shell dredging and substrate removal coupled with restriction in freshwater inflow ended the oyster and shell fishery in Nueces Bay. By 1967, Nueces Bay was considered “fished-out” in terms of oyster and shell (Ward, 1997). By 1990, noticeable reductions in freshwater inflow to the bay and delta were routinely observed and led to salinity increases and even to hypersaline conditions.

Figure 2.8.8. Evidence of dredged oysters for construction (photos from the *Corpus Christi Caller Times*, July 17, 1955).

<u>*Rangia cuneata*</u>

Rangia cuneata is a small clam that thrives in estuaries where mean salinities are less than 12 (Montagna and Kalke, 1995) because they require salinities less than 10 for reproduction and larval survival (Hopkins, et al., 1973; LaSalle and Cruz, 1985). *Rangia* can also play a critical role in regulating ecological processes in shallow water estuaries of the Gulf of Mexico (Wong, et al., 2010).

Middens of *Rangia cuneata* were found in the Nueces Delta (**Figure 2.8.9**). Middens are piles of shells, which were created by local indigenous people as they feasted on the clams (**Figure 2.8.10**). Most of the clam shells exhibit breaks or marks consistent with those made to open the shell for the meat inside. The middens are composed of clams that are uniform in size 51 cm ± 1.6 cm. Based on published growth rates, these clams are likely 5 years old. The maximum life span of *Rangia* is 15-20 years. *Rangia* shells this old (about 5 years) were most likely produced by a large, successfully recruiting population, existing in brackish water conditions for extended periods of time. This is in sharp contrast to current conditions in the Nueces Delta. Two dams were built and the sides of the Nueces River have been diked so fresh water does not spill into the delta as frequently as it did historically (Cunningham, 1998). The delta is now hypersaline for extended periods of time and is a reverse estuary.

The middens in the Nueces Delta indicate the historical freshwater inflow regime was sufficient to maintain low delta salinities in the recent past. Salinities in the 0-15 range are necessary to induce spawning, and embryos and early larvae survive only in the range of 2-15. Although there were large populations of *Rangia* in the past, the recent change in salinity has resulted in complete loss of this population, as none have been found in continuous sampling programs since 1994 (Montagna, unpublished data).

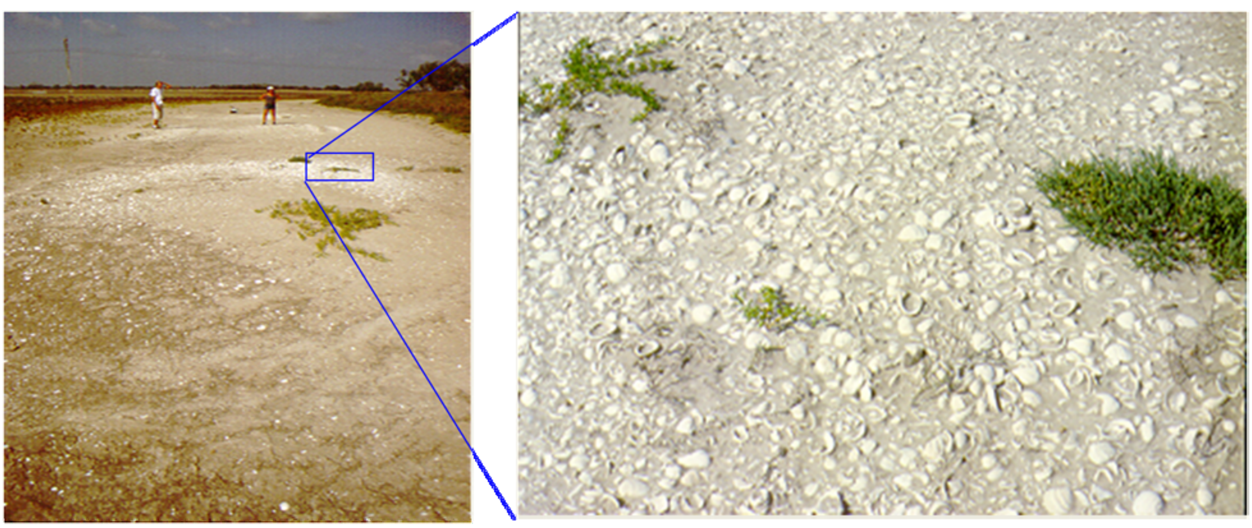


Figure 2.8.9. *Rangia* middens in Nueces Delta. People shown for scale on left, and inset blow up on right. This location on southern edge of Central Rincon Bayou channel, sampled June 2000.

Figure 2.8.10. Example of fossil *Rangia* shells found in middens (white on left) and live shells found in the Nueces River (dark shells on right). Notice cracks made in order to obtain meat from the shells.

2.8.3 Summary

Nothing is more fundamental to the definition and functioning of an estuary than the quantity of freshwater flowing from the river to the embayment (Montagna, et al., 2002). The Nueces estuary is a good example of an estuary at risk because of freshwater impoundments and diversions. The change in the Nueces Estuary is a good example of how changing inflow can severely damage an estuary. Historically, the Nueces system was a "normal" functioning estuary, but the construction of two dams reduced has flow to the point where the system no longer functions as a positive estuary (Montagna, et al., 2009).

Fossil evidence shows that the Nueces Estuary was a "typical" estuarine environment, consisting of freshwater at head and marine conditions at the ocean inlet with a salinity gradient in between that supported two significant bivalve indicator species, *Rangia* and eastern oyster. There are abundant *Rangia* midden mounds found throughout the Nueces Delta today, and the historical literature describes very large oyster populations that coincided with favorable conditions for that species. This is clear evidence that salinities in much of the upper estuary were routinely 10 or less because *Rangia* require these low salinity conditions successfully reproduce. In contrast, live *Rangia* are missing from the Nueces delta today (BOR, 2000).

One of the first accounts of the Nueces Delta by Dr. A.C. Peirce, a naturalist who traveled in the Corpus Christi area about 1890, describes a "big slimy slough, only fit for the habitation of alligators and mud-snakes" (Peirce, 1894; as cited in BOR, 2000). He also describes the water being fresh enough to drink.

We do not have to go back far in time to when Nueces Bay was a productive bay for oysters. In 1904, 400,000 gallons of oysters were marketed, four years later the production had slumped 50 percent and by the 1930s the public reefs were producing only 200,000 gallons, and in some years not more than 70,000 gallons (Oyster Commission, 1937). By the 1930s, the Commission reports no oyster catches in Nueces Bay. That is still true today. While the reduction was likely due to overfishing and dredging, oysters did not come back when fishing and dredging ceased because the salinities were too high.

Some of the impacts to freshwater inflows into the Lower Nueces River, Delta, and Bay occurred during the early 1900s with the construction of the saltwater barrier dam along the Nueces River, and the two railroads being built across the Nueces Delta, which blocked additional flow across the landscape. Other more recent impacts include: the construction of the first reservoir (La Fruta Dam) in the 1930s; construction of the Inner Harbor and partial filling in of the bay; oyster dredging and channel dredging in the 1940s to the 1960s; power plants along the Inner Harbor transferring high salinity (1930s) Corpus Christi Bay water to the lower parts of Nueces Bay; the building of U.S. Highway 37 in the 1950s blocking water to the Rincon Bayou in the Nueces Delta (BOR, 2000); the possible channelization of the Nueces River and intentional deposit of material along the river bank; and oil and gas exploration in the 1960s to the present.

The major impact to freshwater inflows came with the construction of the Wesley Seal Dam in 1958 and the subsequent building of the Choke Canyon Reservoir in 1982. Since the construction of these reservoirs and the subsequent droughts during the 1983-1996 period, freshwater inflows were decreased by 55 percent in the Nueces River (Asquith, et al., 1997) and 99.6 percent in freshwater inflows into the Nueces Delta (BOR, 2000), and average salinities in Nueces Bay have significantly increased (Ward and Armstrong, 1997). Morton and Paine (1984) describe the delta as accreting between the years of 1867 to 1982. Today, the sediment load in the Lower Nueces River has been decreased by over 62 percent (Ockerman and Heitmuller, 2010), and erosion of the delta fronting Nueces Bay is causing the loss of some 6 to 10 acres per year (Rasser, 2009).

The Lower Nueces River historically overbanked approximately 3 times per year before reservoir construction and now the river only overbanks once every 3 years (BOR, 2000; Cunningham, 1999). Because flow to the delta was cutoff, flow did not channel through Rincon Bayou, which is the main stem of the delta, and the delta became an evaporating pond with salinities as high as 200. In fact, the Nueces Delta has become a reverse estuary where lower salinity marine water is brought into the delta by high tides.

The lack of flood events has created three major problems in the Nueces Estuary: lack of freshwater mixing in the bay and delta; reduced sediment load to the bay; and reduced nutrient/detritus loading. These conditions led to the Nueces Bay we see today (Fall 2011), which consists of high salinities that inhibit oyster production, a complete loss of *Rangia* except in only a few km of the Nueces River tidal below the saltwater barrier dam, and loss of sediment supply that exacerbates the eroding delta in addition to the wind, wave, sea level rise and erosion. There is a loss of the salinity gradient that influences a zonation of communities found in an ecologically sound estuary.

In conclusion, Nueces Bay has been transformed through the reduction of freshwater inflows from a productive estuary to a more barren bay system that is an unsound ecological environment.

Section 3. Instream Flow Analyses

The guiding principle applied to the Nueces BBEST's instream flow analyses and associated methodologies is the concept of the "Natural Flow Regime,' which is founded on the understanding 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 principal 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 natural flow regime paradigm relates five critical components of flow characteristics that are known to regulate ecological processes in river ecosystems: 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). 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 3.0.1**). Therefore, modification of any of the components of the flow regime can have cascading effects on the ecological integrity of rivers.

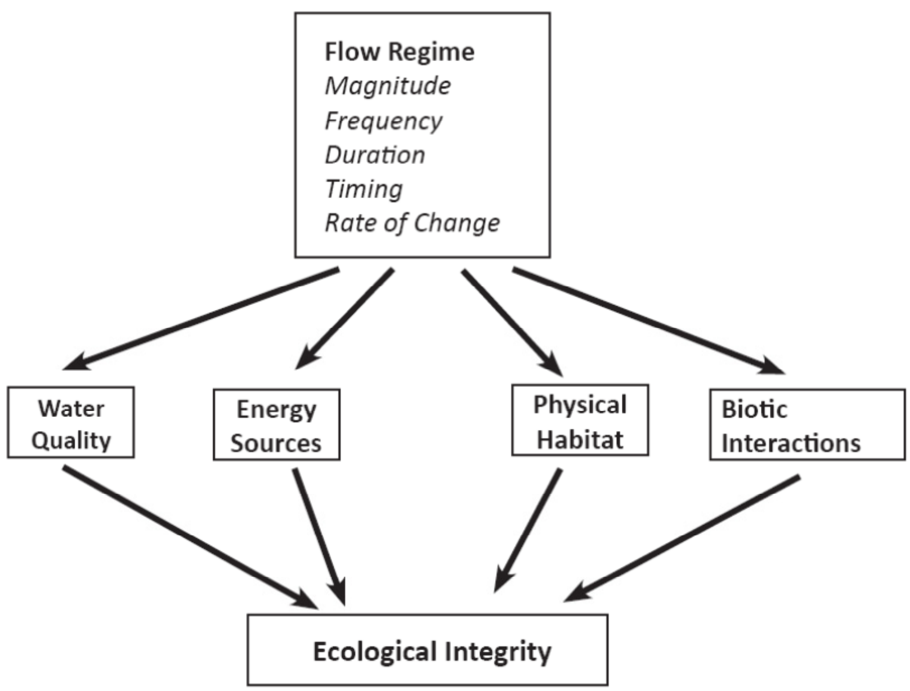


Figure 3.0.1. The five components of the natural flow regime that directly and indirectly affect the ecological integrity of river ecosystems (adapted from Poff, et al., 1997).

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). For example, a recent study by Carlisle, et al. (2011) examined severity of stream flow alteration across the United States and found strong associations between flow alteration and impaired biological communities (i.e. fish and invertebrates).

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 National Research Council (NRC, 2005), and consistent with Maidment, et al. (2005), the SAC (2009) implemented 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, high flow pulses, 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, duration, timing, frequency, and rate of change. HEFR results are then integrated with overlays of biology that include instream 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). **Table 3.0.1** summarizes the ecological functions of various flow components for perennial and intermittent locations in the Nueces River basin, taking into consideration the unique physical characteristics of the basin and its biota (Section 3.3.1 through Section 3.3.3).

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 Niño and La Niña conditions that comprise the El Niño 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 accounted for within the HEFR-based analyses, which can partition the base flow component of the flow regime into low, medium, and high conditions.

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. An example of mesohabitat is a pool or riffle in the river while microhabitat is a relatively small part of a mesohabitat where depth, velocity, and substrate are relatively uniform. 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 (considering both prevalence and persistence) are in turn maintained by variability in the flow regime which 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).

An important consideration for intermittent sites in the Nueces basin is long duration of zero or extremely low flows. Such conditions are natural occurrences for these sites and are important components of the natural flow regime of this system (Table 3.0.1). When dealing with prolonged periods of low or no flow, understanding the ecological consequences of the natural flow regime, as well as specific flow components, is facilitated by consideration of patch dynamics concepts (Pringle, et al., 1988; Townsend, 1989; reviewed in Winemiller, et al., 2010). Patch dynamics concepts can take a landscape perspective (i.e. a focus on formation of spatial patterns and how such patterns affect ecological processes over space or time; Pringle, et al., 1988) or a metacommunity perspective (i.e. emphasis on the importance of periodic disturbances, refugia, and dispersal in maintaining dynamic biological communities within patch mosaics; Townsend, 1989; Lake, 2000). These two perspectives are not mutually exclusive and can be applied together to better understand the dynamics of the same system. For example, the hydrologic processes described in the previous paragraph that give rise to habitat heterogeneity also affect the availability of refugia and dispersal that may determine the persistence of species across the landscape.

Aquatic habitats at intermittent sites in the Nueces River basin are restricted to deeper pools which become isolated refugia during periods of little or no flow, because they retain water when other habitat types, such as riffles and shallow runs, are dry or drying. Hydrologic variability, even minor pulse flows of low magnitude and duration can have potentially major ecological importance in maintaining the quality of refugia habitats (e.g., habitat volume, water temperature, dissolved oxygen) as well as providing short duration periods of connectivity allowing dispersal among refugia. Because intermittent streams experience low or no flow for significant periods of time, the subsistence and base flow categories take on different meaning than applied to perennial streams. In intermittent stream systems such as those identified for this basin, many of the ecological functions typically associated with subsistence and base flows are actually provided by relatively frequent (e.g., multiple times per season) pulse flows of low magnitude and duration. This difference in ecological functions of lower flow levels between perennial and intermittent streams can be seen in Table 3.0.1. Intermittent streams are, therefore, patchy ecosystems dependent on a greater degree of pulse flow variability to maintain their functionality: large scale habitat heterogeneity and diversity are maintained by large pulse flows, whereas persistence of suitable conditions in refugia, as well as temporal connectivity among refugia, are typically dependent upon smaller, but frequent, pulse flows.

Table 3.0.1. Functions of environmental flow components in streams of the Nueces River Basin. Functions listed in italics are distinguished between perennial and intermittent streams, as indicated. Functions in standard font are shared across stream types for the particular flow component.

Flow Component	**Description**	**Biology**	**Geomorphology**	**Water Quality**
Overbank Flows	Floods that go out of the river banks into the floodplain and which typically do not happen every year	Provide migration and spawning cues for some species	Drive lateral movement of river channel forming new habitats (e.g., secondary channels, oxbow lakes)	Facilitate exchange of nutrients, sediments, organics and woody debris
		Recharge floodplain water table	Redistribute coarse substrates (gravel, cobble, boulder) in channel	Provide lateral exchange of organic material and nutrients between river and watershed
		Scour rooted aquatic vegetation from the channel	Shape physical habitats of channel and floodplain	
		Purge invasive species from aquatic and riparian communities		
		Maintain balance and diversity in floodplain forests		
		Provide spawning and nursery areas for fish and other biota		
High Flow Pulses: *High*	Higher in-channel flow pulses that result in substantial increase in depths and velocities and that perform functions associated with higher (i.e., "bankfull") flows	Provide migration and spawning cues for some species	Redistribute some substrates (sand, gravel, cobble)	Flush out silt and fine particulate materials
		Access to in-channel spawning habitats	Prevent riparian vegetation from encroaching into channel	Moderate water quality conditions (i.e. suitable water temperatures, dissolved oxygen levels, etc.) after prolonged subsistence or low flows
		Support growth, survival, and reproduction of aquatic organisms	Shape physical habitat of river channel including pools, runs and riffles	Provide lateral exchange of organic material and nutrients between river and watershed
		Intermittent: Maintain water table levels in floodplain and soil moisture for plants		
		Intermittent: Reconnect isolated habitats allowing dispersal among low-flow refugia (e.g., deep pools)		

Flow Component	Description	Biology	Geomorphology	Water Quality
High Flow Pulses: *Low*	Lower in-channel flow pulses that result in increases in wetted width so that much of the channel is wetted, may result in higher velocities, but do not perform all of the functions of higher flow pulses	Provide spawning cues for some species	Flush out silt and fine particulate materials	Moderate water quality conditions (i.e. suitable water temperatures, dissolved oxygen levels, etc.) after prolonged subsistence or low flows
		Provide access to in-channel spawning habitats		
		Intermittent: Reconnect isolated habitats allowing dispersal among low-flow refugia (e.g., deep pools)		
		Intermittent: Maintain critical aquatic habitats (e.g., riffles) and overall habitat diversity		
		Intermittent: Provide suitable habitat for aquatic organisms		
		Intermittent: Refill pools that serve as low-flow refugia		
		Intermittent: Support survival, growth and reproduction of aquatic organisms		
Base Flows: *Wet*	Normal flow conditions between storm events in a wetter than normal year	Maintain soil moisture for plants		Restore normal water quality conditions after prolonged subsistence or low base flows
		Perennial: Provide suitable habitat for aquatic organisms		
		Perennial: Support growth, survival, and reproduction of aquatic organisms		
		Intermittent: Allow for the persistence of isolated low-flow refugia		
Base Flows: *Average*	Normal flow conditions between storm events in a year with normal rainfall	*Perennial: Support growth, survival, and reproduction of aquatic organisms*		*Perennial: Maintain normal water quality conditions, or restores conditions after prolonged subsistence or low base flows*

Flow Component	**Description**	**Biology**	**Geomorphology**	**Water Quality**
		Perennial: Provide suitable habitat for aquatic organisms		
		Perennial: Maintain diversity of habitats		
		Perennial: Maintain soil moisture for plants		
		Intermittent: Allow for the persistence of isolated low-flow refugia		
Base Flows: *Dry*	Normal flow conditions between storm events in a drier than normal year	*Perennial: Provide connectivity along channel corridor (longitudinal connectivity)*		
		Intermittent: Allow for the persistence of isolated low-flow refugia		
Subsistence Flows	Naturally occurring episodes of low flow during a season that typically do not occur often and do not persist for long periods of time	May shift community structure (e.g., changes in abundance of non-natives, reduction of lotic-adapted and intolerant biota)		*Perennial: Maintain water quality (i.e. suitable water temperatures, dissolved oxygen levels, and other parameters of water chemistry)*
		Perennial: Maintain critical aquatic habitats (e.g., riffles) and longitudinal connectivity		*Intermittent: Decline in water quality (dissolved oxygen, temperature) of refugia due to evaporation and metabolic oxygen demand*
		Intermittent: Aquatic habitats restricted to rapidly drying low-flow refugia		

Environmental flow analyses focusing on instream or fluvial locations at which environmental flow regime recommendations are provided by the Nueces 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 confirm or refine the hydrology-based statistics.

The conclusion of this logical progression is the set of environmental 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 Nueces 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 Nueces 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 Nueces 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

Approximately 60 streamflow gaging stations have been maintained by the USGS in the Nueces River Basin and the Nueces – Rio Grande Coastal Basin at various times during the past 100 years. Many of these stations, however, are no longer in service or have only been placed into service in the last few decades. The 20 streamflow gaging station locations selected by consensus of the Nueces BBEST for performance of environmental flow analyses and issuance of flow regime recommendations are shown in **Figure 3.1.1**. Close enough to the last sentence in the previous paragraph that I think we could delete it here.

3.1.2 Selection of Flow Regime Recommendation Locations

A summary of reference data regarding each of the 20 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 Nueces BBEST in consideration of these factors is discussed in the following subsections.

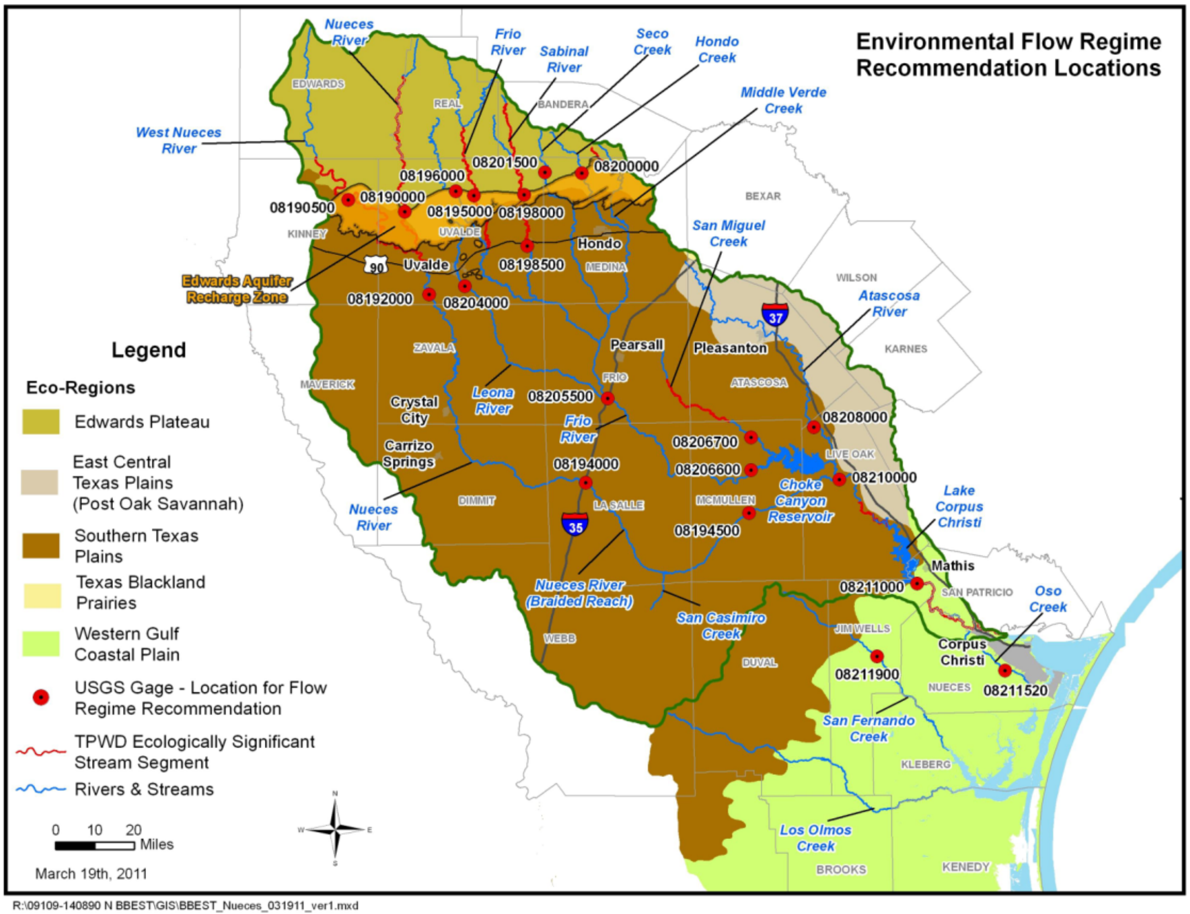


Figure 3.1.1. Environmental Flow Regime Recommendation Locations

3.1.2.1 Hydrology

Key considerations for gage selection with respect to hydrology include period of record, proximity to the Edwards Aquifer recharge zone, 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 20 gages shown in Table 3.1.1 is 65 years. **Table 3.1.2** provides a graphical illustration of the periods of measured streamflow record for each of the 20 gages as well as an indication by green 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, the drainage areas contributing to 18 of the 20 selected gages are essentially uncontrolled or unaffected by impoundment in upstream reservoirs. The Edwards Aquifer recharge zone is the most significant natural feature affecting streamflow hydrology in the Nueces River Basin. Loss rates across the recharge zone have been measured in individual streams at rates ranging from about 50 cfs up to almost 400 cfs (USGS, 1983). Streams at only 9 of the 20 selected gages are classified herein as perennial (i.e. flowing more than 95 percent of the time) while the other 11 gage locations may be reporting zero flow up to half of the time. The Nueces River near Mathis (USGS# 08211000), Oso Creek at Corpus Christi (USGS# 08211520), and San Fernando Creek near Alice are the closest long-term stations to Nueces, Corpus Christi, and Baffin Bays, respectively.

Table 3.1.1. Nueces BBEST Environmental Flow Regime Recommendation Location Reference Data Summary

Pilot Gage	River Basin	USGS Streamflow Gage Name	USGS#	First Full Year of Record	Drainage Area (sq mi)	Controlled Drainage Area (sq mi)	Approximate Percentage Uncontrolled	Perennial (95% Flows > 0 cfs)	90% Exceedance Flow (cfs)[1]	50% Exceedance Flow (cfs)[1]	10% Exceedance Flow (cfs)[1]	WAM Primary Control Point	WAM Unappr. Water Availability (% time)	Potential Reservoir Site	Regional or State Water Plan Reference	TPWD Ecologically Significant Segment	TCEQ Stream Segment	TCEQ 2010 DRAFT 303(d) List[2]	TCEQ Aquatic Life Uses
✓	Nueces	Nueces River, Laguna	08190000	1924	737	0	100%	Yes	23	74	233	Yes	0 - 25	Yes	No	Yes	2112		High
	Nueces	West Nueces River, Brackettville	08190500	1940	694	0	100%	No	0	0	7.7	Yes	0 - 25	No	No	Yes			
✓	Nueces	Nueces River, Uvalde	08192000	1940	1861	0	100%	No	3	25	186	Yes	0 - 25	Yes	Yes	No	2112		High
✓	Nueces	Nueces River, Cotulla	08194000	1927	5171	0	100%	No	0	0	353	Yes	0 - 25	Yes	Yes	No	2105		High
	Nueces	Nueces River, Tilden	08194500	1943	8093	0	100%	No	0	5	720	Yes	0 - 25	No	No	No	2104	IMC, IFC	High
	Nueces	Frio River, Concan	08195000	1924	389	0	100%	Yes	18	67	195	Yes	0 - 25	Yes	No	Yes	2113	IMC, IFC	Exceptional
	Nueces	Dry Frio River, Reagan Wells	08196000	1953	126	0	100%	Yes	2.2	14	64	Yes	0 - 25	No	No	No			
✓	Nueces	Sabinal River, Sabinal	08198000	1943	206	0	100%	No	0	25	120	Yes	0 - 25	Yes	No	Yes	2111		High
	Nueces	Sabinal River, Sabinal (below Edwards outcrop)	08198500	1953	241	0	100%	No	0.1	1.5	45	Yes	0 - 25	Yes	No	Yes	2110		High
	Nueces	Hondo Creek, Tarpley	08200000	1953	95.6	0	100%	No	0.1	12	81	Yes	0 - 25	No	No	No	2114		High
	Nueces	Seco Creek, Utopia	08201500	1962	45.0	0	100%	Yes	0.8	5.3	40	Yes	0 - 25	No	No	No	2115		High
	Nueces	Leona Springs/River, Uvalde[3]	08204000	1939	Spring+			No				Yes	0 - 25	No	Yes	No	2109	B	High
✓	Nueces	Frio River, Derby	08205500	1916	3,429	0	100%	No	0	5.4	150	Yes	0 - 25	No	Yes	No	2117	B	High
	Nueces	Frio River, Tilden[4]	08206600	1933	4,493	0	100%	No	0	19	384	No	0 - 25	No	No	No	2116	DO	High
✓	Nueces	San Miguel Creek, Tilden	08206700	1965	783	0	100%	No	0	2.1	38	No	0 - 25	No	No	Yes	2108	B	High
	Nueces	Atascosa River, Whitsett	08208000	1933	1,171	0	100%	Yes	1.0	11	95	Yes	0 - 25	Yes	No	No	2107	B, DO, IMC	High
	Nueces	Nueces River, Three Rivers	08210000	1916	15,427	5490	64%	Yes	11	132	947	Yes	0 - 25	No	Yes	No	2106	TDS	High
✓	Nueces	Nueces River, Mathis	08211000	1940	16,503	16503	0%	Yes	52	129	1290	Yes	0 - 25	Existing	Yes	Yes	2102		High
	Nueces - Rio Grande	Oso Creek, Corpus Christi	08211520	1973	90.3	0	100%	Yes	1.2	2.4	21	No	0 - 25	No	No	No			
	Nueces - Rio Grande	San Fernando Creek, Alice	08211900	1965	507	0	100%	Yes	0.90	1.9	7.5	No	0 - 25	No	No	No			

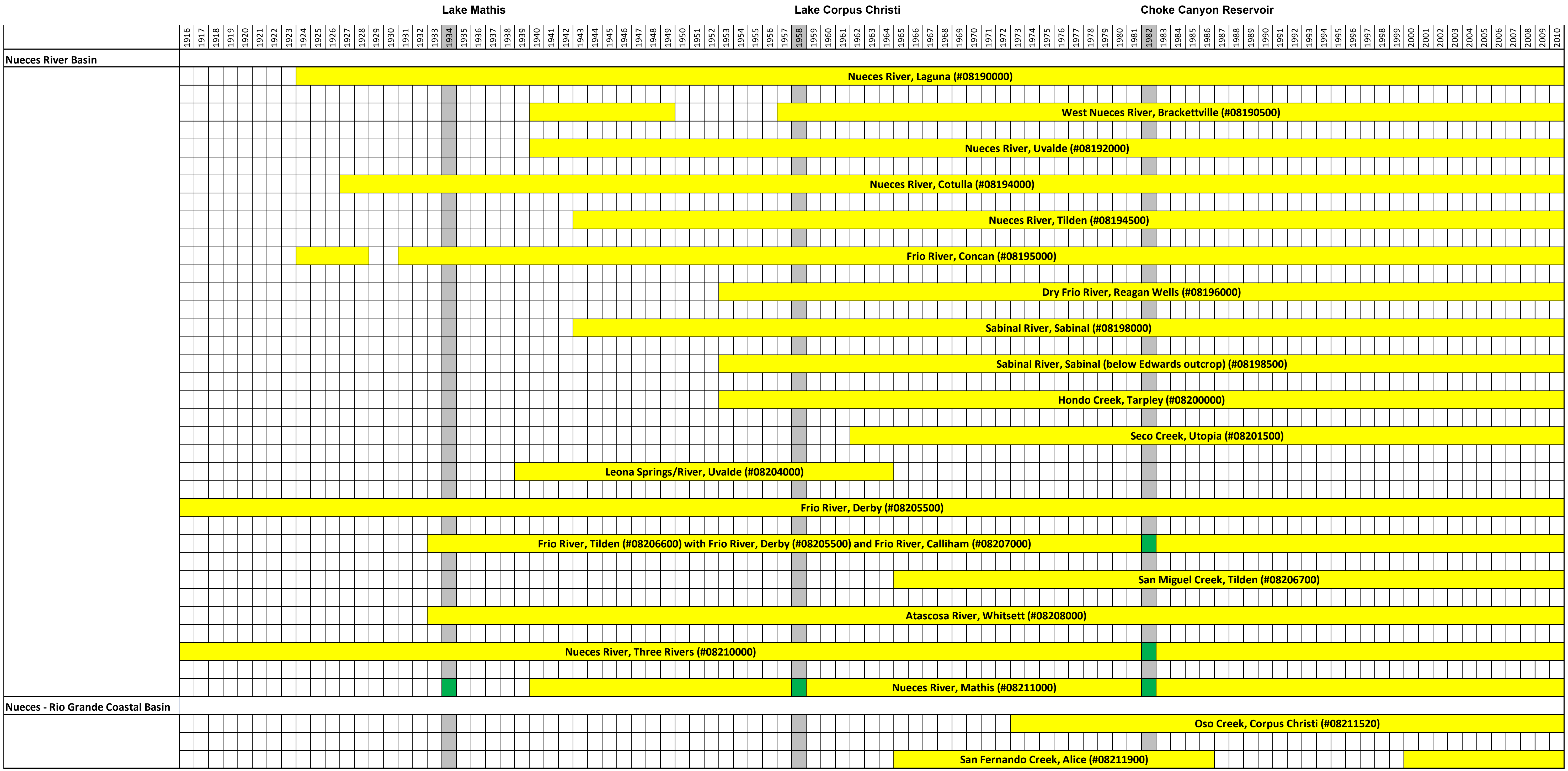
[1] Statistics for period of record through 1996 from USGS Water Resources Data for Texas, Water Year 1996. Exceptions include Frio (Tilden) & San Fernando (Alice).

[2] Key to Abbreviations: IMC = Impaired macrobenthic community; IFC = Impaired fish community; B = Bacteria; DO = Dissolved Oxygen; TDS = Total Dissolved Solids

[3] Records are highly correlated with and have been extended using Edwards Aquifer levels reported for the Uvalde County Monitoring Well (J-27).

[4] USGS streamflow records for this location have been supplemented by records interpolated by drainage area ratio from those for the Frio River near Derby (USGS# 08205500) and at Calliham (USGS# 08207000) available from 1933 through 1978.

Table 3.1.2. Periods of Record for USGS Streamflow Gaging Stations at Nueces BBEST Environmental Flow Regime Recommendation Locations



Daily streamflow records were extended for the Frio River at Tilden (USGS# 08206600) by drainage area interpolation using concurrent streamflow records for the Frio River near Derby (USGS# 08205500) and at Calliham (USGS# 08207000) for the 1933 through 1978 historical period. More specifically, estimated streamflows for the Frio River at Tilden were calculated using the following equation:

$$QT = QD + (QC - QD) * (1064/2062)$$

Where:

QT = Estimated Flow (cfs), Frio River at Tilden

QD = Measured Flow (cfs), Frio River near Derby

QC = Measured Flow (cfs), Frio River at Calliham

and QT must be greater than or equal to zero.

Daily springflow records for Leona Springs (USGS# 08204000) were calculated using a polynomial regression derived by correlation of water levels in the Edwards Aquifer Uvalde County Monitoring Well (J-27) and periodic springflow measurements by the USGS. This polynomial regression equation is:

$$QL = 0.0030554182 * WU3 - 7.8841804168 * WU2 + 6{,}782.50666 * WU - 1{,}945{,}236.4$$

Where:

QL = Estimated Springflow (cfs), Leona Springs at Uvalde

WU = Water Surface Elevation (ft-msl), J-27

and QL must be greater than or equal to zero. The coefficient of determination (r^2) for this equation is 0.93 indicating that 93 percent of the variation in Leona springflow can be explained by the equation based on Edwards Aquifer water levels at J-27.

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 shown in Figure 3.1.1, flow regime recommendation locations have been selected in each of the three major eco-regions occurring in the Nueces River Basin and Nueces – Rio Grande Coastal Basin. From the headwaters to the coast, seven locations are in the Edwards Plateau eco-region, ten are in the South Texas Plains, and three 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 J (Plateau), L (South Central Texas), and N (Coastal Bend). 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 exception of only one stream identified as ecologically significant by the TPWD, West Verde Creek in Bandera and Medina Counties, flow regime recommendation locations have been selected within or very near each stream segment identified as ecologically significant. The reason that the Nueces BBEST chose not to select a flow regime recommendation location on Middle Verde Creek is the lack of long-term daily streamflow records.

The Texas Instream Flow Program (TIFP), developed pursuant to Senate Bill 2 (SB2) of the 77th Texas Legislature, has not included any portions of the Nueces River Basin or Nueces – Rio Grande Coastal Basin among the six river sub-basins identified for priority instream flow studies.

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 one, located in the Edwards Plateau eco-region, exhibits exceptional aquatic life uses. Table 3.1.1 also shows that eight 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 Nueces BBEST recognizes that there may, at some point in time, be 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

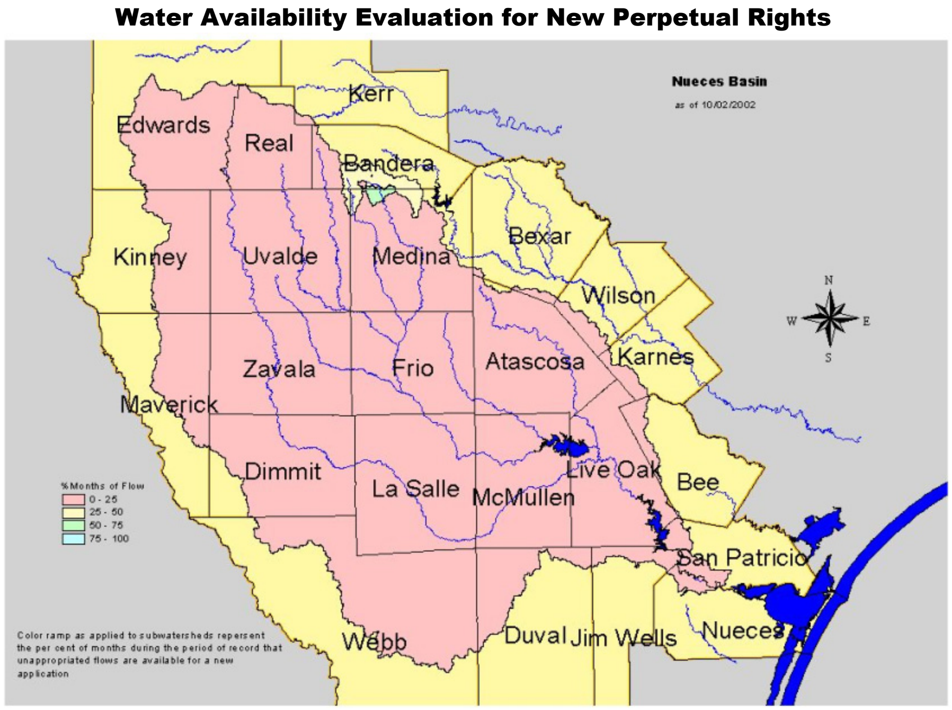
The primary consideration for gage selection with respect to geomorphology or sediment transport processes is to ensure that headwater, transfer, and deposition zones are represented. Referring to Figure 3.1.1, these zones might be assumed to roughly coincide with the Edwards Plateau, the South Texas Plains, and the Western Gulf Coastal Plain, respectively, in the Nueces River Basin. As is apparent in Figure 3.1.1, the Nueces 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

Nueces 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 Nueces 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 **Figure 3.1.2** and **Figure 3.1.3** and shown for selected gage locations in Table 3.1.1. As is readily apparent in these figures and Table 3.1.1, water availability for new perpetual water rights is quite limited due to existing water rights associated with the Choke Canyon Reservoir / Lake Corpus Christi System and Calallen Dam. Table 3.1.1 indicates that the Nueces BBEST has selected seven 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 intended for long-term storage are recommended in the Nueces River Basin or the Nueces – Rio Grande Coastal Basin in the approved 2011 regional water plans. Recharge enhancement dams on the Frio and Sabinal Rivers and Hondo and Verde Creeks on the outcrop of the Edwards Aquifer are recommended in the approved 2011 South Central Texas Regional Water Plan.

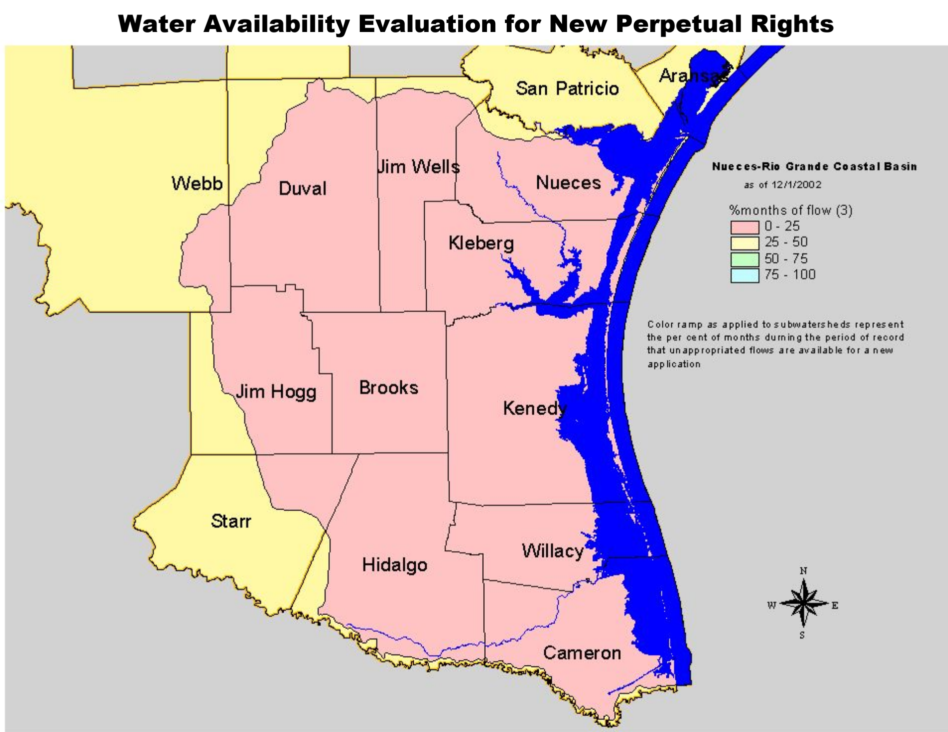
3.1.2.6 Geographic Interpolation

The Nueces BBEST has provided flow regime recommendations at streamflow gaging stations located throughout the Nueces River Basin and in the northern portion of the Nueces – Rio Grande Coastal Basin. These reference locations are, among other things, representative of major streams above and below the outcrop of the Edwards Aquifer and/or existing reservoirs as well as some tributary streams. The Nueces 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 and accounting for the Edwards Aquifer recharge zone, but may also include consideration of springflow contributions, channel losses, other aquifer recharge zones, soil cover complex, and additional factors as necessary and appropriate.



http://www.tceq.texas.gov/assets/public/permitting/watersupply/water_rights/maps/nueces/run3.jpg

Figure 3.1.2. Water Availability in the Nueces River Basin.



http://www.tceq.texas.gov/assets/public/permitting/watersupply/water_rights/maps/nu_rio/run3.jpg

Figure 3.1.3. Water Availability in the Nueces – Rio Grande Coastal Basin.

3.2 Hydrology-Based Environmental Flow Regimes

Once locations for development of environmental flow regime recommendations were selected by the Nueces 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 Nueces BBEST has used hydrologic data in general accordance with SAC guidance issued March 15, 2011 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." Recognizing 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 Nueces BBEST made an early decision 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 verification and 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 Nueces BBEST, and the technical bases for these decisions.

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 Nueces 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 Nueces BBEST decided by consensus during its December 10, 2010 meeting to use the IHA methodology.

IHA uses several parameters which can be set by the user including the rise rate which identifies the beginning of a high flow pulse (HFP) event and overbank, lower pulse, and upper base threshold streamflows which support classification of each daily flow. Values for these parameters used by the Nueces BBEST are summarized for each reference streamflow gaging station in **Table 3.2.1**.

The BBEST reached a consensus decision (December 10, 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 for perennial streams. Similarly, the BBEST reached a consensus decision (December 10, 2010) that flows above the 75th percentile of all flows do not primarily provide the ecological functions associated with base flows, thus the upper base threshold was set to the 75th percentile for perennial streams. These percentiles were calculated using the full period of record and the corresponding flow magnitudes were set as the thresholds in the early period of record and late period of record simulations. These thresholds were chosen with BBEST's understanding that there may be situations (expected to be relatively rare) when flows below the 25th percentile of all flows actually provide ecological services of HFPs, and situations when flows above the 75th percentile of all flows provide ecological services of base flows.

Overbank streamflow thresholds to distinguish (in-bank) HFPs from overbank events in the IHA hydrographic separation step were determined primarily from the National Weather Service (NWS) River Forecast Center website (http://www.srh.noaa.gov/wgrfc/). This website includes descriptions of action stages and various flood stages for many USGS streamflow gaging stations. Available information regarding these stages and the selection of the bankfull stage or overbank threshold is summarized in Appendix 3.2.1. Streamflows corresponding to these stages were extracted from readily available USGS stage and streamflow records.

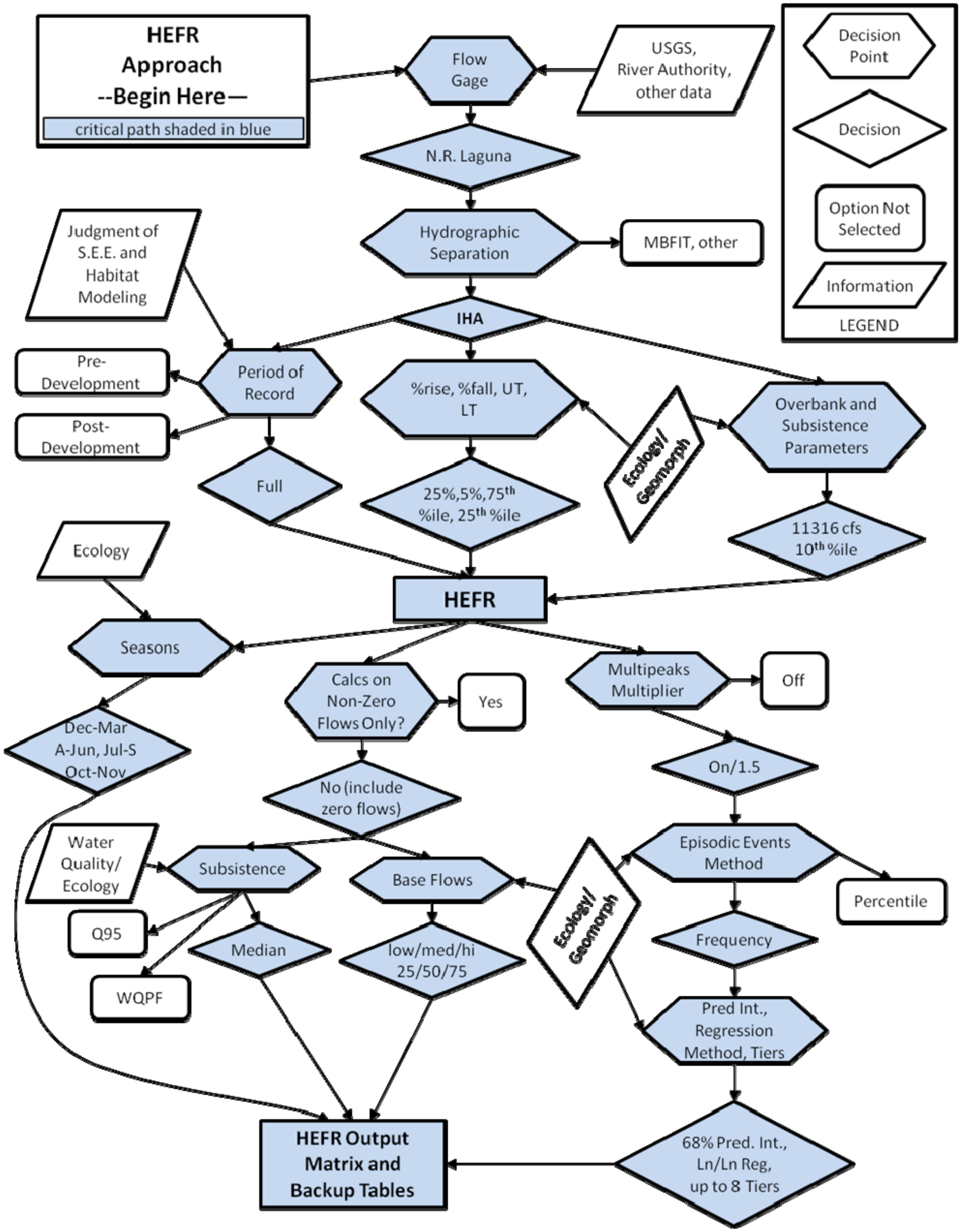


Figure 3.2.1. Hydrology-Based Environmental Flow Regime (HEFR) Approach.

Table 3.2.1. IHA Parameter Selections

USGS Streamflow Gaging Station	Rise Rate Threshold (%)	Overbank Threshold Stage (ft)	Overbank Threshold Flow (cfs)	Lower Pulse Threshold Flow Percentile	Lower Pulse Threshold Flow (cfs)	Upper Base Threshold Flow Percentile	Upper Base Threshold Flow (cfs)
Nueces River at Laguna	25	10	11,316	25	45	75	139
West Nueces River near Brackettville	25	13	13,000	81	3	90	9.7
Nueces River below Uvalde	25	10	7,000	25	12	75	84
Nueces River at Cotulla	25	9	253	25	0.0001	75	82
Nueces River near Tilden	25	11	900	25	0.1	75	125
Nueces River near Three Rivers	25	22	4,600	25	13	75	391
Nueces River near Mathis	25	16	3,021	25	75	75	238
Leona Springs	25	n/a	n/a	n/a	n/a	n/a	n/a
Frio River at Concan	25	11	12,958	25	42	75	120
Dry Frio River near Reagan Wells	25	8.24	4,650*	25	6.6	75	31
Frio River near Derby	25	6	2,655	25	0.0001	75	48
Frio River at Tilden	25	12	1,007	25	1.9	75	81.59
Sabinal River near Sabinal	25	8.68	6,840	25	8.4	75	60
Sabinal River at Sabinal	25	10	1,858	65	3	90	40
Seco Creek at Miller Ranch near Utopia	25	5.31	3,420**	25	1.8	75	16
Hondo Creek near Tarpley	25	8.84	5,710	25	2.9	75	36
San Miguel Creek near Tilden	25	12	1,288	25	0.0001	75	8.4
Atascosa River at Whitsett	25	20	3,000	25	4.1	75	25
Oso Creek at Corpus Christi	25	11	154	25	1.5	75	4.1
San Fernando Creek at Alice	25	4	236	25	1.4	75	2.8

* The median value of all historical annual instantaneous flood peaks was erroneously used to set the overbank threshold in IHA (4650 cfs). A better estimation of overbank would have been to use the median of historical annual instantaneous flood peaks from 1953 to the present (3705 cfs). Ultimately, all episodic events calculated by HEFR using daily average flood peaks were of lower magnitude than 3,705 cfs, so even if 3,705 cfs had been used, there would be no changes to the initial hydrology-based flow regimes.

** The median value of all historical annual instantaneous flood peaks was erroneously used to set the overbank threshold in IHA (3,420 cfs). A better estimation of overbank would have been to use the median of historical annual instantaneous flood peaks from 1962 to the present (3,380 cfs). Ultimately, all episodic events calculated by HEFR using daily average flood peaks were of lower magnitude than 3,380 cfs, so even if 3,380 cfs had been used, there would be no changes to the initial hydrology-based flow regimes.

Flood stage data are not available on the referenced NWS website for the following five locations: Dry Frio River near Reagan Wells, Sabinal River near Sabinal (upstream of the Edwards Aquifer outcrop), Hondo Creek near Tarpley, Seco Creek near Utopia, and Leona Springs. With the exception of Leona Springs, selection of overbank threshold and associated flow for these sites is based on the median (or 2-year return period) flood peak from USGS records. 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 not critical for the construction of the HEFR matrix. The distinction may be of greater importance to the Nueces BBASC, which is charged with considering human impacts and water demands.

At two locations, it was deemed appropriate to extend limited measured streamflow or springflow data available from the USGS. Estimation techniques used for extension of daily streamflow and spring discharge records for the Frio River at Tilden and Leona Springs discharge at Uvalde are described in Section 3.1.2.1.

HEFR requires continuous periods of record and two gages selected for analyses by the Nueces BBEST, the West Nueces River near Brackettville and San Fernando Creek near Alice, have gaps of about seven and 13 years, respectively. In order to use all available data and provide a continuous period of record for HEFR, data from the early period at the Brackettville site were shifted, so that the measured data on March 31, 1950 was assigned to March 31, 1956, with a similar shift for earlier data, so as to join the early data with the measured data starting on April 1, 1956. In this way, a "continuous" period of record was generated, without seasonally shifting any of the data. A similar shift was performed for the San Fernando Creek near Alice, with the difference that at the Alice site, the latter data were shifted to join the early data (because the data record after the gap was much shorter than before the gap). 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 long periods of record is of little consequence.

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 Nueces BBEST have generally acknowledged that riverine ecosystems in the Nueces River Basin and the Nueces – Rio Grande Coastal Basin have exhibited characteristics of sound ecological environments throughout the past century as many ecosystems have transitioned from a natural condition to the somewhat modified conditions typical of the present. This general acknowledgement was confirmed by consensus of the Nueces BBEST on December 10, 2010.

In order to explore streamflow characteristics and potential trends, the Nueces BBEST selected seven representative gage locations or pilot gages for consideration: Nueces River at Laguna, Nueces River below Uvalde, Nueces River at Cotulla, Sabinal River near Sabinal, Frio River near Derby, San Miguel Creek near Tilden, and Nueces near Mathis. **Figure 3.2.2** illustrates a time series of annual flow volumes for the entire period of record for the Nueces River at Laguna USGS gage (blue line with diamonds). The red line (with squares) illustrates a 10 year lagged moving average of the same data. Flow statistics are presented for the periods from January 1924 through December 1969 and from January 1970 through December 2009 for Laguna and other representative gage locations unaffected by Choke Canyon Reservoir. In addition, flow statistics for the entire period of record are shown.

The results for the Nueces River at Laguna suggest that flows have increased with time, as the flow statistics for the latter period of record are significantly greater than 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, 2000a). **Figure 3.2.3** provides flow frequency curves derived from daily streamflow data for the Nueces River at Laguna 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.

Figure 3.2.4 through Figure 3.2.7 provide similar depictions for two additional pilot gages selected by the Nueces BBEST including the Nueces River at Cotulla and Frio River near Derby. Records for the Cotulla (**Figure 3.2.4** and **Figure 3.2.5**) and Derby (**Figure 3.2.6** and **Figure 3.2.7**) gages show apparent increases in flow in the latter portion of the period of record throughout the range of flows observed. These increases are consistent with analyses that document increased precipitation and runoff per unit rainfall in the upstream Edwards Plateau watersheds over comparable time periods (HDR, 2000a). It is noted, however, that precipitation has not changed significantly and runoff per unit rainfall has decreased significantly in the Nueces River subwatershed below Uvalde and above Cotulla (HDR, 2000b).

Figure 3.2.8 and **Figure 3.2.9** provide similar depictions for the Nueces River near Mathis, for which the period of record was sub-divided at 1982 due to the initiation of deliberate impoundment in Choke Canyon Reservoir. Records in the latter portion of the period of record for the Mathis gage show apparent increases up to about the 70th percentile flow due to water supply deliveries from the Choke Canyon Reservoir/Lake Corpus Christi (CCR/LCC) System and apparent decreases above the 70th percentile flow due to impoundment of high flow pulses in the CCR/LCC System.

Upon consideration of these significant changes in streamflow, the Nueces 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 exceptions of those for which the period of record prior to 1970 is insufficient in length to reasonably support hydrographic separation and HEFR application for an early period. Early and late sub-periods were separated between 1969 and 1970 for the sites having sufficient period of record in the Nueces River Basin and Nueces – Rio Grande Coastal Basin unaffected by Choke Canyon Reservoir and between 1981 and 1982 for the two sites affected by Choke Canyon Reservoir (i.e. Nueces River near Three River and Mathis). Results of HEFR applications for all three periods are included as Appendix 3.2.2. On July 29, 2011, the Nueces BBEST chose by consensus to use HEFR results based on the full period of record to form the basis of its instream flow regime recommendations subject to the ongoing ecological overlay process.

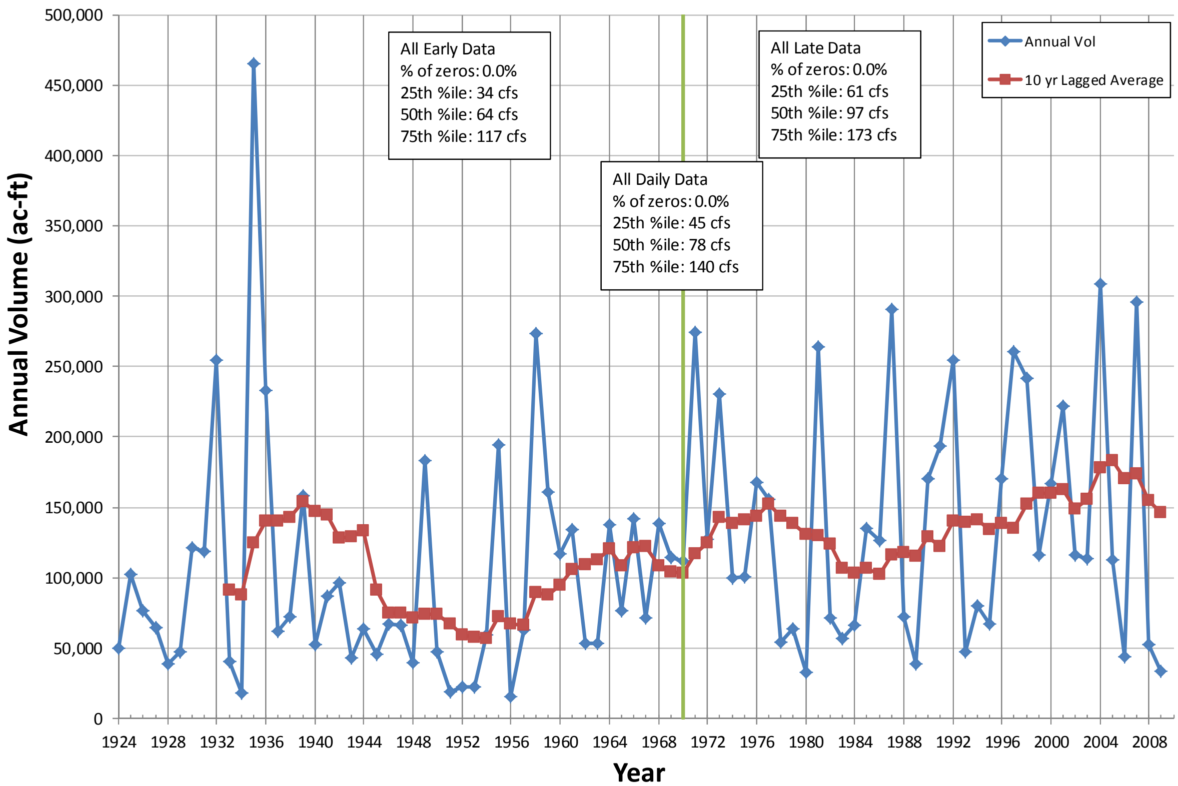


Figure 3.2.2. Historical Streamflow, Nueces River at Laguna.

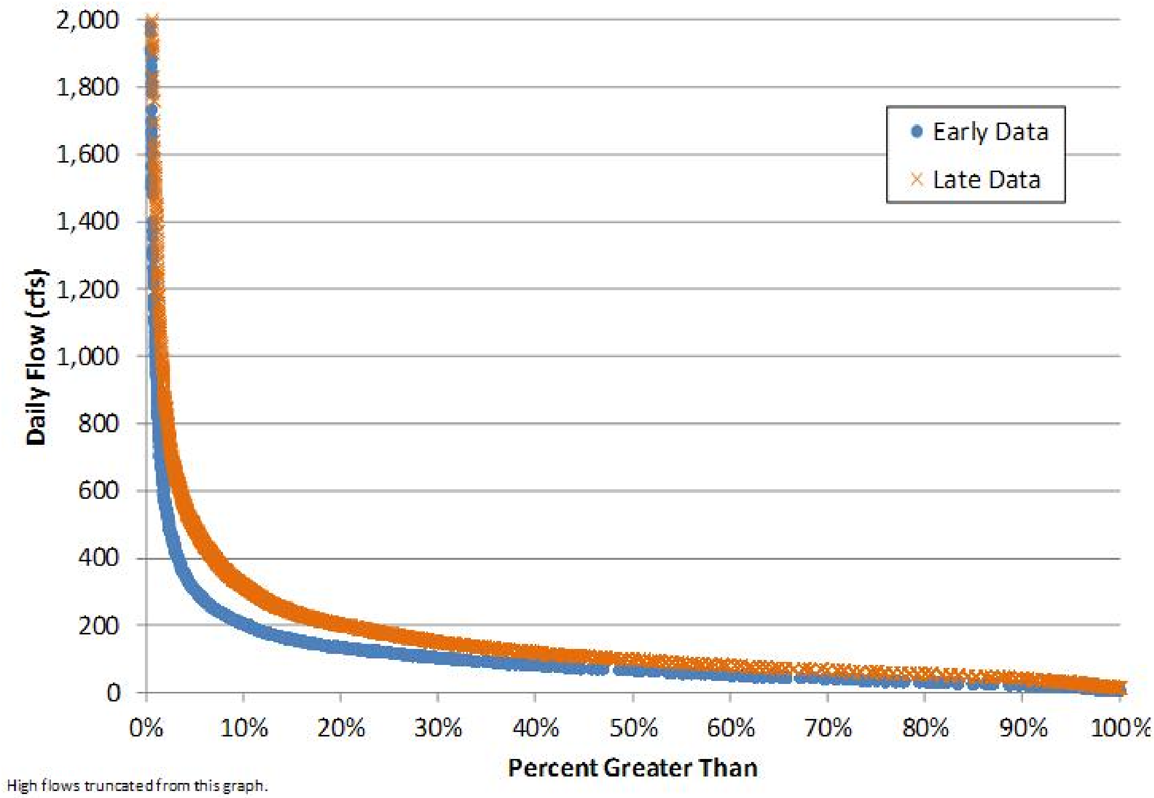


Figure 3.2.3. Historical Streamflow Frequency, Nueces River at Laguna.

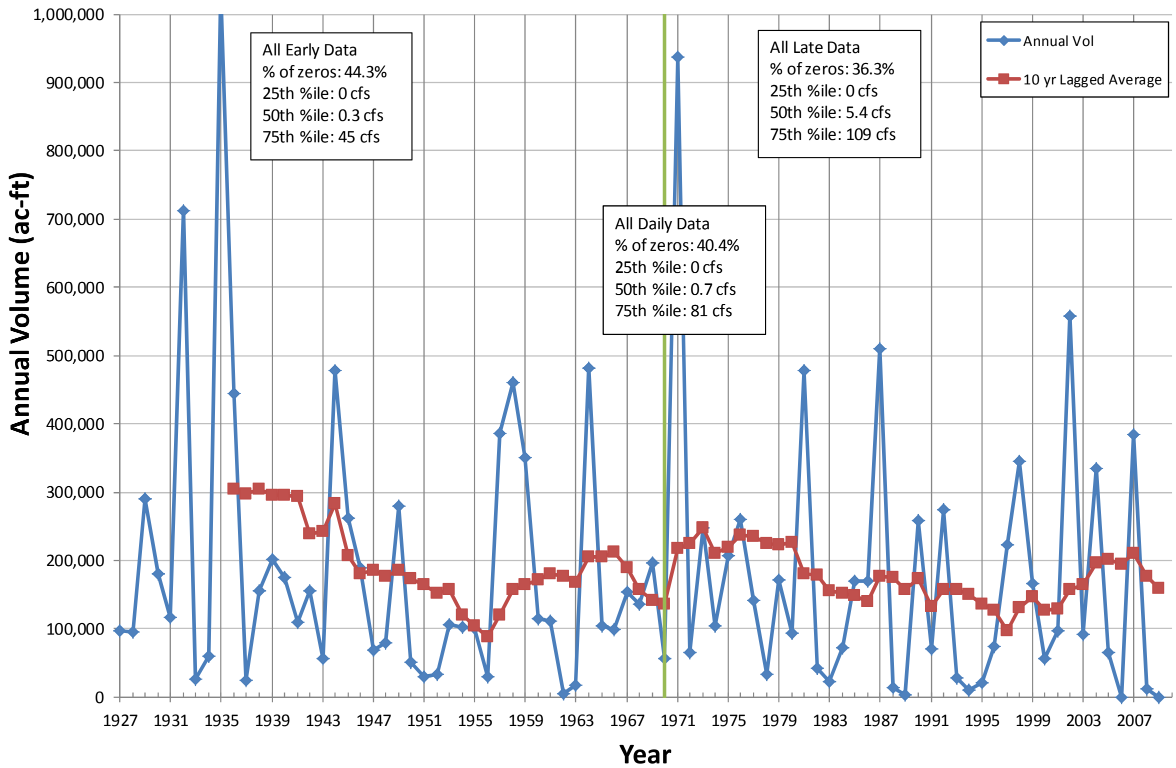


Figure 3.2.4. Historical Streamflow, Nueces River at Cotulla.

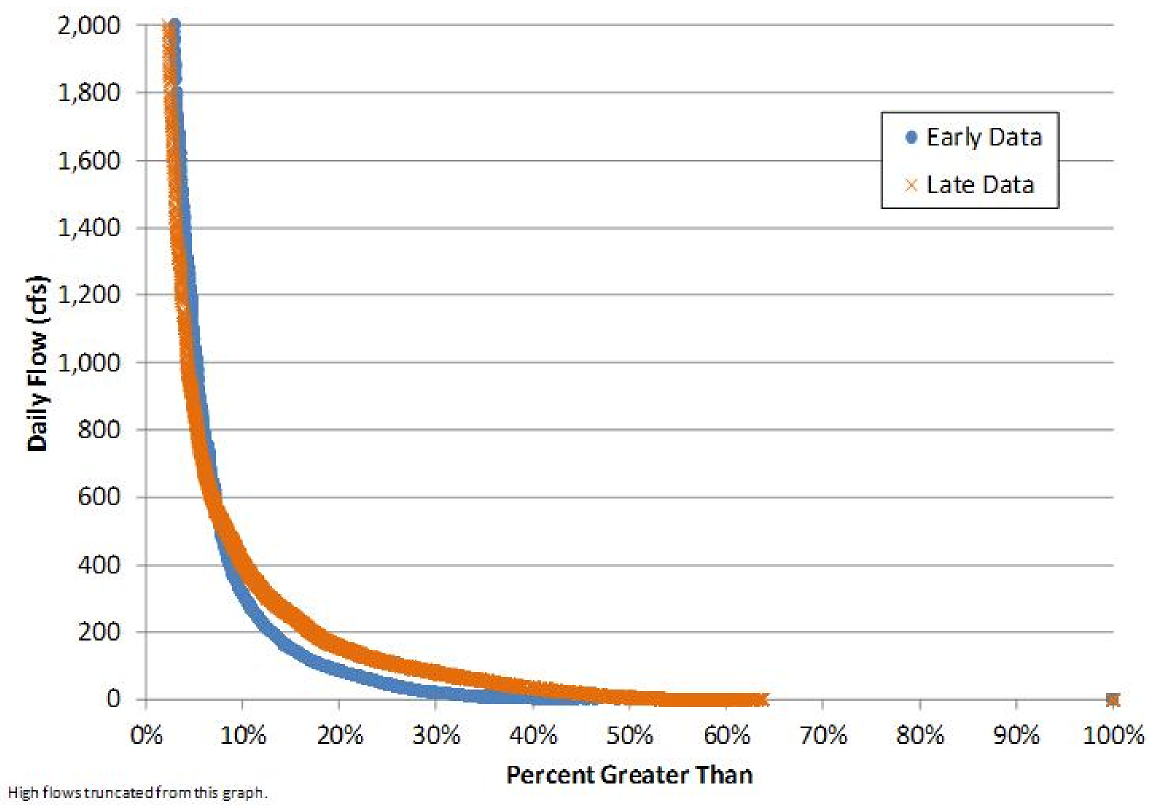


Figure 3.2.5. Historical Streamflow Frequency, Nueces River at Cotulla.

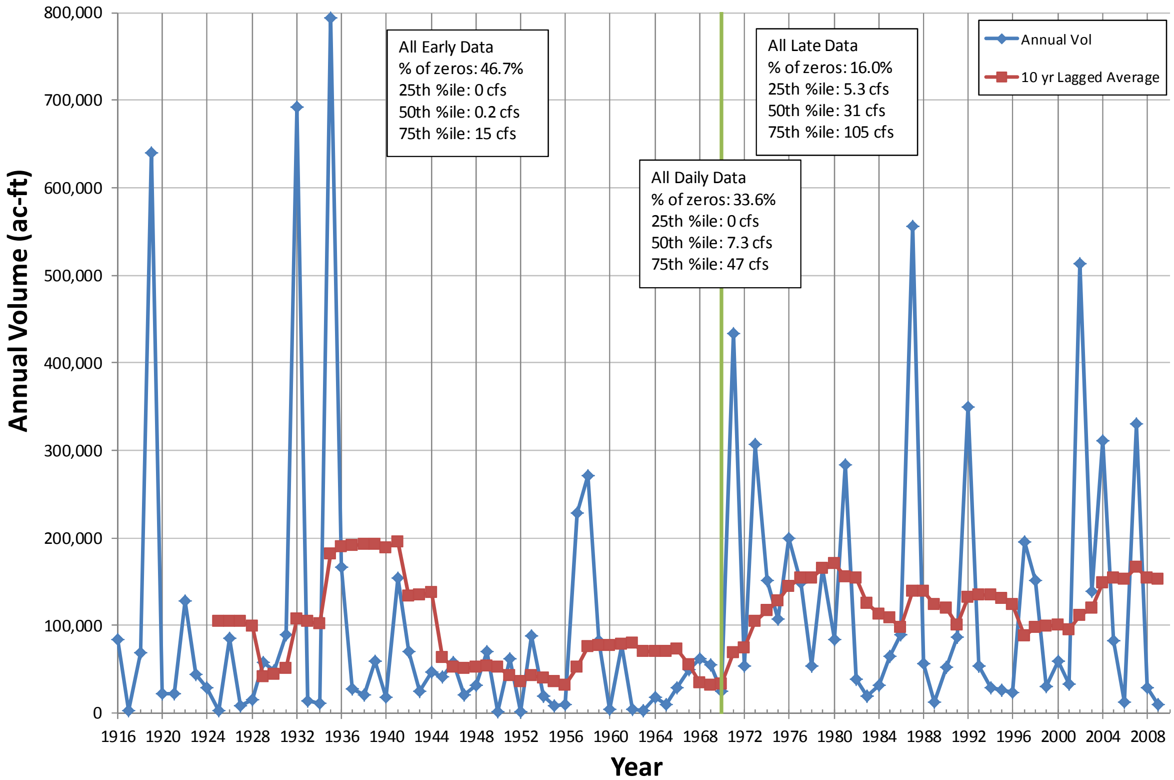


Figure 3.2.6. Historical Streamflow, Frio River near Derby.

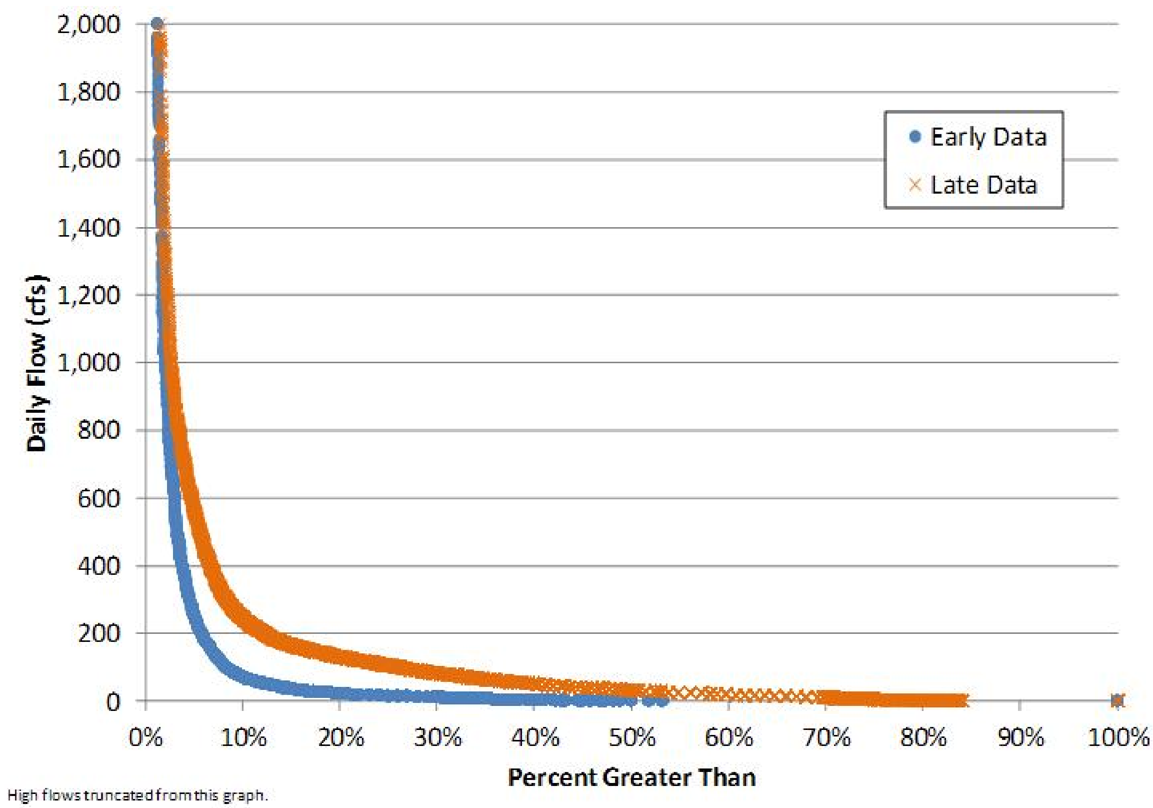


Figure 3.2.7. Historical Streamflow Frequency, Frio River near Derby.

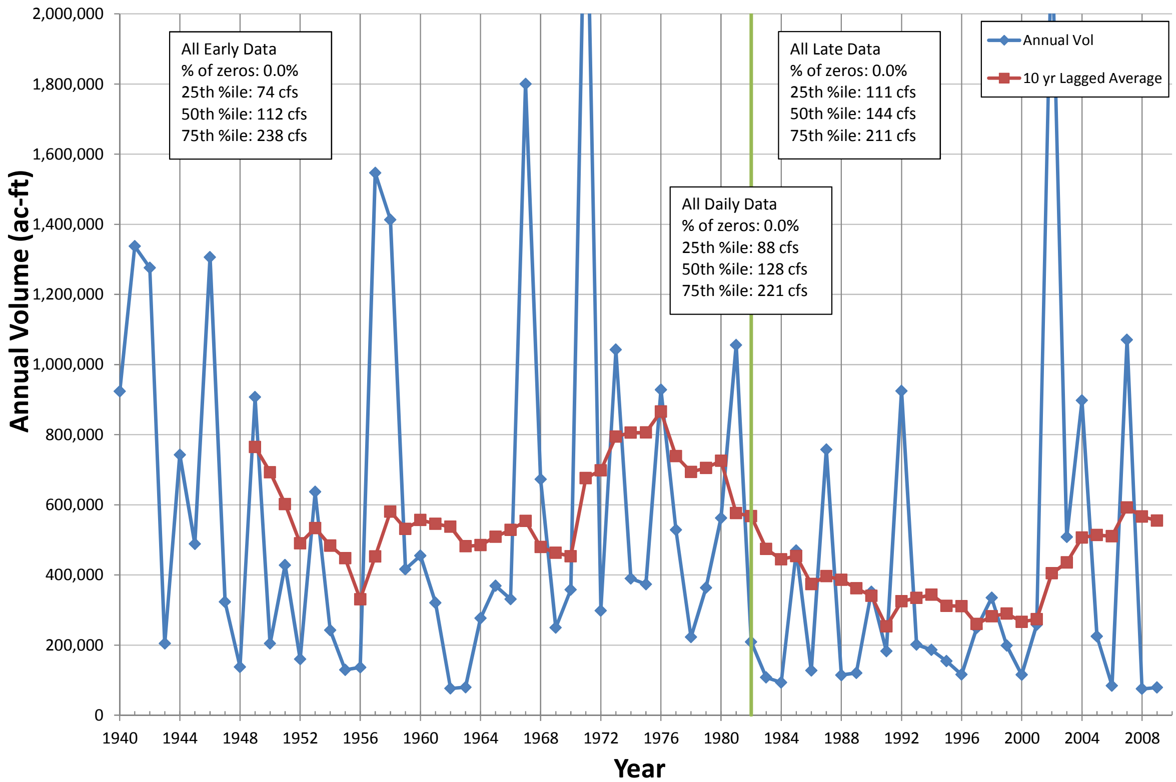


Figure 3.2.8. Historical Streamflow, Nueces River near Mathis.

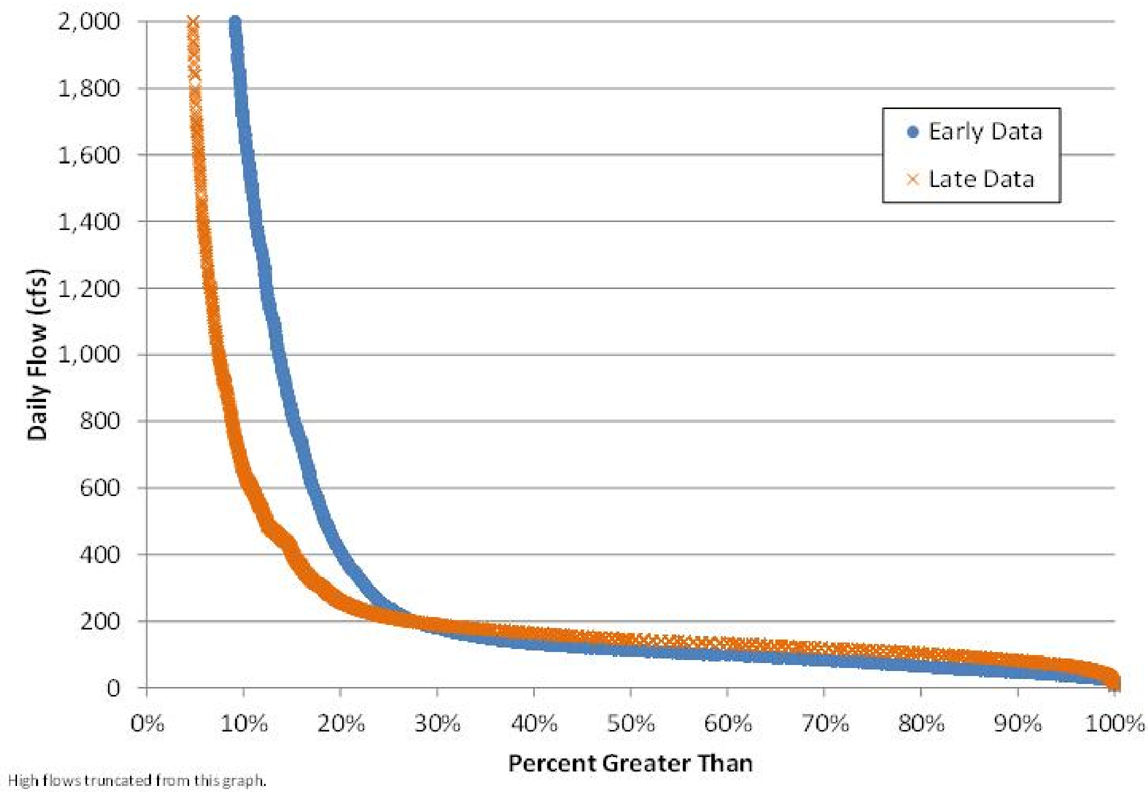


Figure 3.2.9. Historical Streamflow Frequency, Nueces River near Mathis.

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 Nueces BBEST, the Hydrology Subcommittee reviewed natural monthly median flow variations at 10 locations in the Nueces River Basin. This review highlighted some significant differences in the hydrologies of the Edwards Plateau and the South Texas Plains eco-regions (Figure 3.1.1) necessitating the selection of two different seasonal selections by the Nueces BBEST. 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. An earlier Fall season was selected in the South Texas Plain eco-region in recognition of the strong influences tropical storms and hurricanes. For the Edwards Plateau eco-region, the Nueces BBEST selected four seasons as follows: a) Winter (December through March); b) Spring (April through June); c) Summer (July through September); and d) Fall (October through November). For the South Texas Plains and Western Gulf Coastal Plain eco-regions, the Nueces BBEST selected four seasons as follows: a) Winter (November through March); b) Spring (April through June); c) Summer (July through August); and d) Fall (September through October).

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, et al., 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 Nueces BBEST in the following sub-sections.

3.2.4.1 Subsistence Flows

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 Nueces BBEST chose to use the HEFR default calculation of seasonal subsistence flow as the median of the lowest 10 percent 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 Base Flows

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.” The Nueces 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 Nueces 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 4/season, 3/season, 2/season, 1/season, 2/year, 1/year, 1/2-years, and 1/5-years have been calculated and are summarized in the tables in Appendix 3.2.2. The Nueces 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. At the request of the Nueces BBEST, Dan Opdyke, PhD of TPWD briefly examined each of many 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 about a dozen unacceptable regressions were identified (out of more than 800 considered) and these were for seasonal events at three sites. Dr. Opdyke recommended appropriate adjustments to the original HFP volumes and durations which were subsequently considered and approved by the Hydrology and Instream Subcommittee Chairs and reflected in the flow regime recommendations summarized in Section 6.1.

As parameterized by the Nueces BBEST, the IHA hydrographic separation method does not distinguish multiple episodic events when flows are consistently above the 75th percentile of all flows, or when flows in the receding limb of one storm event decrease sharply and are immediately followed by a sharp increase caused by a subsequent storm event. 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, except for the West Nueces River near Brackettville and the Sabinal River at Sabinal (below Edwards outcrop) sites, where a value of 1.25 was used. 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 percent 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.

At some streamflow gage locations, an insufficient number of HFP events occurred historically within a season for HEFR to automatically assign HFP magnitude, frequency, and duration resulting in a blank cell within the standard HEFR matrix. In this situation, the Nueces BBEST requested that Dr. Opdyke determine whether or not 90 percent of the number of events necessary for HEFR to make the assignment had occurred historically. If not, the matrix cell would remain blank and a HFP recommendation would not be included for the associated season at that location. If so, the matrix cell would be manually filled with the HFP magnitude, duration, and frequency associated with the smallest qualifying event. The Nueces BBEST decided by consensus on October 7, 2011 to include these manually filled HFPs in its flow regime recommendations for the Nueces River at Laguna, the Frio River at Concan, the Dry Frio River near Reagan Wells, and the Sabinal River at Sabinal.

3.2.5 Initial Hydrology-Based Flow Regimes

The Nueces BBEST considered initial hydrology-based flow regimes based on the full period of record along with those for the early and late sub-periods of record throughout the ecological overlay process. These flow regimes are included in Appendix 3.2.2. Comprehensive HEFR and hydrographic separation analyses are included in Appendix 3.2.2.

3.3 Biology Overlay

The Nueces BBEST evaluated relationships between flow, instream biology, water quality, sediment movement, and riparian zone biology in the Nueces River Basin to identify flow regimes needed for sound stream environments. Summaries of those evaluations are presented here.

Biological information (Section 3.3) from the Nueces River Basin supports the environmental flow regimes described in this report:

- 80 fish species are recorded for the Nueces River Basin, comprising a wide range of ecological life-histories (e.g., spawning seasons and behaviors, habitat preferences and requirements) and environmental flow relationships, reflecting a need for habitat diversity provided by variation in flows.
- Flow-habitat modeling for the Frio River at Concan, and Nueces River at Laguna and Three Rivers indicates the hydrology-based flow recommendations maintain suitable aquatic habitats for focal species and maintain habitat diversity at these sites.
- Flow-habitat modeling shows how small reductions in base flow recommendations result in rapid and significant reductions in availability of suitable habitat.
- High frequency, but low magnitude and duration, pulse flows serve similar functions as subsistence and base flows for primarily intermittent streams.
- Relatively high diversity of mussels inhabiting a wide range of habitats and requiring a wide range of fish hosts, indicates a need for variable flow regime that supports not only suitable conditions for the mussels species, but also for a variety of fish hosts.
- Aquatic macroinvertebrates have diverse ecologies that require a naturally variable flow regime to sustain native species composition, and these species are important links in stream food webs.

Water quality conditions (Section 3.4) like dissolved oxygen and temperature, important to healthy fish, mussel, and benthic macroinvertebrate communities, were generally at adequate levels under historical flow conditions.

- Low dissolved oxygen levels usually occurred at low flows, typically around subsistence or low base flow levels. Six of nine streams that experience low dissolved oxygen are considered intermittent by the BBEST. The remaining three streams have 90th percentile flows of 1.2 cfs or less.
- Four streams experienced temperatures above water quality standards. Three of those streams have 90th percentile flows of 1.2 cfs or less.

Sediment movement (Section 3.5) critical for maintaining existing instream and riparian habitat was analyzed for the Nueces River at Laguna, Cotulla, and Three Rivers.

- Limiting daily flows remaining in the stream to only amounts protected by the BBEST's environmental flow regime recommendations in this report (i.e., implementation of “infinite infrastructure”) would reduce annual sediment transport by about 86 percent for the Nueces River at Laguna and 59 percent for the Nueces River at Cotulla.
- Any substantial reduction in flows below historical patterns, particularly pulse flows and floods, would cause large reductions in sediment movement and probable changes in habitat.
- The environmental flows recommended in this report, would not appear to provide enough water to preserve existing dynamic equilibriums and existing habitats in Nueces basin streams subject to implementation of “infinite infrastructure.”

Riparian zones and floodplains support plants and animals depending on close proximity to water (Section 3.6).

- Over 160 plant species inhabit riparian zones in the Nueces Basin. More than 20 of the plant species require wetland conditions to be healthy.
- Riparian plants play important roles in managing erosion and sediment deposition as well as providing food and habitat for animals. Different species perform these roles at different levels of flow.

3.3.1 Instream Biology

The Nueces BBEST utilized best available science to evaluate biological relationships with flow regimes for the specific taxa and stream systems found in the Nueces River Basin. A first step in this process for fish, mussels, and other macroinvertebrates was a literature review of species diversity found in the basin, including ecologically important taxa (e.g., threatened or endangered), with a focus on reproductive life-history, habitat affinities and ecological flow relationships. As expected, more detailed information on flow and habitat relationships were available for fish species. When combined with new data on stream cross sections, these more detail fish data allowed for habitat availability/suitability modeling at a subset of our sites. The evaluation of ecological relationships and habitat availability/suitability criteria for a diverse selection of focal fish species across a flow regime is expected to meet habitat requirements of other aquatic taxa as well, including mussels, invertebrates, amphibians and plants.

3.3.1.1 Fish Focal Species Selection, Ecology, and Habitat Suitability Modeling

A fish species list for the Nueces River Basin was compiled using existing taxonomic works (Texas Freshwater Fishes, http://www.bio.txstate.edu/~tbonner/txfishes/), the Fishes of Texas Database (vouchered museum collections; http://www.fishesoftexas.org/about), and collection reports from projects conducted in the basin by the Texas Parks and Wildlife Department. After correcting for taxonomic synonyms, a total of 80 fish species were recorded for the basin from these three sources (**Table 3.3.1**). A handful of the 80 species represent brackish or marine vagrants that were rarely collected in freshwater habitats (e.g., leatherjacket, *Oligoplites saurus*, with a single record in the Lower Nueces River from 1964, or bigmouth sleeper, *Gobiomorus dormitor*, which was collected in the Frio River in 1939 and in Lake Corpus Christi in 1983). Freshwater species native to other basins were also sporadically collected in the Nueces basin, for example white catfish, *Ameiurus catus*, which is native to Atlantic coastal drainages, was collected from a single isolated pond (likely intentionally stocked). Marine or estuarine vagrants, as well as rarely encountered freshwater species not native to this basin, were not considered in our selection of focal species.

Table 3.3.1. Fish species list for the Nueces Basin. Not all species were represented in each source; "x" denotes the source or sources of record. Focal species are in bold. Introduced species are denoted by (*I*).

Scientific name	Common name	Fishes of Texas Database	Texas Freshwater Fishes	TPWD Collections
Achirus lineatus	lined sole			x
Adinia xenica	diamond killifish			
Agonostomus monticola	mountain mullet		x	
Ameiurus catus (I)	white catfish	x		
Ameiurus melas	black bullhead	x	x	x
Ameiurus natalis	yellow bullhead	x	x	x
Anchoa hepsetus	broad-striped anchovy			x
Anguilla rostrata	American eel		x	
Aplodinotus grunniens	**freshwater drum**	**x**	**x**	**x**
Astyanax mexicanus	Mexican tetra		x	x
Atractosteus spatula	alligator gar		x	x
Bodianus rufus	Spanish hogfish			x
Brevoortia patronus	Gulf menhaden			x
Campostoma anomalum	**central stoneroller**	**x**	**x**	**x**
Carassius auratus (I)	goldfish		x	
Carpiodes carpio	**river carpsucker**	**x**	**x**	**x**
Cichlasoma cyanoguttatum (I)	Rio Grande cichlid		x	x
Ctenopharyngodon idella (I)	grass carp			
Cycleptus elongatus	blue sucker		x	
Cyprinella lepida	plateau shiner	x	x	x

Scientific name	Common name	Fishes of Texas Database	Texas Freshwater Fishes	TPWD Collections
Cyprinella lutrensis	**red shiner**	**x**	**x**	**x**
Cyprinella sp.	Nueces River shiner		x	
Cyprinella venusta	blacktail shiner	x	x	x
Cyprinodon variegatus	sheepshead minnow		x	x
Cyprinus carpio (I)	common carp		x	x
Dionda serena	Nueces roundnose minnow	x		
Dorosoma cepedianum	gizzard shad	x	x	x
Dorosoma petenense	threadfin shad	x	x	x
Eleotris pisonis	spinycheek sleeper			
Etheostoma gracile	slough darter	x	x	x
Etheostoma lepidum	**greenthroat darter**	**x**	**x**	**x**
Fundulus grandis	Gulf killifish		x	x
Fundulus pulvereus	bayou killifish		x	
Fundulus similis	longnose killifish		x	
Gambusia affinis	western mosquitofish	x	x	x
Gobiomorus dormitor	bigmouth sleeper	x		
Gobiosoma bosc	naked goby			x
Ictalurus furcatus	**blue catfish**	**x**	**x**	**x**
Ictalurus lupus	headwater catfish	x	x	
Ictalurus punctatus	**channel catfish**	**x**	**x**	**x**
Ictiobus bubalus	**smallmouth buffalo**	**x**	**x**	**x**
Lagodon rhomboides	pinfish			x
Lepisosteus oculatus	**spotted gar**	**x**	**x**	**x**
Lepisosteus osseus	longnose gar	x	x	x
Lepomis auritus (I)	redbreast sunfish	x	x	x
Lepomis cyanellus	green sunfish	x	x	x
Lepomis gulosus	warmouth	x	x	x
Lepomis humilis	orangespotted sunfish	x		
Lepomis macrochirus	bluegill	x	x	x
Lepomis megalotis	**longear sunfish**	**x**	**x**	**x**
Lepomis microlophus	redear sunfish	x	x	x
Lepomis miniatus	redspotted sunfish	x	x	
Lucania parva	rainwater killifish	x	x	
Membras martinica	rough silverside		x	
Menidia beryllina	inland silverside		x	x
Menidia peninsulae	tidewater silverside			x
Micropterus salmoides	**largemouth bass**	**x**	**x**	**x**
Micropterus treculii *(I)*	**Guadalupe bass**	**x**	**x**	
Morone chrysops	white bass		x	x
Moxostoma congestum	**gray redhorse**	**x**	**x**	**x**
Mugil cephalus	striped mullet		x	x
Mugil curema	white mullet		x	
Notemigonus crysoleucas	golden shiner	x	x	x
Notropis amabilis	**Texas shiner**	**x**	**x**	**x**
Notropis buchanani	ghost shiner	x	x	x
Notropis stramineus	sand shiner	x	x	x
Notropis texanus	**weed shiner**	**x**	**x**	**x**
Notropis volucellus	mimic shiner	x	x	
Noturus gyrinus	tadpole madtom	x	x	x
Oligoplites saurus	leatherjacket			x
Oncorhynchus mykiss (I)	rainbow trout	x	x	

Scientific name	Common name	Fishes of Texas Database	Texas Freshwater Fishes	TPWD Collections
Opsopoeodus emiliae	pugnose minnow	x	x	x
Oreochromis aureus (I)	blue tilapia	x		
Pimephales promelas (I)	fathead minnow	x	x	x
Pimephales vigilax	**bullhead minnow**	**x**	**x**	**x**
Poecilia formosa	Amazon molly	x	x	x
Poecilia latipinna	sailfin molly	x	x	x
Pomoxis annularis (I)	white crappie	x	x	x
Pomoxis nigromaculatus (I)	black crappie	x	x	x
Pylodictis olivaris	**flathead catfish**	**x**	**x**	**x**

3.3.1.1.1 Fish Focal Species Selection

One key decision point discussed by the Instream Subcommittee prior to the habitat modeling process was whether to generate models at the scale of guilds (i.e., groups of species assigned to the same habitat type) or individual focal species. We chose to generate models for individual focal species and not generalize to guilds for two primary reasons. First, the guild approach is often useful when incorporating and interpreting results for a large number of species. Using the guild approach, the lack of individual species-level results may be outweighed by reduced complexity that facilitates interpretation on a more general level. However, the fish community is not diverse in Edwards Plateau streams of the Nueces basin so most mesohabitat guilds would only contain one or two species, and interpreting species-specific results is not overly challenging given the number of models needing to be examined. Second, many of our species of interest use multiple habitat types, particularly when all life-history stages are considered together, making discrete classification of species into a single habitat guild problematic. By examining individual species models, our analyses explore potential habitat suitability across the naturally heterogeneous landscape that each species is exposed to and may potentially utilize under different flow conditions, without making assumptions about guild classifications.

Based on available data of species distributions, ecological life-history, and best professional judgment, the BBEST Instream Subcommittee evaluated candidate focal species such that several different habitat types were represented in each eco-region, most habitat types were represented by multiple species, and the diversity of life-history variation in fish species was well represented. Selection of the focal species also considered their suitability for use in monitoring responses at the fish community level under an adaptive environmental monitoring and management program.

We selected 8 focal species for the Edwards Plateau Region and 12 species for the South Texas Brushland and Coastal Plain regions (**Table 3.3.2**). All of the selected focal species (13 fish categories total including juvenile and adult channel catfish separately) are well represented across the three data sources (Table 3.3.1) demonstrating that they are consistent components of the basin's fauna and likely encompass the key ecological and life-history gradients present in the three eco-regions and at the sites identified for analyses. Section 3.3.1.1.2 describes the life histories and flow and habitat preferences for the selected species. It is important to note that species of ecological importance were included when sufficient data on habitat affinities were available, but this was not always possible. Specifically, the Nueces roundnose minnow (*Dionda serena*) and plateau shiner (*Cyprinella lepida*) are Nueces basin endemics for the Edwards Plateau streams that could not be included due to limited data. Endemic species do not naturally occur outside of a particular area. For example, the Nueces roundnose minnow is only found in Edwards Plateau streams. Additionally, tadpole madtom (*Noturus gyrinus*) and alligator gar (*Atractosteus spatula*) could not be included for the Brushland streams for the same reason. We elected to include Guadalupe bass (*Micropterus treculii*) in the analysis even though it is not a native species to the Nueces basin. It has been introduced in the Nueces and Sabinal Rivers and these populations constitute genetically pure stocks free of introgression (i.e. inclusion of genetic material from other species or populations via hybridization) with smallmouth bass or other species within the genus *Micropterus* (black basses). As a result, we felt that it was important to consider the species in our analysis.

Also, we included Guadalupe bass in the analysis for the one site where it does not currently occur (the Frio River at Concan) because it may occur there in the future as it disperses from the Sabinal River population.

Table 3.3.2. Focal species for flow-habitat modeling and their mesohabitat affinities. Primary and secondary mesohabitat preferences are indicated by dark and light shading, respectively.

Focal Species	Riffle	Shallow Run	Deep Run	Shallow Pool	Deep Pool
Edwards Plateau					
Greenthroat darter	X	x			
Central stoneroller	X	X	x	x	
Texas shiner		X	x	x	
Guadalupe bass	x	X	X	X	x
Gray redhorse			X	X	x
Channel catfish (adult)			x	x	X
Longear sunfish		x	X	X	X
Largemouth bass			x	x	X
South Texas Brushland / Coastal Plain					
Channel catfish (juvenile)	X	x			
Red shiner		x	X		
Weed shiner		X	X		
Bullhead minnow		X	X	x	
Smallmouth buffalo			x	x	X
Blue catfish			x	x	X
Channel catfish (adult)			x	x	X
Flathead catfish (juvenile)			x	x	X
Freshwater drum			X	x	x
River carpsucker		x	X	x	
Longear sunfish		x	X	X	X
Spotted gar			x	X	X
Largemouth bass			x	x	X

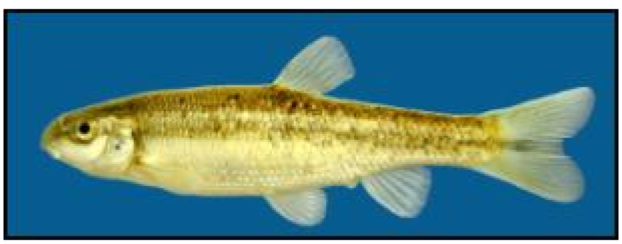
3.3.1.1.2 Ecology and Reproductive Life-History of Focal Fish Species

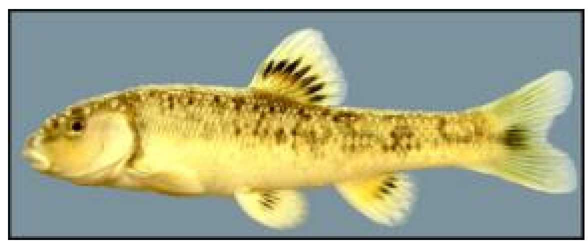
The following focal species were used to develop species-specific habitat availability/suitability criteria. The species were selected based on species' historical and current abundance and having sufficient information available to be considered in the quantitative habitat-based analysis. Species-specific ecology and life history information is derived from the Texas Freshwater Fishes website (http://www.bio.txstate.edu/~tbonner/txfishes/index.htm) with additional information derived from peer-reviewed scientific literature when available. All photographs are by Chad Thomas (Texas State University - San Marcos), unless otherwise indicated, and were copied from the Texas Freshwater Fishes website.

Freshwater drum - *Aplodinotus grunniens*

Freshwater drum are broadly distributed in North America and occur widely throughout Texas, except in the Panhandle region. This species occupies a wide variety of habitats, from clear to turbid rivers, lakes and reservoirs. After attaining a size of 25 mm in length, this species is associated with or near the bottom and its diet is comprised primarily of benthic organisms such as insect larvae, clams, snails, crustaceans and fish. Maximum size is 696 mm total length. Reproductive maturity is attained around age 4, when males and females have reached 203 and 221 mm total length, respectively. Freshwater drum spawn in May and June, usually when water temperatures are between 18-26°C. Spawning takes place in open water, often in large aggregates, and buoyant eggs and sperm are released into the water column. This species has high fecundity, with larger females (e.g., 3.5 kg) producing 600,000 eggs. Water temperatures exceeding 25.6°C and prolonged conditions of low dissolved oxygen concentrations have been noted to cause distress in individuals of this species.

Central stoneroller - *Campostoma anomalum*



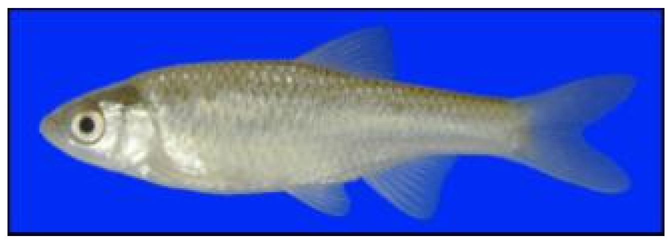


Central stonerollers are widespread throughout the eastern United States. In Texas, they are primarily found in streams of the Edwards Plateau but also occur farther west. This species is often associated with small clear streams with some current throughout most of the year and gravel, rubble or exposed bedrock substrates. They may also occur in tailwater tributaries of reservoirs. Central stonerollers can be very abundant, in some cases forming schools of several hundred individuals. This species is primarily herbivorous, feeding on filamentous algae and diatoms, but also microcrustaceans and aquatic insects. Maximum size is 287 mm total length. Reproductive maturity is likely reached by age 1. In Texas, males build nests from early February through early July and spawning occurs from mid-February to mid-July. Nests are most frequently built in the upstream portions of pools adjacent to riffles, and may or may not be defended by the male. Spawning may also take place in the nests of other species. There are some indications that this species will undertake migrations into smaller streams to spawn in early spring. Fecundity ranges from an estimated 200-4,800 eggs per female for females ranging in size from 65-130 mm standard length. This species displays some intolerance to heavy siltation or pollutants.

River carpsucker - *Carpiodes carpio*

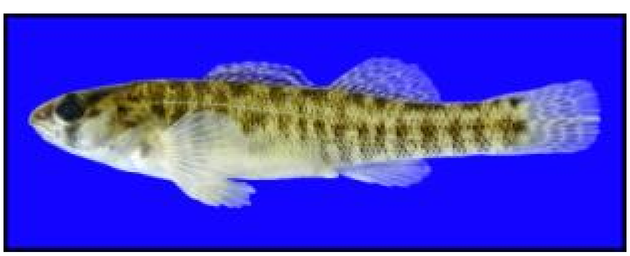
River carpsucker are distributed throughout the central U.S. and Mexico in the Mississippi River basin and other Gulf drainages. In Texas, the species ranges statewide. Adults are typically found in large rivers and reservoirs whereas young individuals may be found in small streams or reservoir tributaries. River carpsucker are often associated with silt or sand in quiet pools of low to moderate gradient rivers and impoundments. They feed on the substrate by suction/filter and consume periphyton, detritus, oligochaetes, aquatic insect larvae, and the like. Maximum size is 609 mm total length. Reproductive maturity may be reached by age 3. Peak spawning occurs from late-May to mid-July when temperatures are around 21°C. River carpsucker migrate upstream in May as temperatures increase and migrate back downstream after spawning. Spawning migrations may be stimulated by river current. Spawning congregations occur over open substrates with eggs fertilized in the water column. Fecundity may reach 200,000 eggs, and a single individual may spawn more than once per season.

Red shiner - *Cyprinella lutrensis*



The distribution of red shiner is throughout the southern Great Plains and into Mexico, including all of Texas. This species occurs in a wide range of habitats including pools and slow-flowing riffles of streams and creeks, creek mouths and medium-sized streams, low gradient rivers and backwaters, and reservoirs. Red shiner diet is generally comprised by terrestrial and aquatic insects as well as algae. Maximum size is 75 mm total length. This species may reproduce in its first year, after attaining a size of at least 24 mm standard length. Spawning occurs mid-April - September and most frequently on clean gravel riffles or on crevices in submerged objects. Average clutch size of 585 eggs may be deposited in up to 16 batches, and a pair may spawn 5-19 clutches over the reproductive season. Although red shiners are generally tolerant of harsh conditions such as siltation and high turbidity, some populations in reservoir tributaries have declined sharply (Matthews and Marsh-Matthews, 1997).

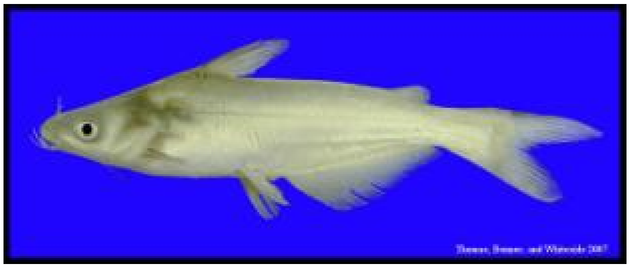
Greenthroat darter - *Etheostoma lepidum*



The Texas distribution of greenthroat darters includes Edwards Plateau streams, especially spring-influenced headwaters. This species occurs in clear water, vegetated rocky riffles. Little information is available on diet for this species; however, congeners typically feed on aquatic invertebrates associated with the benthos.

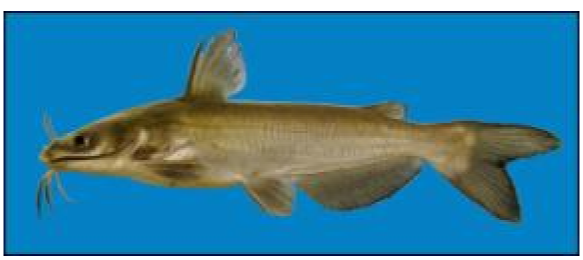
Maximum body size is 64 mm standard length. Greenthroat darters spawn from October or November through May, and increasing water temperatures (e.g., above 23°C) result in a marked drop in reproductive activity. Eggs are laid on vegetation or the underside of rocks. Females may lay multiple batches over the spawning period, totaling over 1,000 eggs. Studies indicate that the distribution of this species is declining due to water supply and habitat alteration.

Blue catfish - *Ictalurus furcatus*



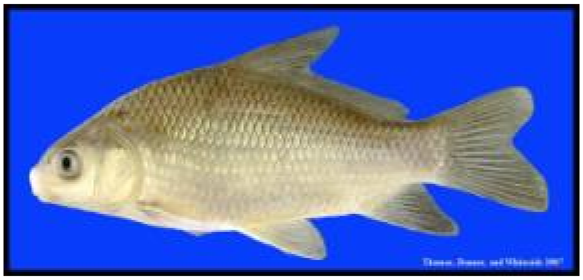
Blue catfish are broadly distributed in major rivers of the Mississippi, Missouri and Ohio basins of central and southern United States and south into Central America. This species occurs statewide in Texas with the exception of the northwestern part of the state. Blue catfish usually inhabit larger rivers and streams, favoring swift chutes and pools with noticeable current, and in turbid rivers and backwaters. They also occur in open waters of large reservoirs. Seasonal movements may be undertaken in response to changes in water temperature. This species has a broad diet, consuming a diversity of benthic invertebrates and fishes, with increasing consumption of larger and more mobile prey as body size increases. Maximum size is 1194 mm total length. Reproductive maturity is reached in the fourth or fifth year and between 490 and 590 mm total length, with males reaching maturity at a smaller size than females. Spawning occurs in late spring and early summer (e.g., April - May in Louisiana) when water temperatures are between 21 and 25°C. Males construct cavity nests, often in pools or backwaters, and parents guard the nest until the young hatch. Little information is available on fecundity of this species.

Channel catfish - *Ictalurus punctatus*



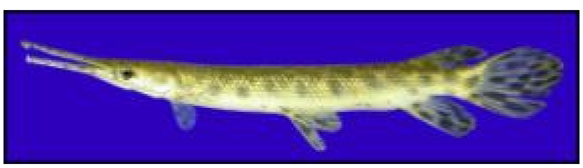
Channel catfish are widespread east of the Rocky Mountains in temperate North America, and are widely distributed throughout Texas (although populations in the upper Rio Grande and Pecos basins may be introduced). This species is typically associated with swift moving medium to large rivers with sand or gravel-rocky substrates and is also common in certain sections of reservoirs or downstream from hydroelectric dams where water current is rapid. In streams, juveniles are often associated with shallower and turbulent habitats such as riffles and areas adjacent to sand bars, whereas adults prefer deep pools with structure such as large rocks or log jams. Adults may move into shallow habitats at night to forage. This species has a broad diet, consuming a diversity of benthic invertebrates and fishes, with increasing consumption of larger prey as body size increases. During flooding, adult channel catfish have been documented to move onto the floodplain and consume terrestrial prey, including various invertebrates and even small mammals and reptiles. Maximum size is 1270 mm total length. Reproductive maturity is reached between 305 and 359 mm total length with females larger than males, which corresponds to maturation between ages 2 and 5 due to highly variable growth rates. Spawning occurs from late spring to early summer when water warms to between 16 and 24°C. Males select and prepare nest sites, often associated with undercut tree roots or rock outcroppings where a cavity is present, and the male guards the nest during juvenile development. Females usually void all eggs in small batches over a period of several hours when spawning with an approximate fecundity of 8,800 eggs per kilogram of body mass for females between 0.45 and 1.81 kg. Adult channel catfish exhibit a general trend of upstream migration (up to hundreds of kilometers) in the spring prior to spawning which is associated with increased flow.

Smallmouth buffalo - *Ictiobus bubalus*



Smallmouth buffalo are widely distributed across the United States and into Mexico, including all of Texas except for the panhandle region. This species is commonly associated with large streams with clear water and modest current and also commonly found in reservoirs. Adult smallmouth buffalo are benthic grazers, consuming invertebrates, algae and detritus. Maximum body size is 909 mm total length. Males reach sexual maturity in 4-5 years at a minimum size of 411 mm total length, whereas females mature at 6 years and 444 mm total length. Spawning occurs from March through September at water temperatures between 16 and 28°C. This species broadcasts spawns over virtually all substrate types and eggs and juveniles are not attended by adults. Fecundity estimates are variable, ranging up to 500,000 eggs for a female exceeding 800 mm total length, and average fecundities closer to 200,000 eggs per female. Only very limited migration has been recorded for this species in reservoirs, and there is a lack of information on migration patterns in streams and rivers.

Spotted gar - *Lepisosteus oculatus*

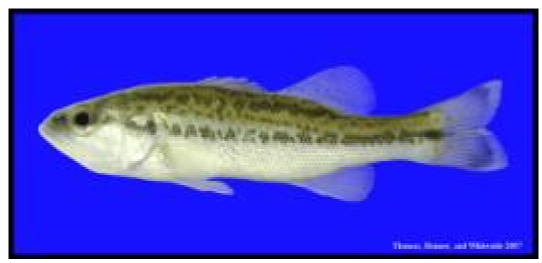


Spotted gar occur from Lake Erie southeastward through the Ohio and Missouri drainages and westward through the coastal-draining basins of Texas. This species is most abundant in clear, quite waters with aquatic vegetation, including the main channel and oxbow lakes, and may enter brackish water along the gulf coast. Juvenile spotted gar appear to favor dense vegetation during the day, moving in to open waters at night, whereas adults utilize deeper water during the day and move into shallower areas at night. There is evidence that this species is less tolerant of turbidity and more strongly associated with vegetation than other gar species. Spotted gar are carnivorous, feeding on increasingly larger prey, mostly fishes, at larger body sizes. Maximum body size is 1,092 mm total length. Sexual maturity is reached at 2-3 years for males and 3-4 years for females. Spawning takes place in early spring (April to early June) over vegetation. This species is an obligate plant spawner with adhesive egg envelopes that stick to submerged vegetation. Eggs and young are not guarded by adults. Recently hatched young have well-developed adhesive organ on the snout to attached to vegetation and a large yolk sac. A female may release over 5,000 eggs with fecundity depending on body size. There is no information on migration for this species, although upstream movements for spawning have been recorded for longnose gar (*Lepisosteus osseus*).

Longear sunfish - *Lepomis megalotis*

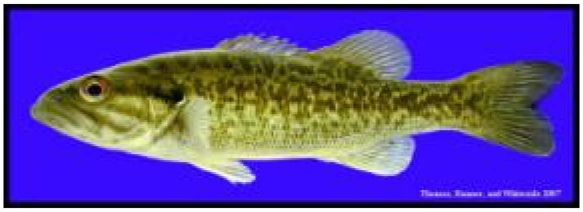

Longear sunfish are wide ranging throughout much of the central United States, and occur statewide in Texas except for the headwaters of the Canadian and Brazos rivers. This species is most abundant in clear, small upland streams with permanent or semi-permanent flow, and may also occur in reservoirs. Longear sunfish feed mainly on aquatic and terrestrial invertebrates and occasionally small fish. Maximum body size is 200 mm standard length. Sexual reproduction is reached after the 2nd year, but parental males are at a size of approximately 75 mm total length, whereas "sneaker" males are at 40 mm total length. Spawning occurs during late spring and early summer over nests in shallow water. Nests are formed by males fanning out a depression, and males actively court females to attract them to the nest. During spawning, smaller "sneaker" males may move into the nest of a parental male to try to fertilize the eggs deposited. After spawning, parental males chase away the female and guard the nest. There is limited or no information on fecundity or migration for this species.

Largemouth bass - *Micropterus salmoides*

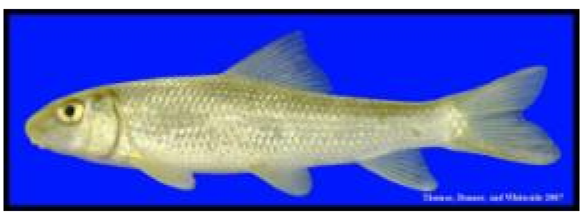
Largemouth bass is a wide-ranging species originally found throughout most of the United States east of the Rocky Mountains, including all of Texas except for the panhandle region. It occurs in lakes, ponds, slow-moving rivers and streams, river backwaters and reservoirs. This species generally prefers clear, quiet waters with aquatic vegetation. Largemouth bass are carnivorous, shifting from a diet dominated by invertebrates at smaller body sizes to larger prey (mostly fishes) as body size increases. Maximum body size is 700 mm total length. Sexual maturity is reached at 250 mm total length for females and 220 mm total for males. Spawning may occur from late winter through early spring, after water temperatures reach 16°C and continuing up to 24°C. Largemouth bass build nests in shallow water, usually near some form of structure such as logs or aquatic vegetation. Males attract females to spawn over the nest, which may contain between 5,000 and 43,000 eggs. Males guard the eggs and fry for several weeks, and do not feed during this time. Limited migration has been observed for spawning in this species, associated with movement to suitable spawning sites. This species is the most sought-after recreational fish in Texas, and has been widely introduced around the world for the same reason.

Guadalupe bass - *Micropterus treculii*



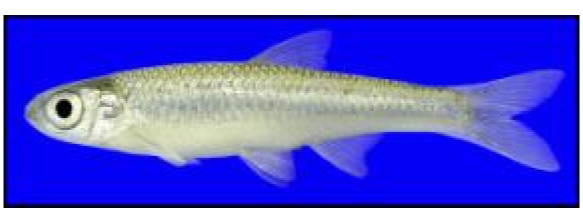
Guadalupe bass, the official state fish of Texas, are endemic to streams of the northern and eastern Edwards Plateau, including portions of the Brazos, Colorado, Guadalupe, and San Antonio basins. Two introduced populations have been established in the Nueces basin. This species prefers streams and small semi-lentic habitats. Guadalupe bass feed primarily on aquatic insects but also consuming small fish, crayfish and terrestrial insects. Maximum body size is 380 mm standard length. Sexual maturity is reached at 1 year for both males and females, at a size of at least 70 mm standard length. Spawning occurs from early March through May or June, over nests built by males in pools near a source of flowing water. Fecundity is positively correlated with body size, with over 9,000 eggs reported for the largest observed females. Young-of-the-year leave the nest and move into deeper and faster flowing water often located above and below riffles during their first summer and fall, and adults return to deeper flowing water after completing spawning. This species is considered vulnerable in southern drainages, and as a species of Special Concern in Texas. Factors identified as important for the continued survival of this species include preservation of high quality stream habitat and water quality, as well as absence of smallmouth bass *Micropterus dolomieu* which readily hybridize and compete with Guadalupe bass.

Gray redhorse - *Moxostoma congestum*



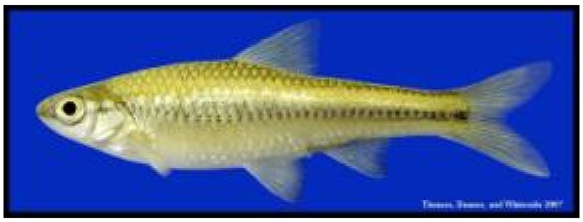
Gray redhorse occur in basins draining into the Gulf of Mexico in the United States and Mexico, and in Texas are generally restricted to streams of the Edwards Plateau. Young and subadults inhabit riffles and gravelly runs, whereas adults are more common in stream pools with firm substrates. Considerable movement among pools can be observed, with individuals foraging while slowing moving between habitats. The diet of this species is broadly comprised of benthic invertebrates, including aquatic insect larvae, snails, small clams, and other small organisms associated with firm substrates. Maximum body size is 514 mm total length. Data on age or size at maturity are limited for this species, but it appears that maturation is delayed until reaching relatively large body sizes. Spawning occurs over clean gravel/cobble/pebble substrates in clear-water creeks during spring, and may include two distinct periods of late February and early March and again in late April and early May. No data are available on fecundity for this species. Adults migrate upstream into smaller creeks to spawn. Populations of gray redhorse are impacted by habitat degradation, such as reduced discharge and habitat fragmentation.

Texas shiner - *Notropis amabilis*



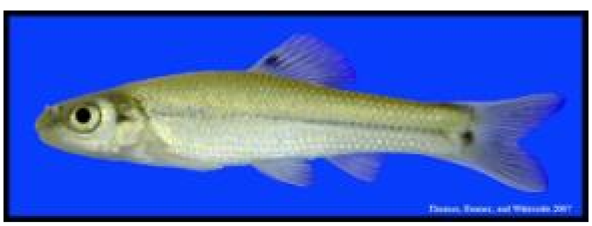
Texas shiner occur from the Rio Grande to Colorado River drainages, primarily within Edwards Plateau streams. This species historically occurred in New Mexico as well but has since been extirpated. Texas shiner are primarily associated with deeper flowing water in springs and flowing pools and runs of headwater tributaries. This species exhibits shifts in habitat use associated with flows and appears adapted to flood-prone existence that typifies desert streams. The diet of this species suggests it is an invertivore drift predator, including aquatic and terrestrial insects. Maximum body size for Texas shiner is 70 mm total length. Breeding individuals are primarily age-1 fish, and the lifespan for this species may only be two years. In Texas, spawning occurs during spring and summer, ranging from February through September. No data are available for spawning habitat for this species; however, other species within the genus *Notropis* are broadcast spawners that scatter eggs over the substrate. Fecundity data are limited, but there is evidence that this species spawns small clutches (from 102 to 286 eggs) on multiple occasions during the spawning period, yielding several cohorts. There is no information available on migration for this species.

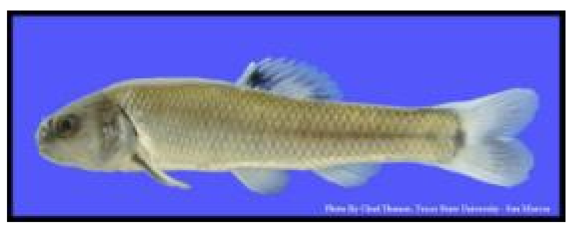
Weed shiner - *Notropis texanus*



Weed shiner occur in the Mississippi River basin from the northern United States south to the Gulf of Mexico, as well as gulf coastal drainages from Florida to the Nueces basin. In Texas, this species is distributed in low-gradient streams and backwaters from the Nueces to the eastern portion of the state. Habitat affinities include slow current with sandy substrates, but exhibit shifts in habitat use associated with increased flows and flooding. Weed shiners readily move onto inundated floodplains. Evidence suggests that population cycles of this species are tied to period of flooding, with abundance positively associated with spring flooding. Maximum body size is 70 mm standard length (87 mm total length) and sexual maturity is reached at 33 mm standard length for females and 30 mm standard length for males (age 1 for both sexes). Spawning occurs from late spring through early summer, and females produce multiple clutches during the breeding season of between 191 and 1,105 eggs per clutch. No data are available for spawning habitat for this species; however, other species within the genus *Notropis* are broadcast spawners that scatter eggs over the substrate. There are no data available for migration for this species.

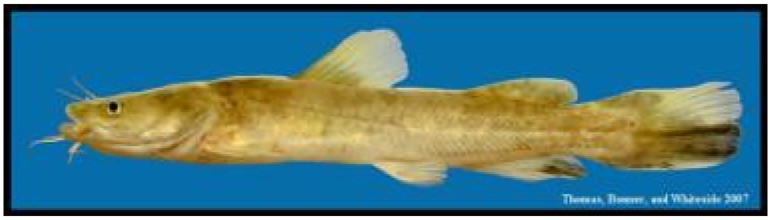
Bullhead minnow - *Pimephales vigilax*





Bullhead minnow occurs throughout the Mississippi River drainage, from Minnesota and South Dakota south to Mexico, Texas, Louisiana, and Mississippi, as well as east to Alabama and Georgia. In Texas the species occurs statewide, although populations in the upper Rio Grande basin and upper Red and Canadian basins may be introduced. Bullhead minnows are found in a variety of low-gradient streams, sluggish pools and backwaters, ditches and impoundments, often over mud substrates. This species has an omnivorous diet, consuming aquatic insect larvae, cladocerans, organic detritus, plant material, algae, etc. Maximum body size is 72 mm standard length, and no information is available on size or age at maturity. Bullhead minnows spawn during summer, from the middle of May through early September, in hole nests that are excavated under solid objects (e.g., rocks, tree limbs, boards) and defended by males. Females lay eggs on the underside of the submerged object, and multiple females may lay eggs in the same nest, which is cared for by the male. Fecundity estimates are not available for this species, and no information is available on potential migration for this species. Bullhead minnows are often used as bait fish and may comprise a large portion of the diet of piscivorous species such as largemouth bass.

Flathead catfish - *Pylodictis olivaris*



The distribution for flathead catfish ranges widely throughout the Mississippi, Ohio and Missouri basins, southward along the Gulf drainages to Mexico. In Texas, the species occurs statewide, typically associated with deep pools of medium to large sized rivers and lower sections of tributary streams, as well as reservoirs. Young-of-the-year typically occur in rubble-bottomed riffles, distributing more widely as they increase in size, with larger adults occurring in deeper water often associated with structure. Juveniles feed primarily on microcrustaceans and aquatic insects, shifting to large prey, predominantly fishes, with increasing body size. Maximum body size is 1410 mm total length. There is variability in estimated size and age at maturity for different locations, with the smallest estimates of maturation occurring after reaching approximately 300 mm total length and females larger than males. Spawning takes place in late June and July in cavity or hole nests under logs or other solid structure. Males aggressively defend the nest and young. Fecundity increases with body size, with up to 60,000 eggs for the largest individual reported and around 5,000 eggs for the smallest size class reported. Flathead catfish are considered sedentary, with fidelity to 1 to 3 home sites that are returned to following nocturnal foraging. However, it is noted that this species has the potential for rapid dispersal and population growth, which combined with large body size and piscivorous diet, leads to concerns when it is introduced in areas outside its native range. This species is widely regarded as a game species.

3.3.1.1.3 Fish Habitat Suitability Criteria

Suitability criteria 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. 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).

Generation of suitability criteria is fraught with difficulties. Some of the most serious of these are constraints affecting the size, timing, and quality of the sample data. These include biases in habitat availability, predation/ competition, low abundance, sampling gear bias, etc. Regardless, practical data collection constraints dictate that suitability criteria are generated from a limited number of fish observations over a small range of conditions.

We developed habitat suitability criteria individually for our focal species using existing fish habitat utilization data. Our starting point was a database developed by TPWD River Studies Program and BIO-WEST, Inc. that was used to develop suitability criteria for both the Guadalupe-San Antonio and Colorado/Lavaca BBESTs. This database utilized data from 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 lower San Antonio River 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 lower San Antonio River (BIO-WEST, 2008b) and its tributaries (BIO-WEST, 2008c).

The habitat suitability criteria (HSCs) for many of our focal species at the two Edwards Plateau sites were developed primarily from data from Dr. Tim Bonner's Blanco River study (Bean, et al., 2007), though some data did come from other sources. Data for the remaining Edwards Plateau species and all species at Three Rivers came from the other datasets. We also obtained data for greenthroat darter from Dr. Tim Bonner's Pedernales River fishes study (Shattuck, 2010). TPWD also added data for spotted gar and weed shiner from other datasets to allow development of criteria for those species. All of the habitat data we used to create

HSC's were from outside of the Nueces River Basin, though they were from similar stream types (i.e., from the same eco-region) to our 3 habitat modeling sites. The exceptions to this were that many data for channel catfish adults, included as a focal species for the Frio at Concan and Nueces at Laguna, are from coastal plains rivers with a higher proportion of deeper habitats than these Edwards Plateau sites.

To develop suitability criteria for depth and velocity, habitat data were divided into equal increments for depth and velocity. We then developed criteria using nonparametric tolerance limits (NPTL; Bovee, 1986). Nonparametric tolerance limits are an approach that sets multiple levels of habitat suitability scores based on break points in the distribution of quantitative habitat data. We applied NPTL's based on the central 50 percent, 75 percent, 90 percent, and 95 percent of the data at the 0.95 confidence level. Tolerance limits for the central 50 percent of the data were used as cutoffs for the most utilized habitat and the range of data between these two points was given a suitability of one. Data between the 50 percent tolerance limits and the 75 percent tolerance limits was given a suitability of 0.5. Data between the 75 percent tolerance limits and the 90 percent tolerance limits was given a suitability of 0.2, and the data between the 90 percent tolerance limits and the 95 percent tolerance limits received a suitability of 0.1. Data points falling outside the 95 percent tolerance limits were considered outliers and given a suitability of zero.

We then reviewed and refined the initial NPTL results at a workshop of BBEST members, agency staff, and our contractors. Depth and velocity criteria for several species were adjusted from initial NPTL results based on best professional judgment. For several deep water species (e.g., blue catfish) we extended the range of 1.0 depth suitability to all depths greater than 1 foot. We did not develop substrate criteria from field data in the database. To develop substrate criteria, all substrate sizes were given an initial suitability of 1.0, which we then lowered for substrate classes that we believe to be less suitable or unsuitable for the focal species. For example, for many Edwards Plateau species, silt was given a suitability of 0. Final HSC's for all focal species are in Appendix 3.3.1.

3.3.1.1.4 Fish Habitat Availability and Suitability Modeling

We utilized flow-habitat modeling in the biological overlay to answer the following question:

> *Do the hydrology-based flow regime recommendations maintain sufficient instream habitat quality, quantity, and diversity that provide a sound ecological environment?*

The focus of this assessment was amount and quality of habitat provided during base and subsistence flows, although we did examine habitat availability and suitability at lower tiers of high flow pulses as well. Our objective was to develop relationships between flow and instream habitat availability for focal species at a subset of gages as a key component of the biological overlay. We used this analysis to evaluate flow recommendations (hydrology-based environmental flow regimes or HEFR outputs). Ultimately, we did not use the analysis to generate new flow recommendations or modify existing flow recommendations for several reasons summarized in *"Summary of fish habitat modeling results and interpretation of primary findings"* below.

Throughout this section, we frequently refer the reader to Appendix 3.3.1, which includes the final report from our contractors (Joe Trungale and Dr. Thom Hardy) that describes field methods and the methods used to develop habitat models. The following description of methods and results is to highlight the reasons for our approach, summarize the contractor's report, and discuss additional analyses subsequent to the report.

Because of time, funding, and drought limitations, we were only able to apply flow-habitat models at a subset of our flow recommendation sites. In selecting locations and our analytical approach we defined the following requirements or objectives:

- Utilize actual field data from our sites in developing flow-habitat models;
- Sites from both the Edwards Plateau and South Texas Brushland, allowing findings from these representative sites to be generalized for understanding flow-habitat relationships in other locations in the Nueces River Basin; and
- Analyses were conducted only on perennial streams because the flow-habitat modeling approach employed is most suitable for perennial streams and not proven for intermittent and ephemeral streams.

Site Selection

We initially selected six sites for analysis, but because three of the sites (Seco Creek, Atascosa River, and Nueces River at Cotulla) were dry or nearly dry due to drought we modeled habitat for three sites, two in the Edwards Plateau and one in the South Texas Brushland. We chose the Nueces River at Laguna and the Frio River at Concan in the Edwards Plateau. We also chose the Nueces River at Three Rivers in the South Texas Brushland because it is a perennial stream in a separate physiographic region and also because it is a flow-regulated stream. Ease of access for field work was also a consideration in site selections.

Modeling Method

We did not have previous habitat modeling or hydraulic models for the Nueces basin to adapt to our use. The basin also does not have an ongoing Texas Instream Flow Program study that might have included habitat modeling and/or mapping as a component of its study design. In order to develop flow-habitat relationships we needed a method that could generate usable estimates of habitat with limited time and money. We were able to contract for the model development. We decided to use a modified PHabSim method (see Appendix 3.3.1). This allowed us to take advantage of the best available science through a minimal amount of additional field work and analysis. With additional time and funding, or if SB2 or other studies had developed them, we would have evaluated other methods such as two dimensional modeling (e.g., River2D) which involve input of more intensive data (i.e., detailed bathymetry). We would also have evaluated methods such as MesoHabSim if we had a longer study period to measure habitat types at different flows.

Field Work

The field data on cross-sections were gathered by staff of the TPWD River Studies Program and TWDB, with assistance and guidance from the contractors. This insured consistency between the field work and models and increased the contractors' familiarity with the data.

The habitat modeling method employed is a representative reach approach in that it seeks to evaluate representative habitats of the site, not necessarily static cross-sections. To achieve this, the field data were gathered with the following objectives:

- All habitat types included in rough proportion of their occurrence;
- Measurements at 3 cross-sections in each habitat type; and
- Cross-sections extending at least up to bankfull, and ideally onto the floodplain.

We had hoped for multiple repeated field measurements of hydrology and hydraulics to strengthen the rating curve of stage and flow and the hydraulics model, but we were severely limited by very low flow conditions due to drought. The exception was the Three Rivers site, where the City of Corpus Christi collaborated by providing releases from Choke Canyon Reservoir, allowing two sets of hydraulics measurements at this site. Obtaining additional sets of field measurements of hydraulics should be a priority for adaptive management (see Section 7) and ongoing refinement of flow recommendations. This would strengthen model outputs and reduce uncertainty in velocities at the upper range of modeled flow.

Modeling

Most of the details of the habitat modeling methodology are presented in Appendix 3.3.1. In addition to the report, another final product from the contract was an MS Excel tool that contains the model as well as its inputs and outputs. The tool also has control cells to enable further analysis using the models for each site. The main outputs for this tool are curves of weighted usable habitat area (WUA) versus modeled flow for each species at each site. Weighted usable area is an estimate of the area of usable habitat for a species based on its habitat suitability criteria (i.e., preferred ranges of depth, velocity, and substrate) and the habitat characteristics present at the site (see Appendix 3.3.1 for details of how WUA is calculated from field data using the HSCs). The tool also has the capability to report the percent of maximum WUA (% of Max) (i.e., the WUA produced at each modeled flow as a percent of the maximum WUA produced by any flow in the range of flows analyzed), the percent of total habitat area at the site identified as suitable (% of Total), and other measures. The controls in the spreadsheet allow analysis using subsets of habitat quality, different flow recommendations (including periods of record and base flow levels), upper ends of percent of maximum WUA analysis, and others. The remainder of this section reports on activities by the BBEST using the tool subsequent to delivery by the contractors.

Analysis

In determining how to use the three site-specific models and the Excel tool provided by the contractors, we addressed the following decision points.

Cross-Sections

The tool can report habitat data for all cross-sections combined or any subset of the cross-sections. Analysis by subsets might be of particular use for species that are most likely to have most of their habitat in a particular habitat type (i.e., pool, riffle, or run) or portion (i.e., upstream or downstream) of the site. The agency staff and contractor classified each cross-section as riffle, pool, or run in the field. Of course, the classification of these cross-sections might change at higher flows and the cross-sections are certainly not uniform (i.e., there are areas of riffle microhabitats in cross-sections classified as runs). However, at the range of flows we are modeling, it is likely that some species would have more habitat in some cross-section types. For example, deep pool species such as largemouth bass are not likely to have much habitat in cross-sections classified as riffles, even at higher base flows. So, the BBEST considered whether to use WUA curves for all cross-sections or to utilize subsets for some species. We did all analyses for all species at all cross-sections and 3-4 subsets: riffle, run, and pool for the Concan and Laguna sites and riffle, shallow run, run, and pool for the Three Rivers site. For evaluation of the flow regimes, we decided to emphasize the totals for all cross-sections. However, we do comment on patterns in WUA in subsets for some species where it is most relevant.

Measure - WUA or % of Max

One of the most important decision points is which variable to use to indicate habitat availability/suitability. In our analysis, we primarily used WUA and percent of maximum WUA in a subset of the range of flows modeled. To make decisions about maintenance of suitable habitat we used percent of maximum WUA. This is because we wanted to ensure that the range of our base flow recommendations would maintain an adequate proportion of habitat possible for each of our focal species in a range of flows that could be considered in the realm of base flows.

A key consideration in the use of percent of maximum area analysis is the range of modeled flows from which the maximum WUA is selected. Our consideration was to include all of the flows that could be considered base flows and likely some buffer on the upper end. As an upper end of this analysis, we selected the flow that is twice the highest HEFR-derived base flow number for all of the periods of record analyzed. These flows were 190 cfs for the Concan site, 208 cfs for the Laguna site, and 324 cfs for the Three Rivers site. These flows correspond approximately to the 89th, 84th, and 74th percentiles of flow for the 3 sites, respectively. The hydrographic separation in the IHA/HEFR analysis assigns all flows above the 75th percentile flow to pulse flow categories. We felt that these percentages fell into a range of flow exceedence percentiles that could be considered base flows without extending too far into pulse flows.

Habitat Quality Thresholds

The model produces a habitat suitability score for each cross-section cell based on the habitat suitability criteria and the observed substrate and modeled depth and velocity values. Each habitat parameter (depth, velocity, and substrate) receives a value between 0 and 1 and the three values are combined as a cubed root of the three values to make a composite habitat suitability score. These values for each cell are then multiplied by cell area and summed across all cross-sections to get total WUA for the site.

The suitability values can also be used to further focus the analysis by summing WUA for certain ranges in composite habitat suitability. For example, a minimum threshold can be set (for the composite score or for individual habitat factor scores) to identify the most suitable or optimal habitat, or to deemphasize sub-optimal or unsuitable habitat. This allows analysis not only of aggregate habitat, but also of habitat "quality." Without using such a threshold, 10 cells of 0.1 (marginal suitability) would score the same as one cell of equal area of 1.0 (maximum suitability). This may or not be of concern depending on the objectives of the analysis.

We wanted to evaluate the range of habitat qualities for our focal species to determine any patterns in marginal, suitable, and optimal habitat across the range of flows. We wanted to ensure that optimal or near-optimal habitat is maintained for focal species by portions of flow recommendations that would meet those requirements. We analyzed three ranges of habitat suitability: 0-0.5 marginal, 0.5-0.8 suitable, and 0.8-1.0 optimal to evaluate potential minimum thresholds of 0.5 and 0.8. A variety of minimum quality thresholds have been utilized by other scientists. The 0.5 and 0.8 thresholds have been previously utilized in Texas by the Texas Instream Flow Program in the Lower San Antonio River study (TIFP and SARA, 2011).

Weighted usable area and percent of maximum curves are presented for each species for a 0.5 threshold in the body of the report and for no threshold and a 0.8 threshold in Appendix 3.3.1. Tables summarizing this analysis are presented below. We evaluated trends in all 3 quality ranges, but based decisions on a minimum threshold of 0.5.

"Enoughness" Thresholds

In evaluating the percent of maximum WUA results we needed to determine a minimum percentage that constitutes sufficient habitat, i.e., an "enoughness" threshold. We evaluated several thresholds including 50 percent, 70 percent, and 90 percent. We decided to use 75 percent to evaluate each focal species' habitat. The decision point was that the recommended flows needed to maintain at least 75 percent of maximum WUA in at least one of the three base flow ranges (Low, Medium, or High also identified as Dry, Average, or Wet due to association with hydrologic conditions) in at least one season. Because one of the functions of subsistence flows is to provide at least a minimal amount of instream habitat, we also applied a 20 percent of maximum threshold for subsistence flows.

Period of Record

We also used the habitat analysis to evaluate hydrology-based flow recommendations resulting from three periods of record (full, early, and late). See Section 3.2 for a description of these three periods of record and reasons for considering them at each site. We did the analysis for all three periods at each of the three sites (Appendix 3.3.1). The result was that, while the late period had slightly higher base flow numbers and as a result provided more habitat area, it was not a significant enough increase to justify using the later period. Therefore, we used the full period for all habitat analyses.

Time Series Analysis and Attainment Frequencies

We used the historical record of flows at the three habitat modeling sites and Flow Regime Assessment Tool (FRAT) outputs (see Section 6.3 for description of FRAT and the scenarios examined) for the Nueces River at Laguna to generate time series of instream habitats using the flow-habitat models. The goal of this analysis was to examine the habitat frequency curves for our focal species and attainment frequencies of the 75 percent percent of maximum WUA threshold historically resulting from our hydrology-based flow regime recommendations and example flow regime application scenarios.

In generation of habitat attainment frequencies we only used the range of flows for which habitat modeling was done (i.e., 1 to 850 cfs). This is because the extension of the curves beyond this range of flows cannot be done with certainty. Therefore, flows in the time series over 850 cfs and under 1 cfs are not included in the attainment frequency analysis. In other words, the resulting attainment frequencies are frequencies for the range of flows between 1 and 850 cfs and not for the entire period of record.

We also used FRAT outputs for the Nueces River at Laguna to generate time series of instream habitats for flows under four scenarios, all using the FRAT output time series from 1934 to 1996: 1) USGS historical flows; 2) WAM regulated flows; 3) regulated flows that would result from the example application; and 4) only those flows protected by the flow regime recommendation. For comparisons at this site, we used only the period of record (1934-1996) from the FRAT analysis to make results most comparable. We summarize this analysis as habitat frequency curves for the 8 focal species for the whole period of record for the Laguna gage. To evaluate the flow regime recommendations, we then plotted habitat frequency curves for the four scenarios on the same graph. Two examples of these graphs are presented in the text below and for all 8 species in Appendix 3.3.1. We also summarize this analysis as the percent of maximum habitat maintained across the range of percent exceedence levels (i.e., the percent of maximum habitat maintained 1 percent, 5 percent, 10 percent, etc. of the time) for the four scenarios.

Because we did not do FRAT analysis for the Frio River at Concan, we are not able to develop time series or attainment frequencies under the flow regime recommendations or flow regime application scenarios. However, we did develop habitat frequency curves for the 8 focal species for the whole period of record of historical flows and assessed the percent of maximum habitat maintained across the range of percent exceedence levels for historical flows.

We also did not have time series or habitat frequency curves for the flow recommendations for the Nueces River at Three Rivers, but we did develop the curves for 3 periods of record of USGS historical flows, the full period (1916-2009), pre-Choke Canyon Reservoir (1916-1981) and post-Choke Canyon Reservoir (1982-2009). We summarize this analysis as habitat frequency curves for the 13 focal species for the whole period of record for the Three Rivers gage. To evaluate the effects of Choke Canyon Reservoir operations on habitat frequencies we plotted habitat frequency curves for the 3 periods of record on the same graph. Two examples of these graphs are presented in the text below and all 13 species in Appendix 3.3.1. We also summarize this analysis as the percent of maximum habitat maintained across the range of percent exceedence levels for the pre- and post-Choke Canyon Reservoir periods.

<u>Results</u>

Site-specific results of flow-habitat analysis are presented and briefly summarized with site-specific conclusions below. Graphs of WUA and percent of Max WUA have vertical bars to illustrate where the hydrology-based flow recommendations intersect the habitat curves. We show bars for the range (i.e., across the four seasons) of subsistence flows, the three levels of base flows and the lower tiers of high flow pulses.

Nueces River at Laguna

The flow-habitat modeling for the Nueces River at Laguna indicates that the hydrology-based flow recommendations for base flows maintain suitable aquatic habitats for focal species and maintain habitat diversity at this site (**Figure 3.3.1** through **Figure 3.3.3**, Table 3.3.3, Appendix 3.3.1). There is a general trend that the range of our Base Flow recommendations does not overlap the peaks of many of the focal species' flow-WUA curves. Despite this, the percent of Max WUA numbers for most species provides enough suitable habitat (**Table 3.3.3**). All of our focal species have several base flow recommendations over 75 percent of the maximum WUA and all have subsistence over 20 percent. Several species do not have over 75 percent maintained in base low range and channel catfish adults do not have base medium over 75 percent. One possible reason contributing to this is that the data used to develop the HSC's for this species were from larger rivers, which may affect the results in the shallower channel at the Nueces River at Laguna. Another factor for all species is that the broad, flat gravelly nature of the channel at Laguna means that large amounts of deep habitats are not created until higher flows in many of the cross-sections.

Shallower species such as greenthroat darter have a higher proportion of optimal habitats (i.e. quality of 0.8 or higher) at lower flows compared to suitable (0.5-0.8 quality) and less suitable (less than 0.5) rather constant across flows. As a result, a high proportion of the habitats available in our range of base flows are optimal habitat. Deeper water species such as channel catfish adults have constant suitable and least suitable habitat area with increasing flows, but have nearly continuously increasing area of optimal habitat with increasing flow.

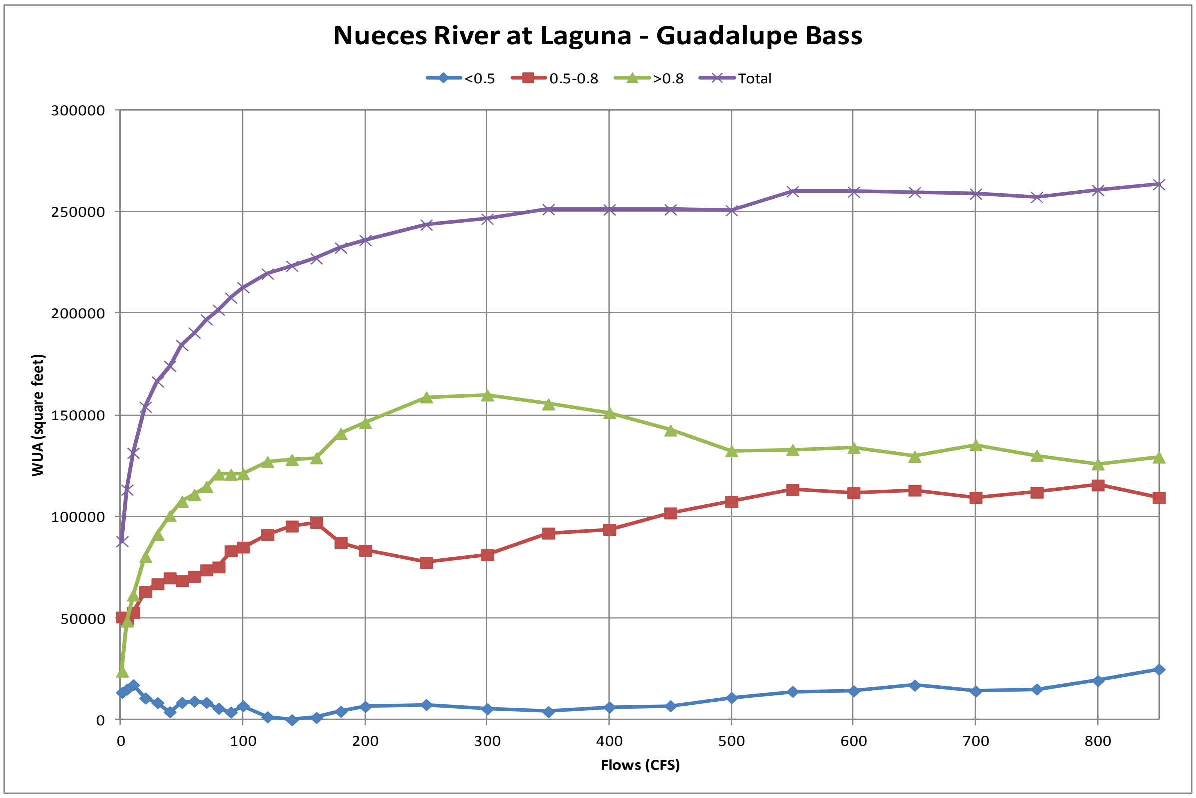


Figure 3.3.1. Four ranges of weighted usable habitat area quality (<0.5, 0.5-0.8, >0.8, and total) versus modeled flow (cfs) for Guadalupe bass (*Micropterus treculii*) at the Nueces River at Laguna.

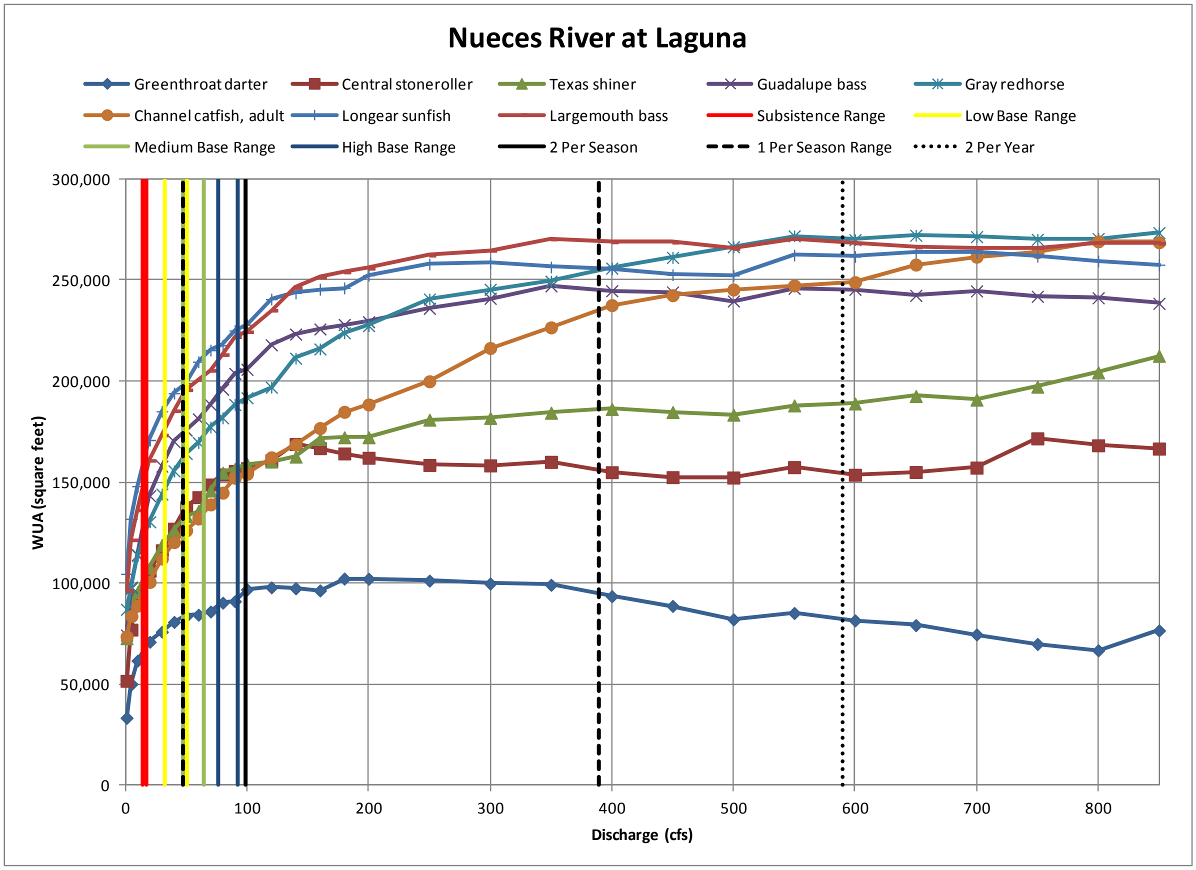


Figure 3.3.2. Weighted usable habitat area with a 0.5 minimum quality threshold versus modeled flow (cfs) for 8 focal species at the Nueces River at Laguna. Vertical bars bracket environmental flow regime components.

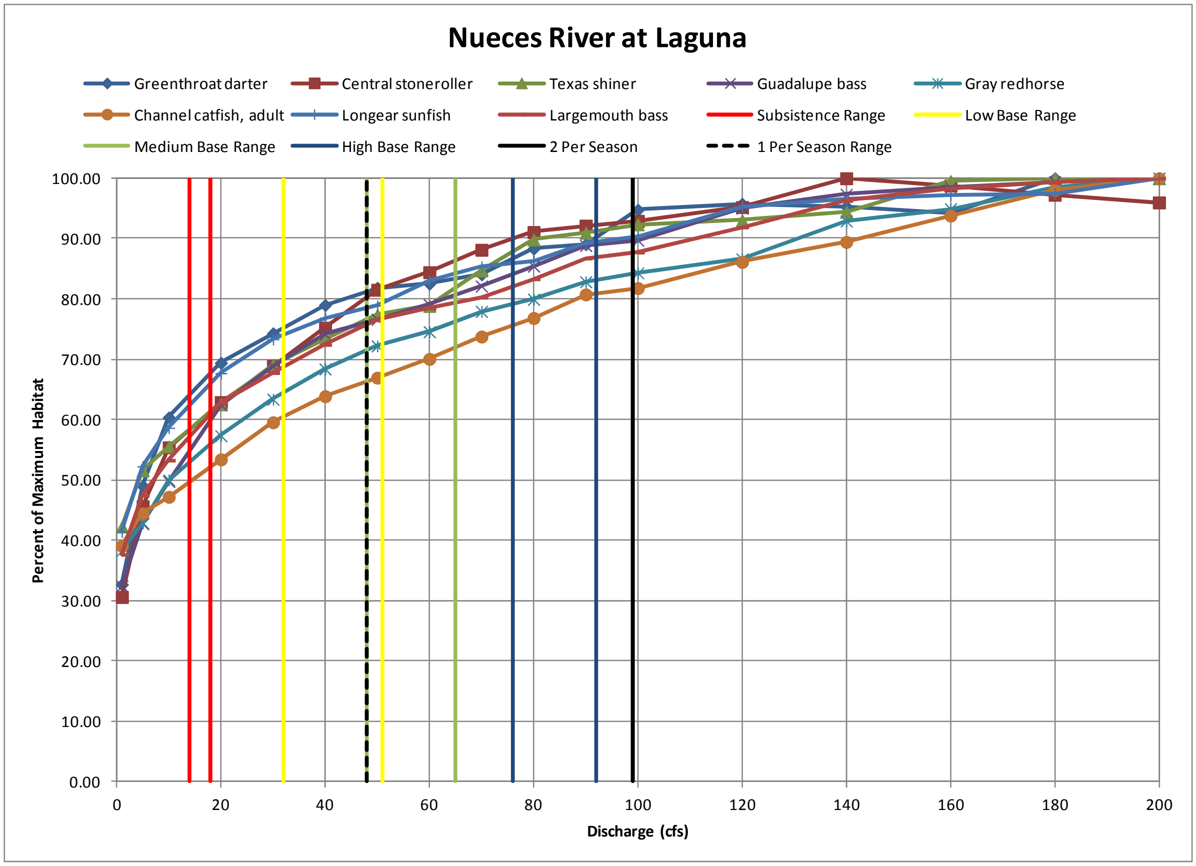


Figure 3.3.3. Percent of maximum weighted usable habitat area with a 0.5 minimum quality threshold versus modeled flow (cfs) for 8 focal species at the Nueces River at Laguna. Vertical bars bracket environmental flow regime components.

Table 3.3.3. Percent of maximum weighted usable habitat area with a 0.5 minimum quality threshold for 8 focal species resulting from Nueces BBEST flow recommendations at the Nueces River at Laguna. Shown are percentages for Subsistence and all three ranges of Base Flows. Shaded cells are those flows meeting "enoughness" thresholds of 20 percent for Subsistence flows and 75 percent for all three ranges of Base Flows.

Focal Species	Flow Component	Percent of Maximum Weighted Usable Area			
		Winter	Spring	Summer	Fall
Greenthroat darter	Subsistence	64%	68%	66%	63%
	Base-Low	82%	80%	75%	79%
	Base-Medium	84%	83%	81%	83%
	Base-High	91%	89%	87%	93%
Central stoneroller	Subsistence	58%	61%	60%	58%
	Base-Low	82%	78%	70%	76%
	Base-Medium	88%	86%	80%	85%
	Base-High	92%	92%	90%	93%
Texas shiner	Subsistence	58%	61%	60%	58%
	Base-Low	78%	75%	70%	74%
	Base-Medium	84%	81%	77%	80%
	Base-High	92%	91%	88%	92%

Focal Species	Flow Component	Percent of Maximum Weighted Usable Area			
		Winter	Spring	Summer	Fall
Guadalupe bass	Subsistence	55%	60%	57%	54%
	Base-Low	77%	75%	70%	74%
	Base-Medium	82%	80%	76%	80%
	Base-High	89%	87%	84%	89%
Gray redhorse	Subsistence	53%	56%	54%	52%
	Base-Low	72%	70%	64%	69%
	Base-Medium	78%	76%	71%	75%
	Base-High	83%	82%	79%	84%
Channel catfish, adult	Subsistence	50%	52%	51%	49%
	Base-Low	67%	65%	60%	64%
	Base-Medium	73%	71%	66%	71%
	Base-High	81%	79%	76%	81%
Longear sunfish	Subsistence	62%	66%	64%	61%
	Base-Low	79%	78%	74%	77%
	Base-Medium	85%	84%	78%	83%
	Base-High	90%	88%	86%	90%
Largemouth bass	Subsistence	57%	61%	59%	56%
	Base-Low	77%	74%	69%	73%
	Base-Medium	80%	79%	76%	79%
	Base-High	87%	85%	82%	87%

The habitat frequency curves indicate that none of the scenarios would be likely to significantly alter the frequency in which habitat amounts occur (**Figure 3.3.4** through **Figure 3.3.6**, Table 3.3.4, Appendix 3.3.1). However, the flow recommendations only scenario would result in the greatest reduction from any of the scenarios examined. Four of the 8 focal species would see no change in the frequency of meeting the 75 percent "enoughness" threshold under any of the scenarios. One additional species (Guadalupe bass) would see no change from historical to the project, but would with the flow recommendations only. The remaining three species (Texas shiner, gray redhorse and channel catfish adults) would see decreases in frequency under both the project and flow recommendation only scenarios. The highest decrease in frequency of attaining the 75 percent minimum threshold under the hypothetical project is a 10 percent decrease (from 50 percent to 40 percent of the time) for channel catfish adults (**Table 3.3.4**). The highest decrease from the flow recommendations only is also for channel catfish adults and is a 30 percent decrease (from 50 percent to 20 percent of the time). The greatest change in the curves is for run and pool species and is in the upper range of habitat areas (Figure 3.3.4, Figure 3.3.6). For example, for Guadalupe bass the frequency of occurrence of habitat areas over 20,000 ft^2 is reduced from approximately 45 percent historically to 20 percent under the flow regime recommendations.

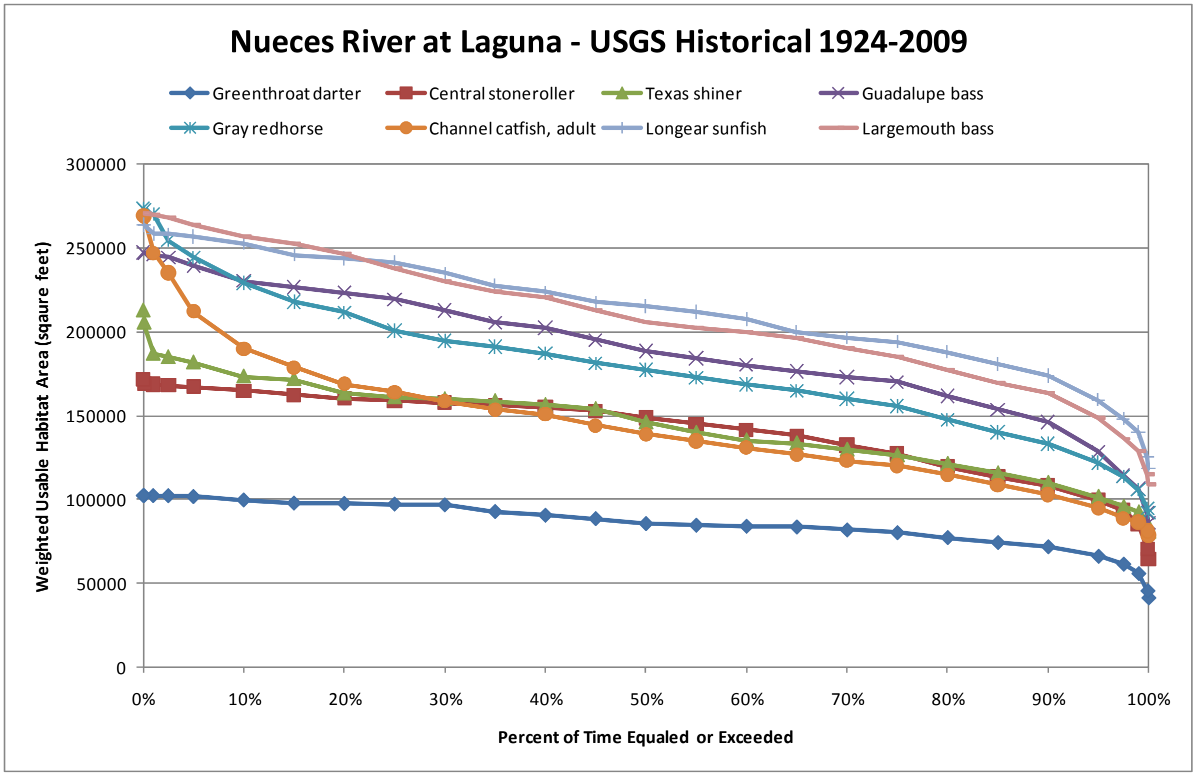


Figure 3.3.4. Habitat frequency curves for 8 focal species for the full period of record of historical flows (1924-2009) at the USGS gage at the Nueces River at Laguna.

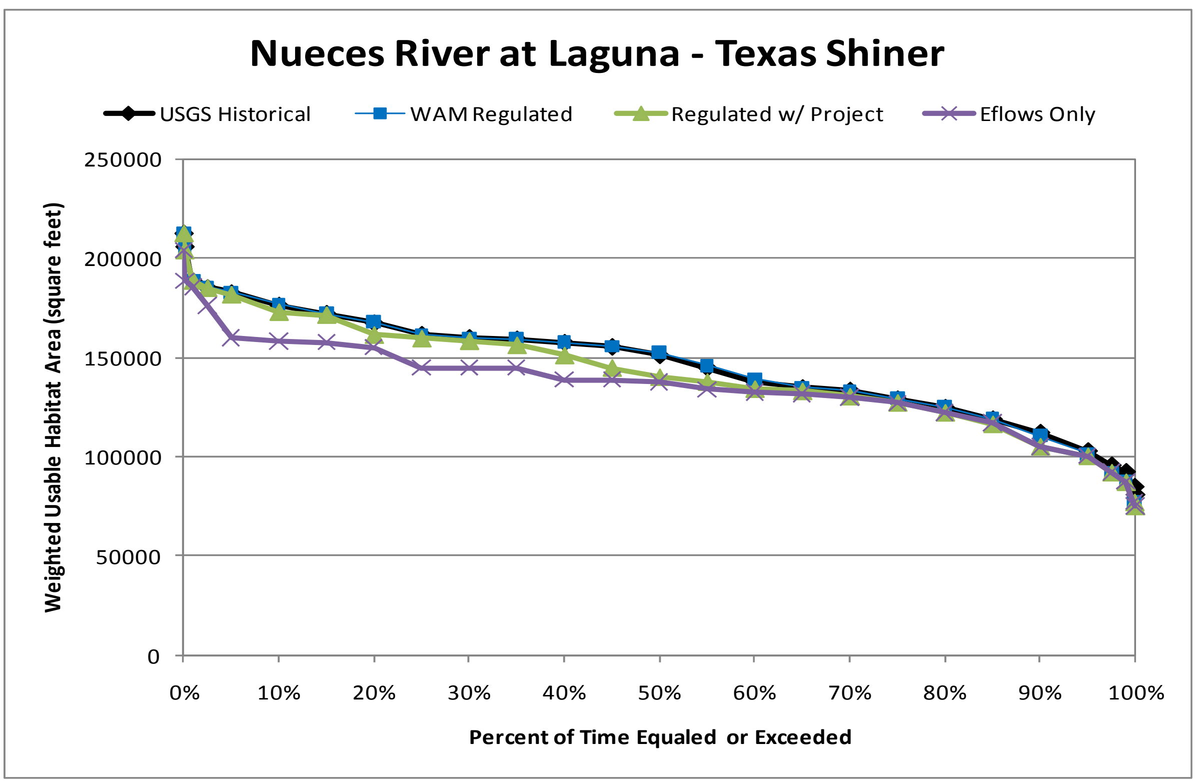


Figure 3.3.5. Habitat frequency curves for Texas shiner at the Nueces River at Laguna under the four example application scenarios (1934-1996).

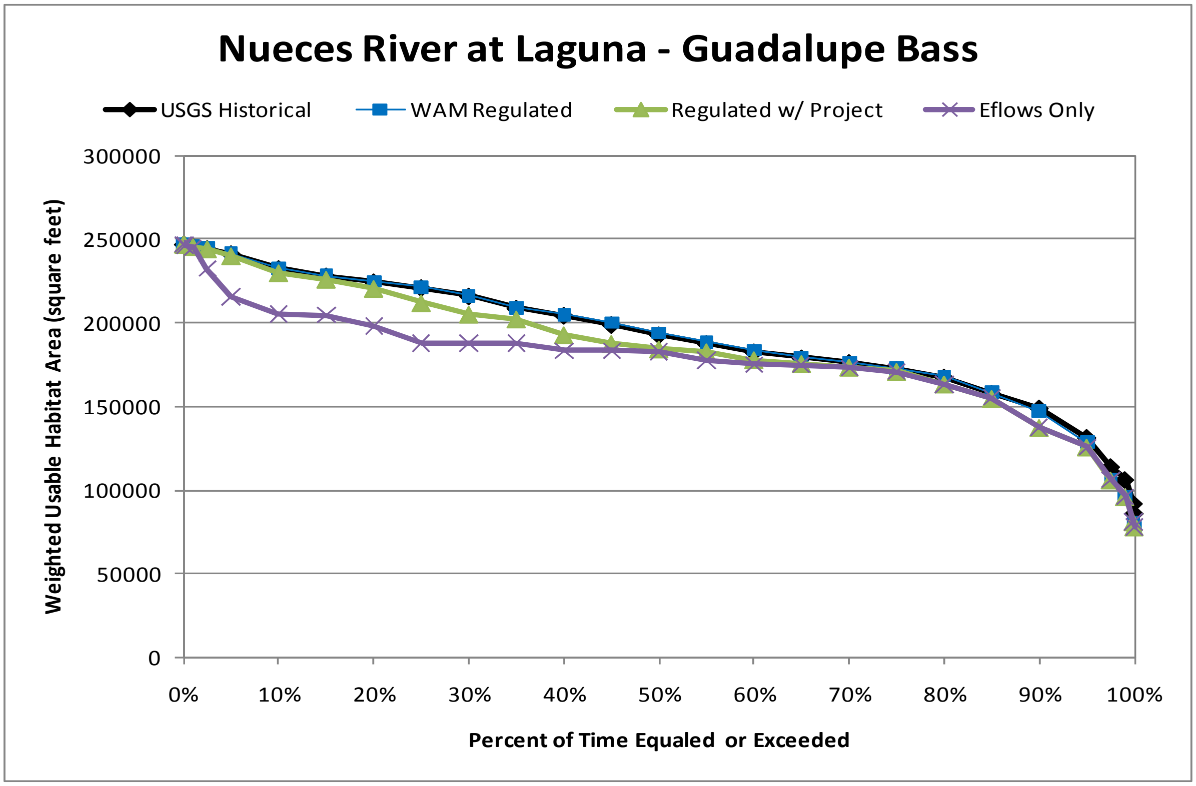


Figure 3.3.6. Habitat frequency curves for Guadalupe bass at the Nueces River at Laguna under the four example application scenarios (1934-1996).

Table 3.3.4. Percent of maximum habitat maintained by the range of percent exceedences examined for the example flow regime application project at the Nueces River at Laguna. For comparison, results are shown for both the USGS historical ("USGS"), regulated flows under project ("Project") and recommended flows only ("Eflows") scenarios. Shaded cells are those exceedence levels that meet the 75 percent threshold.

Percent Exceedence Level	Greenthroat darter			Central stoneroller			Texas shiner			Guadalupe bass			Gray redhorse			Channel catfish, adult			Longear sunfish			Largemouth bass		
	USGS	Project	Eflows	USGS	Project	Eflows	USGS	Project	Eflows	USGS	Project	Eflows	USGS	Project	Eflows	USGS	Project	Eflows	USGS	Project	Eflows	USGS	Project	Eflows
99.99%	41%	35%	35%	38%	33%	33%	47%	44%	44%	38%	34%	34%	41%	39%	39%	42%	40%	40%	47%	43%	43%	43%	39%	39%
99.9%	45%	37%	37%	42%	35%	35%	49%	45%	45%	40%	35%	35%	42%	40%	40%	43%	41%	41%	50%	44%	44%	45%	40%	40%
99%	55%	48%	48%	51%	44%	44%	54%	51%	51%	46%	42%	42%	47%	43%	43%	46%	44%	44%	56%	51%	51%	50%	47%	47%
98%	60%	55%	55%	55%	51%	51%	56%	54%	54%	50%	46%	46%	50%	46%	47%	47%	46%	46%	59%	55%	56%	53%	50%	50%
95%	66%	64%	64%	60%	58%	58%	60%	58%	58%	57%	55%	55%	54%	53%	53%	51%	50%	50%	64%	62%	62%	59%	57%	57%
90%	71%	68%	68%	65%	61%	61%	65%	61%	61%	65%	60%	60%	60%	56%	56%	56%	52%	52%	70%	66%	66%	65%	61%	61%
85%	74%	73%	73%	69%	68%	68%	69%	68%	68%	69%	67%	68%	63%	62%	62%	60%	58%	58%	73%	72%	72%	68%	67%	67%
80%	78%	76%	76%	74%	72%	72%	72%	71%	71%	73%	71%	71%	67%	66%	66%	63%	62%	61%	76%	75%	75%	72%	70%	70%
75%	80%	79%	79%	78%	76%	76%	75%	74%	74%	75%	75%	74%	70%	69%	69%	65%	64%	64%	78%	77%	77%	74%	73%	73%
70%	82%	80%	80%	82%	79%	79%	78%	76%	76%	77%	76%	76%	72%	71%	71%	67%	66%	66%	79%	78%	78%	77%	75%	75%
65%	82%	81%	81%	83%	81%	80%	78%	77%	77%	78%	77%	76%	74%	72%	71%	69%	67%	66%	81%	79%	78%	78%	76%	76%
60%	83%	82%	81%	85%	83%	81%	80%	78%	77%	80%	78%	76%	75%	73%	72%	71%	68%	67%	83%	81%	79%	79%	77%	76%
55%	84%	83%	82%	88%	85%	82%	84%	80%	78%	82%	80%	77%	78%	75%	73%	73%	71%	68%	85%	83%	80%	80%	79%	77%
50%	85%	83%	83%	90%	86%	85%	88%	81%	80%	84%	80%	80%	79%	76%	75%	76%	72%	71%	86%	84%	83%	82%	79%	79%
45%	88%	84%	83%	91%	88%	86%	90%	84%	81%	87%	82%	80%	81%	78%	76%	78%	73%	71%	87%	85%	84%	85%	80%	79%
40%	89%	85%	83%	92%	90%	86%	92%	88%	81%	89%	84%	80%	83%	79%	76%	81%	76%	71%	90%	86%	84%	87%	82%	79%
35%	93%	89%	84%	93%	92%	88%	93%	91%	84%	91%	88%	82%	85%	82%	78%	83%	80%	73%	92%	89%	85%	89%	86%	80%
30%	95%	91%	84%	94%	92%	88%	93%	92%	84%	94%	89%	82%	86%	84%	78%	85%	81%	73%	95%	90%	85%	91%	87%	80%
25%	95%	94%	84%	94%	93%	88%	94%	93%	84%	96%	92%	82%	90%	85%	78%	88%	84%	73%	96%	93%	85%	95%	90%	80%
20%	95%	95%	87%	95%	94%	91%	97%	94%	90%	98%	96%	86%	94%	90%	81%	92%	88%	78%	97%	96%	87%	97%	94%	84%
15%	96%	96%	91%	96%	95%	92%	100%	100%	92%	99%	99%	89%	99%	95%	83%	98%	94%	81%	98%	97%	90%	99%	98%	87%
10%	98%	97%	91%	98%	97%	92%	100%	100%	92%	100%	100%	89%	100%	100%	84%	100%	100%	81%	100%	100%	90%	100%	100%	87%
5%	100%	99%	94%	99%	98%	93%	100%	100%	93%	100%	100%	94%	100%	100%	86%	100%	100%	85%	100%	100%	94%	100%	100%	91%
3%	100%	100%	96%	100%	99%	95%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
1%	100%	100%	99%	100%	100%	98%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
0.1%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
0.01%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Frio River at Concan

The flow-habitat modeling for the Frio River at Concan indicates that the hydrology-based flow recommendations maintain suitable aquatic habitats for all our focal species and maintain habitat diversity (**Figure 3.3.7** through **Figure 3.3.9**; Table 3.3.5; Appendix 3.3.1). However, this site also shows the overall trend that the range of our base flow recommendations does not overlap the peaks of many of the focal species' flow-WUA curves. Despite this, the percent of Max WUA numbers for all species attain our "enoughness" criteria (Table 3.3.5). All species have all or nearly all base flows maintaining over 75 percent of maximum habitat and subsistence flows maintaining over 20 percent. The only number not over 75 percent for any species is the base low number for greenthroat darter.

In the base flow range shallower species such as greenthroat darter have a higher proportion of suitable habitats (i.e. quality of 0.5 to 0.8) compared to optimal (greater than 0.8 quality) and least suitable (less than 0.5) whereas deeper water species such as largemouth bass have the highest proportion of optimal habitats. At the very low end of flows, riffle and shallow run species (greenthroat darter, central stoneroller and Texas shiner) have a high proportion of least suitable habitats. Areas of both suitable and optimal habitats are still increasing in the range of our base flow recommendations.

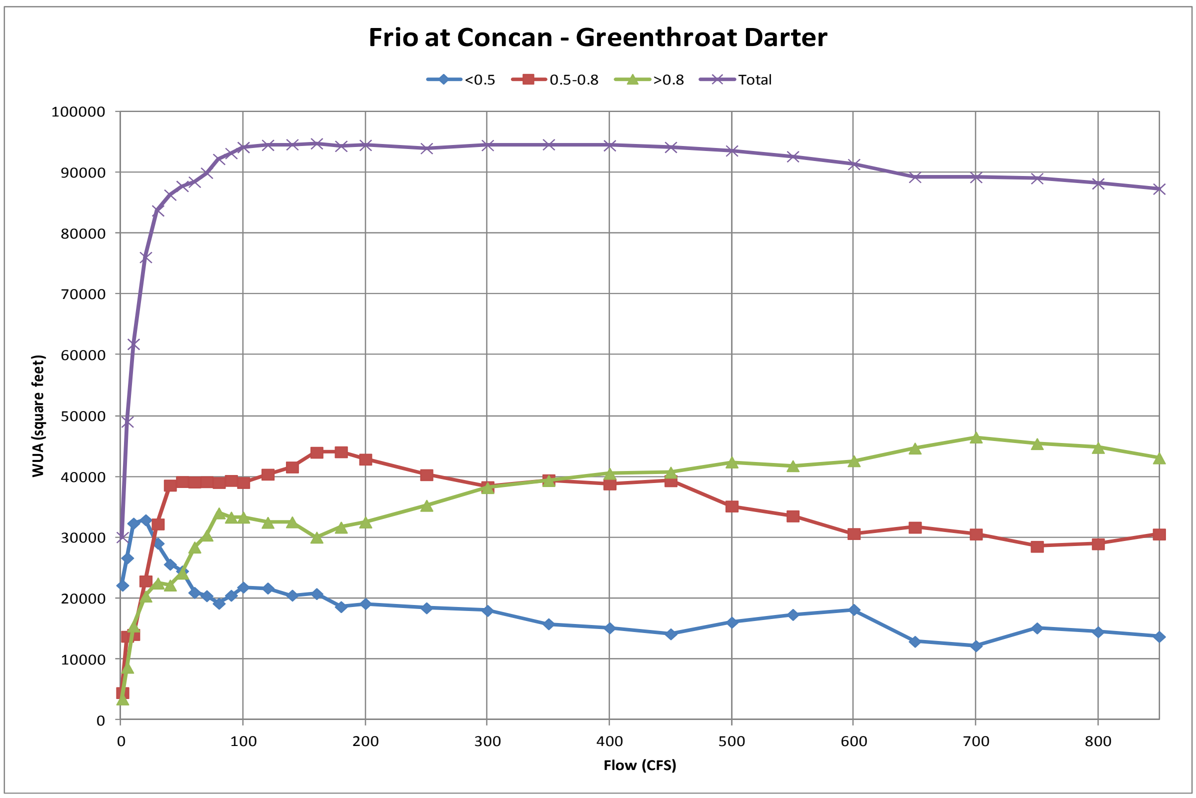


Figure 3.3.7. Four ranges of weighted usable habitat area quality (<0.5, 0.5-0.8, >0.8, and total) versus modeled flow (cfs) for greenthroat darter (*Etheostoma lepidum*) at the Frio River at Concan.

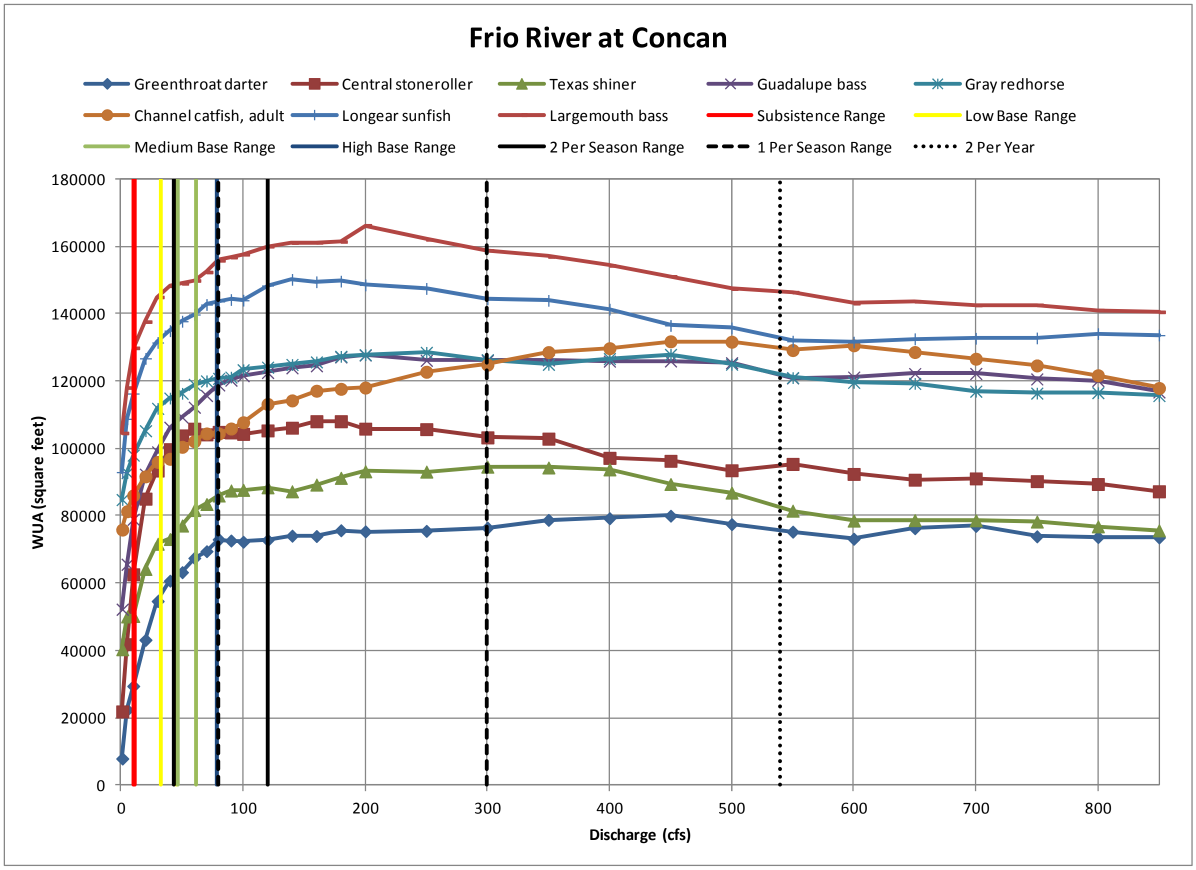


Figure 3.3.8. Weighted usable habitat area with a 0.5 minimum quality threshold versus modeled flow (cfs) for 8 focal species at the Frio River at Concan. Vertical bars bracket environmental flow regime components.

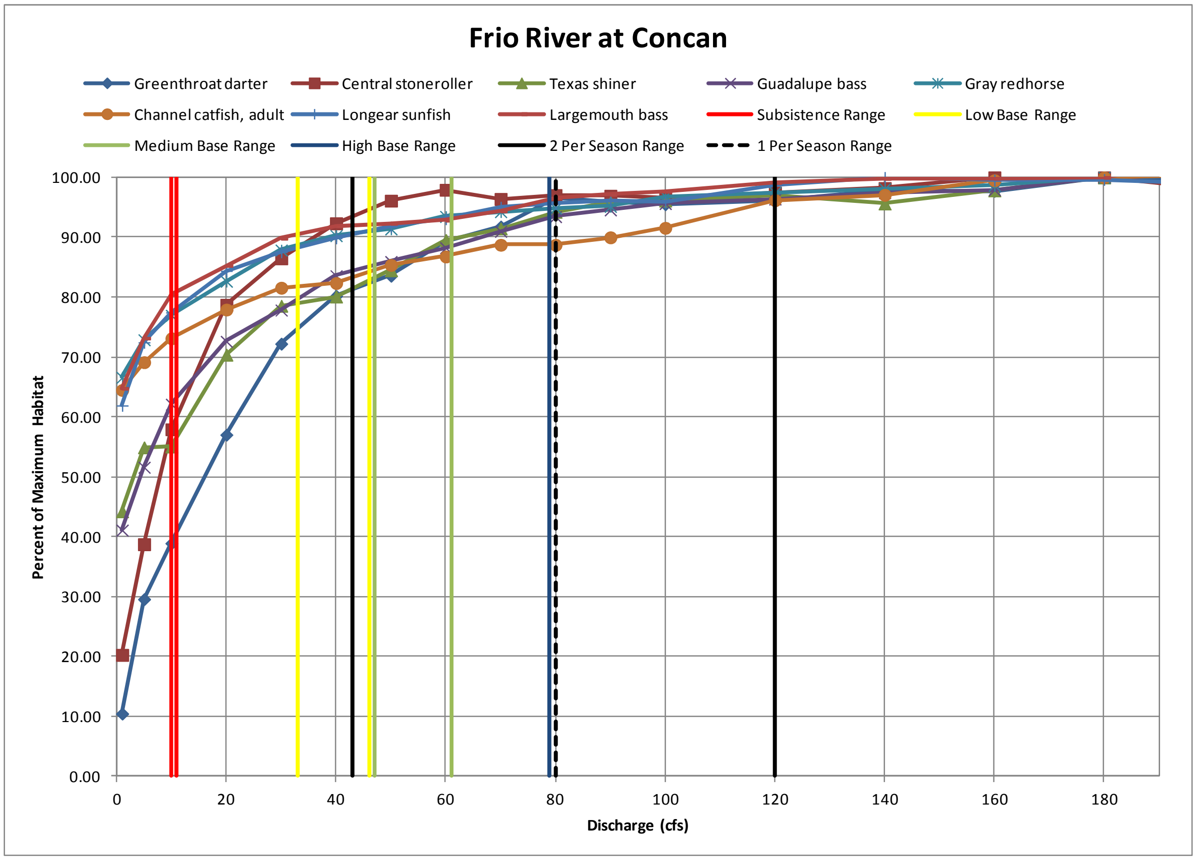


Figure 3.3.9. Percent of maximum weighted usable habitat area with a 0.5 minimum quality threshold versus modeled flow (cfs) for 8 focal species at the Frio River at Concan. Vertical bars bracket environmental flow regime components.

Table 3.3.5. Percent of maximum weighted usable habitat area with a 0.5 minimum quality threshold for 8 focal species resulting from Nueces BBEST flow recommendations at the Frio River at Concan. Shown are percentages for Subsistence and all three ranges of Base Flows. Shaded cells are those flows meeting "enoughness" thresholds of 20 percent for Subsistence flows and 75 percent for all three ranges of Base Flows.

Focal Species	Flow Component	Percent of Maximum Weighted Usable Area			
		Winter	Spring	Summer	Fall
Greenthroat darter	Subsistence	41%	38%	38%	38%
	Base-Low	82%	80%	73%	75%
	Base-Medium	90%	89%	83%	86%
	Base-High	96%	96%	93%	96%
Central stoneroller	Subsistence	60%	56%	56%	56%
	Base-Low	95%	92%	87%	89%
	Base-Medium	97%	98%	95%	97%
	Base-High	97%	97%	97%	97%
Texas shiner	Subsistence	57%	55%	55%	55%
	Base-Low	83%	80%	79%	79%
	Base-Medium	90%	89%	83%	87%
	Base-High	95%	94%	92%	94%
Guadalupe bass	Subsistence	63%	61%	61%	61%
	Base-Low	85%	84%	78%	80%
	Base-Medium	89%	88%	85%	87%
	Base-High	94%	94%	92%	94%
Gray redhorse	Subsistence	78%	76%	77%	77%
	Base-Low	91%	90%	88%	89%
	Base-Medium	94%	93%	91%	92%
	Base-High	95%	95%	94%	95%
Channel catfish, Adult	Subsistence	74%	73%	73%	73%
	Base-Low	84%	82%	82%	82%
	Base-Medium	87%	87%	84%	86%
	Base-High	89%	89%	89%	89%
Longear sunfish	Subsistence	78%	77%	77%	77%
	Base-Low	91%	90%	88%	88%
	Base-Medium	94%	93%	91%	92%
	Base-High	96%	96%	95%	96%
Largemouth bass	Subsistence	81%	80%	80%	80%
	Base-Low	92%	92%	90%	91%
	Base-Medium	93%	93%	92%	93%
	Base-High	97%	97%	95%	97%

For the Frio River at Concan, we did not have a flow time series from which to develop a habitat time series that would result from the flow recommendations to compare to historical habitat frequencies in evaluation of flow recommendations. We also do not have a pre- and post-dam regulation comparison as at the Nueces River at Three Rivers. **Figure 3.3.10** and **Table 3.3.6** show habitat time series for the whole period of record of historical flows at the Frio River at Concan.

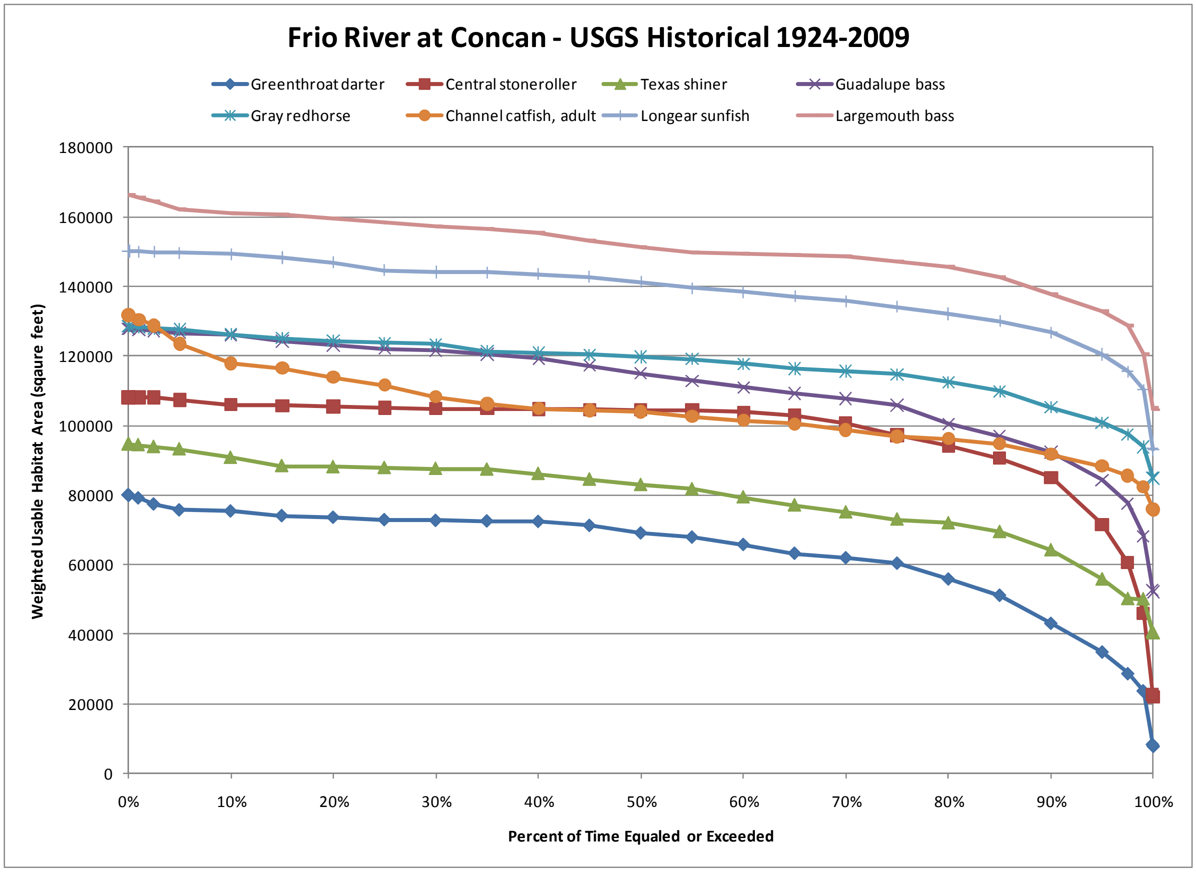


Figure 3.3.10. Habitat frequency curves for 8 focal species for the full period of record of historical flows (1924-2009) at the USGS gage at the Frio River at Concan.

Table 3.3.6. Percent of maximum habitat maintained by the range of percent exceedences examined for the full period of record of historical flows at the Frio River at Concan. Shaded cells are those exceedence levels that meet the 75 percent enoughness threshold.

Percent Exceedence Level	Greenthroat darter	Central stoneroller	Texas shiner	Guadalupe bass	Gray redhorse	Channel catfish, adult	Longear sunfish	Largemouth bass
99.99%	10%	20%	44%	41%	67%	64%	62%	65%
99.9%	11%	21%	45%	41%	67%	65%	62%	65%
99%	31%	43%	55%	54%	74%	70%	73%	75%
98%	38%	56%	55%	61%	77%	73%	77%	80%
95%	46%	66%	61%	66%	79%	75%	80%	82%
90%	57%	79%	70%	73%	83%	78%	84%	85%
85%	68%	84%	76%	76%	86%	80%	87%	88%
80%	74%	87%	79%	79%	88%	82%	88%	90%
75%	80%	90%	80%	83%	90%	82%	89%	91%
70%	82%	93%	82%	85%	91%	84%	90%	92%
65%	84%	95%	84%	86%	91%	85%	91%	92%
60%	87%	96%	87%	87%	92%	86%	92%	93%
55%	90%	97%	90%	89%	94%	87%	93%	93%
50%	91%	97%	91%	90%	94%	88%	94%	94%
45%	94%	97%	93%	92%	95%	89%	95%	95%
40%	96%	97%	94%	94%	95%	89%	96%	96%
35%	96%	97%	96%	95%	95%	90%	96%	97%
30%	96%	97%	96%	96%	97%	92%	96%	97%
25%	96%	97%	96%	96%	97%	95%	96%	98%
20%	97%	98%	97%	97%	98%	97%	98%	99%
15%	98%	98%	97%	98%	98%	99%	99%	100%
10%	100%	98%	99%	99%	99%	100%	99%	100%
5%	100%	99%	100%	100%	100%	100%	100%	100%
3%	100%	100%	100%	100%	100%	100%	100%	100%
1%	100%	100%	100%	100%	100%	100%	100%	100%
0.1%	100%	100%	100%	100%	100%	100%	100%	100%
0.01%	100%	100%	100%	100%	100%	100%	100%	100%

Nueces River at Three Rivers

The flow-habitat modeling for the Nueces River at Three Rivers indicates that the hydrology-based flow recommendations maintain suitable aquatic habitats for focal species and maintain habitat diversity (**Figure 3.3.11** through **Figure 3.3.13**, Table 3.3.7, Appendix 3.3.1). There is a general trend that the range of our Base Flow recommendations does not overlap the peaks of some of the focal species' flow-WUA curves. Despite this, the percent of Max WUA numbers for all species met our "enoughness" criteria (**Table 3.3.7**). All of our focal species have several Base flow recommendations over 75 percent of the maximum WUA and all species but two (smallmouth buffalo and blue catfish) have over 20 percent of maximum maintained by all subsistence flows. Most species have at least some Base numbers below 75 percent, but nearly all are over 75 percent in both their base flow level and cross-section subsets of most relevance. There are several species (smallmouth buffalo, blue catfish, channel catfish adults, freshwater drum, and spotted gar) that do not have percent of Max numbers over 75 percent in the Base Medium level, but all of these are deep run and pool species and do meet the 75 percent threshold in the Base High level. As noted previously, a possible explanation for this is that data used to develop the habitat suitability criteria for these deeper water species were from larger rivers. Also, channel catfish juveniles do not meet the percent of Max threshold in any Base Low number, as is the requirement for riffle species. However, this species does have percent of Max maintained in Base Medium and High flows.

Habitat area for the three ranges of habitat quality show distinct patterns for the Nueces River at Three Rivers. Many shallower water and run species such as weed shiner and other minnows and river carpsucker have a strong peak in optimal habitats (i.e. quality of 0.8 or higher) at lower flows with higher amounts of suitable habitat at higher flows and very little least suitable habitat at any flow. Deeper water species such as blue and channel catfish adults and smallmouth buffalo show the reverse pattern with optimal habitats peaking at higher flows, many peaking above our base flow ranges.

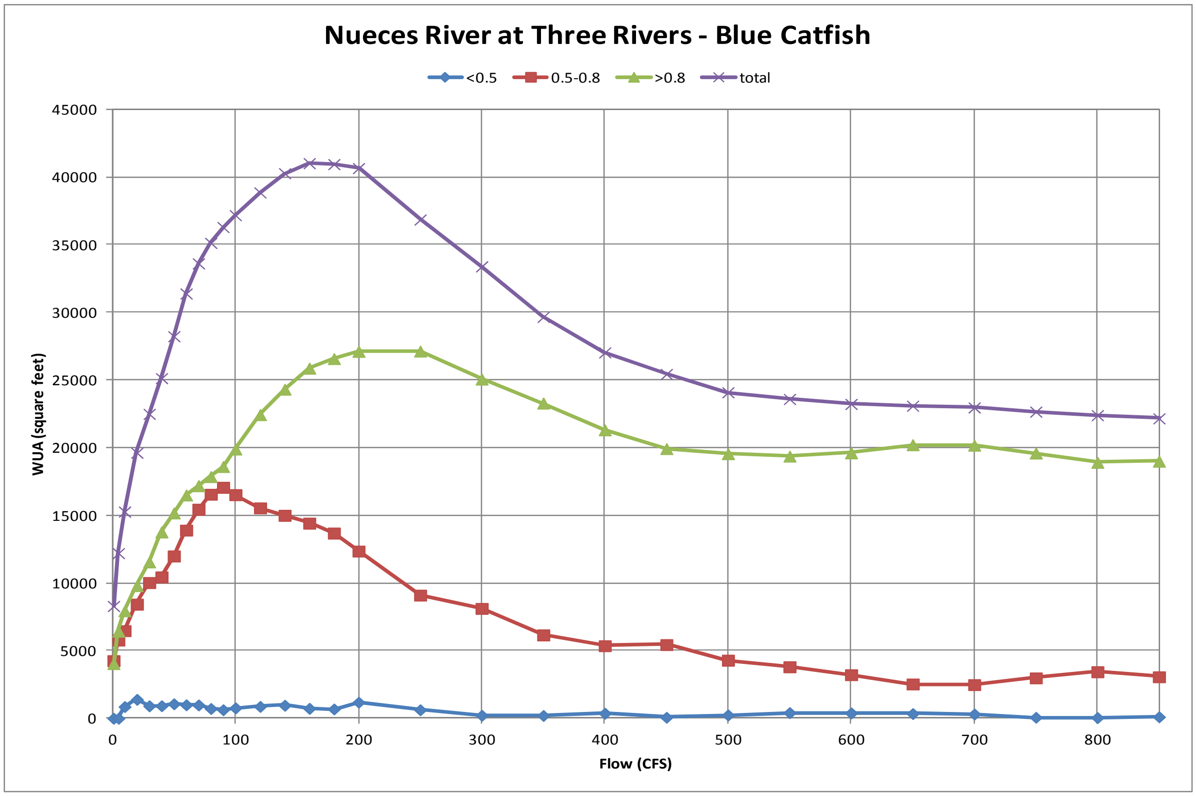


Figure 3.3.11. Four ranges of weighted usable habitat area quality (<0.5, 0.5-0.8, >0.8, and total) versus modeled flow (cfs) for blue catfish (*Ictalurus furcatus*) at the Nueces River at Three Rivers.

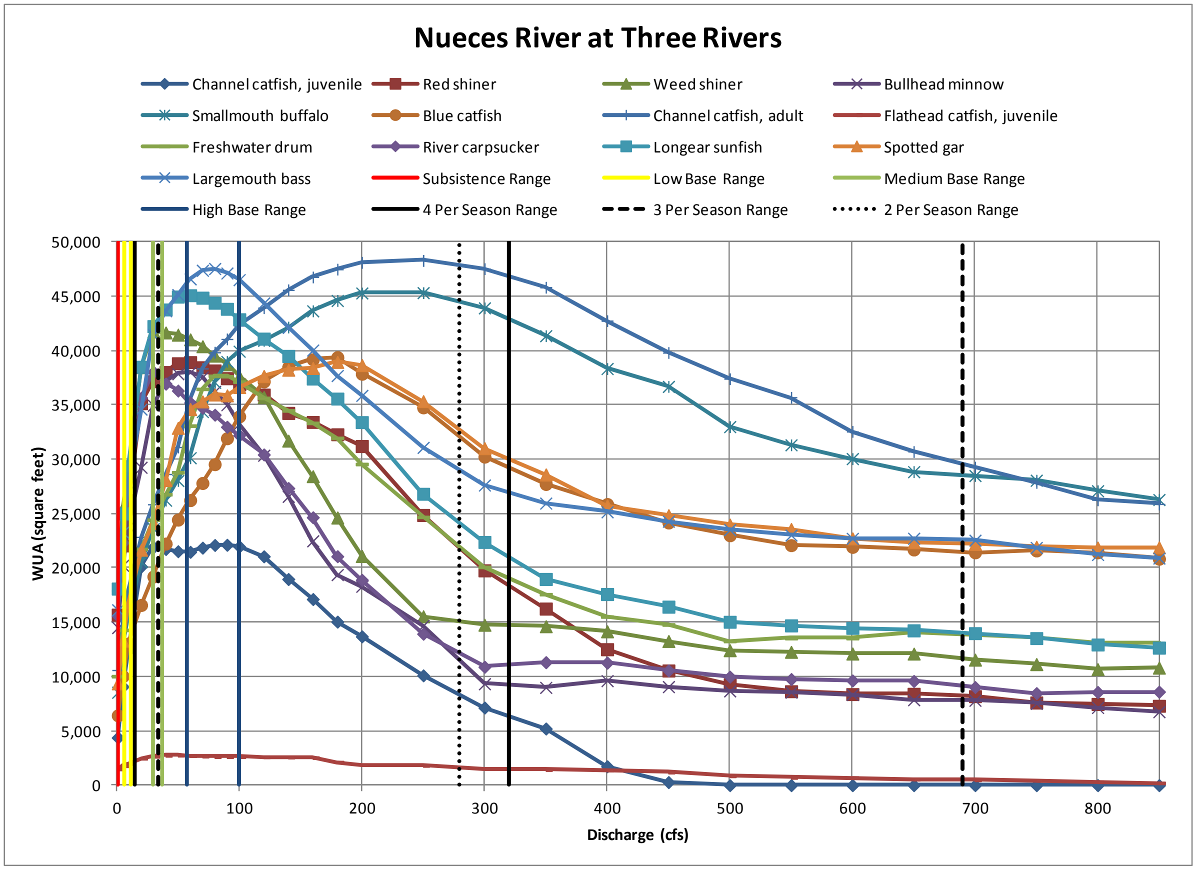


Figure 3.3.12. Weighted usable habitat area with a 0.5 minimum quality threshold versus modeled flow (cfs) for 13 focal species at the Nueces River at Three Rivers. Vertical bars bracket environmental flow regime components.

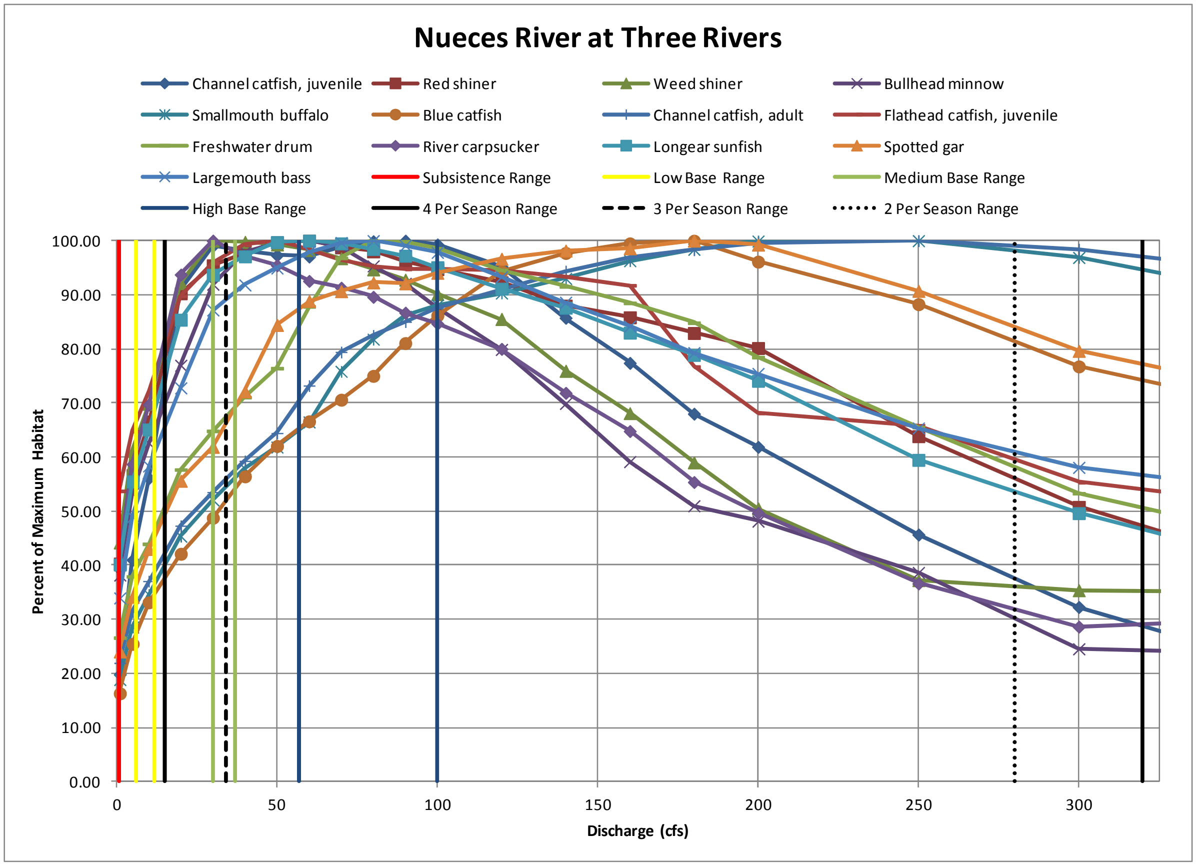


Figure 3.3.13. Percent of maximum weighted usable habitat area with a 0.5 minimum quality threshold versus modeled flow (cfs) for 13 focal species at the Nueces River at Three Rivers. Vertical bars bracket environmental flow regime components.

Table 3.3.7. Percent of maximum weighted usable habitat area with a 0.5 minimum quality threshold for 13 focal species resulting from Nueces BBEST flow recommendations at the Nueces River at Three Rivers. Shown are percentages for Subsistence and all three ranges of Base Flows. Shaded cells are those flows meeting "enoughness" thresholds of 20 percent for Subsistence flows and 75 percent for all three ranges of Base Flows.

Focal Species	Flow Component	Percent of Maximum Weighted Usable Area			
		Winter	Spring	Summer	Fall
Channel catfish, Juvenile	Subsistence	20%	20%	20%	20%
	Base-Low	63%	56%	45%	53%
	Base-Medium	98%	99%	99%	98%
	Base-High	98%	100%	97%	98%
Red shiner	Subsistence	40%	40%	40%	40%
	Base-Low	71%	67%	59%	65%
	Base-Medium	97%	97%	95%	97%
	Base-High	94%	97%	100%	99%
Weed shiner	Subsistence	44%	44%	44%	44%
	Base-Low	74%	70%	63%	68%
	Base-Medium	100%	100%	100%	100%
	Base-High	89%	94%	99%	97%

Focal Species	Flow Component	Percent of Maximum Weighted Usable Area			
		Winter	Spring	Summer	Fall
Bullhead minnow	Subsistence	38%	38%	38%	38%
	Base-Low	65%	63%	56%	61%
	Base-Medium	97%	96%	92%	96%
	Base-High	86%	94%	100%	99%
Smallmouth buffalo	Subsistence	19%	19%	19%	19%
	Base-Low	37%	35%	30%	33%
	Base-Medium	57%	56%	52%	56%
	Base-High	89%	83%	65%	74%
Blue catfish	Subsistence	16%	16%	16%	16%
	Base-Low	35%	33%	27%	32%
	Base-Medium	55%	53%	49%	54%
	Base-High	88%	77%	65%	70%
Channel catfish, Adult	Subsistence	22%	22%	22%	22%
	Base-Low	39%	37%	33%	36%
	Base-Medium	58%	57%	54%	58%
	Base-High	88%	83%	71%	78%
Flathead catfish, juvenile	Subsistence	54%	54%	54%	54%
	Base-Low	76%	72%	67%	71%
	Base-Medium	99%	98%	96%	98%
	Base-High	95%	95%	99%	97%
Freshwater drum	Subsistence	27%	27%	27%	27%
	Base-Low	47%	44%	40%	43%
	Base-Medium	70%	69%	65%	69%
	Base-High	98%	100%	84%	95%
River carpsucker	Subsistence	41%	41%	41%	41%
	Base-Low	75%	70%	62%	68%
	Base-Medium	98%	98%	100%	98%
	Base-High	84%	89%	93%	92%
Longear sunfish	Subsistence	40%	40%	40%	40%
	Base-Low	69%	65%	58%	63%
	Base-Medium	96%	96%	94%	96%
	Base-High	94%	98%	100%	100%
Spotted gar	Subsistence	24%	24%	24%	24%
	Base-Low	46%	43%	36%	41%
	Base-Medium	70%	68%	62%	69%
	Base-High	95%	92%	88%	90%
Largemouth bass	Subsistence	34%	34%	34%	34%
	Base-Low	61%	58%	51%	56%
	Base-Medium	91%	90%	87%	90%
	Base-High	97%	100%	97%	99%

Habitat frequency curves indicate the highest frequencies of habitat amounts being maintained by the post-Choke Canyon Reservoir period (**Figure 3.3.14** through **Figure 3.3.16**, Table 3.3.8). All 13 focal species increased their frequency of meeting the 75 percent "enoughness" threshold, with the average increase being 17 percent and the highest increase being 25 percent (from 30 percent to 55 percent of the time) for largemouth bass (**Table 3.3.8**). There is also a lower overall percent attainment of the 75 percent threshold at this site compared to the two Edwards Plateau sites. As with Laguna, the greatest change in the curves is for deep run and pool species (Figures 3.3.16). This is an expected result due to the generally higher base flows resulting from minimum flow levels out of Choke Canyon for delivery of water downstream to Lake Corpus Christi. A factor that may contribute to post-Choke having higher attainment frequencies is that the habitat modeling was done for the current (post-Choke) river which may represent adjusted channel geometry and characteristics relative to the pre-Choke channel. Significant changes in habitat frequencies could shift fish assemblages. For example, if largemouth bass or other piscivorous fishes prosper under post-Choke Canyon habitat conditions, prey species such as weed shiner could be negatively impacted due to increased predation.

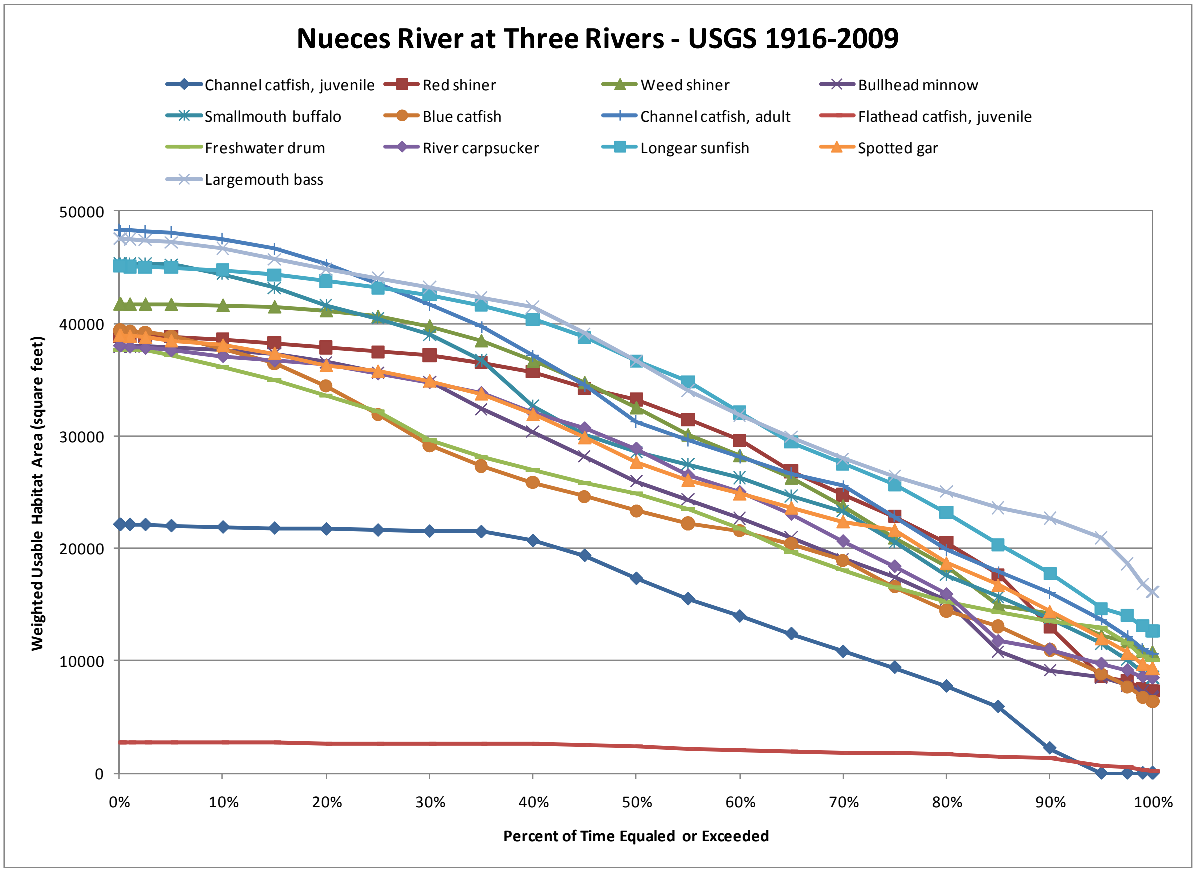


Figure 3.3.14. Habitat frequency curves for 13 focal species for the full period of record of historical flows (1916-2009) at the USGS gage at the Nueces River at Three Rivers.

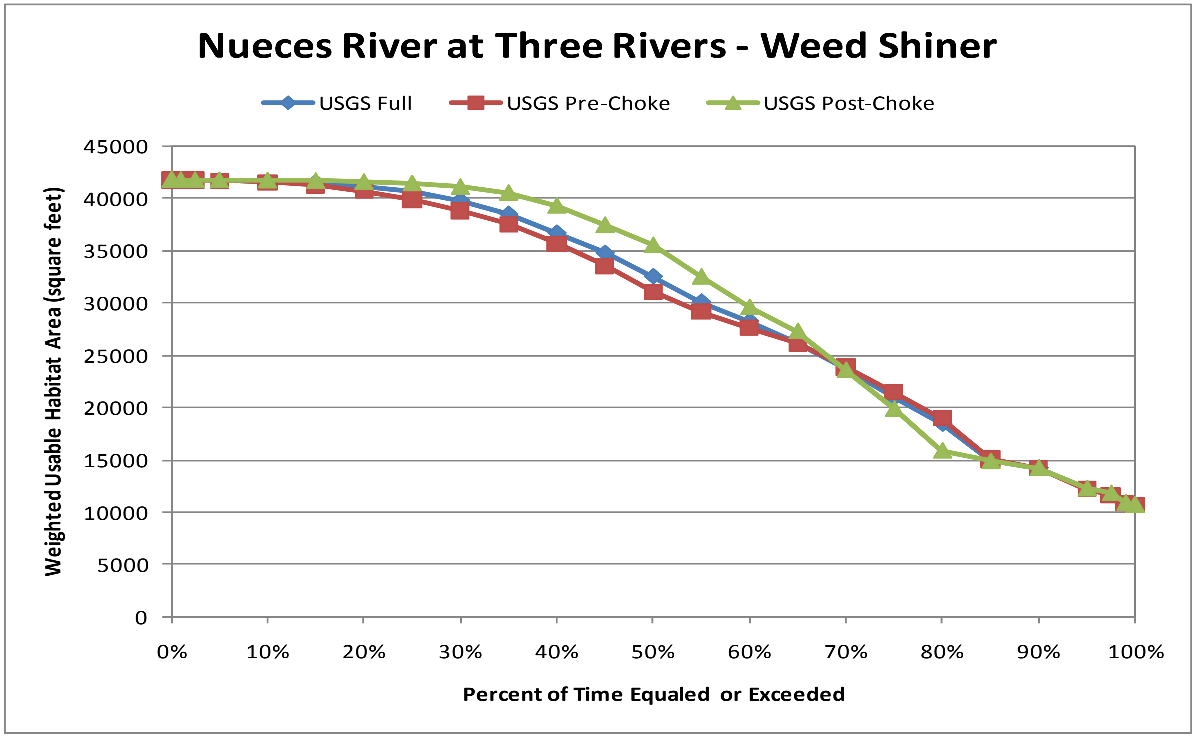


Figure 3.3.15. Habitat frequency curves for weed shiner at the Nueces River at Three Rivers for the full (1916-2009), pre- (1916-1981) and post-Choke Canyon Reservoir (1982-2009) periods.

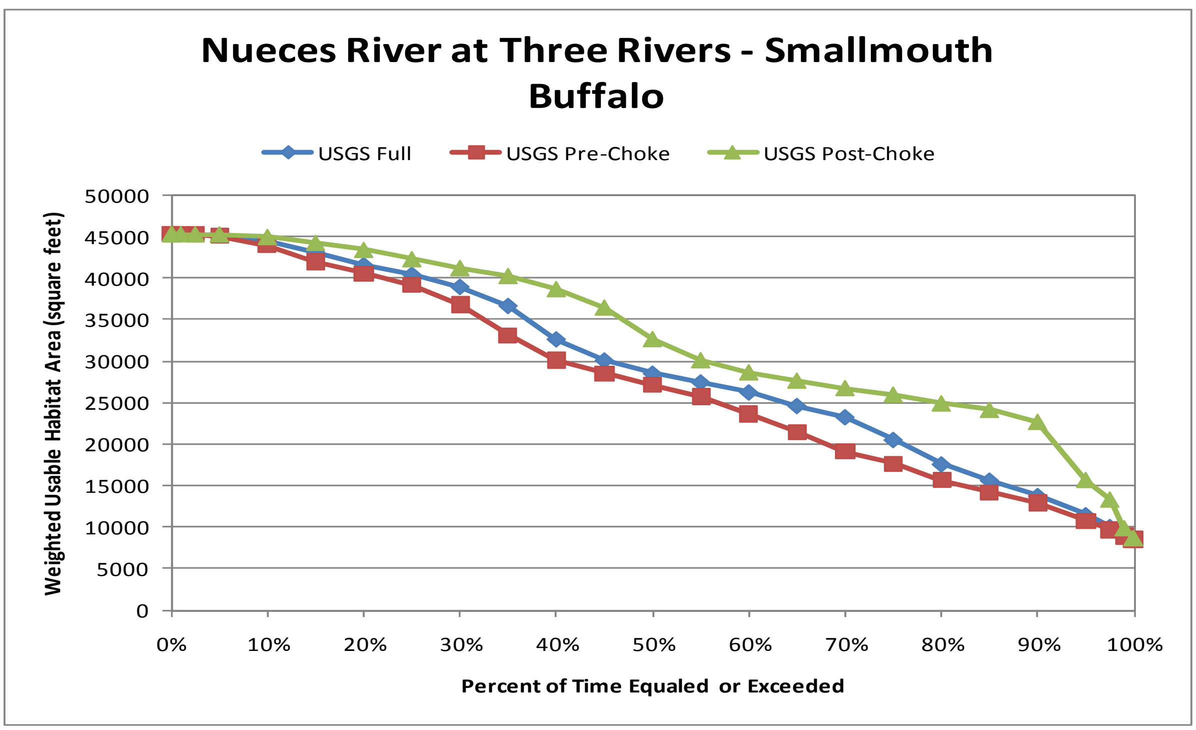


Figure 3.3.16. Habitat frequency curves for smallmouth buffalo at the Nueces River at Three Rivers for the full (1916-2009), pre- (1916-1981) and post-Choke Canyon Reservoir (1982-2009) periods.

Table 3.3.8. Percent of maximum habitat maintained by the range of percent exceedences examined for the 2 periods of record at the Nueces River at Three Rivers. For comparison, results are shown for both the pre-Choke Canyon Reservoir ("Pre") and post-Choke Canyon Reservoir ("Post") periods. Lightly shaded cells are those exceedence levels that meet the 75 percent enoughness threshold.

Percent Exceedence Level	Channel catfish, juvenile			Red shiner			Weed shiner			Bullhead minnow			Smallmouth buffalo			Blue catfish			Channel catfish, adult			Flathead catfish, juvenile			Freshwater drum			River carpsucker			Longear sunfish			Spotted gar			Largemouth bass		
	Pre	Post	Full	Pre	Post	Full	Pre	Post	Full	Pre	Post	Full	Pre	Post	Full	Pre	Post	Full	Pre	Post	Full	Pre	Post	Full	Pre	Post	Full	Pre	Post	Full	Pre	Post	Full	Pre	Post	Full	Pre	Post	Full
99.99%	0%	0%	0%	19%	19%	19%	26%	26%	26%	18%	18%	18%	19%	19%	19%	16%	17%	16%	22%	22%	22%	8%	8%	8%	27%	27%	27%	22%	22%	22%	28%	28%	28%	24%	24%	24%	34%	34%	34%
99.9%	0%	0%	0%	19%	19%	19%	26%	26%	26%	18%	18%	18%	19%	19%	19%	16%	17%	16%	22%	22%	22%	8%	8%	8%	27%	27%	27%	22%	22%	22%	28%	28%	28%	24%	24%	24%	34%	34%	34%
99%	0%	0%	0%	19%	19%	19%	26%	26%	26%	19%	19%	19%	20%	22%	20%	17%	19%	17%	23%	25%	23%	12%	14%	13%	27%	30%	28%	23%	23%	23%	29%	29%	29%	25%	27%	25%	35%	38%	35%
98%	0%	0%	0%	21%	21%	21%	28%	28%	28%	21%	21%	21%	21%	29%	22%	19%	27%	20%	24%	32%	25%	18%	19%	18%	29%	35%	31%	24%	24%	24%	31%	31%	31%	27%	35%	28%	38%	45%	39%
95%	0%	0%	0%	22%	22%	22%	29%	29%	29%	22%	22%	22%	24%	35%	25%	21%	33%	22%	27%	37%	28%	26%	26%	26%	32%	36%	34%	26%	26%	26%	32%	33%	33%	29%	43%	31%	41%	48%	44%
90%	10%	10%	10%	33%	33%	33%	34%	34%	34%	24%	24%	24%	29%	50%	30%	25%	47%	28%	31%	52%	33%	50%	50%	50%	35%	39%	36%	29%	29%	29%	39%	39%	39%	34%	56%	37%	46%	51%	48%
85%	26%	30%	27%	44%	48%	45%	36%	36%	36%	30%	26%	29%	31%	53%	35%	29%	50%	33%	34%	55%	37%	55%	55%	55%	37%	44%	38%	32%	30%	31%	44%	48%	45%	38%	60%	43%	48%	55%	50%
80%	33%	42%	35%	51%	60%	53%	45%	38%	44%	41%	39%	41%	35%	55%	39%	33%	53%	37%	37%	56%	41%	59%	64%	60%	39%	51%	40%	43%	37%	42%	50%	57%	51%	43%	63%	48%	51%	59%	53%
75%	40%	51%	43%	57%	66%	59%	51%	48%	50%	46%	45%	46%	39%	57%	45%	37%	55%	42%	41%	58%	47%	63%	67%	65%	41%	58%	44%	49%	46%	48%	55%	63%	57%	48%	65%	56%	53%	64%	56%
70%	46%	60%	49%	60%	74%	64%	57%	56%	57%	50%	50%	50%	42%	59%	51%	39%	56%	48%	44%	60%	53%	66%	69%	67%	44%	64%	48%	54%	54%	54%	59%	70%	61%	52%	67%	58%	56%	69%	59%
65%	52%	67%	56%	65%	81%	69%	63%	65%	63%	55%	57%	55%	47%	61%	54%	44%	58%	52%	49%	62%	55%	68%	76%	70%	47%	66%	52%	60%	63%	61%	63%	77%	65%	56%	70%	61%	59%	76%	63%
60%	57%	77%	63%	71%	85%	76%	66%	71%	68%	58%	63%	60%	52%	63%	58%	49%	60%	55%	54%	65%	58%	72%	87%	74%	51%	68%	58%	64%	68%	66%	67%	82%	71%	58%	75%	64%	63%	81%	67%
55%	65%	84%	70%	76%	87%	81%	70%	78%	72%	63%	70%	64%	57%	66%	61%	54%	63%	56%	57%	72%	61%	76%	93%	79%	55%	70%	62%	69%	75%	70%	72%	86%	77%	61%	78%	67%	66%	85%	72%
50%	71%	92%	78%	81%	91%	85%	74%	85%	78%	67%	77%	68%	60%	72%	63%	56%	66%	59%	61%	77%	65%	81%	94%	86%	59%	72%	66%	75%	80%	76%	77%	90%	81%	64%	83%	71%	71%	88%	77%
45%	81%	97%	88%	86%	94%	88%	80%	90%	83%	70%	85%	74%	63%	80%	66%	59%	69%	63%	64%	82%	71%	86%	95%	92%	63%	74%	69%	79%	85%	81%	81%	92%	86%	70%	86%	77%	76%	89%	82%
40%	88%	97%	93%	89%	95%	92%	85%	94%	88%	76%	91%	80%	66%	85%	72%	62%	74%	66%	71%	86%	77%	92%	95%	94%	67%	76%	72%	83%	89%	84%	86%	94%	90%	75%	89%	82%	80%	90%	87%
35%	94%	98%	97%	92%	96%	94%	90%	97%	92%	80%	93%	85%	73%	89%	81%	66%	79%	69%	78%	89%	82%	94%	96%	95%	72%	81%	75%	87%	92%	89%	90%	95%	92%	82%	91%	87%	86%	91%	89%
30%	97%	98%	97%	94%	97%	95%	93%	98%	95%	86%	94%	92%	81%	91%	86%	70%	86%	74%	83%	92%	86%	95%	97%	95%	75%	86%	79%	90%	94%	91%	92%	96%	94%	87%	92%	90%	89%	92%	91%
25%	97%	98%	98%	96%	97%	96%	96%	99%	97%	92%	96%	94%	86%	93%	89%	75%	89%	81%	87%	95%	90%	95%	97%	96%	82%	89%	85%	92%	96%	93%	95%	97%	96%	90%	94%	92%	92%	94%	93%
20%	98%	98%	98%	97%	98%	97%	98%	100%	99%	94%	98%	96%	90%	96%	92%	82%	93%	87%	91%	97%	94%	96%	98%	97%	88%	91%	89%	94%	97%	95%	96%	98%	97%	92%	96%	93%	94%	95%	94%
15%	98%	99%	98%	98%	99%	98%	99%	100%	99%	97%	99%	98%	93%	98%	95%	89%	96%	93%	95%	98%	97%	97%	99%	98%	92%	94%	93%	96%	97%	96%	98%	99%	98%	94%	98%	96%	96%	97%	96%
10%	99%	99%	99%	99%	99%	99%	99%	100%	100%	99%	99%	99%	97%	99%	98%	95%	98%	96%	98%	99%	98%	99%	99%	99%	96%	96%	96%	97%	99%	98%	99%	100%	99%	97%	98%	98%	98%	98%	98%
5%	99%	100%	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%	99%	100%	100%	98%	99%	99%	99%	100%	100%	99%	100%	100%	99%	99%	99%	99%	99%	99%	100%	100%	100%	98%	99%	99%	99%	99%	99%
3%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	99%	99%	99%	100%	100%	100%	99%	100%	100%	100%	100%	100%
1%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
0.1%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
0.01%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Summary of fish habitat modeling results and interpretation of primary findings

Overall, the flow-habitat modeling at the three sites analyzed suggests that the hydrology-based flow recommendations maintain suitable aquatic habitats for focal fish species and maintain habitat diversity. There are minor concerns with some focal species in that some species have one or more numbers below 75 percent at base flows for the Nueces River at Laguna and Three Rivers sites, but nearly all have numbers over 75 percent in both their base flow levels and biologically relevant cross-sections (i.e., riffle, pool, or run). All species, except two at Three Rivers, have over 20 percent of maximum maintained by all subsistence flows.

In general, shallow water and run species at all three sites tend to have a higher proportion of optimal habitats (i.e. quality of 0.8 or higher) at lower flows with higher proportion of suitable habitat (0.5-0.8 quality) at higher flows and least suitable (less than 0.5) somewhat constant across flows. As a result, a high proportion of the habitats for these species available in our range of base flows appear to be optimal habitat. Deeper run and pool species generally have a higher proportion of optimal habitat at higher flows with suitable flows peaking just above or within our range of base flows and with relatively little area of least suitable habitat. As a result, a high proportion of the habitats for these species available in our range of base flows are suitable habitat with optimal habitat peaking in lower tiers of high flow pulses.

Despite the fact that most species at all three sites meet our minimum percent of Max threshold, there is a general trend for most species for the Frio River at Concan and Nueces River at Laguna and many deep water species at the Nueces River at Three Rivers that the range of our base flow recommendations does not overlap the peaks of the species' flow-WUA curves. The most likely explanation for this at the Edwards Plateau sites is the shape of the river channel coupled with the uncertainty in the modeled hydraulics at the upper end of the base flow range because field measurements were made during near subsistence flows. Both channels, but particularly the Nueces River at Laguna, are broad and flat and most cross-sections do not have much area of deeper, slower habitats until much higher flows. As a result, most run and pool species curves are still on the rising limb in our base flow range. Another factor that may contribute to this is that the HSC's for some species, particularly deeper water species, were derived from habitat data from larger rivers. The result is that, because of the depth criteria, habitat in these smaller rivers does not reach optimal levels until the greater depths reached at higher flows. At the Nueces River at Three Rivers, this may have contributed to this trend for deeper water species such as smallmouth buffalo, blue catfish, channel catfish adults, freshwater drum, and spotted gar.

Another consequence of the base flow range intersecting the flow-WUA curves on the steeply rising portion of the curves is that <u>even small reductions in base flow recommendations results in significant reductions in habitat</u>. This is particularly the case for nearly all species at the two Edwards Plateau sites and for deeper water species at the Three Rivers site. Tables in Appendix 3.3.1 show the percent of maximum habitat at each modeled flow for all focal species. These tables allow examination of the percent of Max habitat for flows between 1 and 850 cfs other than the various flow levels recommended by the BBEST. For all three sites, much reduction from the range of base flows results in fewer species meeting our minimum percent of Max threshold.

Another important factor for instream habitats that our analysis does not allow examination of is the spatial arrangements of habitat across the site. This analysis only examines overall habitat area and does not include the context of connectivity and patchiness of suitable habitat. In other words, our suitable habitat may be in small, disconnected patches and higher or lower flows might be needed to connect or increase size of suitable habitat patches. In order to address this, a habitat mapping approach such as a 2-dimensional model (e.g., River2D) or MesoHabSim that produces a spatially explicit, continuous map of habitat at the site at multiple flow levels would be necessary. This should be considered in the work plan.

The habitat time series and attainment frequency analyses also generally indicate that our base and subsistence flow regime recommendations would maintain sufficient instream habitat, at least for the Nueces River at Laguna. Most species at this site would not see a major decrease in the frequency of attainment of the 75 percent of maximum WUA threshold under our recommended base flows in the example application or protected flows only scenarios. The analysis for the Nueces River at Three Rivers suggests that the current post-Choke Canyon Reservoir flow regime maintains more habitat more often than the pre-Choke Canyon flow regime and the full period of flows (which our flow regime recommendations are based on) is intermediate between the two. The primary reason for this result is not likely that the reservoir has created a more favorable river channel, but that the generally higher post Choke Canyon flows result in greater depths and more abundant deep run and pool habitat. This has likely increased habitat suitability for many of our focal species at Three Rivers because they are deeper water species. Also, some of our focal species (e.g., red shiner, bullhead minnow), like many exotic invasive species, are somewhat generalist in their habitat preferences.

It is important to consider that the increase in habitat availability and frequency is not necessarily positive when viewed in light of our definition of sound ecological environment. Specifically, such changes to the flow regime may benefit establishment of non-native species that were previously unable to establish under more variable and/or lower flow conditions. Aside from Guadalupe bass, a non-native species of conservation concern, we do not have habitat models for non-native species. Such models would be useful for evaluating potential interactions between modified flow regimes and likelihood of establishment of non-native species (most of which are adapted to relatively stable deep water habitats). Another concern worth reiterating here is that, although available habitat may have increased, its connectivity to upstream segments of the Frio River is restricted by the dam, which may have significant effects on reproductive migrations of some species.

A limitation to our analysis at Three Rivers is that we do not include focal species that are likely to be strictly riffle-dwelling species at this site. It is likely that habitat for riffle-dwelling species is less abundant in the post Choke Canyon period due to reduced riffle habitats at greater flows. Additional modeling for riffle species such as mussels or benthic macroinvertebrates should be considered in the adaptive management phase.

The transferability of this analysis to other sites cannot be reviewed because we do not have modeling data for other sites. However, there are differences in the frequency of attainment of the 75 percent of maximum habitat in the historical USGS flow records, with the Frio River at Concan having the highest attainment frequencies (70-95 percent) relative to the Nueces River at Laguna (50-80 percent) or Three Rivers sites (35-60 percent).

There are two main areas of uncertainty in this flow-habitat analysis which affect the conclusions that can be drawn from this assessment. A primary area of uncertainty is the development of habitat suitability criteria. As noted previously, our criteria for all focal species are derived from habitat data from other river basins. Many of those data are from similar stream types, but for some species the source of the data may have affected results. The ideal situation would be to have fish habitat data for all focal species from the study sites where modeling was conducted, however this was not possible and we used best available data to derive our flow-habitat relationships. In the adaptive management phase, obtaining these data is one main area where the flow habitat analysis should be strengthened and refined. Wherever possible, we should also refine the criteria to include multiple life history stages where this is of interest. For example, spawning habitats may be of particular concern for some species and for others juveniles and adults use distinctly different habitats. These factors are included in our current analysis for only two species (channel catfish and flathead catfish).

The other primary area of uncertainty that should be addressed in adaptive management is the modeling of hydraulics. Due to drought conditions and the short timeline to complete this work, we only have field data on depth and velocity from a single very low flow just above our subsistence recommendations. As a result, our contractors were not able to evaluate the accuracy of the model's extrapolations to higher flows.

In part as a result of the uncertainties described in the paragraphs above, the BBEST decided it was not appropriate to set flow regime values based on the habitat suitability analysis, but it was appropriate to conclude that HEFR-based flows support instream habitat. This uncertainty also identifies areas of future research and monitoring. In the adaptive management phase, effort should be made to revisit the cross-sections at these three sites to obtain at least one additional set of hydraulics measurements near the middle or upper end of the base flow recommendations. This would also allow evaluation of another source of uncertainty, namely the stage-discharge rating curves used at each site (see Appendix 3.3.1).

3.3.1.2 Diversity and Ecology of Freshwater Mussels

Freshwater mussels have historically dominated riverine systems of the southeastern U.S. in terms of benthic biomass (Strayer, et al., 1994; Parmalee and Bogan, 1998). The state of Texas has over fifty species of unionid mussels in multiple river basins (Neck, 1982; Howells, et al,. 1996). Unionid mussels often occur in dense multispecies beds that perform significant functional roles such as removing suspended organic material, moving sediments and providing habitat for other animals (Christian and Berg, 2000; Strayer, et al., 1997; Vaughn and Hakencamp, 2001). Mussel species are sensitive to pollution and other environmental problems, and as a result North American mussel populations have been declining for over a century with 35 species now presumed extinct and nearly 50 percent imperiled to some degree (Shannon, et al., 1993; Williams, et al., 1993; Neves, et al., 1997; Vaughn, 1997). Changes in water flow downstream of dams, channelization, and altered sediment regimes have been cited as having significant impacts on mussel diversity and abundance (Vaughn and Taylor, 1999; Williams, et al., 2008).

A total of 11 species of freshwater mussels have been collected in the Nueces River basin (Howells, 1995-2006; Howells, et al., 1996; BBEST surveys in 2010-2011; **Table 3.3.9**), including the state-listed threatened Golden Orb. Currently, the Golden Orb is being considered for federal listing by the U.S. Fish and Wildlife Service (USFWS, 2011). Most of the records come from in and adjacent to Choke Canyon Reservoir and Lake Corpus Christi (**Figure 3.3.17**). There are no records from the headwaters of the Nueces and it is likely there are no mussels there because of intermittency of water. Mussels are filter feeders that are dependent on availability of suspended food particles, and as such, require flowing water that renews food availability to survive.

Table 3.3.9. Mussel species collected from the Nueces River basin, with habitat associations and host taxa. Most data are from Howells, et al. (1996).

Species	Velocity	Substrate	Depth	Host taxa
Amblema plicata	0 - 45.7cm/s	Silt – Cobble	2.5cm - 1.5m	gar, catfish, white bass, many centrarchids
Anodonta grandis	0 - 57.9cm/s	Mud/Silt	0.3-1.5m	extensive list - see Howells, et al., 1996
Anodonta imbecillis	slow moving	Mud – Cobble	found in reservoirs	may require no host
Cyrtonaias tampicoensis	found in reserviors	Silt – Cobble	found in reservoirs	extensive list - see Howells, et al., 1996
Lampsilis hydiana	no data	Mud – Cobble	no data	unknown
Lampsilis teres	no data	Mud – Cobble	no data	gar and centrarchids
Megalonaias nervosa	standing-fast water	Silt – Boulder	< 22.4m	extensive list - see Howells, et al., 1996
Potamilus purpuratus	slow-moderate	Mud – Gravel	0.5-3m	freshwater drum
Quadrula apiculata	wide range	Mud – Cobble	< 4.6m	unknown
Quadrula aurea	found in reservoirs	Mud – Gravel	found in reservoirs	unknown
Toxolasma texasensis	still waters	Mud – Sand	< 2 m	warmouth, longear

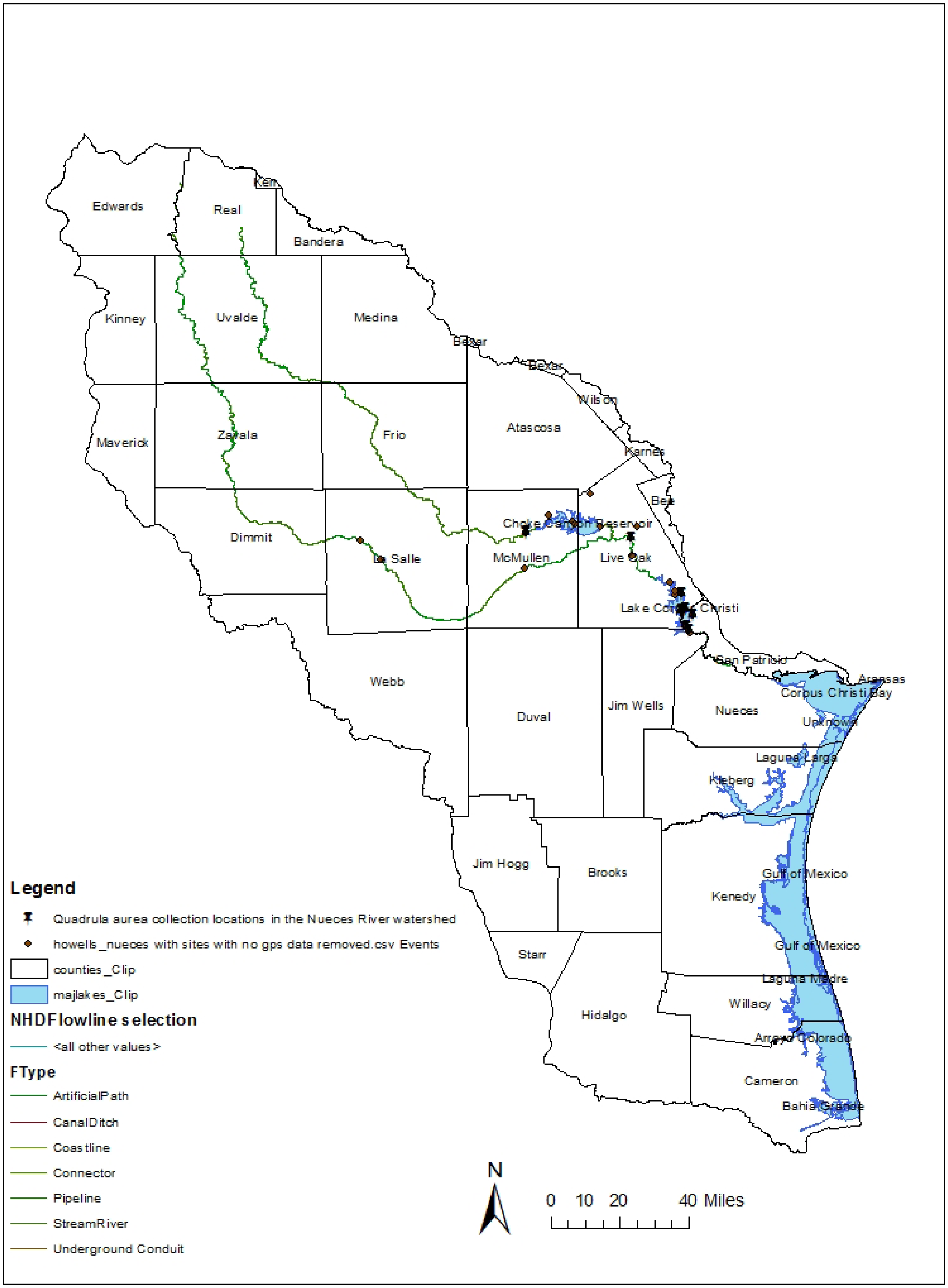


Figure 3.3.17. Collection locations for mussels in the Nueces River Basin.

Even though a number of studies have attempted to relate abiotic factors (substrate, water depth, and current) to mussel occurrence, exactly what factors cause declines have been difficult to determine. Recently, some researchers have shown that hydraulic variables are important both in the formation of beds by their influence on settling of juveniles and also in the ability of adults to survive the shear forces of the water flow (Howard and Cuffey, 2003; Morales, et al., 2006). Unionids live buried in the river sediments so the substrate and its interaction with the flow of water through their microhabitat influence formation and survival of mussel beds. The habitat requirements for many mussel species are unknown. Also, mussels have a larval stage (glochidia) that is dependent on fish hosts. For many of the species in the Nueces, the host is unknown (Table 3.3.9).

Although the BBEST did not use any mussel as a focal species, their habitat requirements of flowing water which is low in sediments make protection of base flows important. In a relatively dry basin like the Nueces, protecting multiple flow regimes would be critical to maintain healthy mussel populations.

3.3.1.3 Diversity and Ecology of Other Aquatic Macroinvertebrates

Macroinvertebrates play a critical role in the structure and function of stream ecosystems; they are the "middlemen" linking lower trophic levels on which they feed (algae, bacteria and fungi) to higher trophic levels where they serve as prey (fish, salamanders, reptiles). As such, they play an important ecological component in stream energy and nutrient cycles. Aquatic macroinvertebrates were not used as indicators of a sound ecological environment by the Nueces BBEST. This is due to the paucity of quantitative information available about this group of organisms and their relationships to stream flow within the Nueces and other river basins.

We acknowledge that our evidence of sound ecological environments does not necessarily represent the ecological soundness of all aquatic organisms, but includes this perspective on macroinvertebrates about the structure and water quality of rivers in the Nueces basin. Although 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 Nueces BBEST members believe this is justified based on the breadth of ecological life-histories of the fish focal species that reflect the primary physical habitat features within river systems, and the basic assumption that macroinvertebrates are distributed within the defined gradients of depth, velocity, and substrates (Pendergrass, 2006).

Hydrologic pattern and variability are key determinants of aquatic community structure and stability (Poff and Ward, 1989; Poff, et al., 1997; Richter, et al,. 1996; Dilts, et al., 2005). Alterations to a natural flow regime may result in decreased diversity and abundance of aquatic species inhabiting lotic systems. In addition, seasonal and interannual flow variability may benefit native species that have developed life history strategies in response to natural flows. Thus, providing a flow regime based on the natural flow paradigm should provide ecological benefits in stream systems (Dilts, et al., 2005).

Reduction in stream flows below levels necessary to maintain aquatic life and instream uses such as water quality, aquatic habitat, and freshwater inflow to bays and estuaries can be detrimental to aquatic ecosystems. While natural fluctuations in flow occur, the exacerbation of these fluctuations due to anthropogenic influences can alter or eliminate springs and streams and their associated biota. This is of particular concern where rare aquatic ecosystems and endemic species are found. For example, although endemic species and rare aquatic ecosystems are found across the state of Texas, the vast majority of the threatened and endangered aquatic ecosystems are associated with the Edwards Plateau (Bowles and Arsuffi, 1993).

Some 281 major and historical springs have been identified as existing in Texas at some time in the past (Brune, 1981). Of the original 31 large springs in Texas only 17 remain and of the four largest springs only two remain, Comal and San Marcos springs (Brune, 1981). The source of the majority of these springs is the Edwards Aquifer, one of the most prolific artesian systems in the world (USFWS, 1996). Primary threats to ecosystems dependent upon the Edwards Aquifer include reduction and cessation of flow due to over-pumping, reduced water quality, non-point source pollution, habitat modifications, the presence of several non-native species, impacts due to recreational activities, and urbanization of the river corridor (USFWS, 1996).

Stream macroinvertebrates are periodically decimated by natural disturbances, such as floods and droughts (Resh, et al., 1988). Recovery after disturbance is achieved through recolonization (Gray and Fisher, 1981).

Hynes (1970) identified the principal recolonization pathways for the benthos as eggs from aerial adults or downstream drift, upstream migration and vertical movements from below the substrate by immatures. Fisher, et al. (1982) found that most aquatic insects recolonized through aerial pathways after a spate (e.g., flash flood) in a desert mountain stream. Many of the early colonizers, such as mayflies and midges are considered opportunistic species with multivoltine (more than a generation/year) life histories believed to be disturbance coping strategies (Poff and Ward, 1989; Williams, 1996). Disturbances influence life histories and community dynamics of aquatic biota (Stanley, et al., 1994). More is known on invertebrate response to flooding (Gray and Fisher, 1981), than drought and intermittency.

Flow regime plays a major role in structuring habitat conditions for stream macroinvertebrates through direct effects, as well as interaction with substrate, food supply and physico-chemical parameters (Ward, 1992). In streams with highly variable or unpredictable flow regimes it is expected that abiotic factors play a more important role in structuring the macroinvertebrate community; whereas in streams with a more predictable discharge pattern, biotic interactions such as predation and competition become more important (Peckarsky, 1983; Ward and Stanford, 1983; Resh, et al., 1988; Poff and Ward, 1989). In perennial streams and intermittent streams with less prolonged periods of drying, abiotic factors such as flooding frequency and predictability structure the macroinvertebrate community; whereas in streams fed by groundwater there is a greater importance of biotic interactions and moderate disturbance from flooding facilitates the coexistence of species (Ward and Stanford, 1983). Diversity can be suppressed by disturbances that are severe or frequent (Ward and Stanford, 1983). High biotic diversity of natural streams is a function of moderate perturbation, maintained by species replacement as changing environmental conditions favor different assemblages of species (Patrick, 1970; Ward and Stanford, 1983). As stability increases, biotic interactions such as predation and competition may increase in importance (Death and Winterbourn, 1995).

Numerous studies show significant effects of hydrologic variability on benthic stream communities (Fisher, et al., 1982; Miller and Golladay, 1996; Paltridge, et al., 1997; Filho and Maltchik, 2000). In addition to altering the flow regime, urban runoff may contain non-point source pollutants such as metals, organic hydrocarbons, nutrients and sediment (Lemly, 1982; Lenat, 1988; Sponseller, et al., 2001). Scoggins (2001) shows that antecedent hydrologic conditions (drought and flood) have marked effects on the results of rapid biological assessments (RBA; Barbour, et al., 1999), and therefore do not necessarily reflect degradation due to non-point source pollutants. These antecedent hydrologic conditions affect the community structure and life history tactics of aquatic insects (Resh, et al., 1988; Feminella, 1996).

Droughts have marked effects, direct and indirect, on macroinvertebrate densities, taxonomic composition, diversity, and overall ecosystem processes (Boulton, 2003; Lake, 2003). Direct effects of drought include decreased flow, reduced habitat, alteration of water quality and lack of habitat connectivity (Lake, 2003). Indirect effects include reduced water quality, reduced food resources and alteration of biotic interactions such as predation and competition (Lake 2003). As water level declines shallow sections, including riffles, are the first to go dry and there is an increase of lentic habitat, which will favor some species over others (Lake, 2003).

In general the response to seasonal drought is both high resistance and high resilience with rapid recovery following drought in most aquatic environments where recolonization from refugia is unimpeded and habitat recovery occurs (Resh, et al., 1990; Boulton and Lake, 1992; Stanley, et al., 1994; Boulton, 2003; Lake, 2003). Mechanisms of resistance to drought conditions include: 1) desiccation resistant life stages; 2) life history adaptation; 3) physiological mechanisms; and 4) behavioral adaptations (Williams, 1996; Magoulick and Kobza, 2003). Size, duration and interspersion of residual pools and macroinvertebrate community analysis in terms of resistance and resilience of Nueces River Edwards Plateau intermittent streams such as the West Nueces at Bracketville, Leona, Sabinal at Sabinal, and Hondo Creek is warranted.

Flooding also has severe impacts on macroinvertebrate communities due to substrate movement and associated dislodgement, scouring, and abrasion (Ward, 1992; Townsend and Scarsbrook, 1997; Collier and Quinn, 2003). Flooding negatively affects macroinvertebrate communities by reducing densities, diversity, and abundances (Fisher, et al., 1982; Molles, 1985; Miller and Golladay, 1996; Shivoga, 2001). Mechanisms of resistance to flooding include: 1) instream refugia; 2) nearby stream refugia; 3) morphological adaptations; 4) life history adaptation; and 5) behavioral avoidance (Lancaster and Belyea, 1997; Collier and Quinn, 2003).

Stability of a community is measured by its resistance and resilience, where resistance is ability to resist change and resilience is the rate of recovery following disturbance (Miller and Golladay, 1996; Lake, 2003). A stable benthic macroinvertebrate community is one which is highly resistant, highly resilient, or both (Miller and Golladay, 1996). Recovery after disturbance is the re-establishment of community structure and function to pre-disturbance conditions and is accomplished by organisms through downstream drift, aerial adults, and from instream refugia (Williams and Hynes, 1976; Miller and Golladay, 1996). The severity of disturbance, predominant recolonization pathways and distance from refugia varies among watersheds and will influence time to recovery, and subsequent taxonomic composition and abundances (Delucchi, 1988; Miller and Golladay, 1996; Filho and Maltchik, 2000).

The macroinvertebrate community is generally highly resistant and resilient to drought, if the stream has drought resistant taxa present (i.e. capable of recolonization upon rewetting, or surviving in the hyporheos ("under the river", substrate - gravel, cobble sediment - materials occurring at depths below the bottom of the river) or intermittent pools), whereas resistance to flooding is low and resilience high (Stanley, et al., 1994; Miller and Golladay, 1996). Filho and Maltchik (2000) suggested that benthic macroinvertebrate community structure had greater resistance to drought than flooding because flooding is less predictable and more sudden in onset. Although macroinvertebrate densities have low resistance and resilience to flood disturbance, taxonomic composition has high resistance and resilience (Miller and Golladay, 1996). This ability of taxonomic composition to remain intact is an important mechanism of recovery to pre-disturbance conditions following drought and flood (Miller and Golladay, 1996).

Apse, et al. (2008) used hypotheses developed from the ecological literature on macroinvertebrates to examine the relationship between increasing water withdrawals and macroinvertebrate metrics, based on the relationship between each metric and disturbance in general. For example, they expected taxonomic richness to decrease with increasing disturbance; i.e. taxonomic richness to decrease with increasing water withdrawals. They also conducted a literature survey to construct hypotheses of the relationships between water withdrawals and functional traits of invertebrate assemblages. Examples of hypotheses of responses of aquatic insects to water withdrawals, diversions, and/or extended periods of low and extreme low flows were:

- Decreased diversity (number of taxa) of grazers and shredders (McKay and King, 2006). This is equivalent to an increase in generalist feeders (collector-gatherers).
- Increase in the abundance of individuals with small body size at maturity (Richards, et al., 1997; Rader and Belish, 1999).
- Decrease in the abundance and number of taxa that are rare in the drift (species rare in the drift could not replenish lost populations when more favorable flow conditions were present; this is equivalent to an increase in abundance of invertebrates common in the drift) (Rader and Belish, 1999).
- Increase in abundance and number of taxa that are multivoltine (Richards, et al., 1997).
- Increase in abundance and number of taxa that are obligate depositional (Richards, et al., 1997).
- Increase in abundance and number of taxa with high thermal tolerance (eurythermal); decrease in abundance and number of taxa that are cold stenothermal - adapted to narrow range of cold temperatures (Lake, 2003).

Use of a hypothesis driven assessment of the natural flow regime, including spates, drought, and water withdrawals on the structure and function of benthic macroinvertebrate communities is a productive avenue of research for rivers in the Nueces River Basin in further defining a sound ecological environment.

Existing Case Studies and Species of Concern for the Nueces Basin

As part of an impairment verification monitoring project, Ecological Communications Corporation (Walther and Palma, 2004) conducted biological data collections and analyses for the Upper Frio River (Segment 2113). The biological data considered included macroinvertebrates. Segment 2113 appears on the State of Texas' 303(d) list as impaired for exceptional aquatic life based on low dissolved oxygen concentrations previously identified by the TCEQ. Segment 2113, the Upper Frio River, is formed by the union of the East and West Frio Rivers in Real County, and extends 47 miles downstream to just above the crossing at U.S. Highway 90 in Uvalde

County. Rapid Bioassessment Protocol generally resulted in scores that indicate that this reach of the Frio River supports "High" aquatic life use and scores ranged from high to exceptional aquatic life use.

Macrobrachium ohione, commonly known as the Ohio shrimp or Ohio River shrimp, is a species of freshwater shrimp found in rivers throughout the Gulf of Mexico and Atlantic Ocean drainage basins and has been reported from the Nueces River, below Lake Corpus Christi Dam (Bowles and Aziz, 2000). Bowles and Aziz (2000) noted reasons for decline among populations of river shrimp are varied and include river impoundment and destruction of riverine habitat, water quality degradation, diminished stream flows, competition and predation from exotic species. River impoundment in particular may negatively impact river shrimp by stopping upstream migration necessary for completion of their amphidromous (moving from freshwater rivers to and from saltwater bays and estuaries to reproduce) life cycle. River shrimp migrate from the river downstream to the estuary during spring flow pulses and juvenile shrimp return to the river from the estuary during the summer when flows are low (Reimer, et al., 1974). According to Reimer, et al. (1974), salinities near 15 may act as a barrier to the movement of *M. ohione* into the spawning grounds of the species in Galveston Bay, Texas. Thus, diminished fresh-water inflows into estuaries may result in higher salinities and possibly increased larval mortality for these species. The role of Choke Canyon Dam and freshwater inflows to Corpus Christi Bay on this river shrimp in the Nueces basin warrants further study.

3.4 Water Quality

The BBEST reviewed water quality information obtained from the TCEQ for Nueces basin streams to identify relationships between flow and water quality. TCEQ manages water quality data collected by different agencies for streams across the state. These data are collected using quality assured methods to ensure their accuracy and are stored in the TCEQ's Surface Water Quality Monitoring Information System database. The TCEQ uses these data to check if bodies of water are meeting water quality criteria and designated uses.

The state's surface water quality standards (TCEQ, 2011a), set by the TCEQ and approved by the U.S. Environmental Protection Agency, set water quality criteria and desirable aquatic life uses for many of the state's water bodies, including streams in the Nueces Basin. For example, the dissolved oxygen water quality criterion for the Nueces River at Cotulla is 5 mg/L as a minimum daily average with a minimum instantaneous value in a day not dropping below 3 mg/L and not remaining below 5 mg/L for more than 8 hours. This standard should protect "high aquatic life use" in this portion of the Nueces River. "High aquatic life use" means the biological community in the stream contains (relatively speaking):

- Many different species with different feeding habits (ex. predators, filter feeders, etc.);
- Regionally expected species; and
- Species sensitive to environmental stress.

TCEQ assesses water quality every two years to evaluate compliance with water quality criteria and desired uses. The most recent assessment was completed in 2010 (TCEQ, 2011b) (**Table 3.4.1**). Concerns described in Table 3.4.1 include variables which may almost be exceeding water quality criteria or which are exceeding screening levels. For example, there is a concern that the Nueces River at Cotulla is not meeting its water quality standard of 5 mg/L for dissolved oxygen. This means that during the 7 years of data from this location reviewed for the assessment, some instantaneous measurements of oxygen were below 5 mg/L but none were less than 3 mg/L. Although the TCEQ has not established criteria for chlorophyll-*a*, nitrate, or phosphorus, it has established screening level concentrations. For example there is a concern for high chlorophyll-*a* in the Nueces River at Mathis. TCEQ has a chlorophyll-*a* screening criterion of 14.1 µg/L. The chlorophyll-*a* measurements from the Nueces River at Mathis had an average chlorophyll-*a* concentration of 21.8 µg/L during the 7-year assessment period. Chlorophyll-*a* represents amounts of microscopic plants (algae) in the water. High levels of chlorophyll-*a* are indicators of elevated nutrient concentrations (N and P) and of oxygen levels that have the potential to drop to harmful levels.

Table 3.4.1. 2010 water quality assessments conducted by TCEQ for streams in the Nueces Basin (TCEQ, 2011c; TCEQ, 2011d).

Location	Impairment	Year Impairment/ Concern Identified	Potential Sources of Impairments and Concerns
Nueces Bay	Zinc in oysters. Concern for iron in sediment and bacteria at recreational beaches.	2010	Past industrial wastewater discharge. Sources for concern not identified.
Nueces River tidal (as it enters Nueces Bay)	Concern for high chlorophyll-*a* (not impaired).	2010	Nonpoint source and unknown
Nueces River at Mathis	Concern for high chlorophyll-*a* (not impaired).	2010	Nonpoint source and unknown
Nueces River at Tilden	Impaired fish and impaired macrobenthic community.	2010	Nonpoint source and unknown
Nueces River at Three Rivers	Elevated total dissolved solids. Concern for high chlorophyll-*a* (not impaired).	2006	Nonpoint source and unknown
Nueces River at Cotulla	Concern identified for low dissolved oxygen (not impaired).	2010	Nonpoint source and unknown
Nueces River at Laguna	Concern identified for impaired fish community.	2010	Nonpoint source and unknown
Atascosa River at Whitsett	Elevated bacteria[1], depressed dissolved oxygen[2], impaired fish community[2], and impaired macrobenthic community[2]. Concern for high chlorophyll-*a*, nitrate, and possibly impaired habitat (not impaired).	1996 for bacteria and dissolved oxygen, 2006 for impaired fish community, 2010 for impaired macrobenthic community	Municipal wastewater discharge for dissolved oxygen, impaired fish community, and habitat; nonpoint source and unknown for other concerns
San Miguel Creek	Elevated bacteria. Concern for high chlorophyll-*a* and low dissolved oxygen (not impaired).	2006	Nonpoint source and unknown
Leona River	Elevated bacteria. Concern for high nitrate (not impaired).	2006	Municipal wastewater discharge for nitrate, nonpoint source for bacteria
Sabinal River below the Edwards Outcrop	Elevated nitrate.	2002	Municipal wastewater discharge for nitrate
Frio River at Concan	Impaired fish community and impaired macrobenthic community. Concern for possibly impaired habitat (not impaired).	2006	Nonpoint source and unknown
Frio River at Derby	Elevated bacteria. Concern for high nitrate (not impaired).	2008	Nonpoint source and unknown
Hondo Creek at Tarpley	Concern for high nitrate (not impaired).	2010	Not identified
Oso Creek near Corpus Christi	Elevated bacteria. Concern for high nitrate, total and orthophosphorus, low dissolved oxygen and chlorophyll-*a*.	2002	Municipal wastewater discharge, urban runoff/ storm sewers
San Fernando Creek near Alice	Elevated bacteria. Concern for nitrate, and total and orthophosphorus.	2006	Municipal wastewater discharge, septic tanks, and nonpoint sources
Baffin Bay	Concern for high chlorophyll-*a* and iron in sediment.	2010	Nonpoint source
Oso Bay	High bacteria for contact recreation and for oyster waters and low dissolved oxygen. Concerns for high chlorophyll-*a* and total phosphorus.	2004 (bacteria); 1996 (low dissolved oxygen)	Urban runoff/storm sewers
Unnamed tributary of Oso Creek	Concern for high total and orthophosphorus.	2010	Not identified
West Oso Creek	Concern for high total phosphorus.	2010	Not identified
Corpus Christi Inner Harbor	Concern for high ammonia, nitrate, and iron in sediment.	2010	Point source discharges, urban runoff, and storm sewers
Corpus Christi Bay	Elevated bacteria at recreation beaches. Concerns for high iron in sediment.	2010	Not identified

[1] These impairments and concerns are for one reach of the Atascosa River
[2] These impairments and concerns are for another reach of the Atascosa River

The BBEST compared assessments in Table 3.4.1 to its charge of determining if streams selected by the BBEST had acceptably sound environments in the context of their flow regimes. The following impairments and concerns are not believed to have significant relationships between flow and environmental health.

- Bacteria impairments identified for the Atascosa River, San Miguel Creek, Leona River, Frio River at Derby, Oso Creek, and San Fernando Creek are based on bacteriological criteria set to protect humans swimming in those water bodies from diseases. Bacterial criteria are not intended to protect fish, other aquatic organisms, and riparian zone communities and are not indicators of the health of those parts of the stream environment. Therefore, the BBEST did not consider elevated bacteria in determining environmental flow regimes.
- Elevated total dissolved solids (salt) impairment in the Nueces River at Three Rivers is based on criteria to protect raw drinking water supplies from salt levels too high for raw drinking water supplies. Elevated salt in this portion of the Nueces River probably results in part from drainage from naturally saline soils in the Middle Nueces Marsh between Cotulla and Tilden (USDA, 1994). Salt measurements in the Nueces River at Cotulla averaged 680 µSiemens/cm (a measure of salt) while salt averaged twice as much, 1,380 µSiemens/cm, downstream at the Nueces River at Tilden. When the weather is dry, evaporation high, and there is little or no flow in this stretch of the river, salt levels probably increase naturally. Conversely, salt levels decline naturally when flows are high. It is believed the riparian and aquatic communities have adapted to this natural variation in salt levels.
- Nueces Bay oysters have levels of zinc too high for safe human consumption. Zinc was discharged by an industrial facility years ago next to the bay. Since the zinc discharge has stopped, zinc levels are expected to decline naturally over time. Zinc is not known to harm the oysters.
- Elevated levels of nitrate, phosphorus, and chlorophyll-*a* in some cases result from municipal wastewater discharges, nonpoint sources of pollution, and septic tanks. High chlorophyll-*a* may be caused by excess levels of nitrogen and phosphorus. Elevated chlorophyll-*a* represents high concentrations of microscopic plants in the water which can increase photosynthetic production of oxygen. Although photosynthesis is an important source of oxygen, high concentrations of algae can use much of the dissolved oxygen at night when they are respiring. As a result oxygen levels can decline to levels harmful to fish during the night as high concentrations of algae stop producing oxygen and continue using it, together with microbial respiration associated with decaying organic matter. These conditions are more likely to be exacerbated when flows are low, nutrients and algae are concentrated, and temperatures are high (hotter water has lower ability to contain oxygen than does cold water and higher thermal conditions increase metabolic activity of hetertrophic microorganisms, algae and ectotherms, like fish).

Impaired fish and macrobenthic communities were assessed at four sites: Nueces River near Laguna and Tilden, Frio River near Concan, and Atascosa River near Whitsett. Because these impairments may indicate an unsound environment at these sites, the BBEST discussed these assessments with TCEQ staff. The original field work upon which some of the assessments were based was done in 2003 or 2004. TCEQ's Total Maximum Daily Loads program decided to do more biological testing which finished in 2011. The additional work consists of use attainability analysis. Possible outcomes of this new field work are:

- The original designated use of high (Nueces and Atascosa) or exceptional (upper Frio) aquatic life uses may be determined to be appropriate, but the analysis originally used to determine use impairment may not have been adequate;
- The original designated use may be determined to have been appropriate and achieved (overriding the original determination from the 2003-2004 work);
- The original designated use may be determined to have been inappropriate which might or might not change the original interpretation of use impairment; or
- The original designated use may be determined to be appropriate and not achieved (current status).

At this time, TCEQ's interpretation is that the possible impairments are not related to changes in flow regime for these sites.

Comparison of Flow to Dissolved Oxygen and Temperature

The BBEST's analysis focused on relationships between flow and dissolved oxygen, and flow and temperature because of the critical roles those two variables play in maintaining healthy streams. The BBEST intended to see if flow changes negatively impacted stream health by changing dissolved oxygen and temperature. Analysis was conducted at all sites (Appendix 3.4.1).

Water quality data from the TCEQ used by the BBEST extended from 1968 through August 2010 although data for some sites was only collected for a relatively short period of this time (TCEQ, 2010). Daily average flow data for this analysis was obtained from the USGS for the sites and dates at which dissolved oxygen and temperature measurements were made (USGS, 2011). Data were reviewed to determine where measurements suggested water quality standards for dissolved oxygen and temperature may not have been met (**Table 3.4.2**).

Table 3.4.2. Water quality criteria, dissolved oxygen, and temperature data review for Nueces Basin streams. Shaded cells represent sites where there was one or more dissolved oxygen values below the daily average dissolved oxygen value or where one or more temperature values exceeded the maximum temperature value.

Location (station identifiers)	Period of Record for Water Quality Data	Dissolved oxygen (water quality criteria for dissolved oxygen, mg/L)	Temperature (water quality criteria for temperature, °F)	Desired aquatic life use
Nueces River at Laguna (12999, 13000, 13005, 16704)	1972-2010	No data below 5.0	No data above 90	High
West Nueces River at Brackettville	No data	Considered intermittent with perennial pools. Assumed limited aquatic life use with 3.0 mg/L as a minimum daily average with the minimum in a day not dropping below 2 mg/L and not remaining below 2 mg/L for more than 8 hours.[1]		
Nueces River at Uvalde (12997, 14253, 17438)	1968-2004	No data below 5.0	No data above 90	High
Nueces River at Cotulla (12995)	1972-1987	2.3 minimum (5.0)	No data above 90	High
Nueces River at Tilden (12973, 12974, 17897)	1972-2010	2.1 minimum (5.0)	No data above 90	High
Nueces River at Three Rivers (12979, 20701)	1968-2010	No data below 5.0	No data above 90	High
Nueces River at Mathis (12964)	1978-2010	No data below 5.0	No data above 91	High
Frio River at Concan (13006)	1972-2010	No data below 6.0	No data above 90	Exceptional
Dry Frio River at Reagan Wells (13661)	1982-2001	Considered intermittent with perennial pools. Has limited aquatic life use with 3.0 mg/L as a minimum daily average with the minimum in a day not dropping below 2 mg/L and not remaining below 2 mg/L for more than 8 hours.[1]		
Frio River at Derby (13024, 12035)	1972-2010	1.1 minimum (5.0)	No data above 90	High
Frio River at Tilden (13023)	1972-2010	1.3 minimum (5.0)	No data above 90	High
Sabinal River near Sabinal (12994, 14939)	1973-2010	No data below 5.0	No data above 90	High
Sabinal River below the Edwards Outcrop (12993)	1968-2010	No data below 5.0	No data above 90	High
Hondo Creek at Tarpley (13010)	1975-2010	No data below 5.0	96.8 maximum (90)	High
Seco Creek (13012-13018, 13729, 13730)	1975-2010	No data below 5.0	96.8 maximum (90)	High
Leona River at Uvalde (12986-12990, 12992, 18418)	1974-2010	3.0 minimum (5.0)	No data above 90	High
San Miguel Creek at Tilden (12983, 12984)	1972-2010	1.2 minimum (5.0)	No data above 95	High
Atascosa River at Whitsett (12980)	1968-2010	2.9 minimum (5.0)	No data above 90	High
Oso Creek in Corpus Christi (13028, 13029)	1971-2010	0 mg/L dissolved oxygen minimum for Oso Creek. Considered perennial. Has high aquatic life use with 5.0 mg/L as a minimum daily average with the minimum in a day not dropping below 4 mg/L and not remaining below 4 mg/L for more than 8 hours.[1]	97.8°F in Oso Creek.	
San Fernando Creek near Alice (15975-15977)	1997-2003	3.1 mg/L dissolved oxygen minimum Considered perennial. Has high aquatic life use with 5.0 mg/L as a minimum daily average with the minimum in a day not dropping below 4 mg/L and not remaining below 4 mg/L for more than 8 hours.[1]		

[1] Site-specific water quality criteria have not been established for these streams.

Streams with low dissolved oxygen measurements are illustrated in **Figure 3.4.1**. Nine sites had dissolved oxygen measurements below their water quality criteria and six of the sites are intermittent. Seven sites are in the South Texas Brush Country and two are in the Coastal Plain. The six streams that are intermittent are Nueces River at Cotulla and Tilden, Frio River at Derby, Frio River at Tilden, San Miguel Creek, and Dry Frio River at Reagan Wells. The three perennial streams, Atascosa River, Oso Creek, and San Fernando Creek, with occasional low oxygen levels had lows flows, less than or equal to 1.2 cfs at least 10 percent of the time. Statistically significant relationships between flow and dissolved oxygen were not found at any sites. However, a pattern of low dissolved oxygen at low flow was observed at several stations. **Figure 3.4.2** shows dissolved oxygen measurements in the Nueces River at Cotulla. All dissolved oxygen measurements below 4 mg/L at this site were measured when daily average flow was less than 2 cfs. At the nine sites, low dissolved oxygen values occurred most frequently in warmer months from May through September.

Four streams, Hondo Creek, Seco Creek, Nueces River at Three Rivers, and Oso Creek, had temperatures above water quality criteria (**Figure 3.4.3**). Hondo and Seco creeks flow over wide, limestone bedrock channels that are not shaded by riparian vegetation. Water depth is relatively shallow at flows within the range of the base flows. Shallow water in a wide channel without shading contribute to the high temperatures measured at these two locations (**Figure 3.4.4**). The recommended base flow regime values for Seco Creek are less than or equal to 7 cfs. The highest temperatures occurred at 3 cfs. Seco, Hondo, and Oso creeks have relatively low flows with at least 10 percent of flows less than or equal to 1.2 cfs. The three high temperature observations in the Nueces River at Three Rivers occurred between 1982 and 1985 after completion of Choke Canyon dam in 1982 and before the reservoir filled in 1987. It is possible those high temperatures were associated with relatively long periods of low flow. The three high temperatures occurred at flows less than 23 cfs, less than the lowest medium base flow recommended for this site.

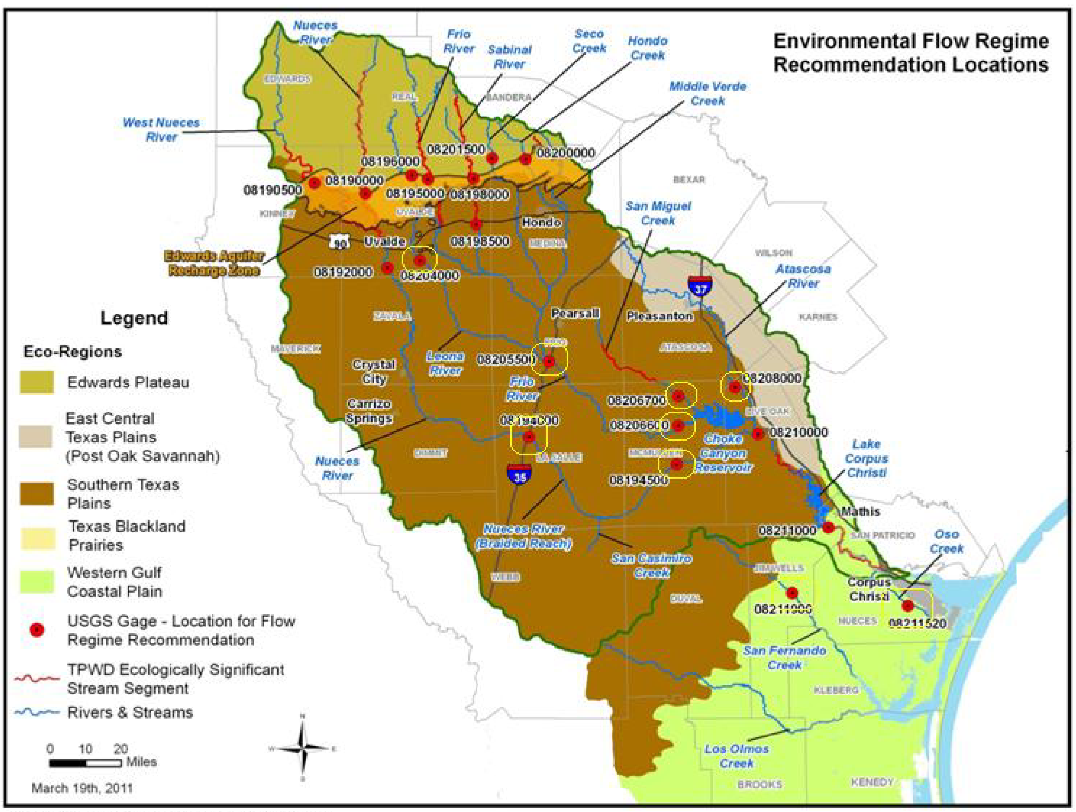


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Figure 3.4.1. Stream sites with low dissolved oxygen in the Nueces Basin.

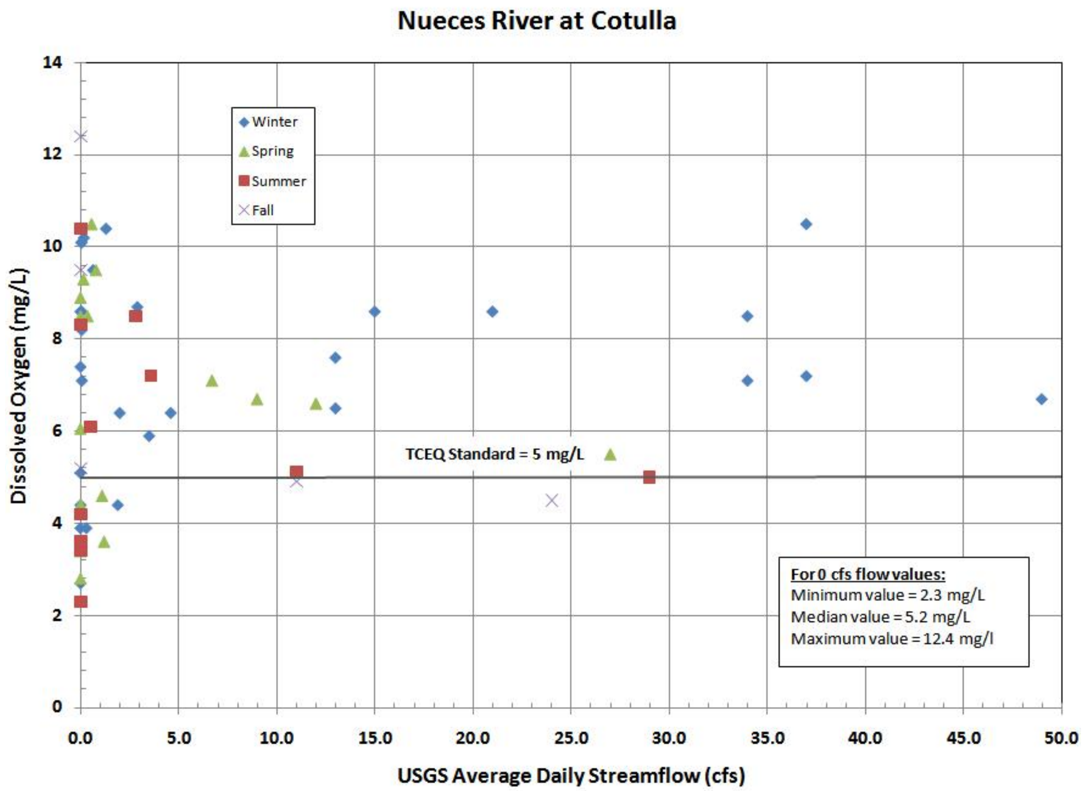

Figure 3.4.2. Flow and dissolved oxygen in the Nueces River at Cotulla from 1972-1987.

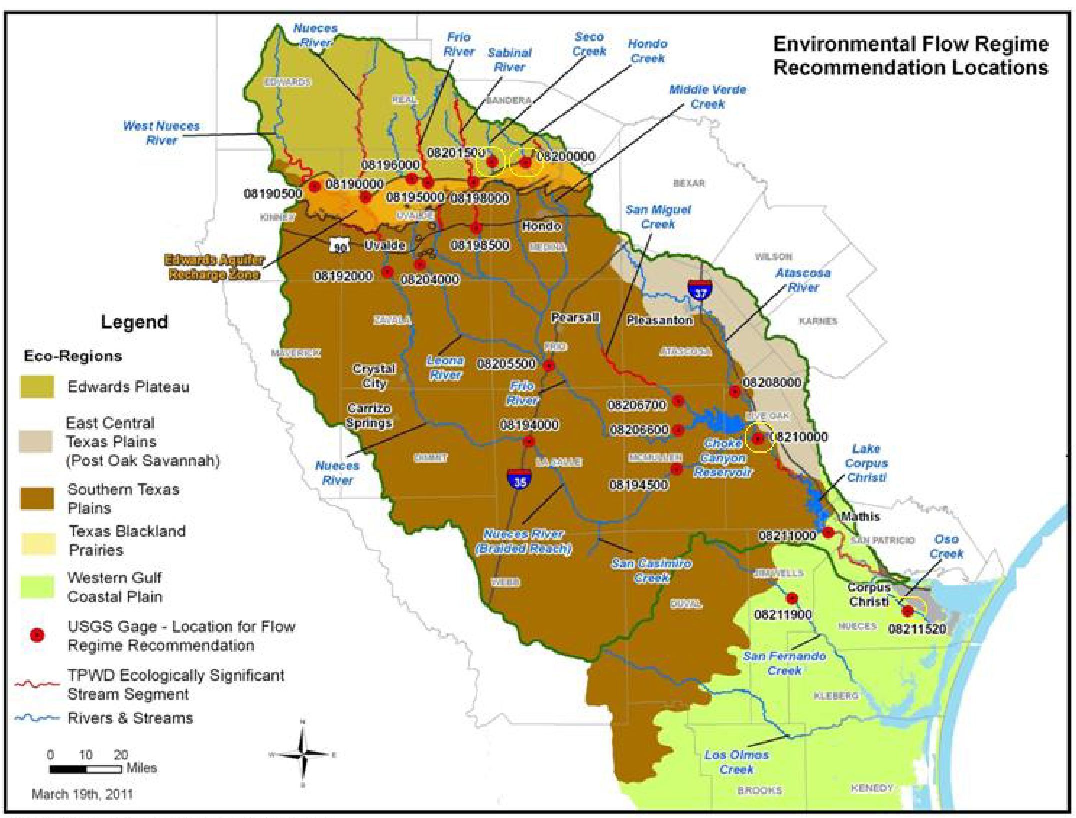

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Figure 3.4.3. Stream sites with high temperatures in the Nueces Basin.

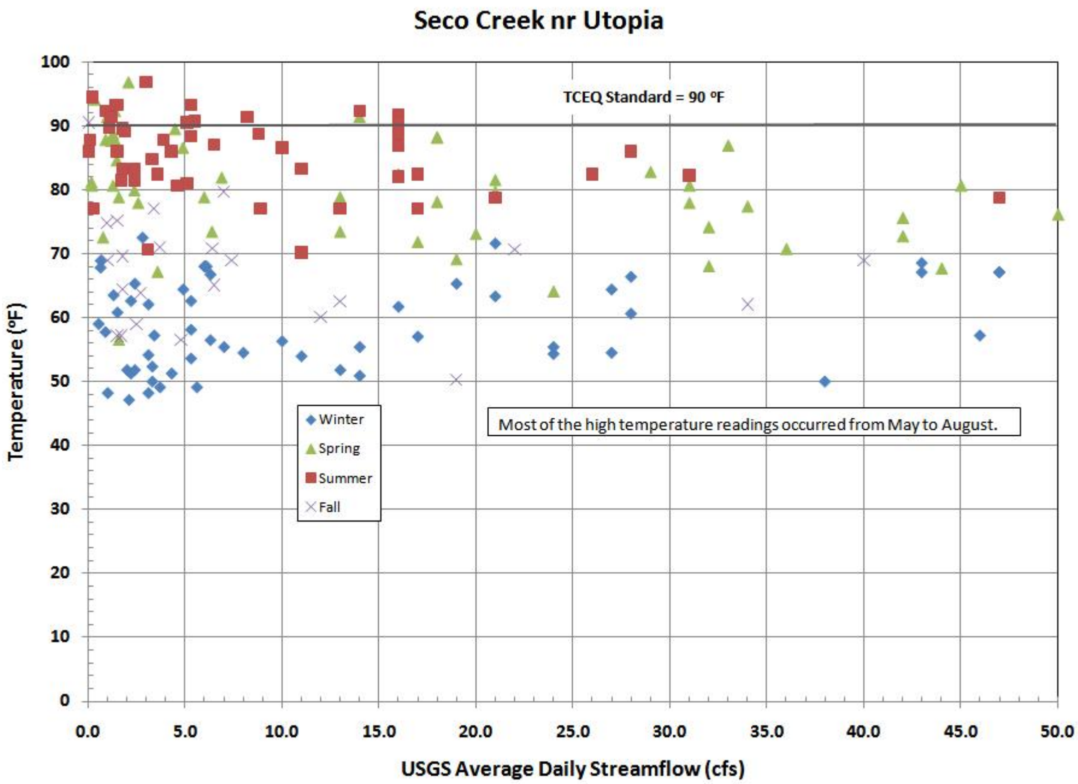


Figure 3.4.4. Water Temperature in Seco Creek near Utopia.

Conclusions

Analysis of dissolved oxygen and temperature data from 1968 through 2010 did not reveal statistically significant relationships between flow and those variables. However this analysis confirmed patterns observed in many other rivers. When flows decline in some streams to near subsistence levels, oxygen concentrations may drop to stressful levels for fish and other aquatic organisms. High temperatures in Hondo and Seco creeks are believed natural, however they demonstrate that temperatures in some streams may become stressful when flows decline. The absence of riparian vegetation that shades these streams reflects the value of riparian shading in maintaining water temperatures at levels.

3.5 Geomorphology (Sediment Transport)

Geomorphology, when applied to streams, is the study of, "… the physical processes that form and maintain stream channels and habitats, flush fine sediments, and transport sediment" (TWDB, 2008). It examines erosion and deposition in streams through the interactions of flow, sediment load, stream channel slope, sediment particle size, and channel shape. It is basically the study of how flowing water shapes the land.

A river channel changes as flows fall and rise. Small increases in flow lift fine silt and clay from the stream bottom or shore and move them to quieter water where they settle out. Rainfall-generated pulses may erode shoreline and form new islands or bars as sediment falls back to the bottom or along the shore. Floods wash soil from the floodplain into the river in some places and in other places, soil carried by the flooding river is captured among the plants in the riparian zone and floodplain. This process continues over seasons and years. If volumes and patterns of flow do not significantly change, the river channel remains in a dynamic equilibrium. This dynamic equilibrium means even though sediments move in and out of the river and the river channel moves back and forth, the general river shape does not substantially change.

The shape of the river creates different habitats for fish, aquatic insects, and plants as well as animals and plants using the riparian zone. These habitats include shallow areas with fast flowing water and deeper areas with still water. Substantial changes in flow change the dynamic equilibrium of sediment erosion, deposition, and movement. As a consequence, the shape of the river, type of bottom sediment, and habitat diversity may change. These changes affect habitats in and along the river. Extreme, long-term, changes in habitats may cause some characteristic plants and animals to disappear and create opportunities for undesirable plants and animals to invade. These long-term biological changes may result in the loss of sound environments.

Once dynamic equilibrium is shifted by a large change in long-term flow, the river channel remains unstable while erosion, deposition, and sediment movement establish a new dynamic equilibrium. The new dynamic equilibrium will change widths, depths, slope of the channel, and number of bends in the channel (Schumm, 1969). Different combinations of habitats will be created.

The TWDB, on behalf of the Nueces BBEST, analyzed changes in sediment transport that might occur in the Nueces basin with changes in flow patterns. The TWDB report of its analysis is included in Appendix 3.5.1. Analyzes were conducted for the Nueces River at Laguna, at Cotulla, and at Three Rivers. These analyses generally indicate how changes in flow may affect sediment movement.

BBEST conclusions from the analyses are:

1) Limiting daily flows remaining the stream to only amounts protected by the BBEST's environmental flow regimes in this report (i.e., implementation of “infinite infrastructure”) would reduce annual sediment transport by about 86 percent for the Nueces River at Laguna and 59 percent for the Nueces River at Cotulla.
2) Most sediment is transported by higher pulse flows.
3) Any substantial reduction in flows, particularly pulse flows and floods, would cause large reductions in sediment movement and probable changes in habitat. These potential changes may threaten existing sound environments. The environmental flows recommended in this report, would not appear to provide enough water to preserve existing dynamic equilibriums and existing habitats in Nueces basin streams subject to implementation of “infinite infrastructure.” Large reductions in the peak flows, volumes, and frequencies of pulse and flood flows pose the greatest threat to existing stream shapes. Wolman and Miller (1960) reported that sediment movement shaping the channel depends on how high pulse flows get and how often they occur.
4) If a large diversion or combination of smaller diversions are proposed in the future which could significantly change flow regimes, site-specific analysis of sediment transport should be conducted to determine possible changes to river shape and resulting changes to ecological health. The need for analysis of sediment transport/channel shape (geomorphic analysis) is described in Texas Environmental Flows Science Advisory Committee guidance (SAC, 2009; SAC, 2011).

Science regarding flows that maintain the physical character/habitats of rivers reflects the importance of adequate sediment transport. Channels should be stable if the amount of sediment moving in a reach of stream is within 10 percent of the amount of sediment entering the reach (Biedenharn, et al., 2000). If flows are significantly reduced, sediment coming from upstream will accumulate in the river. Environmental standards adopted in the United Kingdom allow diversion of 7.5 to 30 percent of the natural daily flow depending on possible effects on stream shape, flows, and desired ecological status (Acreman, et al., 2010).

Study Locations

Nueces River at Laguna:

Soils of the Nueces watershed upstream of this location in Uvalde County are predominantly thin layers, 2 to 18 inches thick, of clay and loam overlying limestone bedrock, fractured limestone, or caliche (USDA, 1976). Stream bed materials consist primarily of gravel, coarse gravel, and bedrock with some silt and organic matter near the shores (Trungale and Hardy, 2011).

Nueces River at Cotulla:

Relatively deep clayey loams and sandy loams are the primary soils of LaSalle County around the Nueces River near Cotulla (USDA, 1994). Stream bottom sediments are typically clay, silt, sand, and gravel.

Nueces River at Three Rivers:

Soils of Live Oak County drained by this part of the Nueces River are a mixture of thin to very deep clayey, sandy, and gravelly loams (USDA, 2006). Stream sediments are primarily sand with silt and slight amounts of organic matter (Trungale and Hardy, 2011).

Analysis

Stream sediments were collected from each location in 2011 and analyzed by the TWDB. Particles were largest at the Nueces River at Laguna where all particles were larger than sand and about 95 percent of all particles were gravel-sized (**Figure 3.5.1**). At the Nueces River at Cotulla, about 37 percent of all particles were sand with most of the remaining particles gravel-sized (**Figure 3.5.2**). Finest sediments were measured from the Nueces River at Three Rivers where 91 percent of the sediment particles were sand (**Figure 3.5.3**).

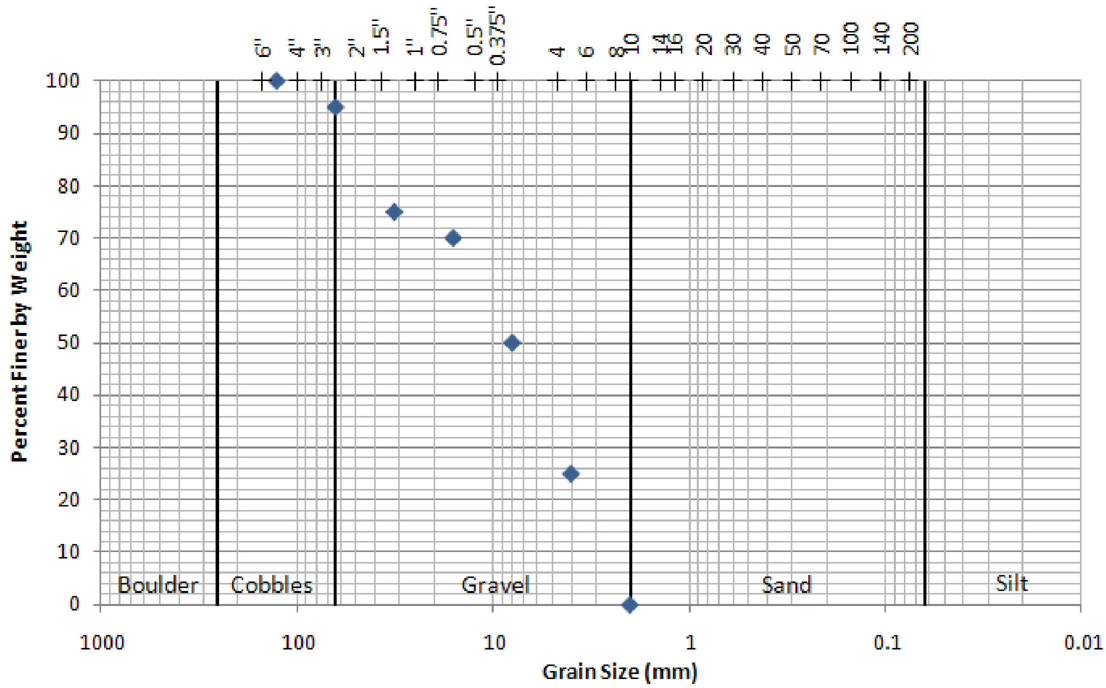


Figure 3.5.1. Size distribution of sediment particles from the Nueces River at Laguna, 2011. (Graph created by TWDB).

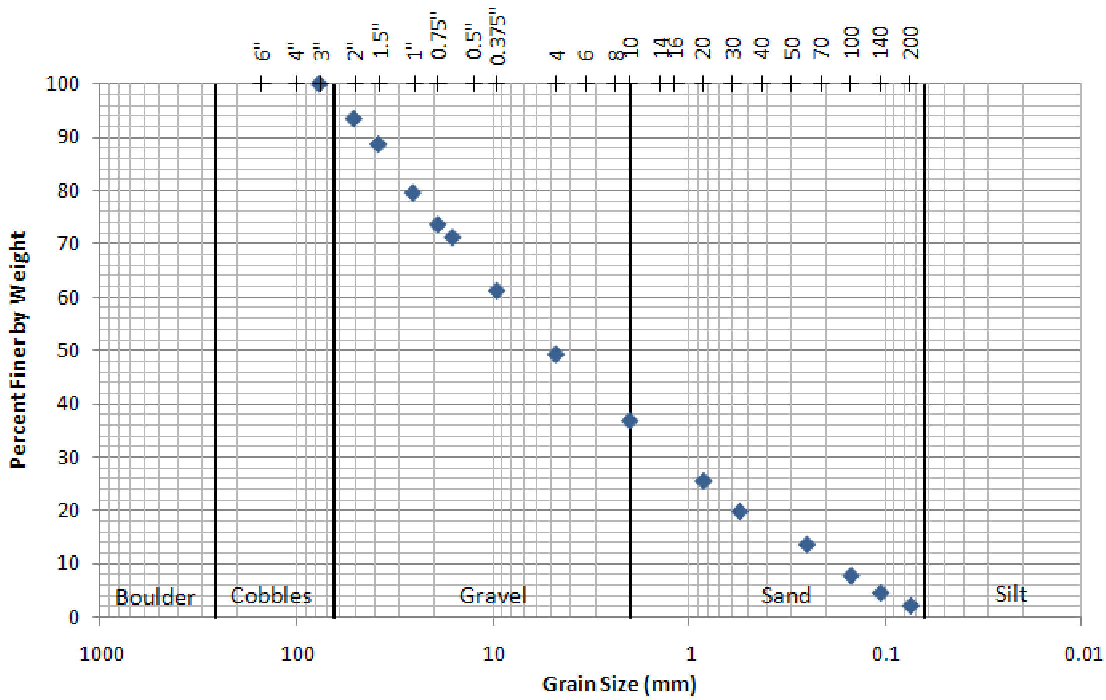


Figure 3.5.2. Size distribution of sediment particles from the Nueces River at Cotulla, 2011. (Graph created by TWDB).

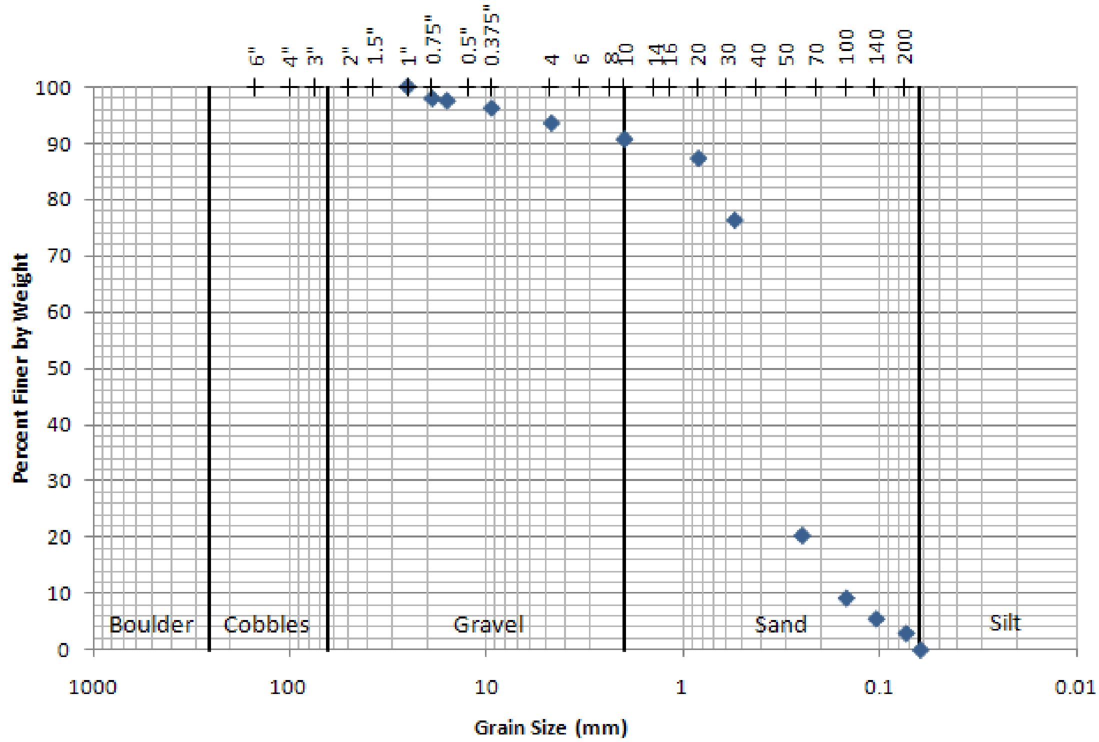


Figure 3.5.3. Size distribution of sediment particles from the Nueces River at Three Rivers, 2011. (Graph created by TWDB).

Flow data as daily average flow (cubic feet per second) and measurements of average velocity, channel width, depth, computed energy slopes, and stream bed gradation were obtained from the U.S. Geological Survey for each site. These data combined with sediment size data (Figure 3.5.1 through Figure 3.5.3) were input into a computer model, SAMWin, and equations generated to estimate tons of sediment carried as river flows increase (**Figure 3.5.4**, **Figure 3.5.5** and **Figure 3.5.6**). SAMWin is a computer model that calculates erosion, deposition, and movement of sediments in streams and to help evaluate channel stability.

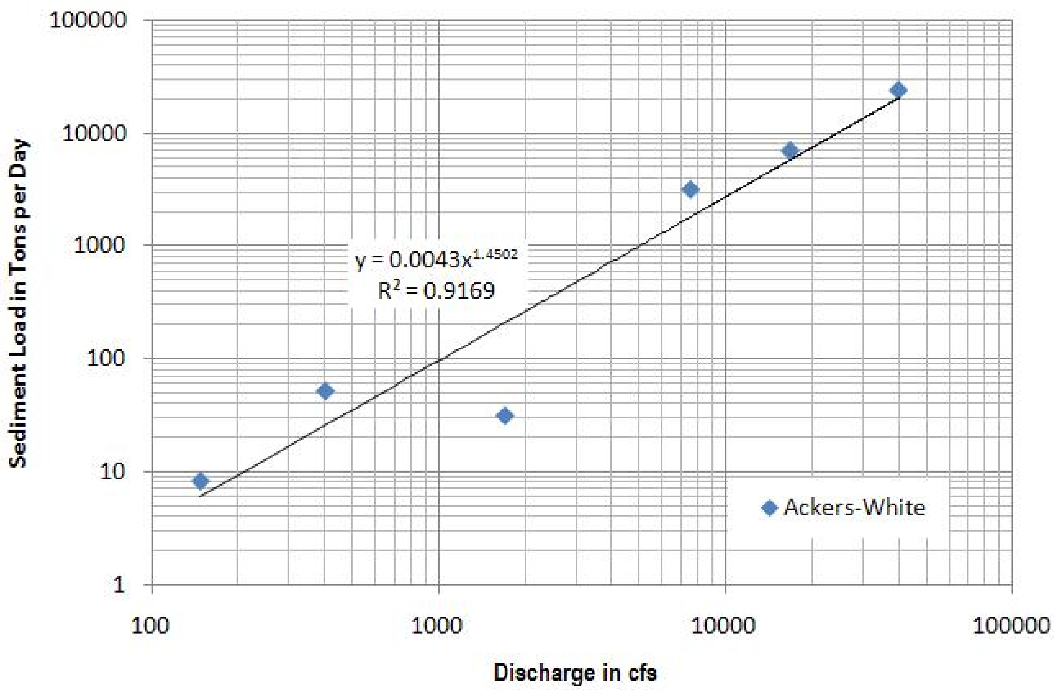


Figure 3.5.4. Sediment rating curve for the Nueces River at Laguna. Blue diamonds represent estimates of sediment load made possible by collection of flow and channel data by USGS. Estimates were made using appropriate sediment transport equations as recommended by SAMWin. (Graph created by TWDB).

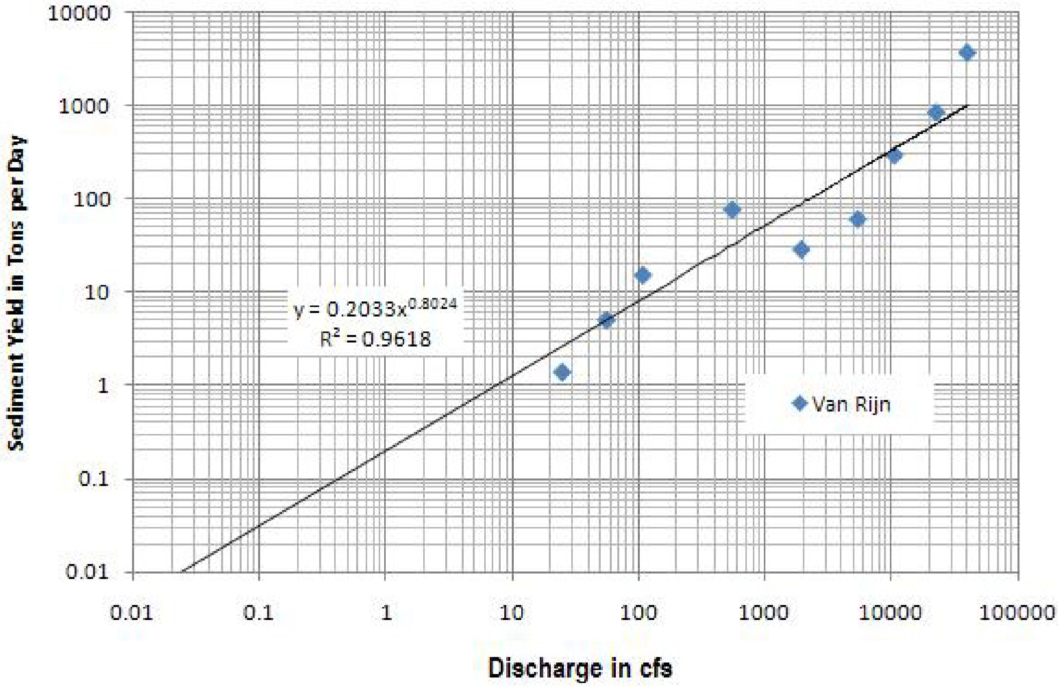


Figure 3.5.5. Sediment rating curve for the Nueces River at Cotulla. Blue diamonds represent estimates of sediment load made possible by collection of flow and channel data by USGS. Estimates were made using appropriate sediment transport equations as recommended by SAMWin. (Graph created by TWDB).

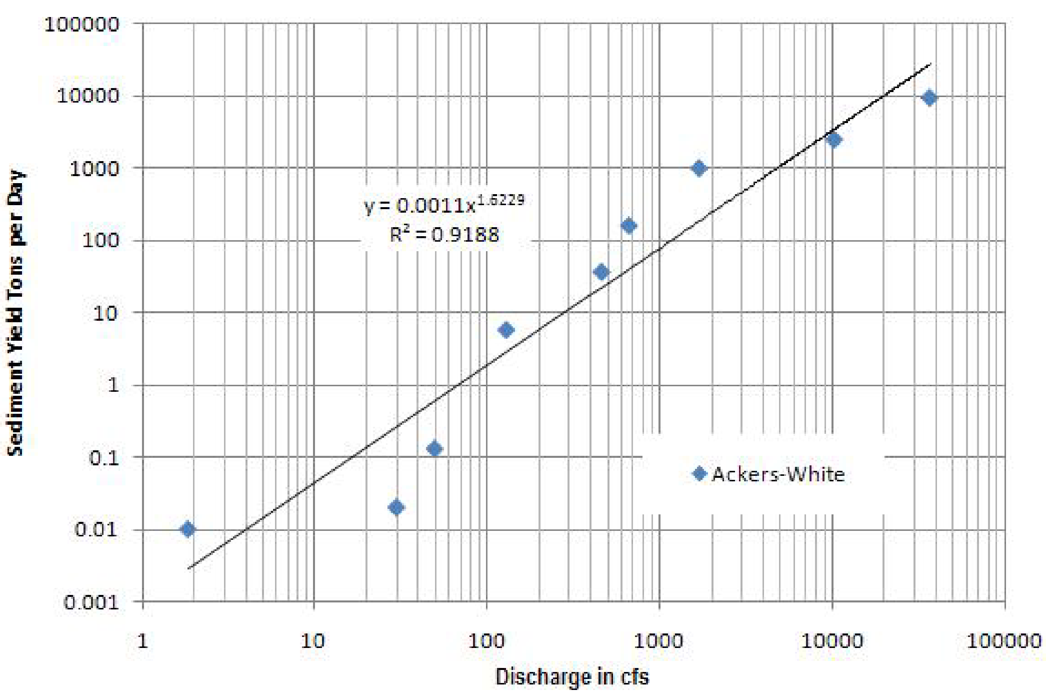


Figure 3.5.6. Sediment rating curve for the Nueces River at Three Rivers. Blue diamonds represent estimates of sediment load made possible by collection of flow and channel data by USGS. Estimates were made using appropriate sediment transport equations as recommended by SAMWin. (Graph created by TWDB).

Flow Scenarios

Sediment amounts transported by different variations of flow were calculated for each site. Flow scenarios were tested to understand how sediment movement might vary with different environmental flow regimes. Daily average flow was calculated for every day during the scenario's time period. In these comparisons, the baseline condition is the "regulated" flow in the river and sediment moved by that flow during an average year from 1934-1996. Regulated flows are determined from the water availability (WAM) model that calculates how much water would flow in the river if all existing water rights permits were using all the water they were permitted to use and no water returned to the river.

Analysis of the different flow scenarios also included the percent of time each flow would have occurred. An example is shown in **Figure 3.5.7** for the Nueces River at Cotulla. This example shows that about 50 percent of the time the flow from 1927-1969 was greater than 0.4 cfs and that from 1970-2009, about half the flows were greater than 8 cfs.

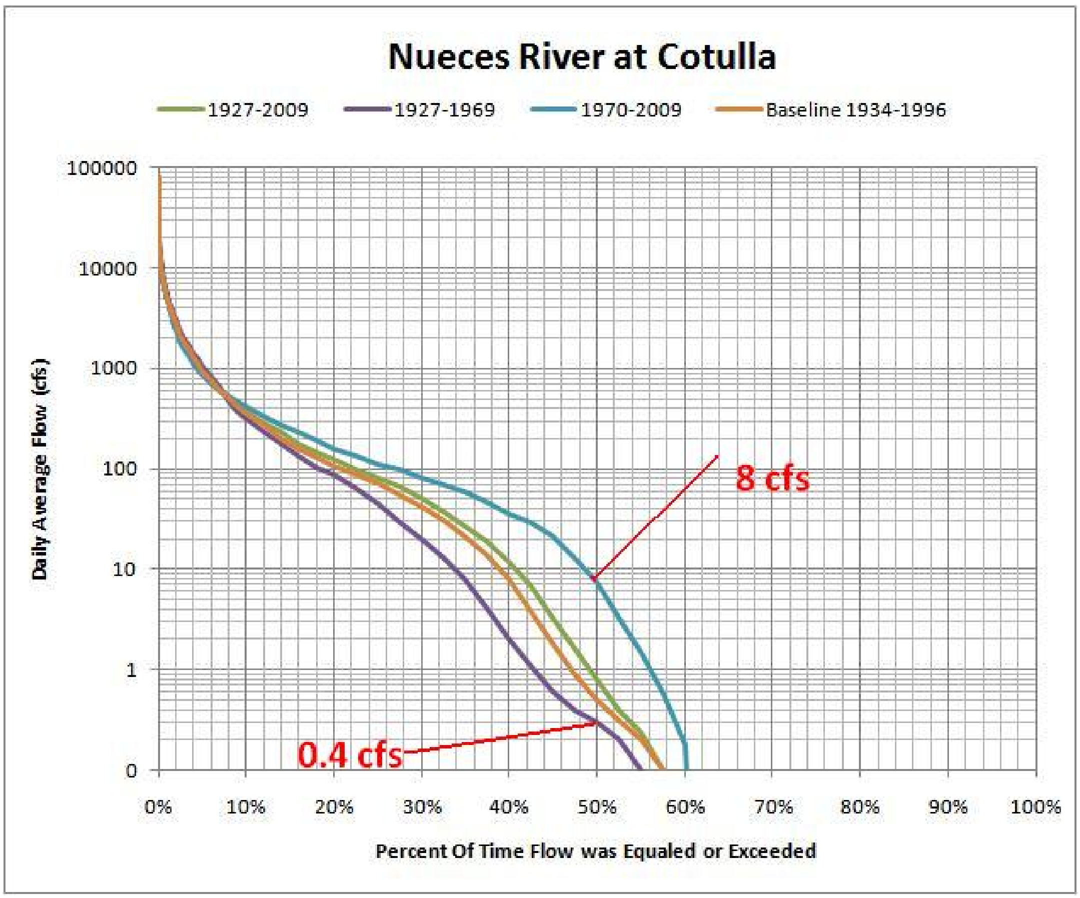


Figure 3.5.7. Nueces River at Cotulla flow frequency (flow distribution) curve for different periods of records and hydrological conditions.

The BBEST evaluated three combinations associated with pulses for the Nueces River at Laguna and Cotulla. The first option included all pulses recommended by the BBEST. All sites have pulse recommendations for 1/5 year, 1/2 year, 1/1 year, and 2/year pulses. If there were enough seasonal pulses historically, each site also has 1/season and 2/season pulses for each season. As mentioned earlier in this report, if enough pulses occurred in the period of record, 3/season and 4/season pulses could be included for intermittent streams on the Edwards Plateau (Nueces River at Laguna) and for South Texas Brush Country streams (Nueces River at Cotulla).

TPWD determined mathematical relationships between the peak of pulse in cfs, the total volume of water transported by the peak, and the number of days the pulse endured for each site and for each category of pulse at each site. The equation developed for each pulse category at each site allowed HEFR to identify an upper bound, lower bound, and central tendency of volume and duration for each pulse flow. Determination of pulse bounds and central tendency is explained earlier in this report. For example, the Nueces River at Laguna has a 1/season pulse recommendation in the winter of 48 cfs. At this location, a pulse of 48 cfs has a:

- Lower bound volume of about 200 acft. This means 84 percent of pulses of 48 cfs would be expected to carry more than 200 acft of water;
- Central tendency volume of about 550 acft. This means half of pulses of 48 cfs would be expected to carry more than 550 acft and half would be expected to carry less than 550 acft; and
- Upper bound volume of 900 acft. This means that 84 percent of pulses of 48 cfs would be expected to carry less than 900 acft.

These tests allowed the BBEST to evaluate the effect of choosing different periods of record on sediment transport. The scenarios also showed the BBEST how different pulse flow combinations might affect sediment movement.

Results

<u>Nueces River at Laguna</u>

Scenario 1: Reservoir off the stream channel with a storage capacity of 43,997 acft and ability to pump from the river into the reservoir at a maximum rate of 400 cfs.

Scenario 2: One very large project or a combination of projects diverting all water from the river except the environmental flow regime flows. This scenario is sometimes referred to as the "infinite infrastructure" scenario and refers to one or more entities taking all of the water out of the river except for the environmental flow regime flows. This is considered a scenario that is unlikely to occur. For example, it is unlikely that any diversion project could divert all the flow in a major flood.

- Variation 1: How much sediment moved in the river from 1924-1969 using historical flows without the scenario?
- Variation 2: How much sediment moved in the river from 1970-2009 using historical flows without the scenario?
- Variation 3: How much sediment moved in the river from 1924-2009 using historical flows without the scenario?
- Variation 4: How much sediment moved in the river from 1934-1996 using regulated (WAM) flows (baseline condition) without the scenario?
- Variation 5: How would the scenario affect flow and sediment transport (using 1934-1996, regulated flows), using BBEST subsistence, base, and pulse flows; upper bound volumes and durations on all levels of pulse flows (BBEST recommends using upper bounds on volumes for seasonal and two per year pulses only), with flows regulated by hydrologic condition managing diversions to 3 levels of base flow and subsistence flow?
  - Scenario 1: Off-channel reservoir in place, and
  - Scenario 2: No off-channel reservoir in place; only water in the river would be BBEST recommendations with modifications described in Variation 5.
- Variation 6: How would the scenario affect flow and sediment transport (using 1934-1996, regulated flows) using BBEST subsistence, base, and pulse flows; central tendency volumes and durations on all levels of pulse flows, with flows regulated by hydrologic condition managing diversions to 3 levels of base flow and subsistence flow?
  - Scenario 1: Off-channel reservoir in place; and
  - Scenario 2: No off-channel reservoir in place; only water in the river would be BBEST recommendations with modifications described in Variation 6.
- Variation 7: How would the scenario affect flow and sediment transport (using 1934-1996, regulated flows) without pulses larger than seasonal pulses (the lower pulses) in the flow regime? This variation would not include the larger pulses and floods that occur twice a year, once a year, once

every two years, or once every five years. It would included flows regulated by hydrologic condition managing diversions to 3 levels of base flow and subsistence flow

- Scenario 1: Off-channel reservoir in place; and
- Scenario 2: No off-channel reservoir in place; only water in the river would be BBEST recommendations with modifications described in Variation 7.

Table 3.5.1. Nueces River at Laguna. Amounts of sediment moved under different environmental flow conditions. Percentages in parenthesis represent the percent of the baseline value that is considered to best represent historical flow and sediment movement.

Variation	Average Annual Water Remaining in the River (acft)	Average Annual Sediment Moved by River (Tons)
Variation 1: 1924 – 1969 (historical flows)	99,600 (88%)	7,335 (100%)
Variation 2: 1970 – 2009 (historical flows)	140,200 (123%)	7,337 (100%)
Variation 3: 1924 – 2009 (historical flows)	118, 500 (104%)	7,336 (100%)
Variation 4: 1934 – 1996 (Baseline) (regulated, WAM, flows)	114,200 (100%)	7,328 (100%)
Variation 5, Scenario 1: Off-channel reservoir with upper bounds on pulse volumes and durations	104,878 (92%)	6,954 (95%)
Variation 5, Scenario 2: “Infinite infrastructure” with upper bounds on pulse volumes and durations	62,868 (55%)	1,446 (20%)
Variation 6, Scenario 1: Off-channel reservoir with central tendency of pulse volumes and durations	102,965 (90%)	6,903 (94%)
Variation 6, Scenario 2: “Infinite infrastructure” with central tendency of pulse volumes and durations	51,728 (45%)	918 (13%)
Variation 7, Scenario 1: Off-channel reservoir with only seasonal pulses	101,765 (89%)	6,857 (94%)
Variation 7, Scenario 2: “Infinite infrastructure” with only seasonal pulses	40,777 (36%)	206 (3%)

Average annual flow that varied around the baseline flow of 114,200 acft/yr did not significantly affect the amount of sediment moved by the river (Table 3.5.1). Even though annual average flow varied from 88 percent to 123 percent of the baseline flow, the average annual sediment transport changed less than 1 percent. The relatively small differences (less than 1 percent) in average annual sediment moved in variations 1-4 compared to larger relative differences in annual average flow (4 to 23 percent from baseline) result from the types of flows that occurred within each period. For example, a high flow pulse may disturb and move more sediment than a long period of base flow with the same total volume of water as the high flow pulse. A similar pattern is seen in variations 1-4 in Table 3.5.2.

<u>Nueces River at Cotulla</u>

Scenario 3: Reservoir on the river with a conservation storage capacity of 527,600 acft.

Scenario 4: One very large project or a combination of projects diverting all water from the river except the environmental flow regime flows. This scenario is sometimes referred to as the "infinite infrastructure" scenario and refers to one or more entities taking all of the water out of the river except for the environmental flow regime flows. This is considered a scenario that is unlikely to occur. For example it is unlikely that any diversion project could divert all the flow in a major flood.

Sediment moving in the river and flow remaining in the river were calculated using several different variations of this scenario.

- Variation 1: How much sediment moved in the river from 1924-1969 using historical flows without the scenario?
- Variation 2: How much sediment moved in the river from 1970-2009 using historical flows without the scenario?
- Variation 3: How much sediment moved in the river from 1924-2009 using historical flows without the scenario?
- Variation 4: How much sediment moved in the river from 1934-1996 using regulated (WAM) flows (baseline condition) without the scenario?
- Variation 5: How would the scenario affect flow and sediment transport using 1934-1996, regulated flows, using BBEST subsistence, base, and pulse flows; upper bound volumes and durations on all levels of pulse flows (BBEST recommends using upper bounds on volumes for seasonal and two per year pulses only), with flows regulated by hydrologic condition managing diversions to 3 levels of base flow and subsistence flow?
  - Scenario 3: On-channel reservoir in place, and
  - Scenario 4: One very large project or a combination of projects diverting all water from the river except the environmental flow regime flows.
- Variation 6: How would the scenario affect flow and sediment transport using 1934-1996, regulated flows, using BBEST subsistence, base, and pulse flows; central tendency volumes and durations on all levels of pulse flows, with flows regulated by hydrologic condition managing diversions to 3 levels of base flow and subsistence flow?
  - Scenario 3: On-channel reservoir in place; and
  - Scenario 4: One very large project or a combination of projects diverting all water from the river except the environmental flow regime flows.
- Variation 7: How would the scenario affect flow and sediment transport using 1934-1996, regulated flows, without pulses larger than seasonal pulses (the lower pulses) in the flow regime? This variation would not include the larger pulses and floods that occur twice a year, once a year, once every two years, or once every five years. It would included flows regulated by hydrologic condition managing diversions to 3 levels of base flow and subsistence flow
  - Scenario 3: On-channel reservoir in place; and
  - Scenario 4: One very large project or a combination of projects diverting all water from the river except the environmental flow regime flows.

Table 3.5.2. Nueces River at Cotulla. Amounts of sediment moved under different environmental flow conditions. Percentages in parenthesis represent the percent of the baseline value that is believed to best represent historical flow and sediment movement.

Variation	Average Annual Water Remaining in the River (acft)	Average Annual Sediment Moved by River (Tons)
Variation 1: 1924 – 1969 (historical flows)	194,440 (108%)	4,129 (102%)
Variation 2: 1970 – 2009 (historical flows)	171,771 (95%)	4,169 (103%)
Variation 3: 1924 – 2009 (historical flows)	183,515 (102%)	4,148 (102%)
Variation 4: 1936 – 1996 (Baseline) (1934-1996, regulated (WAM) flows)	**180,631 (100%)**	**4,051 (100%)**
Variation 5a: On-channel reservoir with upper bounds on pulse volumes and durations	45,196 (25%)	2,160 (53%)
Variation 5b: "Infinite infrastructure" with upper bounds on pulse volumes and durations	30,775 (17%)	1,660 (41%)
Variation 6a: On-channel reservoir with central tendency of pulse volumes and durations	40,796 (23%)	1,925 (48%)
Variation 6b: "Infinite infrastructure" with central tendency of pulse volumes and durations	21,848 (12%)	1,227 (30%)
Variation 7a: On-channel reservoir with only seasonal pulses	31,105 (17%)	1,500 (37%)
Variation 7b: "Infinite infrastructure" with only seasonal pulses	8,007 (4%)	642 (16%)

Average annual flow between 95 and 108 percent of the baseline flow of 180,631 acre-feet per year did not significantly affect the amount of sediment moved by the river (**Table 3.5.2**).

Nueces River at Three Rivers

Scenario: Choke Canyon Reservoir on the river constructed in 1982.

Sediment transport and flow were calculated using two variations of this scenario.

- Variation 1: What was the average annual estimated sediment transport from 1916-1981 (historical flows) before Choke Canyon Reservoir was constructed upstream of the site?
- Variation 2: What has been the average annual estimated sediment transport from 1982-2009 (historical flows) after Choke Canyon Reservoir was constructed upstream of the site?

Table 3.5.3. Nueces River at Three Rivers. Amounts of sediment moved pre- and post-Choke Canyon construction. Percentages in parenthesis represent the percent of the baseline value best representing historical condition in flow and sediment movement.

Variation	Average Annual Water Remaining in the River (acft)	Average Annual Sediment Moved by River (Tons)
Variation 1: 1916-1981Baseline (historical flows)	**627,000 (100%)**	**103,500 (100%)**
Variation 2: 1982-2009 (historical flows)	402,300 (64%)	47,500 (46%)

Average annual sediment movement dropped to 46 percent of sediment moved before Choke Canyon (**Table 3.5.3**) (**Figure 3.5.8**). The TWDB scientists' review of U.S. Geological Survey gage data from the river indicated the stream channel appears to be stable. It was also noted the U.S. Geological Survey chooses gage locations in part based on their resistance to erosion and sediment deposition. This may have made it more difficult to detect channel change at the gage location since reservoir construction.

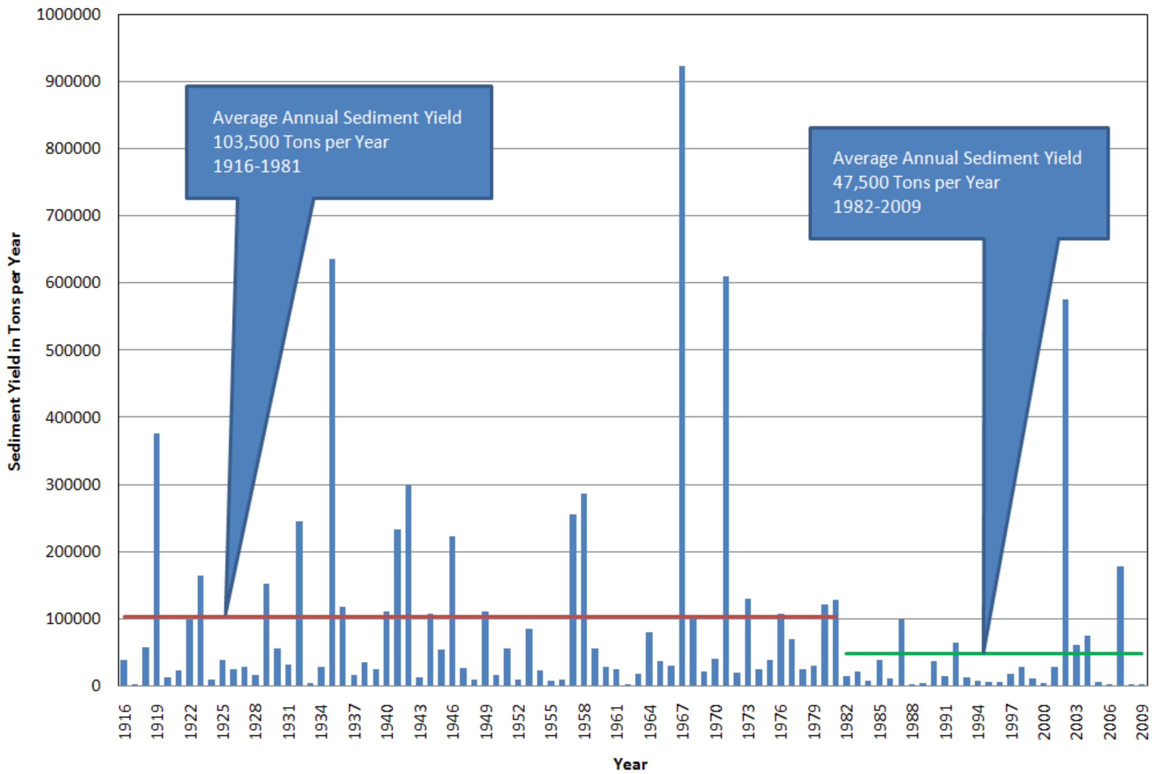


Figure 3.5.8. Annual sediment yield of the Nueces River at Three Rivers, pre- and post-construction of Choke Canyon dam. (Graph created by TWDB).

Conclusions

Period of Record:

The BBEST evaluated three different periods of record which could be used to calculate environmental flow regimes. Those included the early period (start of flow measurement through 1969), 1969-2009 (late period), and start of data collection through 2009 (entire period). For the Nueces River at Laguna and Cotulla, sediment transport during different periods of record varied less than 3 percent from the baseline estimate (Table 3.5.1 and Table 3.5.2). The BBEST concluded that there was no significant difference between periods of record based on the minor differences in estimated sediment transport over the years.

Limits on Pulses, Pulse Volumes, and Durations:

The Nueces River at Laguna had 1/season pulses for each season and 2/season pulses for the spring. The Nueces River at Cotulla had 1/season pulses for each season, 2/season pulses for winter, spring, and fall, and 3/season pulses for spring.

The amount of sediment moved by the Nueces River at Laguna would drop by about 37 percent (1,446 to 918 tons per year) if the central tendencies of volume and duration were used instead of the upper bounds of volume and duration (Table 3.5.1). This difference would be seen if the only water in the river was that provided by the environmental flow regime. In the Nueces River at Cotulla, the amount of sediment would decline by 26 percent (1,660 to 1,227 tons per year) if the central tendencies of volume and duration were used instead of the upper bounds of volume and duration (Table 3.5.2) and if the only water in the river was that provided by the environmental flow regime.

Based on other factors, the BBEST had preliminarily agreed (prior to receipt of the sediment transport analysis from the TWDB) to use the upper bound of duration on all pulse flows, the upper bound of volume for all pulse flows that occur twice per year or are seasonal, and the central tendency of volume for all pulses that occur once per year or less frequently. The BBEST decided to accept its preliminary recommendations for pulse flows after reviewing this sediment transport analysis.

Sediment transport with only 1/season and 2/season pulses was compared to sediment transport with the entire range of pulses recommended by the BBEST. If the only water in the river was provided by the environmental flow regime, the amount of sediment moved in the Nueces River at Laguna would decline by 78 percent (918 to 206 tons per year) with only seasonal pulses and pulse volume and duration limited to central tendency values (Table 3.5.1). For the Nueces River at Cotulla, the amount of sediment moved would decline by 48 percent (1,227 to 642 tons per year) if the only water in the river was provided by the environmental flow regime including only seasonal pulses with central tendency values for pulse volume and duration (Table 3.5.2). The BBEST considered these results confirmation of the need to include larger pulses than only seasonal pulses in flow regimes in order to protect sound environments.

Additional Resources:

Simple animation of sediment transport: http://highered.mcgraw-hill.com/sites/0072402466/student_view0/chapter10/animations_and_movies.html#.

Earth's Waters: Rivers and Sediments: http://ga.water.usgs.gov/edu/earthriverssed.html.

Role of Sediment Transport, a PowerPoint presentation: http://www.forwatershed.org/TheRoleofSediment-TransportinStreamCondition.pdf.

Description of Streams and Drainage Systems: http://www.tulane.edu/~sanelson/geol111/streams.htm.

3.6 Riparian Zone

3.6.1 Riparian Zone Introduction

"Riparian zone" is the land from the water's edge up to land only exposed to water from rainfall runoff. Riparian zones are underwater when rivers flood or their flow increases (**Figure 3.6.1**). Water may flow back and forth underground between the river and adjacent land (Naiman and Decamps, 1997) in the riparian zone. Sand bars and islands, exposed stream banks, and floodplains above the stream banks are part of the riparian zone. Since the riparian zone is part of the floodplain, in addition to islands and bars, it may have channels, ridges, swales, cut-off channels (oxbow lakes), and terraces (Naiman and Décamps, 1997).

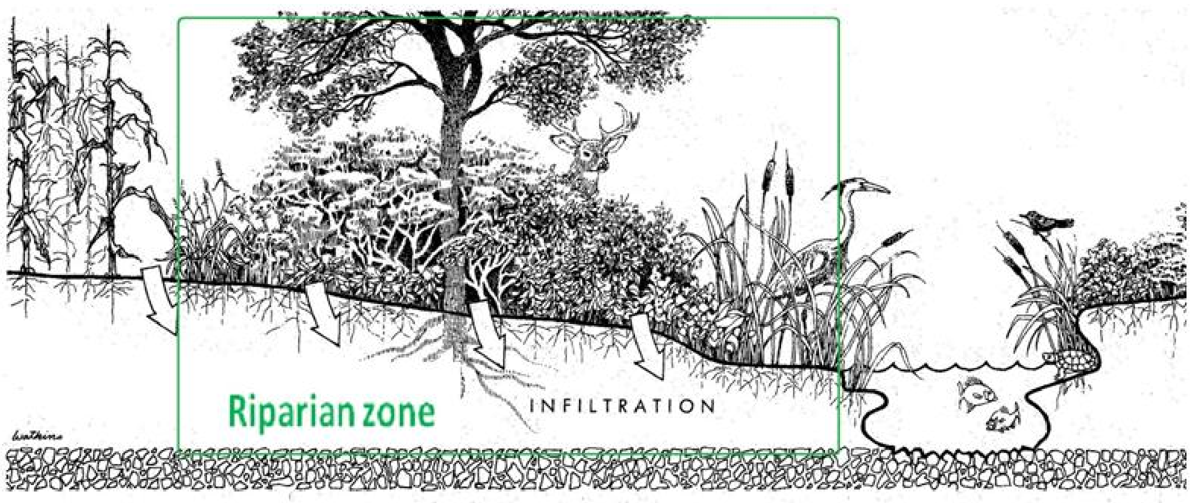


Figure 3.6.1. Riparian Zone Illustration (University of Wisconsin, 2006).

Streams have riparian zones whether or not they flow year-round (perennial streams) or if they are intermittent, only flowing part of the year. Riparian communities are the plants and animals inhabiting riparian zones. The riparian zone along a reach of river is sometimes called a riparian corridor. Riparian corridors allow wildlife to travel long distances under cover of the riparian plants. Both riparian zones and wetlands flood but differ in that water drains from riparian zones but is retained in wetlands for relatively long periods (Arthington and Zalucki, 1998).

Natural, healthy streams experience a wide range of flows from low flows that occur during droughts, normal (or base) flows that may be higher during wet years and lower during dry years, pulses of flow that follow rainfall events, and floods that wash far out of the stream banks. Healthy riparian communities adapt to variability in the flow regime that occurred in the past (Naiman, et al., 2005). The range of flows from low subsistence flows to floods interact with plants and animals to maintain riparian communities. Substantial, long-term changes in flow patterns threaten riparian zone and floodplain environmental health. The BBEST's analysis in this section describes relationships between different flows and riparian communities along with ecological benefits created by a healthy floodplain community.

Texas riparian areas are best defined by the National Research Council (Miller, et al., 2010) which described riparian areas.

> *"Riparian areas are transitional between terrestrial and aquatic ecosystems and are distinguished by gradients in biophysical conditions, ecological processes, and biota. They are areas through which surface and subsurface hydrology connect water bodies with their adjacent uplands. They include those portions of terrestrial ecosystems that significantly influence exchanges of energy and matter with aquatic ecosystems (i.e. a zone of influence). Riparian areas are adjacent to perennial, intermittent, and ephemeral streams, lakes, and estuarine-marine shorelines." (National Research Council, 2002)*

Flow, soil, and vegetation interact to support a sound riparian zone:

1) Fallen leaves, branches, and dead plants increase organic matter in the soil and protect soil from erosion by covering it.
2) Large branches and trunks from dead trees stabilize channels when they lodge in sediments along the shoreline.
3) During floods, plants reduce flood energy, slow rainfall runoff into the stream, capture sediments along the banks and in the floodplain, filter pollutants, and increase infiltration of rain into the soil. Trapped sediments, particularly those with high amounts of organic matter, store water.
4) Plants shade streams, reducing evaporation, lowering water temperatures, and providing temperature refuges for wildlife during summer (McMahan and Inglis, 1980).
5) Flows create habitat for plants requiring wetter soils than needed by upland plants.
6) Plants provide cover, habitat, and movement corridors for mammals, birds, including neotropical migratory songbirds, reptiles, amphibians, and insects which require access to water or protection from predators.
7) Plants provide berries, nuts, seeds, insects, and grasses for wildlife food.
8) Aquatic turtles and the Texas indigo snake (*Drymarchon melanurus erebennus*), a state-threatened species of snake, lay their eggs in riparian zone soils. The Texas indigo snake is sensitive to drought but lives in a semi-arid environment where it relies on being relatively close to water in order to survive (Dixon and Werler, 2005).
9) Flows influence groundwater levels which in turn influence riparian trees (Merritt, et al., 2010).

A riparian plant community covering 70 percent more of the riparian area, with healthy plants with soil retaining capability, will dissipate flood energy, stabilize banks, trap sediments, and capture water in the banks that will be released back to the stream at low flows. A wide variety of aquatic, semi-aquatic and terrestrial habitat will be provided and there will be colonizing opportunities for additional species. The community usually includes living and dead, grasses, woody, and broad-leaved, non-woody plants some of which require nearly constant exposure to water and others that can grow well in periodically wet environments.

EPA (2008) summarized extensive scientific literature on the ecological function of intermittent streams in the arid southwestern U.S. Many of those functions are provided by intermittent streams of the arid Nueces basin.

- Lizards and certain snakes use dry riparian habitat when a stream is not flowing. Increased use may be related to increased availability of prey, increased density of cover for protection from predators, and increased relative humidity.
- Some species of turtles, snakes, and amphibians require the water provided by Arizona streams for survival.
- Lowland leopard frogs in Arizona depend on perennial pools in streams with bedrock bottoms for spawning habitat.
- Couch's spadefoot toad, Scaphipus couchi, which is found in Texas can metamorphose from egg to small toad in 7.5 days.
- Number of species of birds and their abundance are higher in riparian zones in Arizona than in uplands.
- Riparian zones in dry areas are important to migrating songbirds.
- A study of wetlands in Nebraska found that intermittent wetlands had more species of insects and greater diversity of insects than did perennial wetlands.
- Intermittent flows may stimulate food production for insects resulting in greater numbers of insects produced.
- Production of insects and accumulated organic matter in perennial pools feed perennial streams when flow washes the pool out into the perennial stream.

Additional research has shown that the Rio Grande leopard frog breeds in pools along flowing streams and are usually found in clear streams or perennial pools (Lannoo, 2005).

Some factors affecting environmental health of riparian zones and floodplains include availability of groundwater, declining water tables from pumping and diversions, disturbance of beds and banks, temperature changes, wildlife and livestock browsing and grazing, removal of vegetation for cultivation, and land development which changes runoff and sediment delivery patterns. Studies investigating relationships between stream flow changes and riparian and floodplain communities in the Nueces basin were not found while preparing this report. A number of studies have described riparian and floodplain plant communities in the basin (USFWS, 1983; Swihart, 2005; TPWD, 2005; and TPWD, 2011).

USFWS (1983) summarized information about Nueces watershed riparian communities. Pecan/elm forest occupied 17,200 acres of the riparian zone in the Edwards Plateau to just below the Balcones Escarpment. Pecan/elm/live oak forest covered another 578 acres of the riparian zone downstream of the Balcones Escarpment. The live oak/elm/hackberry community covered most of the riparian zone, about 142,000 acres, downstream of the Balcones Escarpment. 58,000 acres of Gulf cordgrass (*Spartina spartinae*), referred to as the "Middle Nueces Marsh" occupied the floodplain in LaSalle and McMullen counties where the river occupied braided channels (**Figure 3.6.2** and **Figure 3.6.3**). The only forested areas in the Nueces watershed are the riparian zones of streams and relic stream channels and floodplains that streams have moved away from.

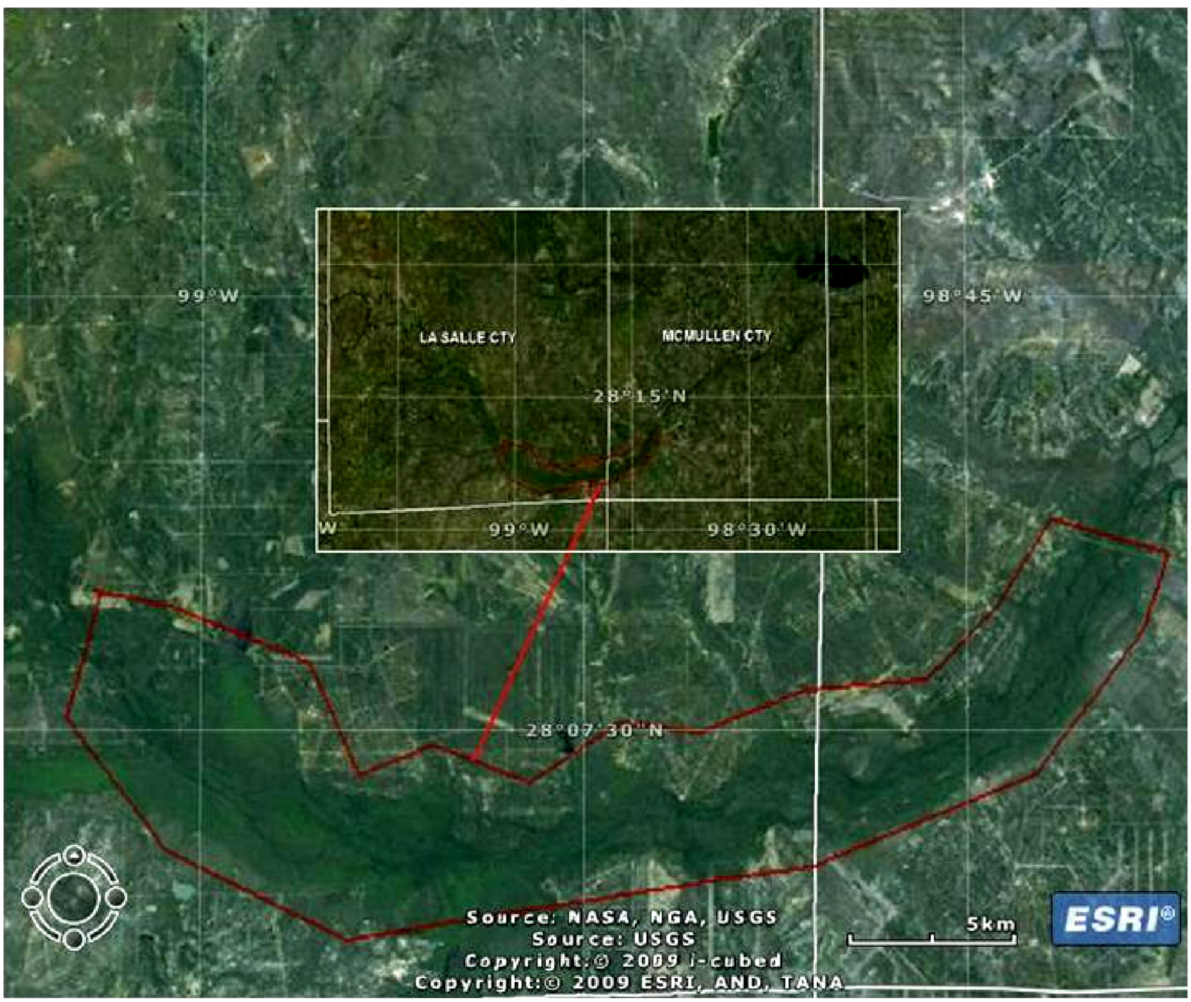


Figure 3.6.2. Middle Nueces Marsh between Cotulla and Three Rivers.

Figure 3.6.3. Gulf cordgrass in the Middle Nueces Marsh (USDA, 1994).

HDR (2000) summarized accounts of early Spanish explorers and settlers suggesting similar trees were present in the Nueces basin riparian zone to tree communities seen now. One 1691 account indicated that pecans, live oaks, and mesquite were thick in the Nueces River valley. A 1721 expedition reported "…a great number of pecans and other types of trees in the vicinities of the ravine and creek…." when they crossed Turkey Creek, a tributary to the Nueces River. Ecological function of riparian zones is reflected in part by the expedition's descriptions of abundant turkey, quail, buffalo, and rabbits in the area. In 1854, cypress and cedar were noted along the Sabinal River in Uvalde County. The 1873 Texas Almanac described all the streams in the Edwards Plateau along with the Frio and Nueces rivers as "…lined with timber…cypress, hackberry, cottonwood, pecan, oak of many kinds, and hickory." The Nueces River in its upper reaches on the Edwards Plateau was vegetated with "…chestnut, Texas red oak, scrapberry, wild mulberry, and black willow." Tributaries to the west were "…well-marked with hackberry, green ash, retama and black willow."

Variations in weather and geology across the Nueces basin play key roles determining plant communities in riparian zones and floodplains. Soils adjacent to the streams are loose sand, gravel, silt, and clay washed down through erosion into the floodplain. These accumulations of soil are referred to as Quarternary alluvium, meaning they have been eroded and deposited sometime during the past 2.5 million years. In the Edwards Plateau portion of the watershed to the northwest, these alluvial deposits tend to be relatively shallow over limestone bedrock. Alluvial deposits are the soil, sand, and gravel eroded and washed into the stream valley. Moving off the Edwards Plateau into the South Texas Brush country towards the coast, alluvial deposits are deeper and limestone is no longer present. In the Coastal Bend, alluvial deposits may be close to clay formations referred to as the Beaumont or Lizzie formations (TPWD, 2011). Soil depth in the riparian zone, soil types, soil permeability, and salt levels influence groundwater movement in the riparian zone.

Rainfall rates decrease moving westward across the watershed and moving inland from the coast. Rainfall averaged 32 inches per year in San Antonio (1971-2000, National Climatic Data Center, Office of the State Meteorologist) just to the east of the Nueces watershed and 23 inches per year near Cotulla along the western edge of the drainage basin during the same period. Average annual rainfall at Corpus Christi from 1971-2000 was 27 inches per year.

3.6.2 Nueces River Basin Floodplain and Riparian Vegetation

3.6.2.1 Edwards Plateau

The Frio River on the Edwards Plateau upstream of the Balcones Fault is bordered by high limestone canyon walls in many areas. Bald cypress and sycamore grow next to the river along the east branch of the Frio while ashe juniper, little black walnut, and Texas persimmon are found further from the river bank. Little black walnut is common along the west branch of the Frio where bald cypress is absent. Texas persimmon and chinkapin oak grow further from the shore along the Frio's west branch (Wood and Wood, 1988). TPWD (2005) stated that Frio River banks in the Edwards Plateau were lined with bald cypress, sycamores, pecans, black willow, and Spanish oak. The same TPWD report which concluded this portion of the Frio River is an ecologically significant stream segment, based much of its conclusion on the riparian zone which provides "…nesting, migration, and wintering habitat for a variety of birds." This portion of the river also includes a Riparian Conservation Area. Riparian Conservation Areas are areas along streams that are identified to protect riparian and aquatic ecosystems during site-specific project planning and implementation.

Swihart (2005) studied the riparian plants growing along the Frio River upstream of IH-35 (**Figure 3.6.4**). She focused on the area within the "scour line" which she described as "…the highest point at which gravel is exposed from the river washing over it." Most of the area within the scour line was covered with bare rock. The three plants occurring most frequently along the river were Kleberg's bluestem grass, frogfruit which can live in wetlands, and sneezeweed which can be found in sunny, wet areas (University of Texas at Austin, 2011a). Large trees included sycamores, bald cypress, black willow, and pecans along this portion of the Frio River.

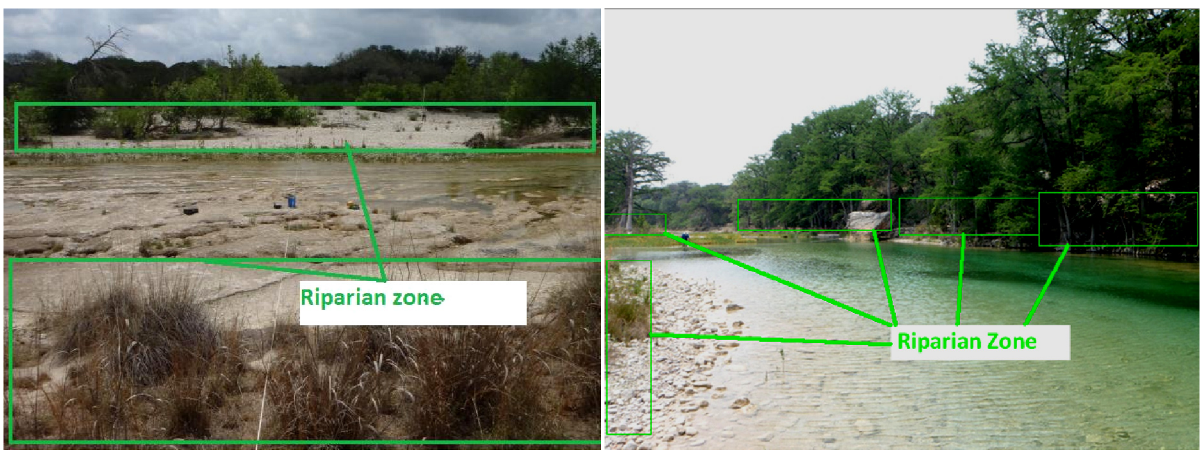


Figure 3.6.4. Frio River at Concan Riparian Zone [May 18, 2011, flow of 13 cubic feet/second as a daily average (USGS, 2011)].

The Sabinal River's riparian zone above the Balcones fault is dominated by bald cypress and sycamore near the bank. Further up the bank, pecan, net leaf hackberry, live oak, and little black walnut are found along with Texas persimmon and chinaberry. The upper reach of the Sabinal River, unlike the Frio River (Wood and Wood, 1988), usually consists of small pools and flows primarily during wet periods. Limestone canyons border much of the narrow river along this reach. Sycamore, little black walnut, and common button bush grow along the shore while ashe juniper, Texas oak, bigtooth maple, white shin oak, and Texas persimmon grow further up the bank (Wood and Wood, 1989).

TPWD (2005) described the banks of the Nueces River on the Edwards Plateau as being lined with pecans, cedar elm, and oak which provide important habitat for birds. TPWD (2005) included bald cypress, sycamore, pecan, and black willows as important riparian plants for the West Nueces River. **Figure 3.6.5** shows part of the Nueces River at Laguna riparian zone. Plants visible on the left shore in the photo include switchgrass, eastern gamagrass, button bush, *Baccharis*, and little walnut.

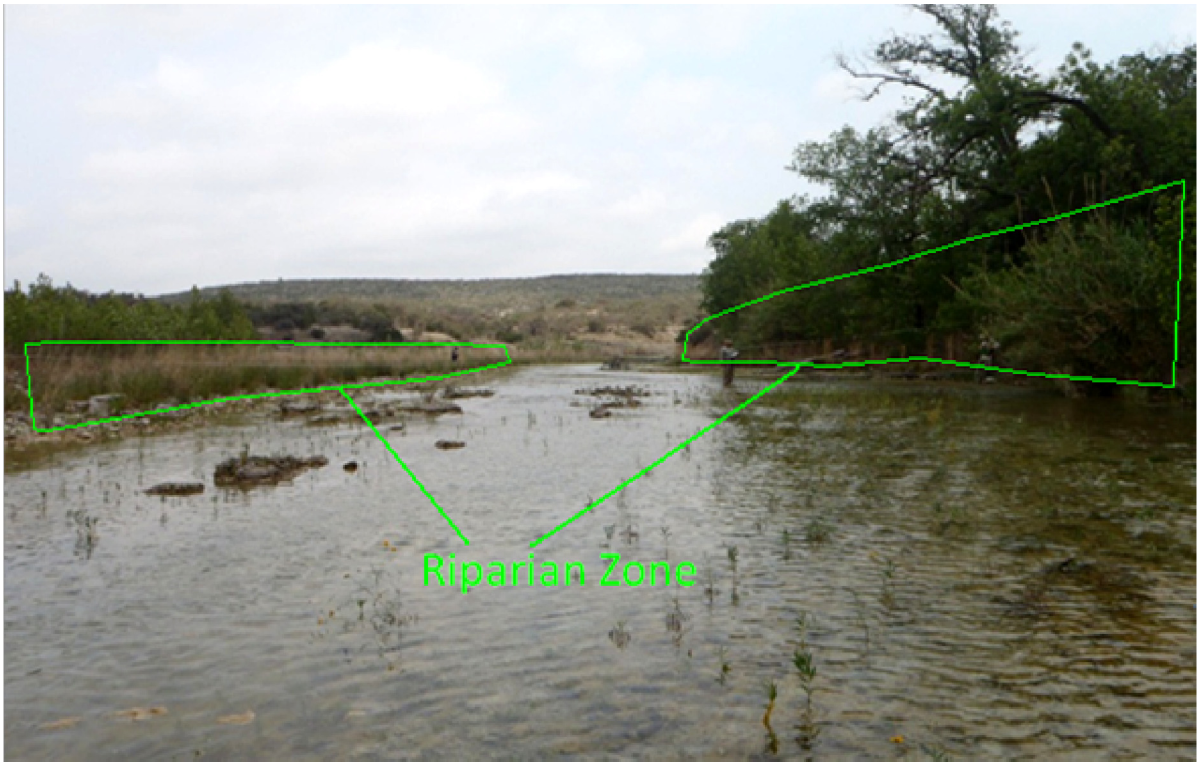


Figure 3.6.5. Nueces River at Laguna [May 19, 2011 flow of 20 cfs as a daily average (USGS, 2011)].

3.6.2.2 South Texas Brush Country

Gulf cordgrass, spiny aster, and big sacaton play an important role dissipating flood energy in this part of the basin. These plants are the dominant vegetation in many of the overflow channels and swales.

Riparian plants along the lower reaches of the Frio River upstream of Choke Canyon Reservoir include Mexican ash and black willow next to the river with cedar elm, live oak, and sugarberry as the taller trees and Texas persimmon and chittamwood growing underneath them a little further from the river (Miller, et al., 2010). Further upstream on the Frio River, pecan, castor bean, and honey mesquite grow next to the river with taller pecan, net leaf hackberry, live oak, and Texas persimmon common further from the river.

The Sabinal River riparian area is narrow and sometimes nearly absent because of clearing for cultivation and grazing (Miller, et al., 2010). Cedar elm and little black walnut grow close to the river while net leaf hackberry and desert sumac are the taller trees further from the river. Brazilian bluewood, Texas persimmon, and Texas mountain laurel grow under the hackberry and sumac. The riparian zone transitions moving upstream with bald cypress along the river's shore and live oak, net leaf hackberry, and pecan growing further from the shore near the Balcones Fault and Texas persimmon and soapberry commonly growing underneath them (Wood and Wood, 1989).

Live oak, net leaf hackberry, and cedar elm are common riparian trees along the Leona River. Texas persimmon, Texas mountain laurel, and chittamwood grow in the riparian zone under the trees (Miller, et al., 2010). Riparian areas along the upper portion of the Leona River are dominated by live oak which decreases in importance downstream. Pecan and Mexican ash are relatively more important in the middle and lower reaches of the Leona River (Wood and Wood, 1989).

USFWS (1983) described the riparian community beginning about 20 miles downstream of Cotulla as dominated by Gulf cordgrass in the floodplain. This area is in the "Texas Saline Inland Prairies" Texas Ecological Systems Classification (TPWD, 2010) which has relatively salty soils caused by repeated flooding and evaporation. San Miguel Creek's riparian community includes green ash, black willow, cedar elm, pecan and live oak (TPWD, 2005). **Figure 3.6.6** illustrates the riparian zone of the Atascosa River near Whitsett.

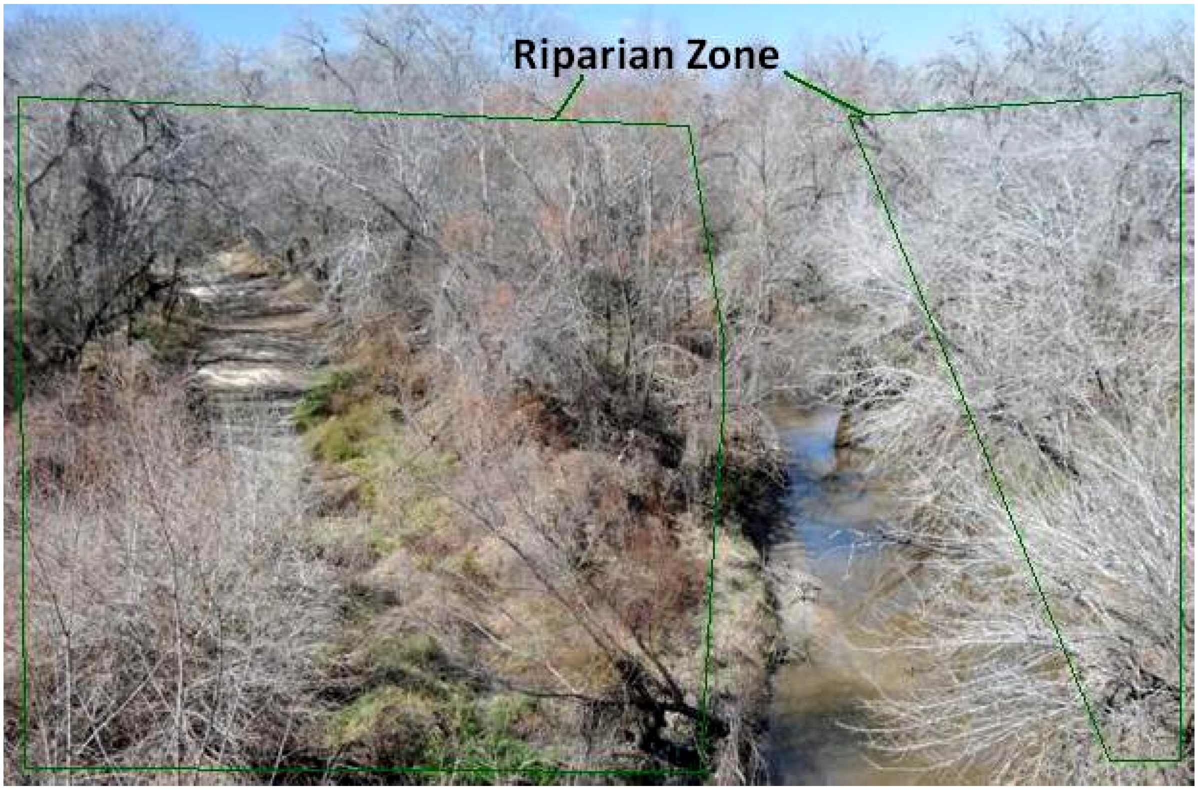


Figure 3.6.6. Atascosa River near Whitsett on January 28, 2011 [daily average flow of 13 cfs (USGS, 2011)].

3.6.2.3 Coastal Bend

The USGS (1983) described a significant riparian area on the Nueces River about 20 river miles downstream of Lake Corpus Christi, referred to as Griffin Island. Griffin Island at the time it was described was about 900 acres of sloughs and oxbows with wetland plants like arrowhead (*Saggitaria*), sedges (*Carex spp.*), spiny aster, willows, and buttonbush. The riparian forest included cedar elm, hackberry, ash, and live oak.

Oso and San Fernando creeks are located in the Texas Ecological Systems Classification's "Tamaulipan Floodplain (TPWD, 2010)." Trees in the riparian area may include honey mesquite, huisache, sugar hackberry, anacua, cedar elm, and granjeno. Grasses and shrubs may dominate parts of these riparian areas and other parts may be relatively bare.

3.6.2.4 Texas Ecological Classification Program

TPWD's Texas Ecological Systems Classification Program maps plant communities in riparian zones and floodplains (TPWD, 2010). The program's Phase 3 maps the middle Texas coast including 4 Nueces basin sites for which the BBEST has developed environmental flow regimes. The program used advanced remote sensing techniques and spatial analysis of existing digital data related to ecoregions, soils, elevation models, aerial and satellite imagery, and hydrology, among other ecosystem variables. The smallest area of land assigned to a particular plant community is 33 feet by 33 feet. Plant classification data and supporting documentation can be downloaded through links provided on the TPWD project website: http://www.tpwd.state.tx.us/landwater/land/maps/gis/tescp/index.phtml.

TPWD (2010) described the riparian and floodplain communities along the Frio River near Derby (where the river is crossed by IH-35) (**Figure 3.6.7**). Downstream of the interstate, the riparian community is the "South Texas Floodplain Hardwood Forest and Woodland." Upstream of the interstate the riparian community transitions into the "Edwards Plateau Floodplain Hardwood Forest" and the "Edwards Plateau Floodplain Deciduous Shrubland."

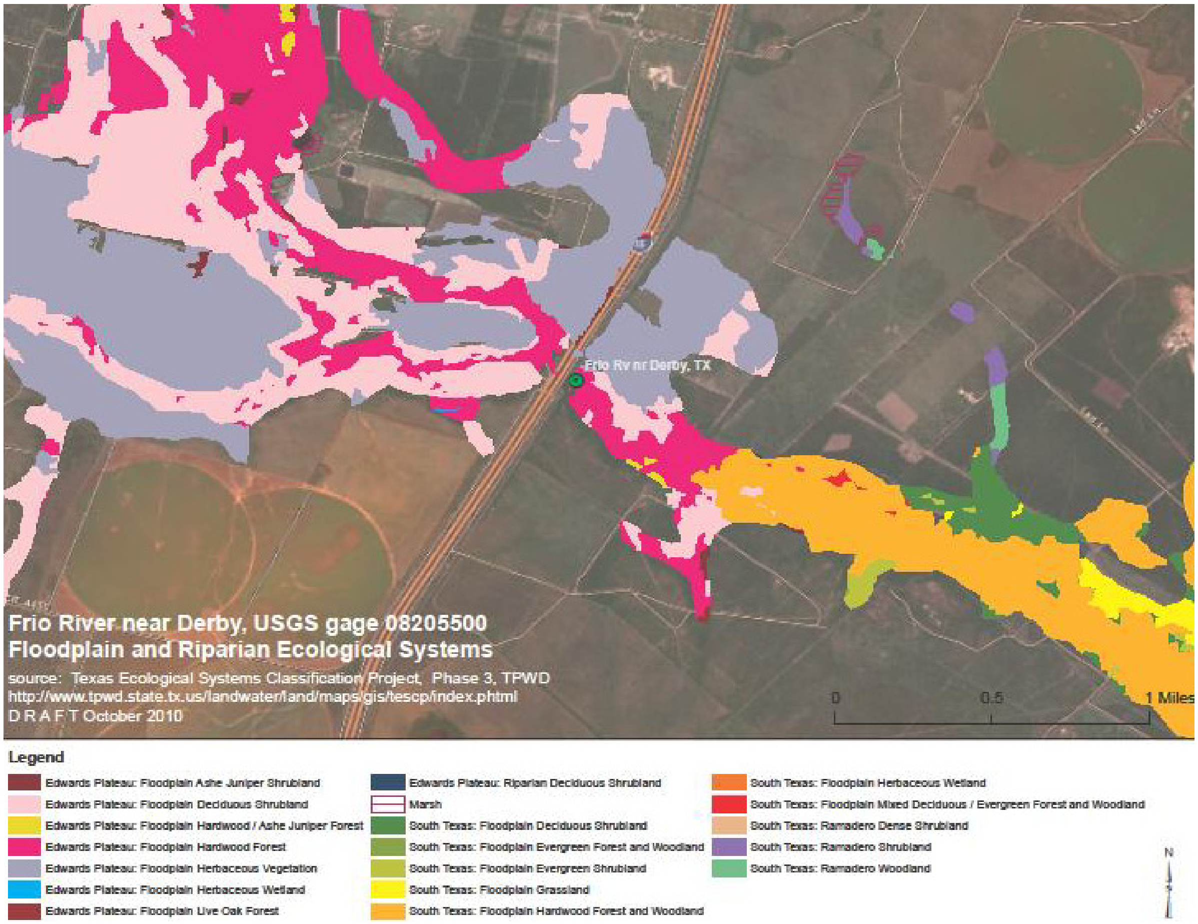


Figure 3.6.7. Frio River at Derby Texas Ecological Systems Classification Map (TPWD, 2010). The confluence of the Leona and Frio rivers is immediately upstream of IH-35 in this photo.

The riparian and floodplain communities along the Nueces River at Cotulla, Tilden, and Mathis have been characterized by TPWD (2010) (**Figure 3.6.8** through **Figure 3.6.11**). "South Texas Floodplain Hardwood Forest and Woodland" and "South Texas Floodplain Deciduous Shrubland" plant communities cover much of the riparian zone and floodplain along the Nueces River at Cotulla and Tilden. A May 20, 2011 site visit by the BBEST to the Nueces River at Cotulla and downstream of Cotulla found ash, black willow, button bush, mesquite, hackberry, spiny aster, frogfruit, and a variety of grasses were common components of the riparian plant community. "South Texas Floodplain Hardwood Forest and Woodland" borders the river downstream of Choke Canyon Reservoir (Figure 3.6.9) and Lake Corpus Christi until the plant community becomes dominated by the "Coastal Bend Floodplain Hardwood Forest." (TPWD, 2010) (**Figure 3.6.12**).

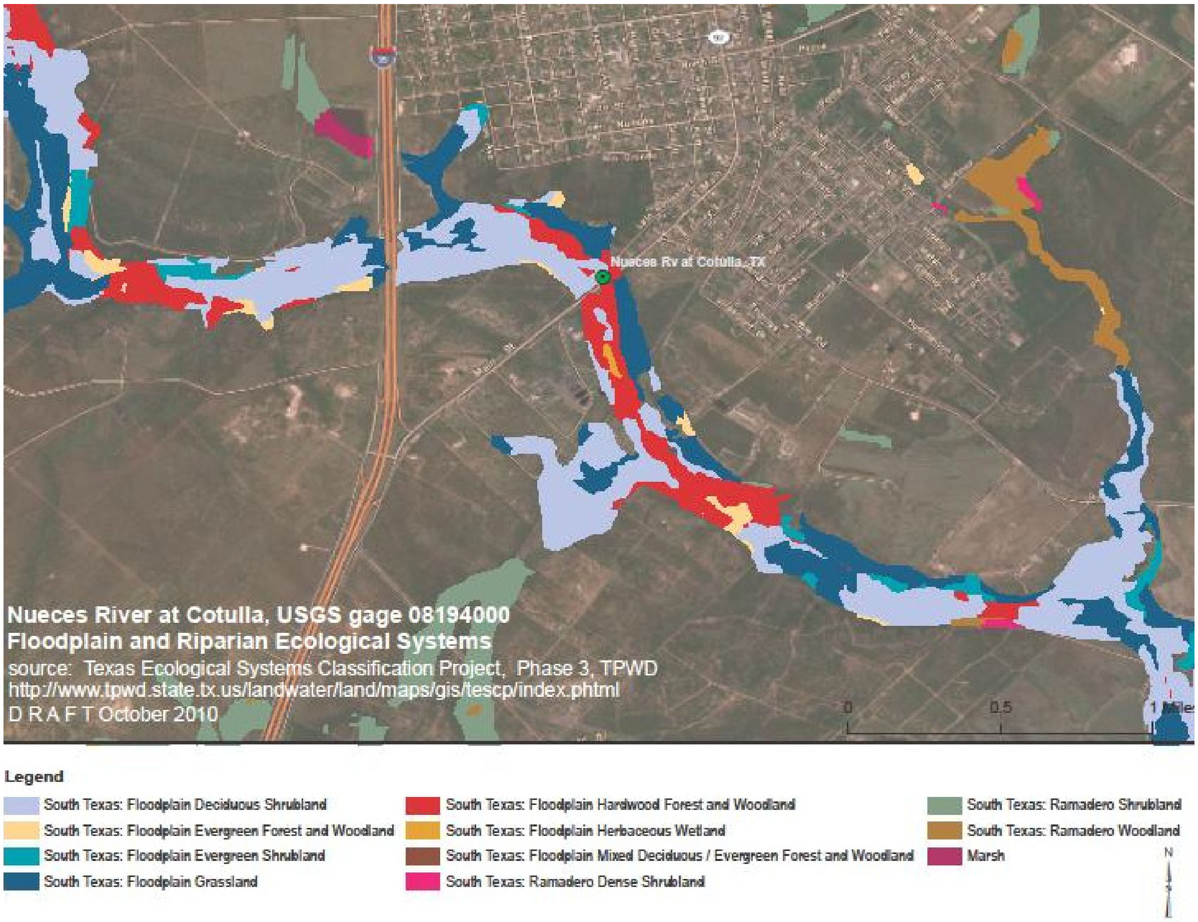


Figure 3.6.8. Nueces River at Cotulla Texas Ecological Systems Classification Map (TPWD, 2010).

Figure 3.6.9. Nueces River at Cotulla Riparian Zone. View is downstream from the green dot labeled "Nueces Rv at Cotulla, TX" on Figure 3.6.5. Photo on the left from bridge and photo on the right from the river bed. Both facing downstream from the bridge. Taken May 20, 2011 (BBEST, 2011).

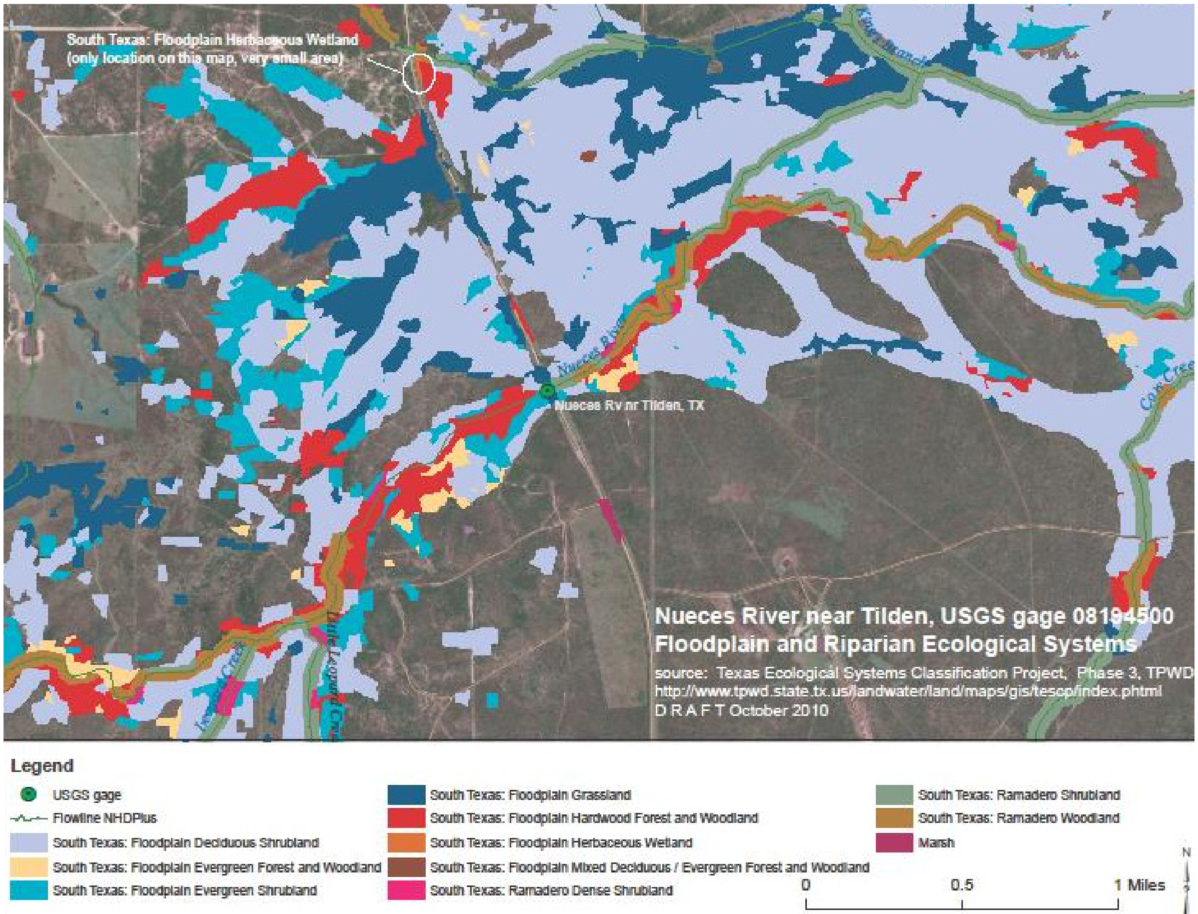


Figure 3.6.10. Nueces River at Tilden Texas Ecological Systems Classification Map (TPWD, 2010).

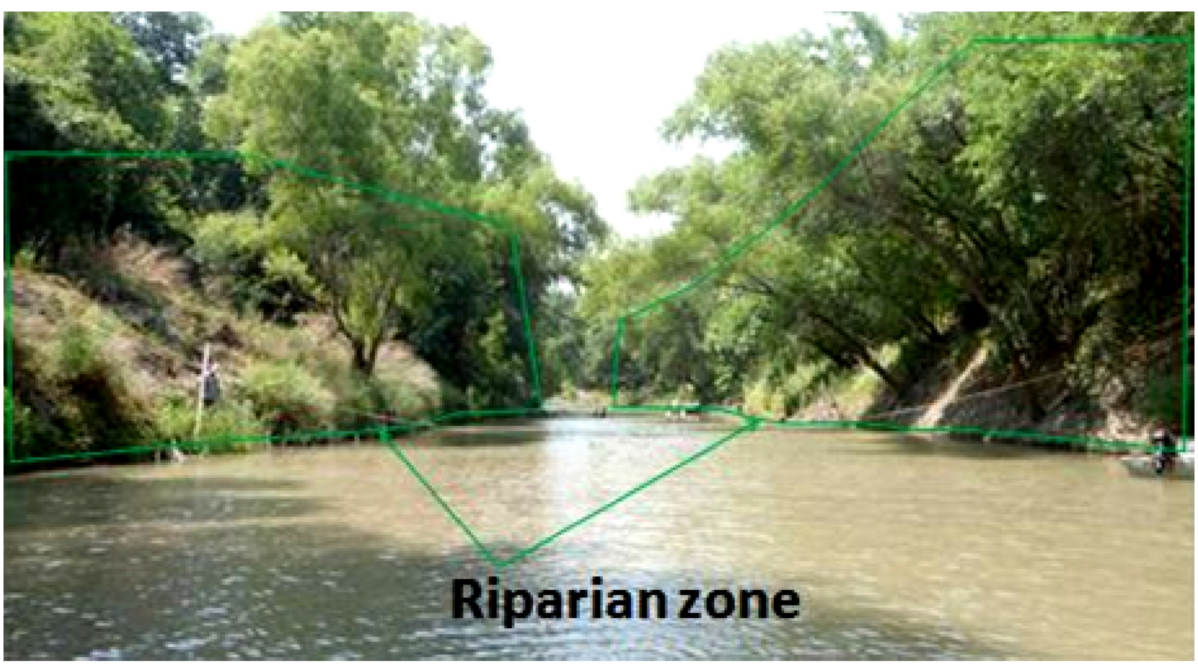


Figure 3.6.11. Nueces River at Three Rivers Riparian Zone. Daily average flow during the study period in which the photograph was taken ranged from 27-164 cfs (USGS, 2011).

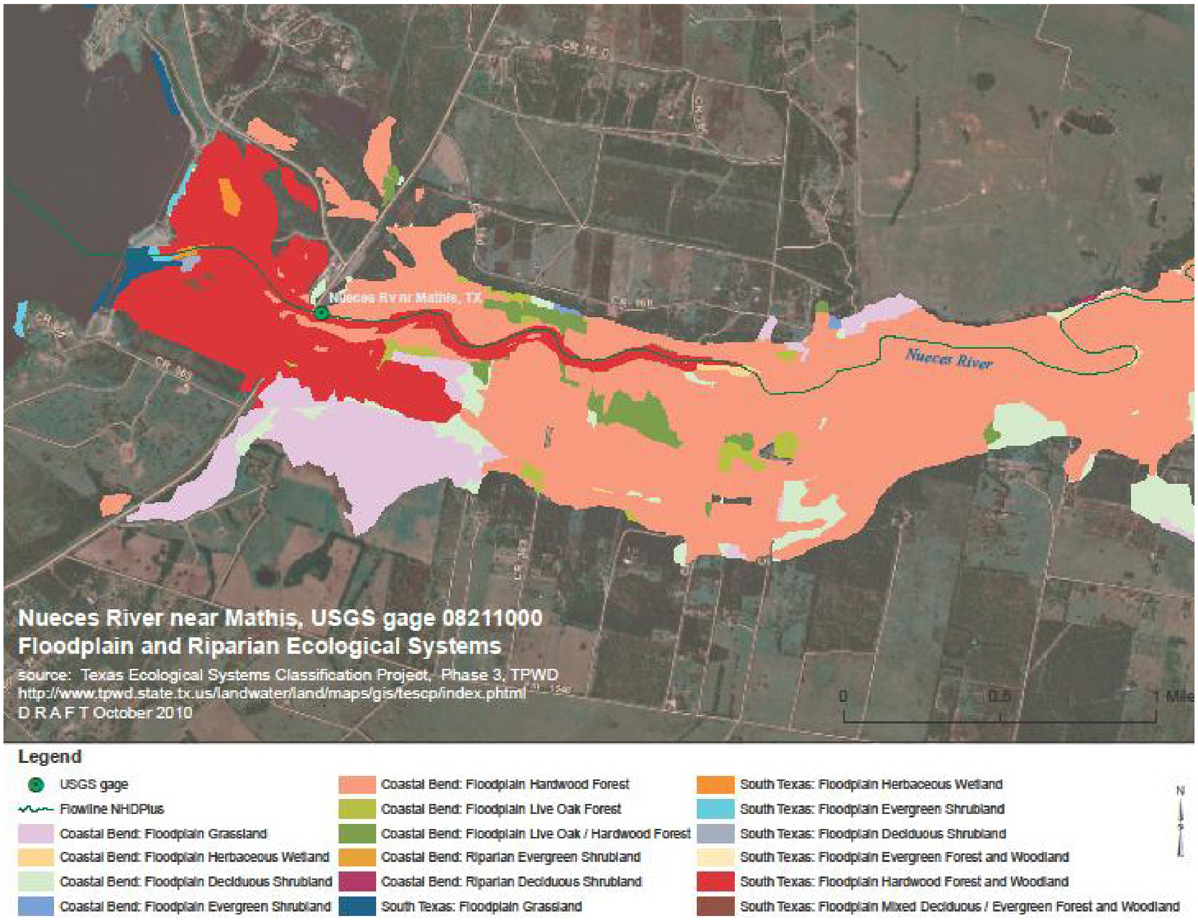


Figure 3.6.12. Nueces River at Mathis Texas Ecological Systems Classification Map (TPWD, 2010).

3.6.3 Riparian Plants of the Nueces River Basin and Their Relationships with Water and Ecological Roles

Over 300 species of plants have been identified from the riparian zones and floodplains in the Nueces basin. At least eleven species are "obligate wetland plants" meaning they almost always live in wetlands. The Nueces River Authority's field guide to riparian plants reports 20 common obligate wetland species in the riparian zones of the basin (NRA, 2010). Obligate riparian plants depend on a high water table, fresh sediment deposits, and tolerate flooding (Kondolf, et al., 1996). Some may colonize flood-scoured sediments while others play an important role in stabilizing sediments. At least sixteen types of plants rarely if ever occur in wetlands. Hundreds of other plant species live in habitats that are sometimes wet but which most of the time are relatively dry.

Forty-eight common facultative and facultative wetland species dominate riparian areas along most Nueces basin streams and do "the work" in the riparian zone (Jones-Lewey, personal communication, 2011). Facultative plants are as likely to be found in a wetland as upland while facultative wetland plants are more likely to be found in a wetland but occasionally grow in uplands. Even those these plants do not need wetlands to survive, they perform important ecological roles in floodplains and riparian zones. They stabilize soil against flooding, provide shelter for some riparian species that are slower growing, and can continue to provide food and cover for wildlife when conditions are too dry for plants that almost always require wet soils.

As described earlier, the Nueces basin is a semi-arid basin with average annual rainfall rates ranging between 23 to 32 inches per year. The upper basin, across the Edwards Plateau, has relatively thin, mineral soils. The arid condition and thin soils, limit soil moisture and groundwater levels which in turn limit riparian zones and floodplains of Nueces basin streams. However valley shape, size, sediment and soil type are the main factors limiting riparian development in these headwater streams (Jones-Lewey, 2011, personal communication). In both the upper and lower parts of the basin, riparian health is limited by adequate cover of healthy plants which can contribute to sediment movement during pulse flows.

Many of the area's riparian and floodplain plants tolerate dry conditions and also live outside the floodplain. They may grow in denser concentrations adjacent to streams or be more productive where there is more frequent access to water. Their presence in the floodplain may be related to more frequent exposure to water in moist soils or episodically elevated groundwater or shady conditions. For example wood oats, *Chasmanthium latifolium*, which tolerates dry soils, does well in full shade (TPWD, 2011). Switchgrass, *Panicum virgatum*, is a facultative wetland plant found across the upper basin which plays an important role in stabilizing soils. Gulf cordgrass and spiny aster are important soil stabilizers and facultative wetland plants in the South Texas Brush Country portion of the basin. Species like mesquite, do not tolerate flooding but tolerate droughts. Plants with different requirements for soil moisture, access to water, sunlight, and interactions with other plants create the biological diversity and productivity found in the Nueces floodplain. Although these floodplains are relatively dry and infrequently flooded compared to wetter areas east of the Nueces basin, stream flow and elevated groundwater are critical to maintenance of a healthy floodplain community in the Nueces basin.

Typical plants of Nueces basin floodplains are listed in **Table 3.6.1**. Selected riparian plants of the over 200 species identified by NRA (2010), Miller, et al., 2010 (plants of the Frio and Sabinal river riparian zones on the Edwards Plateau), TPWD (2010) (plants of the riparian zones and floodplains of the Edwards Plateau, South Texas Brush Country, and Coastal Bend), and Swihart (2005) (30 plants covering the greatest area along the upper Frio riparian zone) are listed below. For some species, relationships with water are identified and ecological roles are reviewed. The wetland indicator category for each type of plant is identified. The stability rating is also shown for each plant. Stability rating refers to the ability of the plant to help resist erosion by water. Values range from 1, equal to bare ground, to 10, equal to anchored rock (NRA, 2010).

Definitions of wetland indicator status:

UPL (obligate upland) – almost never found in wetlands	FACU (facultative upland) – occasionally found in wetlands (up to a 33% probability of being found in a wetland)	FAC (facultative) – as likely to be found in a wetland as to be found upland	FACW (facultative wetland) – usually found in wetlands but occasionally found upland	OBL (obligate wetland) – almost never found outside of wetlands
Dry	→	→	→	Wet

Table 3.6.1. Riparian Zone and Floodplain Plants of the Nueces Basin, Texas. A positive (+) or negative (−) sign is used for the facultative categories. The (+) sign indicates a frequency towards the wetter end of the category (more frequently found in wetlands) and the (−) sign indicates a frequency towards the drier end of the category (less frequently found in wetlands).

Name	Ecological Role	Edwards Plateau	South Texas Brush Country	Coastal Plain	Regional Wetland Indicator Status	Stability Rating (NRA, 2010)
Acacia farnesiana, sweet acacia	Leaves used for forage and flowers feed bees (Wikipedia, 2011).	X	X	X	FACU	
Acer negundo, boxelder Most common on moist soil and deep alluvial soils near streams, drought tolerant, may survive flooding up to 30 days (Rosario, 1988).	Seeds and other parts of the tree used by birds and wildlife as food. Because of its delayed production of seeds, seeds are available to wildlife for more of the winter.	X		X	FACW-	6
Andropogon glomeratus, bushy bluestem Grows in moist soils, saturated in some seasons (NRCS, 2006).	Seeds eaten by birds and small mammals. Provides nesting material for birds (University of Texas, 2011b).	X			FACW+	5
Arundo donax, giant reed		X (NRA, 2010)	X		FAC+	7
Baccharis neglecta, Roosevelt weed	During floods catches debris which may be colonized by other riparian species (NRA, 2010).	X	X		FAC	6
Brickellia spp., brickelbush	Important colonizer of disturbed sediments/gravel bars (NRA, 2010).	X			UPL	4
Carex emoryi, river sedge	Grows along the water's edge and is an important stabilizer of soil (NRA, 2010).	X			OBL	9
Carya illinoinensis, pecan Grows on well-drained soils not subject to prolonged flooding. Seedlings survive short periods of flooding, Seed dispersal is principally by water and animals. Floating nuts can be carried considerable distances by flood water. Best growth on riverfront ridges and well-drained flats (Coladonato, 1992).	Excellent source of food, nesting, and den habitat for wildlife (TPWD, 2011). Fallen trees and branches provide instream habitat (NRA, 2010).	X	X	X	FAC+	6
Celtis ehrenbergiana, granjeno	Browsed by wildlife. Important stabilizer of riparian soils in drier areas (NRA, 2010).	X	X	X	UPL	5-6

Name	Ecological Role	Edwards Plateau	South Texas Brush Country	Coastal Plain	Regional Wetland Indicator Status	Stability Rating (NRA, 2010)
Celtis laevigata, sugarberry, and *C. laevigata* var. *reticulata* (netleaf hackberry) Seedlings intolerant of flooding. Trees cannot tolerate prolonged flooding or water-saturated soils, and grow best in the drier areas of forested wetlands. Commonly succeeds eastern cottonwood (*Populus deltoides* var. *deltoides*) and black willow (*Salix nigra*) on new land created by rivers (Sullivan, 1993).	Fruits are a preferred food of turkeys and are eaten by a variety of birds and other animals (Sullivan, 1993). Browsed by deer (NRA, 2010).	X	X	X	FAC	5-6
Cephalanthus occidentalis, common buttonbush Grows where there is intermittent flooding. Found in medium to wet soils (NRCS, 2004).	Excellent food and cover for waterfowl (TPWD, 2011). Stabilizes soils (NRA, 2010).	X	X	X	OBL	8
Chasmanthium latifolium, Indian woodoats	Good food and cover for mammals and birds (TPWD, 2011).	X		X	FAC	5
Chloracantha spinosa, spiny aster	Stabilizes riparian soils and protects from erosion (NRA, 2010).	X	X	X	FACW-	8
Chromalaena odorata, cruciata Seeds float downstream after landing on water. Flood events transport silt with seeds downstream (Global Invasive Species Database, 2011).			X			
Cladium mariscus ssp. jamaicense, sawgrass	Important stabilizer of soils. Seeds eaten by birds (NRA, 2010).	X			OBL	9-10
Condalia hookeri, brasil	Fruits are good food for wildlife and plant is excellent cover for birds (TPWD, 2011).	X	X	X		
Diospyros texana, Texas persimmon	Fruit are an excellent food source for small and large mammals and many birds. Shrubs provide good cover for mammals and birds (TPWD, 2011).	X	X	X		5
Eleocharis spp., spikerush		X		X	OBL	6
Elymus virginicus. Virginia wildrye Tolerates wet soils and seasonal flooding (Sanderson, et al., 2010).	Good food source for mammals and birds and cover for small mammals (TPWD, 2011).	X		X	FAC	
Forestiera acuminata, eastern swampprivet Seeds may be dispersed by catfish and water (Adams, et al., 2007). Requires moist soils (Francis, 2011).	Excellent source of food and cover for birds, large, and small mammals (TPWD, 2011).			X	OBL	
Fraxinus berlandieriana, Mexican ash	Stabilizes riparian soils. Larval host for several species of butterflies (NRA, 2010).		X	X	FAC	6

Name	Ecological Role	Edwards Plateau	South Texas Brush Country	Coastal Plain	Regional Wetland Indicator Status	Stability Rating (NRA, 2010)
Fraxinus pennsylvanica, green ash Flood tolerant. Studies indicate it is more common on temporarily flooded sites (Gucker, 2005). Some seed dispersal is by water (Burns and Honkala, 1990).	Seeds eaten by birds and wildlife (Burns and Honkala, 1990).	X		X	FACW-	
Fuirena simplex, porcupine sedge	Helps colonize barren areas (NRA, 2010).	X			OBL	5
Juglans microcarpa, little walnut Seeds dispersed by animals or water, grows along rocky streambottoms, in canyons and arroyos, and on first terraces of dry river beds. Moisture is generally obtained from flowing or ephemeral streams and flash floods (Tirmenstein, 1990).	Nuts provide food for mammals (TPWD, 2011). Colonizes and stabilizes exposed gravel bars in the river (NRA, 2010).	X			FAC-	7
Juncus spp., rushes	Colonize newly deposited sediments. Grazed by wildlife (NRA, 2010).				FACW	6
Lobelia cardinalis, cardinal flower	Provides food for hummingbirds and butterflies (NRA, 2010).					5
Morus rubra, red mulberry Moderately tolerant of flooding; will withstand inundation for a complete growing season, but is killed by inundation over two growing seasons	Berries are an excellent food source for fish and wildlife (TPWD, 2011).	X		X	FACU	6
Panicum virgatum, switchgrass Tolerant of flooding (Bransby, 2010).	Root systems penetrate over 10 feet into the soil, add organic matter, and increase soil water infiltration and nutrient-holding capacity. Cover for deer, rabbits, turkeys, and quail (Bransby, 2010). Excellent erosion control (TPWD, 2011).	X	X		FACW	9
Parkinsonia aculeata, Jerusalem thorn	Stabilizes banks and floodplains. Browsed by deer (NRA, 2010).		X		FACW-	6
Paspalum distichum, knotgrass	Quickly colonizes areas washed bare after pulse flows (NRA, 2010).	X			FACW	6
Phyla nodiflora, turkey tangle fogfruit		X	X		FACW	4

Name	Ecological Role	Edwards Plateau	South Texas Brush Country	Coastal Plain	Regional Wetland Indicator Status	Stability Rating (NRA, 2010)
Platanus occidentalis, American sycamore Can grow in river bottoms saturated for 2–4 months however grows best when groundwater levels drop and permit soil to be aerated during the growing season (Burns and Honkala, 1990). Seeds, which tolerate flooding often settle on muddy flats that provide the very moist conditions needed to germinate (Sullivan, 1994). Seeds are dispersed primarily by wind and water from February–May and germinate better when submerged (USFWS, 1977). Seedlings flooded for up to 40 days grow poorly and are less resistant to drought after extended exposure to flooding (Tang and Kozlowski, 1982).	Seeds eaten by some birds, beavers, and squirrels. Used by wood ducks for nesting. Cavities in trees used by cavity-nesting birds and mammals (Sullivan, 1994). Trees fallen in the channel may create nursery pools for small fish and aquatic insects (NRA, 2010).	X		X	FAC+	6
Populus deltoids, eastern cottonwood Unless wet, seeds must reach a suitable germination site within 1–2 weeks to avoid desiccation. High flows in late spring generate bare, moist, mineral substrate and silt deposits where cottonwood normally become established. Best sites have water tables 2 to 6 feet below ground. Floods during the dormant season or floods of short duration during the growing season may help cottonwood trees by fully recharging subsoil moisture and reducing competing vegetation that tolerates dry conditions (Burns and Honkala, 1990). May be stressed by wetter than normal summer soil conditions (Dudek, et al., 1998). Seedlings need continuous access to wet soil (NRA, 2010).	Chief source of propolis, a brownish, waxy material collected by bees from the buds and used to seal small holes in the hive. Eaten by beavers. Used by turkeys for roosting (TPWD, 2011).		X, on San Miguel Creek (Jones-Lewey, 2011, personal communication)	X	FAC	7
Prosopis glandulosa, mesquite Occurs along the outer floodplain. Not particularly flood tolerant (Steinberg, 2001).		X	X	X	FACU	5
Salix nigra, black willow Seeds are distributed by water and wind, and must reach a seedbed within 12–24 hours, unless floating in water. Seed viability declines in a few days under dry conditions. Very moist, almost flooded mineral soil is best for germination and development. Seedlings grow best when there is abundant moisture available throughout the growing season. Can survive more than 30 days of inundation. Intolerant of drought (Burns and Honkala, 1990).	Root mats stabilize soil adjacent to the river (Burns and Honkala, 1990). Food for deer and beavers (NRA, 2010).		X	X	FACW+	7
Scirpus spp., bulrush	Roots stabilize soils and resist flooding (NRA, 2010).				OBL	9

Name	Ecological Role	Edwards Plateau	South Texas Brush Country	Coastal Plain	Regional Wetland Indicator Status	Stability Rating (NRA, 2010)
Sesuvium sp.	May be eaten by wildlife for its salt content (Jones-Lewey, personal communication, 2011).			X	FACW	4
Solidago canadensis, Canada goldenrod	Provides food for insects and butterflies (NRA, 2010).	X			FACW	6-7
Spartina spartinae, Gulf cordgrass	Geese and sandhill cranes use Gulf cordgrass stands. Mottled ducks are also known to nest in dense clumps (NRCS, 2011). Roots stabilize soils (NRA, 2010).		X (USFWS, 1983)		FACW+	9
Sporobolus wrightii, big sacaton	Stabilizes riparian soils (NRA, 2010).				FAC	9
Taxodium distichum, bald cypress Water is necessary for seed dispersal (few seeds are disseminated by animals). Seedlings establish after 1–3 months on saturated or wet, organic, or peaty soils but die if inundated for 2-4 weeks (Burns and Honkala, 1990). Stagnant water reduces growth (probably as a result of changed CO_2 and O_2 conditions in the water) (Donovan, et al., 1988).	Seeds are eaten by turkeys, squirrels, and wood ducks. Bald eagles and ospreys nest in upper branches. Roots provide cover for fish (Burns and Honkala, 1990). Roots protect banks from erosion. Fallen trees in riparian zone or channel help stabilize soils (NRA, 2010).	X		X	OBL	9
Tripsacum dactyloides, eastern gamagrass Tolerates extended periods of flooding. Approximately 3–10 weeks of cold, moist weather conditions are necessary for germination (NRCS, 2008).	Good food and cover for mammals and birds (TPWD, 2011). Protects pecan and cypress seedlings from grazing (NRA, 2010).	X	X (NRA, 2010)	X	FAC+	9
Typha domingensis, southern cattail	Stabilizes soils and increases resistance to flooding (NRA, 2010).			X	OBL	9
Ulmus americana, American elm Tolerates some flooding during the dormant season but not prolonged flooding during the growing season (Burns and Honkala, 1990).	Leaves decompose more rapidly than many other tree species and add potassium, calcium, and other nutrients to the soil. Is considered a soil-improving species (Burns and Honkala, 1990).	X		X	FAC	6
Ulmus crassifolia, cedar elm	5-10 percent of wild turkeys' diet may come from cedar elm seeds and buds (Burns and Honkala, 1990).	X	X	X	FAC	6

3.6.4 Environmental Flow Regime Components and Sound Riparian Environment

3.6.4.1 Perennial Pools and Subsistence Flows

Depending on soils, groundwater levels, and stream flow, groundwater may flow from the adjacent alluvium or shallow aquifer into the stream. Perennial pools and subsistence flows supported by groundwater flow provide refuge for fish, aquatic turtles, snakes, and birds during droughts. Mammals, birds, reptiles, amphibians, and insects living in the riparian zone increasingly rely on these low flow conditions as their only source of water during drought. Young egrets and herons hatched in the spring, have easier access to the small fish, crayfish, and aquatic insects they eat when flows are low.

Grasses and other small plants sprout and grow further down the river bank providing additional forage for grazing animals in the riparian zone. These grasses and small plants will provide habitat for small fish and insects when water levels rise again. As these plants decompose when drowned by higher flows, they become food for snails and aquatic insects. Nutrients from these decomposing plants are released and support the riverine food web by growing plankton. Plankton in turn become food for freshwater clams. Riparian shrubs and trees that die or become stressed during droughts, shed branches and leaves that become food for aquatic insects and habitat for fish when the water level rises again. Their branchs, trunks, and root mats can provide instream habitat and help stabilize stream channels.

In parts of the Nueces River, groundwater ensures perennial pools always have water. The Nueces BBEST visited the river downstream of Cotulla and observed pools that have persisted over the past 40 years although the river has stopped flowing about 40 percent of the time during the same period (**Figure 3.6.13**).

Figure 3.6.13. Nueces River perennial pools downstream of Cotulla on May 20, 2011 (Nueces River flow of zero cfs) (Nueces BBEST, 2011).

3.6.4.2 Base Flows

The BBEST recommended three levels of base flow which provide a relatively small part of the normal flow variability the streams normally experience. Groundwater seepage into streams is more likely to occur at low base flows while stream flow may seep into the groundwater at high base flows. At base flows, many riparian plants reach their peak productivity at the high temperatures and light regimes provided during warmer months when their root systems are not flooded. Base flows allow riparian seedlings that have sprouted to establish their root systems and grow big enough to withstand flooding. Semiaquatic turtles lay their eggs in the spring and base flows allow the eggs to develop and hatch without being drowned. Juvenile mammals, birds, reptiles and amphibians have access to water at base flows with less risk of being drowned by flood flows. Interchange between groundwater and stream flow varies soil moist at different soil depths and distances from the shore. Moist soils sustain many of the riparian plants and may stress some upland plants that invaded the riparian zone. Under base flow conditions, water from pulses that has soaked into the groundwater, drains back out of the soil, providing the well-drained soils that some riparian plants need for growth. Some riparian plants living along the shore at the water line require the continuous exposure to water provided by base flow regimes. Some reaches of Edwards Plateau streams have base flows supported by groundwater issuing from multiple springs along their shores.

3.6.4.3 Pulses

Pulses increase nutrient exchange between the streams and land in the floodplain and riparian zone. Increasingly large pulses pick up more organic matter, leaves and plants, and transport them to the stream or to other parts of the riparian zone where the organic matter enriches the soil. Pulses erode and transport sediment. Eighteen percent of the estimated total suspended sediment load for the Nueces River below Corpus Christi came from erosion of the stream banks and bed (USGS, 2010). Pulses may wash accumulated soil and organic matter off riparian areas and create moist, bare areas for seeds to settle and germinate. Larger pulses may wash enough sediment to create islands in the stream or new bars long the shores. These new islands and bars create new habitat for riparian species to establish. Pulses also raise groundwater and soil moisture adjacent to the stream. When groundwater and soil moisture is raised, upland plants that have invaded the riparian zone or floodplain may be killed or growth-inhibited. Conversely water tolerant-riparian and floodplain plants may experience enhanced growth or set more fruit or seeds. Root growth may be stimulated as roots follow receding water levels deeper and become more stable. Colonizing plants will grow on gravel bars and capture sediment in subsequent pulses (Jones-Lewey, personal communication, 2011). As pulses recede, small pools and puddles will remain in parts of the stream channel. These small pools provide water used by amphibians to breed. As with subsistence flows and perennial pools, these small pools provide access to birds and mammals which prey on the fish and other aquatic animals stranded in the pools.

Seasonal pulse flows recharge the shallow aquifers adjacent to the streams and increase fish access to hiding places among the plants that grew along the shore at lower flows. Fish, aquatic insects, and crayfish feed on the terrestrial insects captured in these pulses. Nutrients are interchanged between the riparian zone and the stream as shorelines are submerged and nutrients in the form of live and decaying plants, or mineral nutrients accumulated along the shore are washed back into the river. Seasonal pulses also moisten the soil around riparian seedlings higher on the shore or on islands that have sprouted and need moist soil long enough to become established. Seasonal pulses provide the extra water without the high water levels and velocities that would wash out young plants before they were established.

High pulses that occur once or a few times a year transport seeds of riparian and floodplain plants and as the pulses recede, the extended period of moisture following the pulse, allows seeds to germinate and send roots into the soil. Overbank flows occur relatively infrequently, once every several years, and interact with the riparian zone and floodplains in ways similar to pulses but on larger scales. Overbank flows may drown upland vegetation that has invaded the riparian zone during extended periods with normal flows. Portions of the stream channel, riparian zone, and floodplain are eroded or vegetation is washed away. These newly eroded, wet areas are colonized by different species of riparian plants that may not tolerate the shade of an established riparian plant community. Eroded sediment may build up in the stream bed creating new islands and bars. These islands and bars also provide habitat for riparian plants to establish. Dead and eroded trees and shrubs that are washed into the river create new habitat for fish and semiaquatic animals like turtles and snakes.

3.6.5 Additional Resources

Nueces River Authority's "Riparian Network Project" website. Excellent resource for information about riparian systems in the Nueces basin. http://www.nueces-ra.org/CP/LS/.

"Arizona's Riparian Areas". Description of riparian systems and relationships to flow in arid environments like portions of the Nueces basin. http://ag.arizona.edu/extension/riparian/

"Streamside Management in the Hill Country: An Edward's Plateau Landowner's Guide". Description of Edwards Plateau riparian systems. http://gbrtrust.org/documents/publications/HillCountryStreamsideManagement.pdf.

Section 4. Freshwater Inflow and Estuary Analyses

4.1 Hydrology, Salinity, and Inflow Characterization Methodology

The Nueces Bay and Delta complex has been the subject of much scientific study during the last two decades. Thus, the Nueces BBEST has some of the best science available including years of gaged data with robust empirical salinity measurements to make predictions concerning freshwater inflow to the estuary as they relate to estuarine organismal response. Our freshwater inflow analyses focused on the Nueces Bay and Delta, where the majority of the impacts occur in this estuary (see Section 1.3 and Section 2.8 for details).

Our procedures to estimate the amount of freshwater inflow to maintain a sound ecological environment are based on the following serial tasks:

1) characterize historical patterns of hydrology, salinity, and flood events to determine the relationship between inflow and salinity;
2) use empirical data and TxBLEND modeling to examine inflow conditions and how salinity in the estuary responds under dry, moderate, and wet conditions;
3) identify focal species (marsh plants, benthic infauna, and nekton) for which we could develop quantitative metrics between salinity and ecological integrity as evidenced by abundance, distribution, and diversity patterns for use as indicators of estuarine health; and
4) make recommendations for baseline freshwater inflow needs and a regime to maintain these estuarine indicators in a healthy state.

The sections below provide a summary of the scientific data and analyses we used to arrive at our freshwater inflow recommendations that can be found in a summary table in Section 4.5.

4.1.1 Historical Patterns of Hydrology, Salinity, and Flood Events

To examine historical inflow patterns, initial analyses involved creating basic annualized inflow charts during the period of record from 1941 to 2009. Estimates of historical freshwater inflows into the Nueces Estuary were provided by the Texas Water Development Board (TWDB). The TWDB provides details of how these inflows were calculated in a report on the coastal hydrology for the Nueces Estuary (TWDB, 2011) included as Appendix 4.1.

The historical patterns showed variable patterns of annual inflows. However, there are clear trends of flow with much less water reaching the estuary during the post-1982 time period following the construction of Choke Canyon Reservoir (see Section 2.8 for extensive historical review). **Figure 4.1.1A** shows the Nueces BBEST estuarine inflow recommendations where the red line represents subsistence flow (30,000 acft/yr, a flow to occur only during extreme drought conditions), the green is base flow (166,000 acft/yr, the management goal with a flow that would maintain a sound ecological environment), and the yellow is high flow (750,000 acft/yr, during and as a result of flood events). The current Agreed Order inflow amounts are shown in **Figure 4.1.1B**. The logical progressions of how the science team arrived at these inflow numbers is described in detail below and summarized in Section 6.

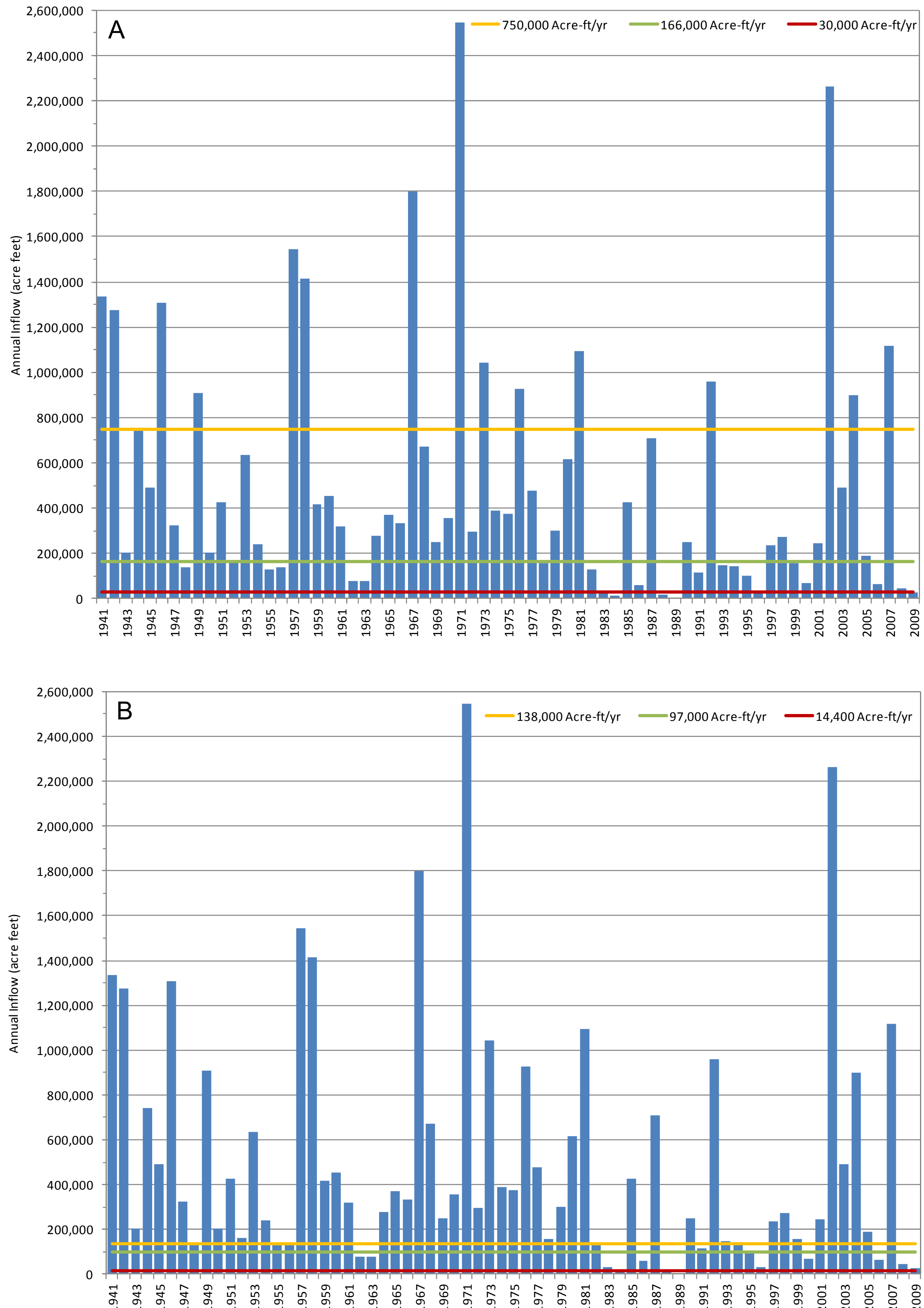


Figure 4.1.1. Annual cumulative inflow for Nueces Bay with Nueces BBEST inflow recommendations (A) and current agreed order inflows (B). The Mathis gage (#08211000) was used for inflows from 1941-1976; the Mathis gage + ungaged watershed was used from 1977-2009 (TWDB, 2011).

Additionally, monthly patterns of freshwater inflow into the Nueces Estuary were plotted over several different time periods relating to when the dams were built. In Figure 4.1.2 below, the green line represents mean (A) and median (B) monthly inflow from 1941–1957 before Wesley Seale Dam was constructed forming Lake Corpus Christi. See Section 2.8 for extensive historical review for the history of dam construction and historical water patterns. During this time period, there are two distinct inflow pulses throughout the year, spring and fall. Inflow after the impoundment of Lake Corpus Christi and before the impoundment of Choke Canyon Reservoir is shown by the red line (1958-1982). Two annual pulses remain in the spring and fall, but much of the spring pulse is captured by Lake Corpus Christi. After the impoundment of Choke Canyon Reservoir (black line from 1983-2009) there is no longer a spring pulse, but one in the summer, which is most likely attributed to tropical storm activity. The fall pulse is very low, and most is captured by the two reservoirs. Mean monthly flows (**Figure 4.1.2A**) show general patterns of pulses and floods because mean flow values are typically strongly affected by high flow events. Conversely, median monthly flows (**Figure 4.1.2B**) usually reflect base flows not substantially influenced by these pulses. Median flows show that spring and summer were periods of relatively high base flow before reservoir construction. Median flow patterns also show that base flows lost much of their seasonal variation after reservoir construction. This suggests the estuary may have experienced impacts to ecological functions that depend on seasonal variability in base and pulse flows.

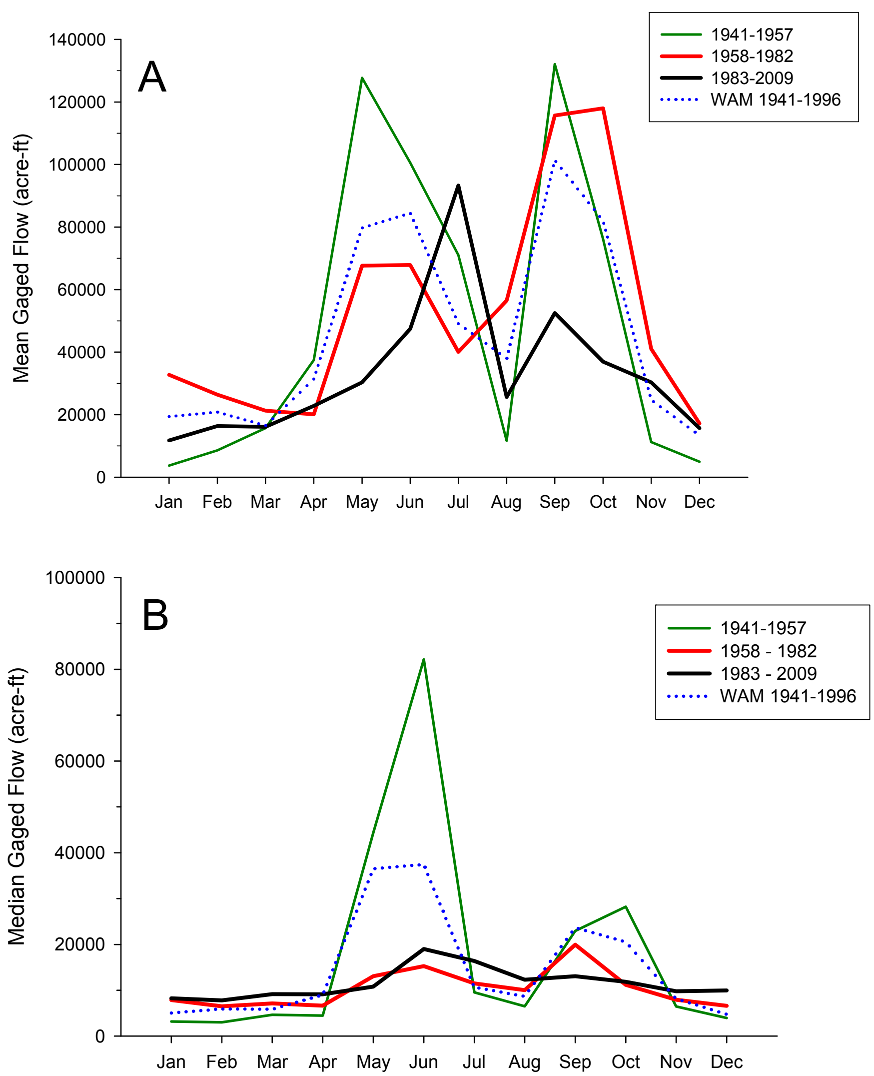


Figure 4.1.2. Historic flow patterns into the upper Nueces Estuary. Mean gaged inflow (A) and median gaged inflow (B) for 3 time periods from the Mathis gage (#08211000) and the WAM (water availability model) naturalized inflow.

4.1.2 Salinity Characterization Under Dry, Moderate, and Wet Conditions

Using historical inflow (TWDB, 2011), the BBEST chose dry, average (moderate), and wet years to model salinity patterns under these variable flow regimes (Figure 4.1.1; **Figure 4.1.3**). Salinity patterns were then characterized during these time periods using data from TxBLEND modeling (**Figure 4.1.4**) and empirical data from fixed salinity stations in Nueces Bay (Figure 4.1.6). Dry years used for TxBLEND modeling were 1996 and 2000; average year was 1997; and wet years were 2003-2004.

Using outputs from TxBLEND modeling, it is very apparent that freshwater inflow greatly influences salinity in Nueces Bay, but has little influence on salinities in Corpus Christi Bay. The maps below show that even during a very wet year like 2004, Corpus Christi Bay, Baffin Bay, and Upper Laguna Madre show little impact from the freshwater coming into the system via Nueces River given the marine nature of these bays (**Figure 4.1.5A**). Because of these salinity patterns, BBEST focused on salinity patterns in Nueces Bay exclusively. A closer examination of Nueces Bay shows this body of water is heavily influenced by freshwater inflow, and during dry conditions, it becomes a more marine and even hypersaline system (**Figure 4.1.5B**). Therefore, the majority of remaining analyses to determine freshwater inflow recommendations for the Nueces Estuary focused on Nueces Bay and Delta. Below are details about how TxBLEND maps were created and how empirical data were used to support TxBLEND conclusions.

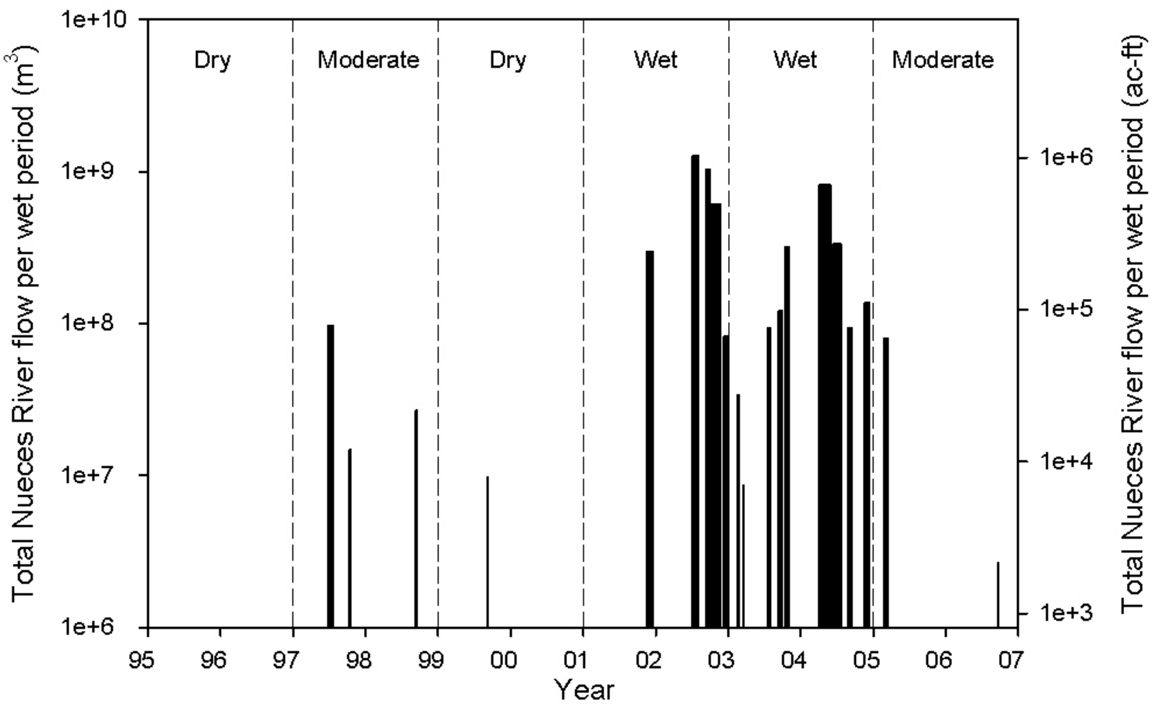


Figure 4.1.3. Wet periods and two-year bins from 1995-2007. From January 1994 to August 2000, wet periods were classified as daily flow rates exceeding 4.2 x 10^6 m^3 Nueces River flow. From August 2000 to February 2008, wet periods were classified as daily flow rates exceeding 2.6 x 10^6 m^3 Nueces River flow.

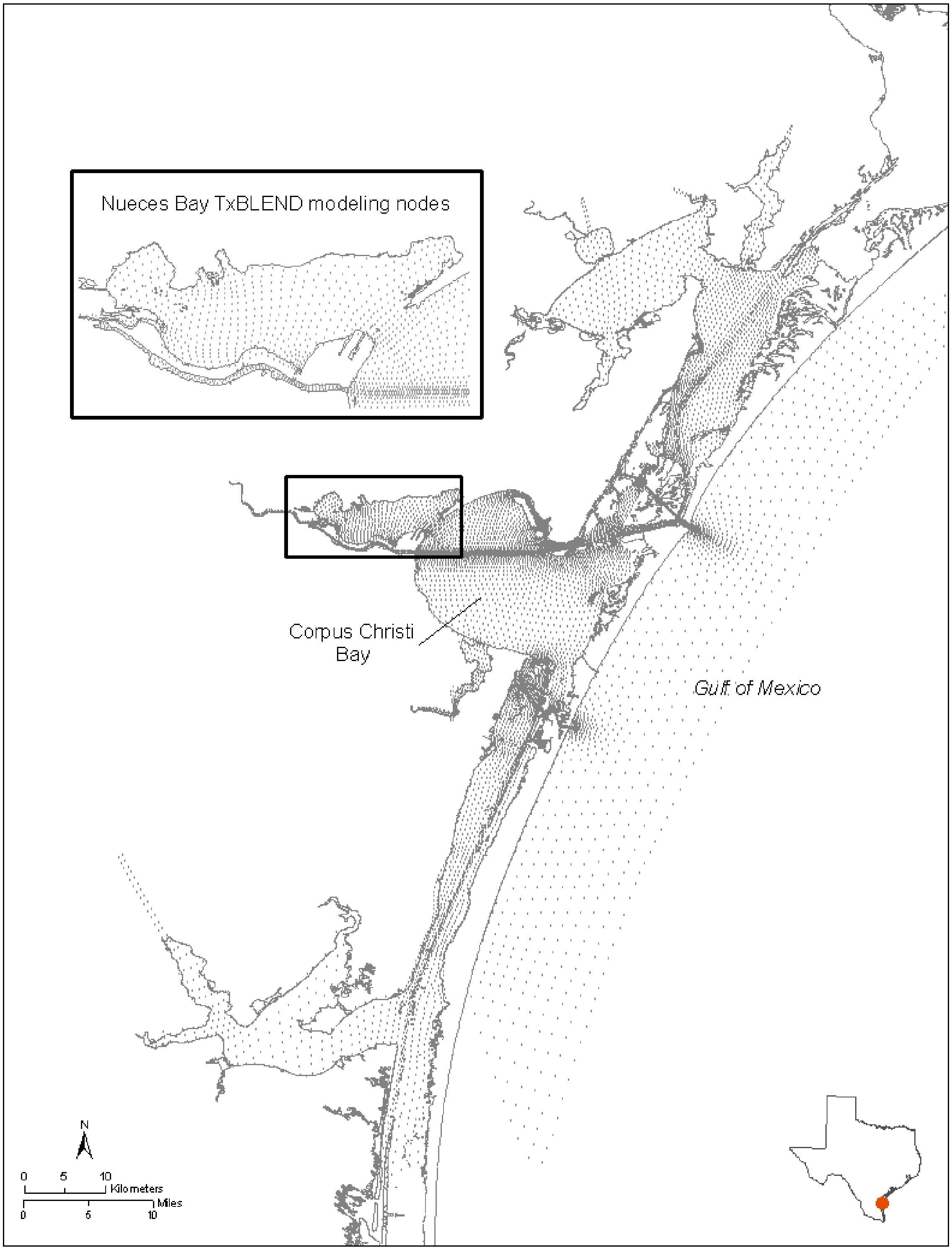


Figure 4.1.4. TxBLEND nodes used to model salinity in the Nueces Estuary.

Salinity patterns predicted by TxBLEND modeling

Using TxBLEND, salinity was modeled annually during the above inflow periods for the entire Nueces Estuary (**Figure 4.1.5A**), as well as for Nueces Bay only (**Figure 4.1.5B**). Salinity was also modeled monthly for the Nueces Estuary and for Nueces Bay, and these figures can be found in Appendix 4.2. Salinity patterns were developed in a Geographic Information System (GIS) using TxBLEND modeled average monthly salinity data points, or nodes. The TxBLEND hydrodynamic model simulates the effect of inflows on salinities in the bay using a finite element grid made up of nodes and linear triangular elements across the bay and neighboring bay systems. The computational grid used for this BBEST application consists of 11,009 nodes and extends into connected bays to account for the continuity of water movement and salinity transport between the bays; approximately 600 nodes are located in Nueces Bay as shown in Figure 4.1.4. The original salinity data file exceeded three million records for the full period of record, 1988 to 2009. For detailed technical information about the TxBLEND model please refer to documentation provided by the TWDB.

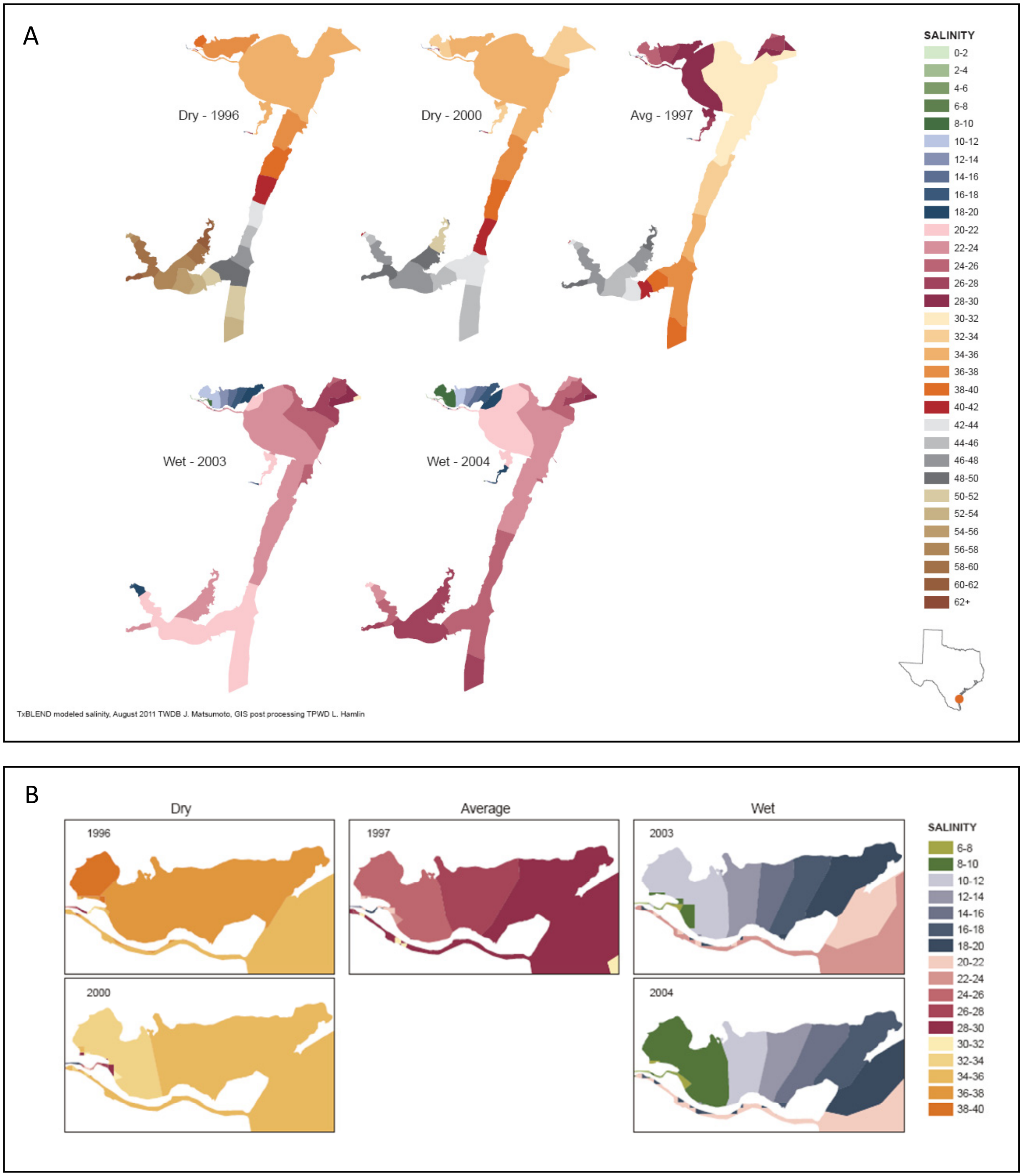


Figure 4.1.5. Nueces Estuary salinities in dry, average, and wet years as predicted by TxBLEND models (A); Nueces Bay salinities in dry, average, and wet years as predicted by TxBLEND models (B).

GIS processes were applied to translate the salinity data for 11,009 nodes in the computational grid into contoured salinity patterns. For GIS methods refer to Appendix 4.2. In all, 65 maps were produced illustrating average monthly and average annual salinity patterns during representative dry, average, and wet hydrologic time periods identified by the BBEST team

Freshwater inflow greatly influences salinity in Nueces Bay during all years, but has little influence on salinities in Corpus Christi Bay or other adjacent bays. Examining the maps above, it is very apparent that, even during a very wet year such as 2004, Corpus Christi Bay, Baffin Bay, and Upper Laguna Madre show little impact from freshwater given the marine nature of the bay (Figure 4.1.5A). Because of these salinity patterns, the Nueces BBEST focused on salinities in Nueces Bay. A closer examination of Nueces Bay shows this body of water is heavily influenced by freshwater inflow, and during dry conditions it becomes a more marine system (Figure 4.1.5B).

Historical salinity patterns from empirical salinity data

Probably nowhere else on the Texas coast is there as an extensive real-time salinity monitoring program as in Nueces Bay. Several salinity measuring stations ("SALT" stations) have been collecting salinity on a daily basis (**Figure 4.1.6**) since the early 1990s. To further characterize historical salinity patterns in response to freshwater inflow, empirical salinity data from Nueces Bay was plotted with gaged inflow from the Calallen alternate hydrology (#08211500) (TWDB, 2011). The SALT03 salinity station (Figure 4.1.6) was used because it was the most appropriate gage based on its historical use for numerous studies. In addition, the proximity of SALT03 to the Nueces River had the best relationship with Nueces River inflow (more details on this relationship are discussed below).

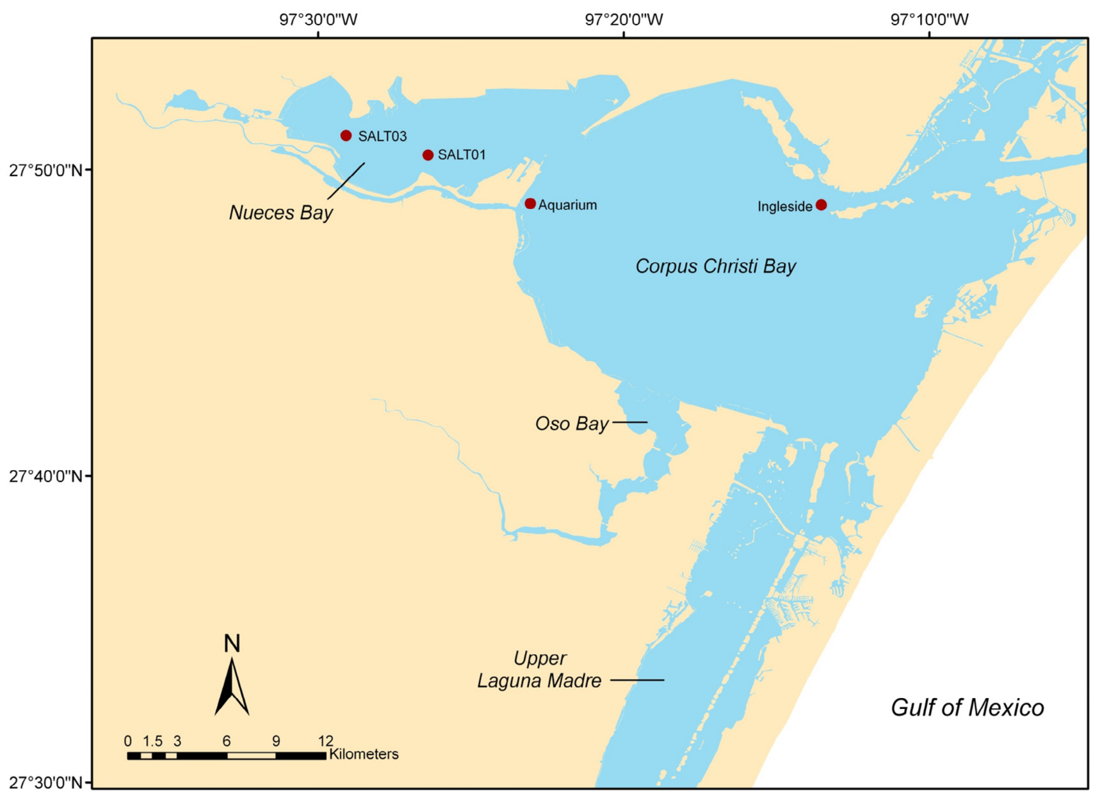


Figure 4.1.6. Study map of Nueces Estuary showing salinity stations.

We also plotted the modeled TxBLEND salinity from a node very close to SALT03. The salinity response in the bay gave very similar predictions whether using TxBLEND or the empirical measurements. Thus, these results further validated the predictive capability of our models. During dry, wet, and average years there is a clear inflow-salinity relationship (Figure 4.1.7 A-C); however, the bay's response is largely dependent on the antecedent conditions in the bay. For example, in dry years salinity remains high and increases over time because of little inflow and high evaporation rates. In both dry and average years, there is an almost immediate salinity response with either high or low inflow pulses (**Figure 4.1.7A** and **Figure 4.1.7B**). The salinity is immediately reduced with a pulse of freshwater, but without prolonged inflow, salinity increases again. However, during wet years there is a much different salinity response that is largely determined by the bay's salinity condition in the prior month (**Figure 4.1.7C**). High inflows will reduce salinity as in dry and average years, but if the salinity remains low due to ongoing wet conditions, a subsequent high flow cannot further reduce salinity because the previous saline conditions were already low. Clearly, these patterns show the importance of knowing the antecedent salinity when predicting salinity response to freshwater inflow.

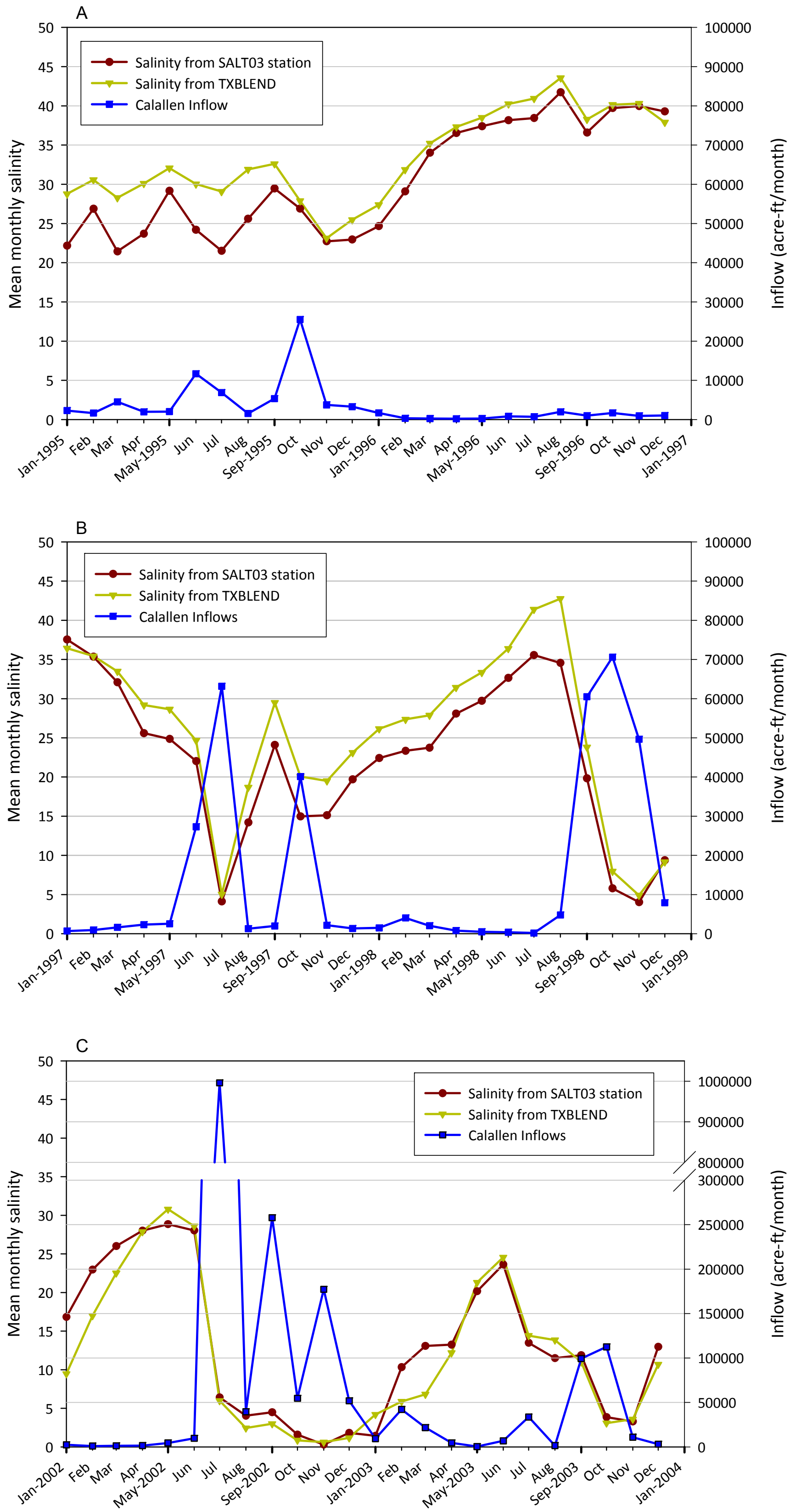


Figure 4.1.7. Cumulative monthly inflow and mean salinity from SALT03 station and modeled TxBLEND salinity near SALT03 during (A) dry years 1995-1996, (B) average years 1997-1998, and (C) wet years 2002-2003. Gaged inflow was from the Calallen gage alternate hydrology (#08211500) (TWDB, 2011).

4.2 Salinity Gradient Methodology

Establishing mathematical relationships between salinity and inflow are essential in order to determine the volume of inflow that will generate the desired salinities (i.e., base flow) for a sound ecological environment based on the indicator species. Using average monthly salinity from empirical data at the SALT03 station (Figure 4.1.6) and cumulative monthly inflow from the Calallen gage alternate hydrology, a variety of models were used to calculate how much inflow would produce acceptable salinities. A simple linear regression using the $\log_{10}$ of monthly total inflow and monthly mean salinity (**Figure 4.2.1**) showed a strong negative relationship between salinity and inflow. Outputs from this model were used to help calculate inflow needed to achieve a desired salinity for indicator species in Nueces Bay. For example, the Nueces BBEST selected a salinity of 10 for high flow conditions. Therefore, solving the equation from the regression for inflow based on a salinity of 10 (Figure 4.2.1) would give an inflow of approximately 750,000 acft/yr. Additional details on inflow recommendations based on the equation below can be found in Section 4.5.

Additionally, antecedent (previous month) salinity conditions were incorporated into the linear model (**Figure 4.2.2**) which improved our ability to predict salinities at different inflows. If Nueces Bay achieves a sound condition with freshwater inflow in the future, the equation that incorporates salinity from the previous month will help in the adaptive management process to evaluate future freshwater inflow needs.

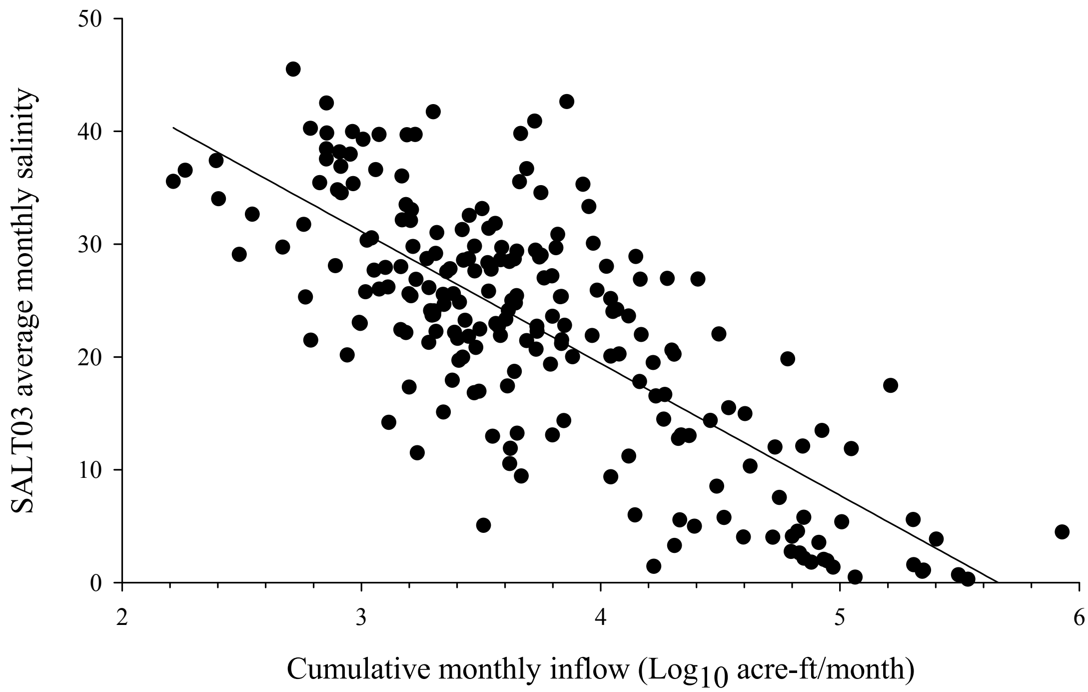


Figure 4.2.1. Linear regression of cumulative monthly inflow and average monthly salinity at SALT03 station. Cumulative inflow was from Calallen gage alternate hydrology (#08211500). Salinity = 66.183 - (11.690 x $\log_{10}$(inflow)); R^2 = 0.58.

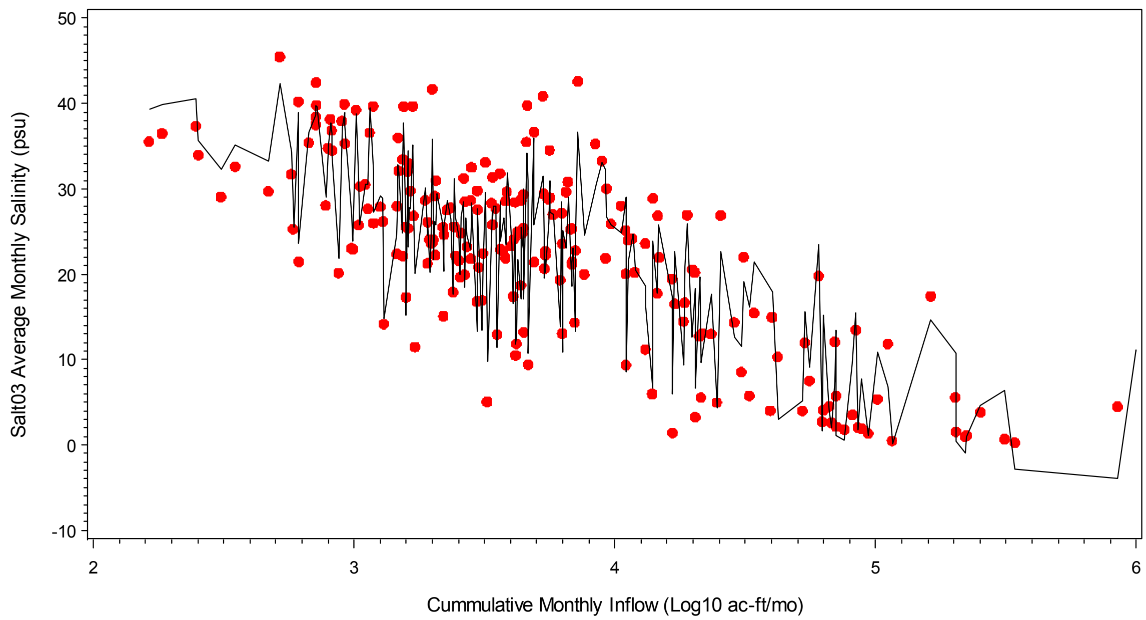


Figure 4.2.2. Regression of cumulative monthly inflow and average monthly salinity at SALT03 station including the previous month's salinity. Cumulative inflow was from Calallen gage alternate hydrology (#08211500). Antecedent flow equation: salinity = 32.85 - (6.648 x $\log_{10}$(inflow)) + (0.648 x previous month salinity); $R^2 = 0.90$.

Because a major focus of this study was the Nueces Delta (where two indicator species occur), it was necessary to calculate similar salinity-inflow relationships for this area. Paired regressions of Rincon Bayou discharge versus Nueces River discharge were performed for no flow and positive flow into Rincon Bayou (**Figure 4.2.3**). This relationship was also taken into consideration when making the inflow recommendations outlined in Section 4.5.

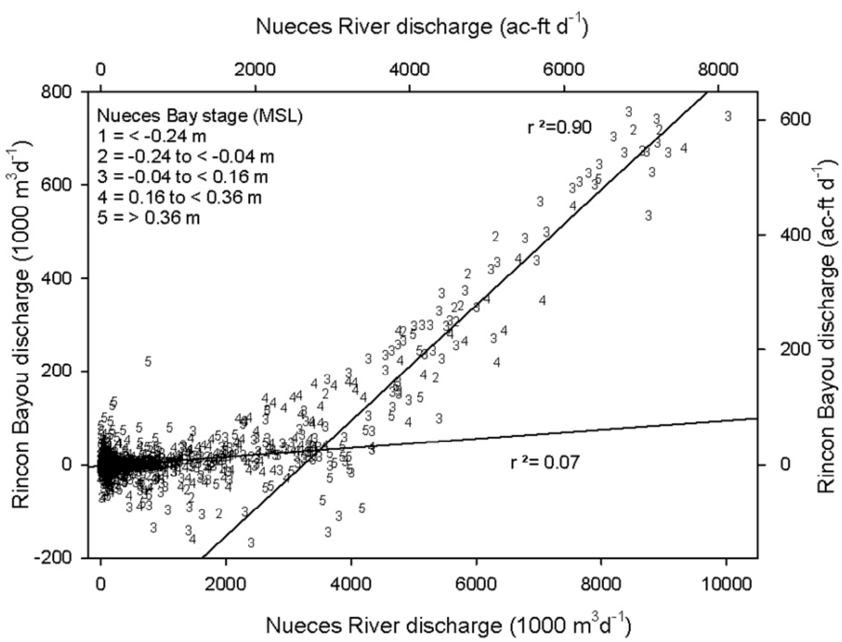


Figure 4.2.3. Paired regressions of Rincon Bayou discharge versus Nueces River discharge for no flow and positive flow into Rincon Bayou. Points are labeled by Nueces Bay stage (Montagna, et al., 2009).

4.3 Focal Species and Indicators of Estuarine Health

The Nueces BBEST was charged with creating base inflow regime recommendations that protect a "sound ecological environment" and that maintain the productivity, extent, and persistence of key aquatic habitats in the bays and estuaries. Our work summarized in Section 4.2, the salinity gradient methodology, developed a tool for generating a freshwater inflow regime. These mathematical models allowed the science team to create a salinity gradient throughout the Nueces Bay and Delta that would re-establish desired salinities typical of a healthy estuary as documented in our historical study (see Section 2.8). These favorable salinity gradients are assumed to occur 80 percent of the time under base flow conditions. Clearly, the next step was to develop a suite of indicator species that show clear and well-documented responses to salinity and would allow the determination of an inflow recommendation and regime for a sound environment.

4.3.1 Selection of Estuarine Focal Species

As with the salinity data, the science team was able to rely on a wealth of scientific studies that are available in the Nueces Estuary as well as develop new modern regression approaches for some indicators (e.g., fish and crustaceans). These data and analyses allowed us to recommend target salinities that would produce a sound ecological environment. Smooth cordgrass (*Spartina alterniflora*), benthic macroinfauna, eastern oyster (*Crassostrea virginica*), blue crabs (*Callinectes sapidus*), and Atlantic croaker (*Micropogonias undulatus*) were the primary indicators for establishing a freshwater inflow regime for the Nueces Estuary. There were clear and strikingly independent convergences on the ideal salinity and inflow regime needed for these organisms whether in the bay or in the delta. These similarities provided the Nueces BBEST a powerful suite of organisms on which to base our recommendations for freshwater inflow. **Figure 4.3.1** summarizes the ideal salinity ranges for the suite of indicator species ranging from marsh plants to vertebrate fish species. Cleary, sessile species such as eastern oyster would have been desirable indicators species, and they certainly occurred historically at much higher abundances (See Section 2.8). Unfortunately, there was not enough reliable quantitative data in this region to use this species as an indicator. However, the oyster's ideal salinity falls within the same general range as the other indicator species (Cake, 1983), and it is expected that oysters would recover under these inflow recommendations. Thus, the science team suggests oysters will still provide a future "qualitative" indicator species of healthy bay conditions, and the condition of the species should be monitored for future studies.

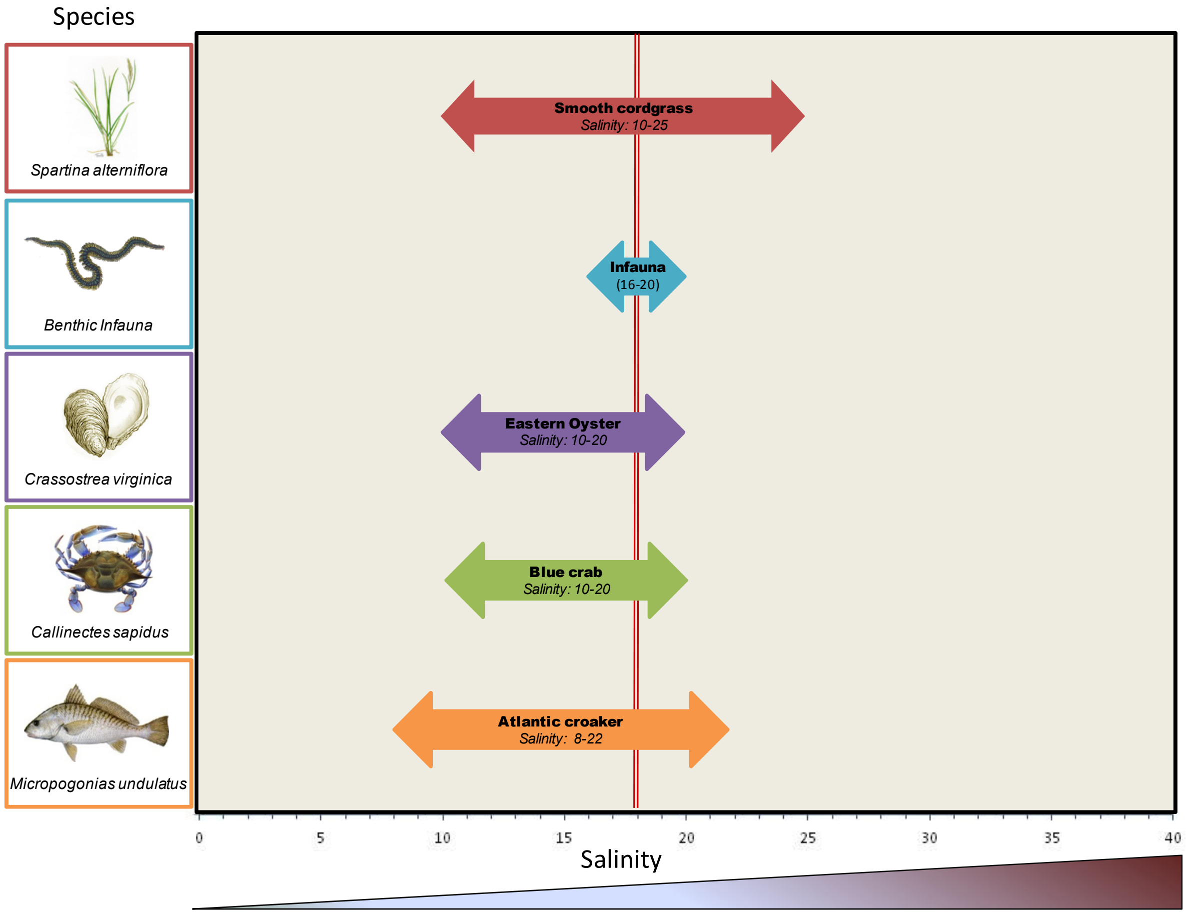


Figure 4.3.1. Indicator species profile showing salinity preferences in Nueces Delta and Nueces Bay.

4.3.2 Vegetation

Plant zonation within salt marshes follows strong physiological gradients that are defined primarily by frequency and duration of inundation, soil salinity, and nutrient availability (Chapman, 1974; Adam, 1990). Zonation of vegetation can occur along the length of an estuary in response to salinity gradients and other physical parameters as mentioned above. Plant distribution may also be influenced by physical disturbance (Baldwin and Mendelssohn, 1998), interactions between plant species that help at least one of the species without hurting the other (Bertness, 1991), and inter-specific competition (Bertness, 1991). In salt marshes, like the Nueces Delta, high marsh and low marsh habitats represent extremes along the stress gradient that are characterized by distinct vegetation assemblages. In addition to this spatial gradient in the Delta, extreme variability in climate can produce periodic disturbances that are often followed by germination of plants tolerant of poor growing conditions in newly created bare areas (Alexander and Dunton, 2002).

Prior to the 1950s, overbank flooding from the Nueces River was a regular source of freshwater to the Delta. Such flooding became infrequent when channelization routed river flows around the Delta and directly into Nueces Bay (BOR, 2000). Reservoir construction in the Nueces River basin reduced water availability to the Delta by as much as 99 percent (about half the reduction in Nueces Delta inflow was caused by drought from 1983-1996), severely attenuating flood peaks (Irlbeck and Ward, 2000). These reductions of freshwater inflows into the Delta have increased surface and porewater salinities (Ward and Armstrong, 1997) and have compromised the ecological function of the Delta (Ward, et al., 2002).

As mentioned above, the Nueces BBEST has identified *S. alterniflora*, which exhibits a strong correlation with salinity, as an indicator species allowing freshwater inflow regimes to be made based on salinity requirements for this plant. Emergent plants such as *S. alterniflora* benefit salt marsh ecosystems in a variety of ways. Their aboveground vegetation provides physical structure used as larval refuge and habitat by a variety of nekton species (Boesch and Turner, 1984; Keer and Zelder, 2002). The presence of aboveground vegetation creates lower flood water velocities and increased sediment accretion that allows salt marshes to preserve optimum flooding patterns and keep pace with sea level rise (Morris, et al., 2002). This decrease in flood water velocities also has the potential to provide some measure of protection from storm surges associated with tropical hurricanes (Morton, et al., 1984; Gedan, et al., 2010). The presence of emergent vegetation contributes to long term stability of salt marshes because their belowground root systems can bind sediments and stabilize substrate (Gedan, et al., 2010).

Spartina alterniflora typically occupies a narrow band at the interface between permanently submerged and intertidal areas. As a result, individuals can be subjected to a wide variety of environmental conditions corresponding to their inundation state. These areas are characterized by frequent flushing of interstitial porewater and moisture saturated sediments. Inundation frequency of intertidal salt marsh sediments is primarily controlled by the interaction between freshwater inflows, tidal forcings, and direct precipitation (Ward, 1985). However, on the Texas coast and in the Nueces River Delta inundation frequency corresponds strongly to meteorological influences such as wind driven exchange and atmospheric fronts (Rasser, 2009). Frequent inundation results in sediment porewaters that reflect the salinity of tidal creek water (Webb, 1983). During drought or extreme low water periods, sediments may become dry due to porewater drainage and evaporation. This often results in elevated porewater salinities and salts are concentrated at levels exceeding the physiological tolerance of *S. alterniflora*.

This species reacts positively to moderate freshwater flooding which alleviates salt stress for the plants as well as increases germination, and accelerates expansion (Zelder and Onuf, 1984; Alexander and Dunton, 2002; Forbes and Dunton, 2006). Field and laboratory studies have indicated that *Spartina* grows optimally at porewater salinities typical of freshwater and brackish marshes (Phleger, 1971). For example, Webb (1983) found that porewater salinities exceeding 25 resulted in significant reduction in density, height, and standing biomass. A similar threshold controlling the abundance and distribution of *S. alterniflora* with respect to porewater salinity has been observed in the Nueces River Delta. Coverage of *S. alterniflora* declines rapidly at elevated porewater salinities and immediate death of individual plants has been observed at salinities greater than 93-115 (Hester, et al., 1998).

The salinity tolerance for this species has given the Nueces BBEST another tool for identifying freshwater inflow regimes that will create a salinity gradient within the Nueces system and ultimately provide the basis for a healthy estuary.

<u>Methods</u>

The abundance and distribution of smooth cordgrass (*Spartina alterniflora*) in the Nueces River Delta was monitored over a nine year period from 2001 to 2010 as part of the Rincon Bayou Diversion Project. The resulting dataset documents observed changes in seasonal plant community composition/coverage in response to changes in tidal creek and soil porewater characteristics (salinity and nutrients) at five sites along a transect of the Rincon Bayou. The composition/coverage of emergent plants for this time period was determined on a percent cover basis within 0.25 m^2 quadrats. Measurements were taken at 2-m intervals along 11 parallel transects (44 quadrats/site) at each of the five sites. Soil characteristics were obtained by extracting water from 2.5 cm diameter soil cores by centrifugation. The extracted water was analyzed for salinity using a handheld refractometer (Reichert Scientific Instruments, Buffalo, NY).

<u>Population Dynamics</u>

Spartina alterniflora individuals were observed at three sites (254, 270, and 450) in the low marsh near Nueces Bay (**Figure 4.3.2**). The abundance of this species fluctuated from a minimum cover near 0 percent to a maximum cover of approximately 66 percent (Summer 2004, Site 270). There was no consistent relationship between time of year (season) and standing coverage of *S. alterniflora*. However, seasonal increases in cover occurred primarily (74 percent) during the spring and summer (Figure 4.3.2).

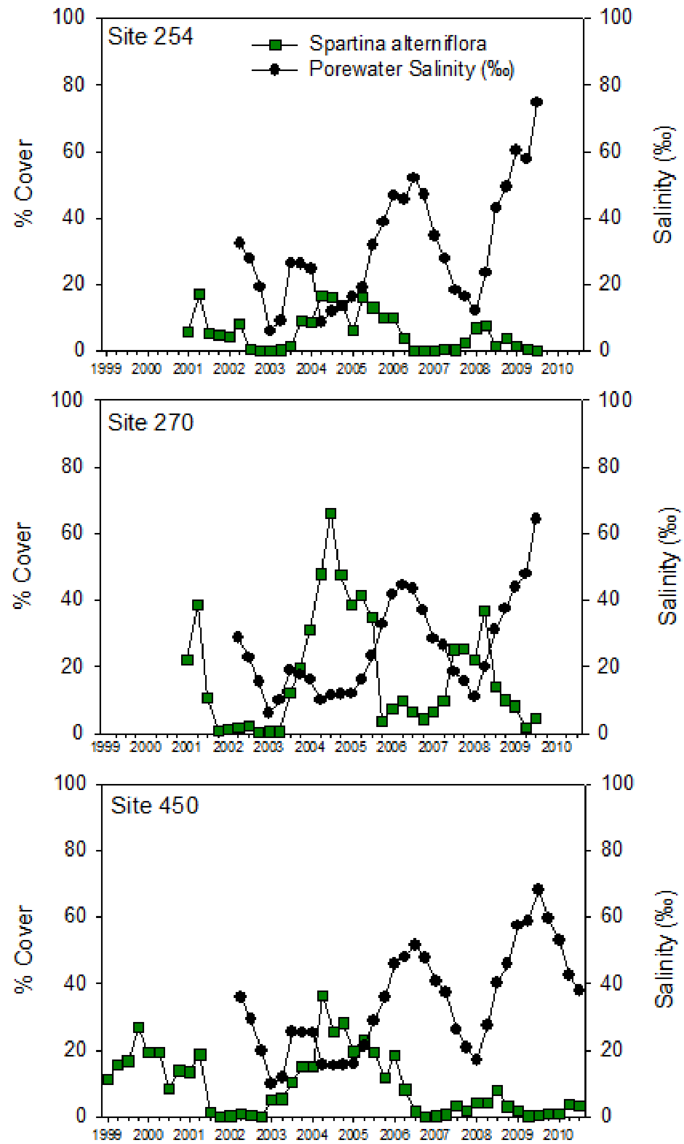


Figure 4.3.2. Porewater salinity (3 point running mean) and percent cover of *Spartina alterniflora* along the creek bank in the low marsh. Porewater salinities exceeding 25 result in coverage declines of *Spartina alterniflora*.

<u>Observed Salinity and Freshwater Inflow Relationships</u>

Spartina alterniflora abundance was negatively correlated with porewater salinity (**Figure 4.3.3**). This species was abundant during periods when porewater salinities were low, but scarce during periods of high porewater salinity (Figure 4.3.3). Time series and regression analysis indicated a porewater salinity breakpoint of 25 (Figure 4.3.2 and Figure 4.3.3). Observed salinities exceeding this breakpoint were coincident with precipitous declines in *S. alterniflora* coverage (Figure 4.3.2). This finding is consistent with previous research in other areas of the Gulf of Mexico showing that *S. alterniflora* grows best at salinities less than full strength sea water and typical of estuarine environments.

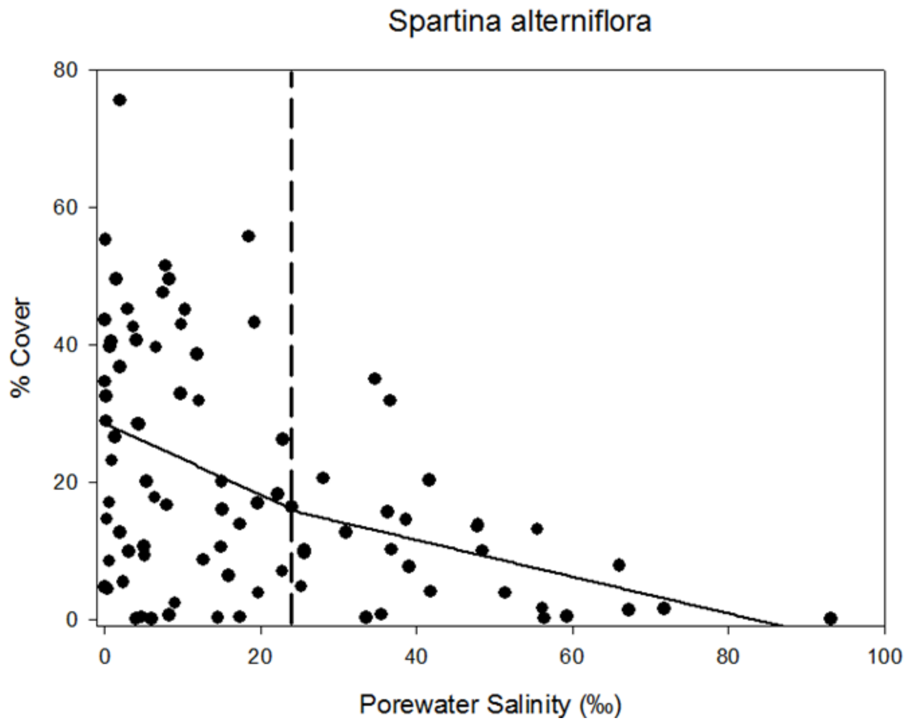


Figure 4.3.3. Relationship between cover of *Spartina alterniflora* and porewater salinity. Piecewise linear regression indicates a clustering of data points during periods when porewater salinities were less than 25. This salinity target requires inflows through the Rincon Bayou of approximately 37,936 CMD (30.7 acft/day).

The relationship between porewater salinity and freshwater inflows was examined using a regression analysis (**Figure 4.3.4**). Quarterly measurements of porewater salinity were compared against average daily inflows to the Rincon Bayou (USGS gauge #08211503). This analysis was limited to commonly observed inflows. Anomalous inflow events resulting from the passage of tropical storms were excluded in the analysis of the relationship between freshwater inflow and porewater salinity because they would unrealistically bias the results. Porewater salinity was related to freshwater inflows down the Nueces River and to the Rincon Bayou (Figure 4.3.4, **Table 4.3.1**). Periods of low freshwater inflow were characterized by high porewater salinities while periods of relatively high freshwater inflow were characterized by low porewater salinities (Figure 4.3.4). Maximum coverage of *S. alterniflora* occurred in 2004 and 2008 (Figure 4.3.2). Both years were preceded by wet periods with relatively large and numerous freshwater inflow events such as those that occurred in 2007 and 2004.

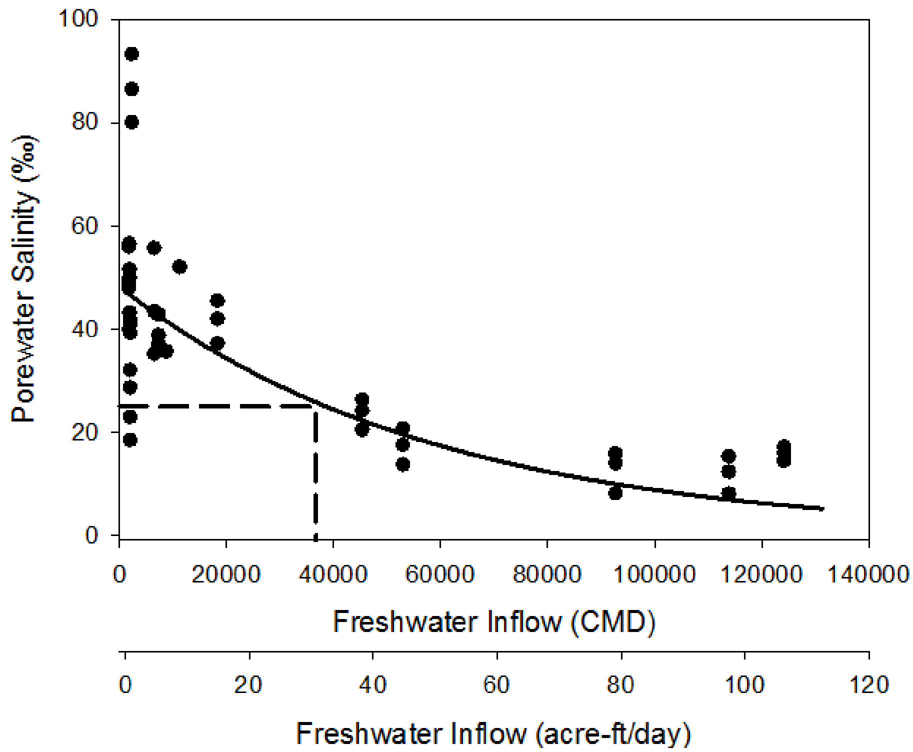


Figure 4.3.4. Relationship between freshwater inflow (Rincon Bayou Channel: USGS #08211503) and porewater salinity along the creek bank in the low marsh. Regression curve is a best fit line for an exponential decay function. Dashed line indicates flow required to obtain a salinity target of no greater than 25.

Table 4.3.1. Nueces River Inflow needs for attainment of a maximum 25 porewater salinity target for sustaining *Spartina alterniflora* in the Nueces Delta. Numbers represent median cumulative inflows (USGS gauge #08211500) for quarterly periods of high *S. alterniflora* abundance. The total required annual flow is 166,000 acft (2.05E+8 m^3).

Nueces Delta Porewater Salinity Target (‰)	Nueces River Flow (acre-ft)			
	22000 (244 / day)	88000 (978 / day)	38000 (422 / day)	18000 (200 / day)
	Nueces River Flow (m^3)			
	2.71E+7 (3.01E+5 / day)	1.09E+8 (1.21E+6 / day)	4.68E+7 (5.20E+5 / day)	2.22E+7 (2.47E+5 / day)
25	**Winter**	**Spring**	**Summer**	**Fall**

Freshwater Inflow Target

The observed relationship between porewater salinity and freshwater inflow was investigated with respect to *S. alterniflora* abundance. It was determined that achieving a porewater salinity target of 25 requires approximately 38,000 CMD (30.8 acft/day) through the Rincon Bayou. Scaling of the daily inflow target (30.8 acft/day, Rincon Bayou) to an annual inflow target yields a value of approximately 11,242 acft/yr for the Rincon. This value is much greater than observed annual inflows to the Rincon Bayou from 1982 to 1999 when inflows to the Rincon Bayou and upper Nueces River Delta averaged only 540 acft/yr (Irlbeck and Ward, 2000). The yearly inflow required to achieve the 25 salinity target (11,242 acft/yr) is approximately 26 times the average inflows observed between 1982 and 1999. However, 11,242 acft/yr is only 14 percent of inflows observed in the period from 1958 to 1982 (Irlbeck and Ward, 2000).

Freshwater inflows to the Rincon Bayou were investigated with respect to Nueces River flow in order to facilitate comparison among indicator species' inflow targets. The seasonal (3 month) cumulative inflow to Nueces Bay via the Nueces River (USGS gauge #08211500) was computed in order to capture variability due to seasonal precipitation extremes. This method was particularly useful in determining inflow targets because the seasonal cumulative inflow could be directly compared to seasonal records of *S. alterniflora* abundance. Table 4.3.1 lists the seasonal Nueces River inflow targets selected as the median inflow values during the spring, summer, and fall seasons when *S. alterniflora* abundance exceeded 20 percent cover. Inflow targets were rounded to the nearest 1,000 acft. There was no clear relationship between winter freshwater inflow and winter coverage of *S. alterniflora* due to the timing of plant senescence during this season. As a result, the winter recommendation was set as the average winter inflow computed for all years between 2003 and 2011. Nueces River inflow targets ranged from a spring maximum of 88,000 acft to a winter minimum of 22,000 acft for a total of 166,000 acft annually (Table 4.3.1). Higher inflows during the spring and early summer were necessary in order to flush salts from the soil, promote clonal growth, and facilitate *S. alterniflora* seedling germination. Low freshwater inflows during the last 30 years may explain the observations of generally low *S. alterniflora* abundance in the Nueces Delta with the exception of low salinity periods following large freshwater inflow events such as those that occurred in 2003, 2004, and 2007.

4.3.3 Benthos

For the past 25 years, researchers have been studying the effect of freshwater inflow on benthic communities and productivity in Nueces Bay and Delta (Montagna, 1989, 1999, 2000; Montagna and Yoon, 1991; Kalke and Montagna, 1991; Montagna and Kalke, 1992, 1995; Montagna and Li, 1996, 2010; Montagna, et al., 2007; Kim and Montagna, 2009; Montagna, et al., 2009; Pollack, et al., 2009; Montagna and Palmer, 2011). These studies have demonstrated that long-term hydrological cycles affect water quality and regulate benthic abundance, productivity, diversity, and community structure. Benthos are excellent bioindicators of environmental effects because they are very abundant and diverse, are sessile, and long-lived relative to plankton (Montagna, et al., 2010). Therefore, benthos are good biological indicators of freshwater inflow effects because they integrate changes in temporal dynamics of ecosystem factors over long time scales and large spatial scales. Overall, these studies demonstrate that freshwater inflow is important to maintain secondary productivity and functional diversity in estuaries, which is required to maintain estuarine health and sustainability.

The Nueces BBEST utilized macrobenthic data to assess ecosystem health as it relates to change in freshwater inflow by assessing benthic habitat health, and benthic productivity in Nueces Bay and Delta. However, inflow itself does not affect ecosystem dynamics; it is the change in estuarine condition primarily salinity, nutrients, and chlorophyll, which drives change in biological resources (SAC, 2009). Thus, the goal is to relate changes in water column dynamics with change in benthic dynamics as a way of gathering information to develop salinity targets that will ultimately lead to the recommendation of environmental flows. Another positive attribute to this analysis is that there is a large amount of benthic macrofauna data for both the Nueces Bay and Delta.

Prior to the first major dam being constructed on the Nueces River in 1958, freshwater inflow events in the lower Nueces River caused high water levels to spill into Rincon Bayou, the main stem channel for the Nueces Delta (**Figure 4.3.5**). The remaining flows would remain in the Nueces River before flowing into Nueces Bay, the largest secondary bay within the Nueces Estuary. Since 1958, the flow that enters Rincon

Bayou and the Nueces Delta has decreased by 99 percent (about half the reduction in Nueces Delta inflow was caused by drought from 1983-1996) (Irlbeck and Ward, 2000). This decrease in flows has created a 'reverse estuary', whereby salinity increases upstream rather than downstream as would occur in a normal estuary. Concern over the changes in salinity structure, especially in Rincon Bayou, has initiated projects to increase inflow into Rincon Bayou. Simultaneous macrobenthic monitoring over a variety of 'natural' and managed inflows to Rincon Bayou and the Nueces Delta have allowed relationships among macrofauna community characteristics and freshwater inflows to be determined within the upper Nueces Estuary, including Rincon Bayou, the Nueces Delta and Nueces Bay.

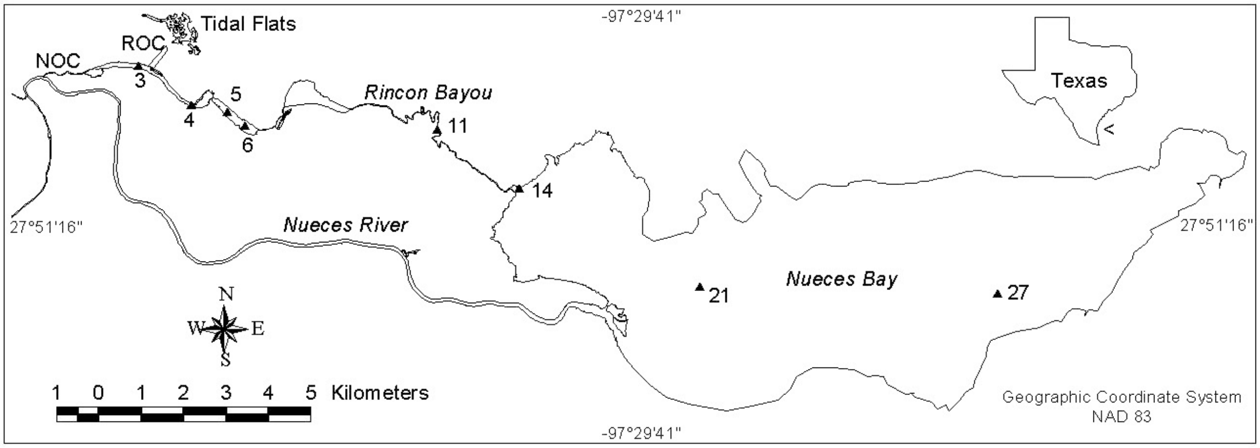


Figure 4.3.5. The upper Nueces Estuary. ROC = Rincon Overflow Channel. NOC =Nueces Overflow Channel (taken from Palmer, et al., 2002).

In 1995, the channel between the Nueces River and Rincon Bayou (Nueces Overflow Channel) was deepened to decrease the minimum flooding threshold and allow larger and more frequent quantities of freshwater into Rincon Bayou and the Nueces Delta. This overflow channel restored normal salinity patterns in the upper reaches of Rincon Bayou, but only for short periods of time as flows were generally too small and infrequent (Palmer, et al., 2002). Flows through the overflow channel only occurred 15 percent of the time (Montagna, et al., 2009). Both salinity and nutrients in Rincon Bayou varied depending on whether they were in a wet or dry period and which region of the estuary they occurred (Montagna, et al., 2009). Water quality in the lower Rincon Bayou/Nueces Delta was more similar to water quality in Nueces Bay than in the upper Rincon Bayou.

In a study by Montagna, et al. (2009), inflow into Rincon Bayou was binned into 2-year periods and classified as being wet, dry, or moderate (**Figure 4.3.6**). Spatial and long-term (2-year binned) temporal changes in water quality were significantly correlated with changes in macrofaunal community structure (Montagna, et al., 2009). Macrobenthic and vegetative communities in the upper Rincon Bayou were significantly different to the communities of the lower Rincon Bayou (and Nueces Bay for macrofauna) regardless of whether a 2-year period was classified as dry, wet or moderate. Large freshwater pulses (>10^6 m^3, 35 x 10^6 ft^3) increased macrobenthic productivity in upper Rincon Bayou (**Figure 4.3.7**; Palmer, et al., 2002). Using a non-linear model, macrofaunal biomass and diversity, two indicators related to benthic productivity, peaked at salinities of 19 and 9 respectively (**Figure 4.3.8**; Montagna, et al., 2002). However actual peaks in biomass and diversity in this study (Palmer, et al., 2002) occurred at salinities of 19 and 16, respectively.

In contrast to the response of macrofaunal communities to salinity in Rincon Bayou, macrofaunal biomass in Nueces Bay has been modeled to increase with increasing salinity and therefore decreasing freshwater inflows (Kim and Montagna, 2008). In the Nueces Estuary, as in the three other Texas estuaries studied, higher salinities allow an increase in biomass of deposit feeding macrofauna (mostly polychaetes) and a subsequent decrease in filter feeding macrofauna (e.g., most bivalves, some polychaetes). In the Nueces Estuary, filter feeders biomass is maximized when and where salinities are approximately 20 (**Figure 4.3.9**, 70 percent of mean salinity of 28).

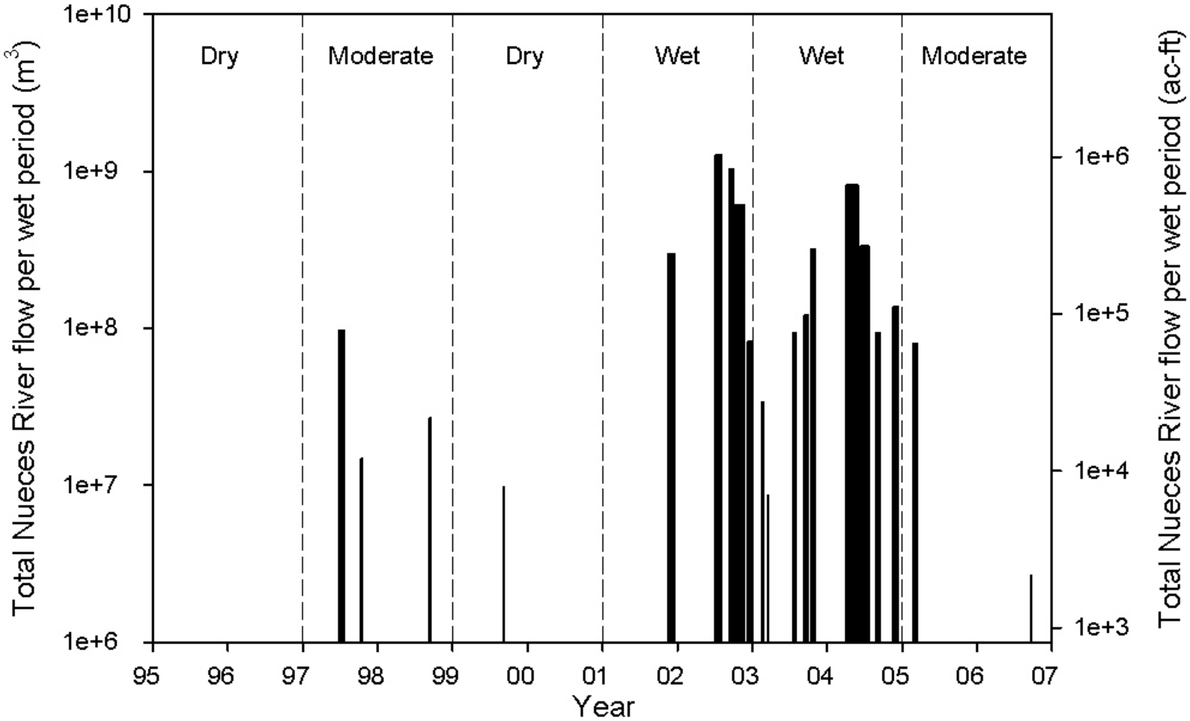


Figure 4.3.6. Wet periods and two-year bins from 1995-2007. From January 1994 to August 2000, wet periods were classified as daily flow rates exceeding 4.2 x 10^6 m^3 Nueces River flow. From August 2000 to February 2008 wet periods were classified as daily flow rates exceeding 2.6 x 10^6 m^3 Nueces River flow.

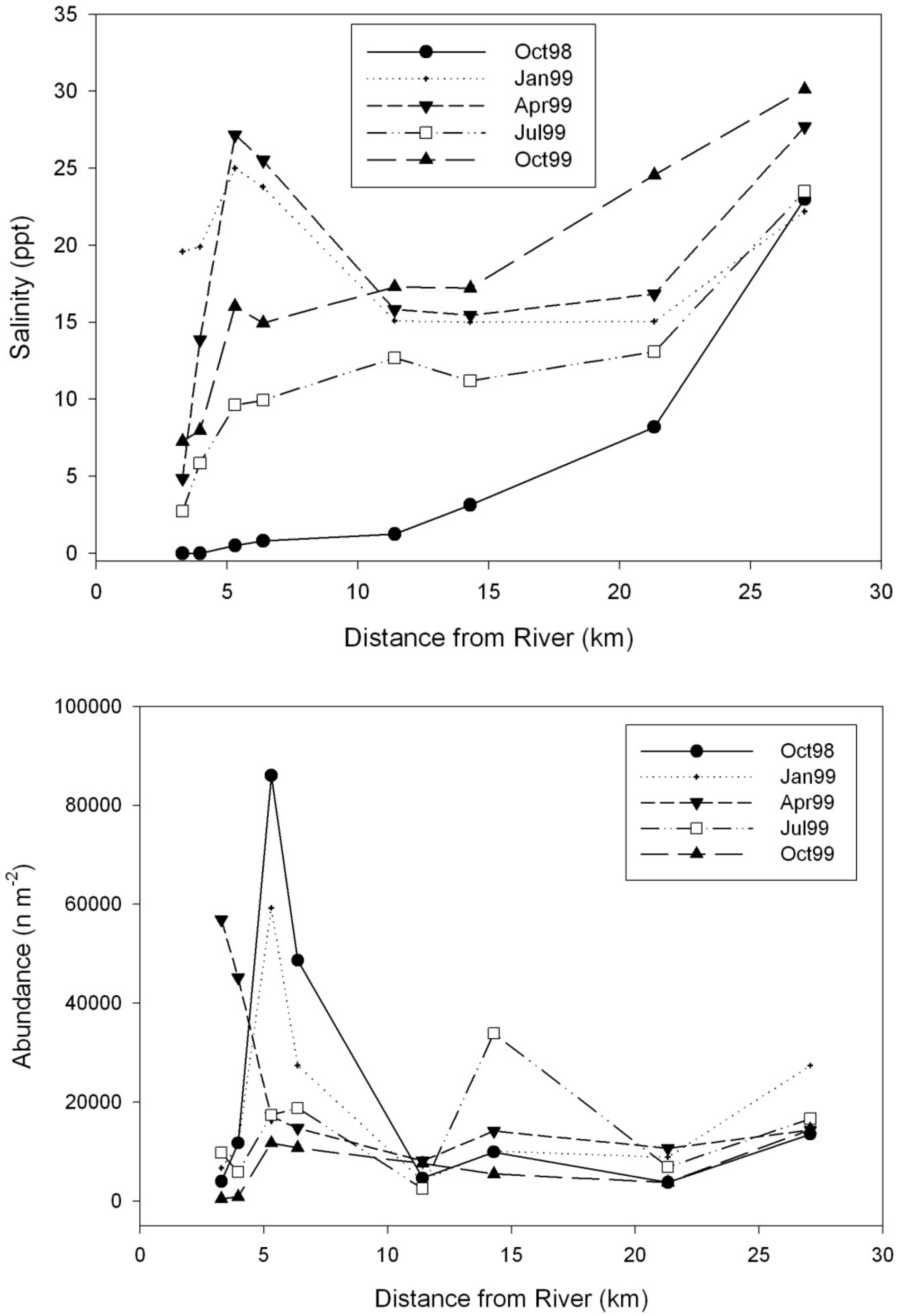


Figure 4.3.7. Salinity and abundance over time in Rincon Bayou and Nueces Bay. Distance from the river represents the distance from the point water enters the Nueces overflow channel. For sampling locations see Figure 4.3.5. (Taken from Palmer, et al., 2002).

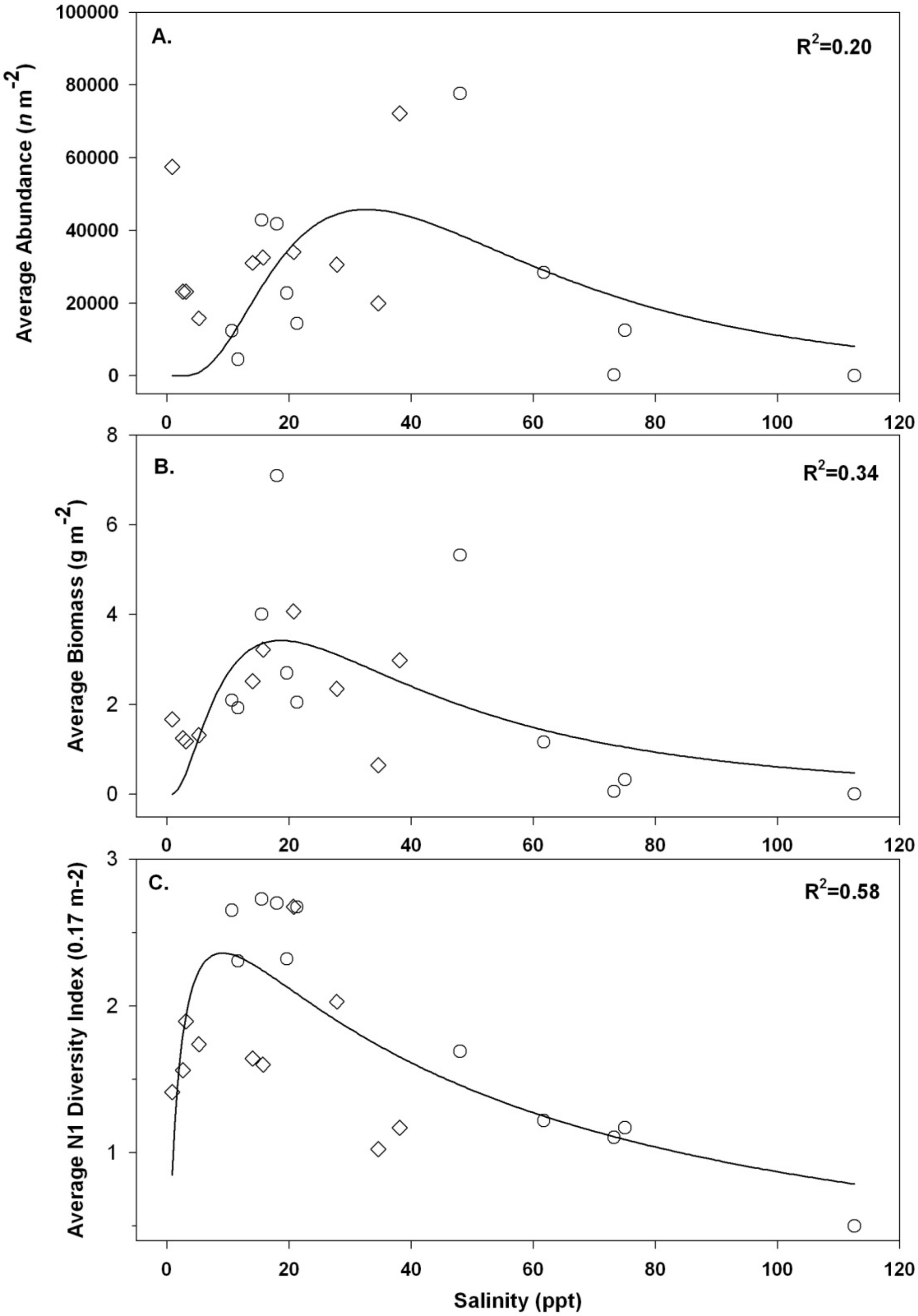


Figure 4.3.8. Macrofauna community response as a function of salinity. Abundance (A), biomass (B), and N1 diversity (C), and nonlinear response to salinity (solid line) at each time period. Circles represent periods of rising salinity and diamonds represent periods of falling salinity. (Taken from Montagna, et al., 2002).

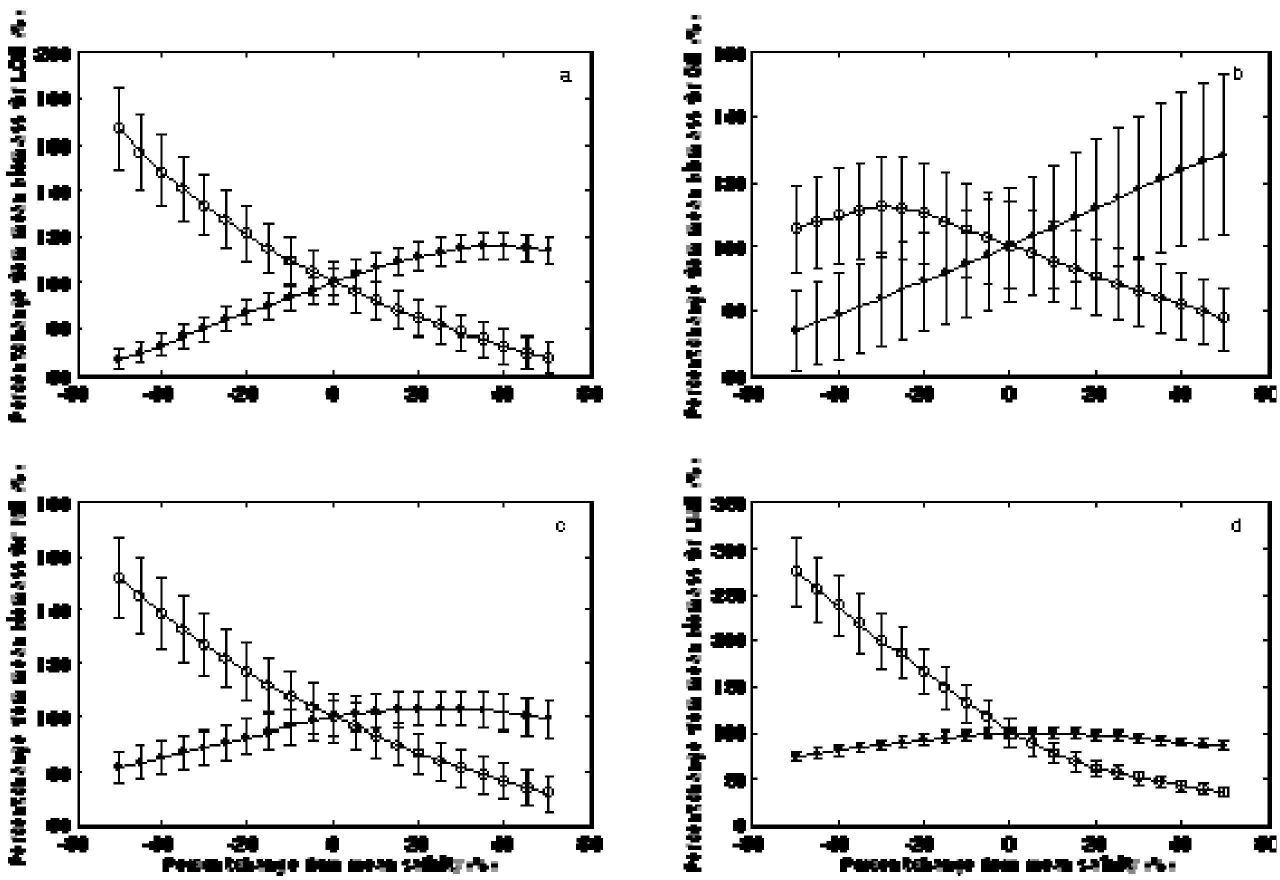


Figure 4.3.9. Percent change from mean benthic biomass simulated with percent change of mean salinity (-50 percent to 50 percent) and corresponding nutrients for deposit (filled circles), and suspension feeder biomass (open circles) in Lavaca-Colorado (a); Guadalupe (b); Nueces (c); and Laguna Madre Estuary (d) along the Texas Gulf Coast. The error bars represent the standard error.

As a result of the numerous studies in the Nueces Estuary, we can estimate an optimal salinity range for each of Nueces Bay and Rincon Bayou. The optimal salinity for Nueces Bay is 20. This value is based on the maximum biomass of filter feeding macrofauna at a salinity of 20. As a comparison to recent salinities in Nueces Bay, the mean daily salinity in the upper-mid Nueces Bay from 1992 to 2010 is 22 with a standard deviation of 11 (station SALT03, DNR, 2011). Optimal salinities for macrofauna in upper Rincon Bayou range from 16 to 19 depending on whether you use macrofaunal diversity or biomass as your proxy for productivity. As a comparison, the mean salinity from 1995 to 2007 in upper Rincon Bayou was 25 (mean salinity from 1997-2007 was 19; Montagna, et al., 2009).

4.3.4 Oysters

Freshwater inflow into Texas estuaries has been identified as an important factor in regulating distribution and abundance of oysters (Dekshenieks, et al., 2000; Pollack, et al., 2011). The eastern oyster, *Crassostrea virginica*, provides important ecological and economic benefits to coastal ecosystems and human communities. As filter feeders, oysters remove phytoplankton and other particles from bay water (Newell and Jordan, 1983), and as reefs expand they create habitat for other fish and invertebrates (Zimmerman, et al., 1989; Lenihan, et al., 2001). Environmental factors, such as salinity and temperature, control oyster reproduction, survival, and growth in estuarine systems. In particular, the combination of high salinity and temperature increases oyster mortality due to disease (e.g., *Perkinsus marinus*) and predation (e.g., crabs, oyster drills) (Gunter, 1955; Garton and Stickle, 1980; Andrews and Ray, 1988; Chu, et al., 1993).

The eastern oyster is broadly euryhaline, but is most common in Texas bays with a salinity range of 10 to 30. Salinities outside this range tend to stress physiological and reproductive processes by limiting growth (Quast, et al., 1988) and impacting spatfall (Hopkins, 1931; Gunter, 1955). Survival of oyster populations during salinity fluctuations is dependent upon the range of fluctuation as well as the rate and duration of change (Quast, et al., 1988). Salinity changes may also alter the biotic profile of an oyster reef (Hoese, 1960). Tunnell, et al. (1996) wrote that the major threat to oyster reefs within Coastal Bend estuaries include reduced freshwater inflows, turbidity from dredging operations, and uptake of point and non-point source pollution.

Historically, Nueces Bay used to support abundant shellfish (i.e. shrimp and oysters) populations (**Figure 4.3.10**). Shellfish in Nueces Bay generally require a range of salinities between 10 and 20 (Montagna, et al., 1998).

The obvious relationship with oysters and salinity, oyster's important role within the estuarine community, and the historical presence within Nueces Bay make oysters an ideal candidate as a focal species for the Nueces BBEST to develop future bay salinity targets for recommending freshwater inflow regimes.

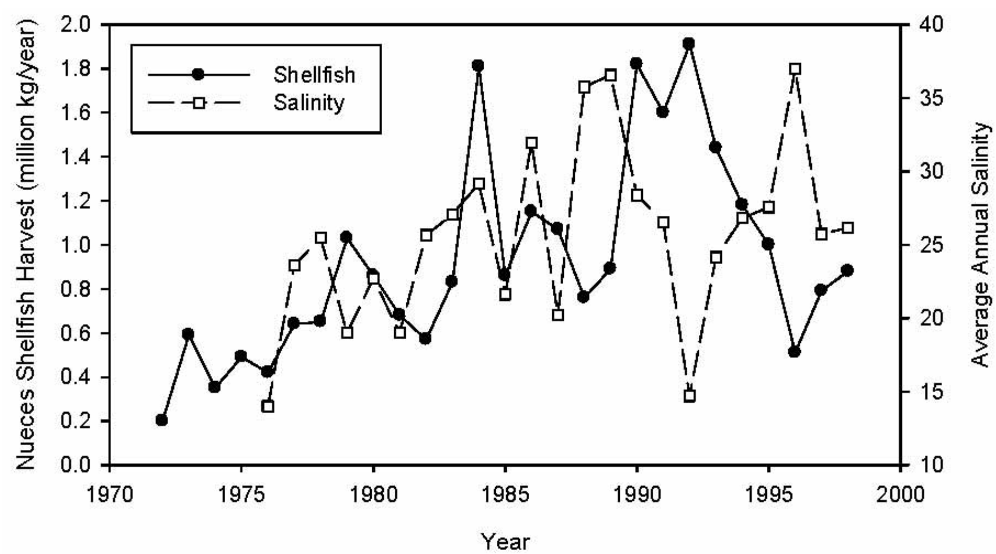


Figure 4.3.10. Average annual shellfish harvest and salinity in Nueces Bay. Source: Montagna, 2009.

4.3.5 Crustaceans and Fish

To determine the influence of salinity (used as a proxy for freshwater inflow) to crustacean and fish abundance in Nueces Bay over the past several decades, catch data were obtained from the Texas Parks and Wildlife Department (TPWD). TPWD's coast-wide fisheries bag seine monitoring program was established in all Texas bay systems in 1977 and continues to present. From the complex analyses described below, two species stood out as excellent freshwater inflow indicator species because of their clear response to salinity; blue crab (*Callinectes sapidus*) and Atlantic croaker (*Micropogonias undulatus*). Although fish and crustaceans are mobile and can move in response to changes in the physical environment, Atlantic croaker and blue crab both have distinct salinity preferences and are found in high abundances, making them useful indicators of freshwater inflow into Nueces Bay.

For this report, TPWD monthly bag seine data (for details see Martinez-Andrade, et al., 2005; Froeschke and Froeschke, 2011) from Nueces Bay (n = 3,220) were analyzed on the most abundant species (29 total) using boosted regression trees (BRTs). This analysis examined relationships between crustacean and fish distribution and environmental variables to predict the probability of capture across a range of environmental conditions. The environmental variables used were month, year, distance from river mouth, salinity, dissolved oxygen (DO), turbidity, temperature, and depth. Salinity, temperature, turbidity, and DO were collected in surface waters (0-15 cm) during each sampling event. All variables were measured during each sampling event. Analyses were carried out using R (version 2.10.0, R Development Core Team, 2009) and the "gbm" library supplemented with functions from Elith, et al. (2008). The model was fit to allow interactions using a tree complexity of 5 and a learning rate of 0.01. Ten-fold, cross-validation of training data was used to determine the optimal number of trees necessary to minimize deviance and maximize predictive performance. The BRT model output was then used to predict probability of capture in Nueces Bay under varying salinity regimes.

Below are the detailed results for the two indicator species for freshwater inflow, blue crab and Atlantic croaker. Please see Appendix 4.3 for examples (BRT outputs and maps) of species with varied salinity responses and for BRT model outputs for all remaining species.

<u>Blue Crab</u>

Blue crab, *Callinectes sapidus*, is an estuarine-dependent, euryhaline crustacean with a complex life cycle. They are a very important commercial fishery in Texas, and they play a critical role in estuarine food webs by transferring carbon from the benthos to the nekton (Hines, 2003). They are excellent freshwater inflow indicators because of their specific salinity ranges and tolerances (Patillo, et al., 1997). Salinity highly influences blue crab abundance in Nueces Bay (**Figure 4.3.11**; **Figure 4.3.12**) with their preferred range approximately 10 - 20 (**Figure 4.3.13**). Blue crab abundance in Nueces Bay dramatically decreases above and below this salinity range.

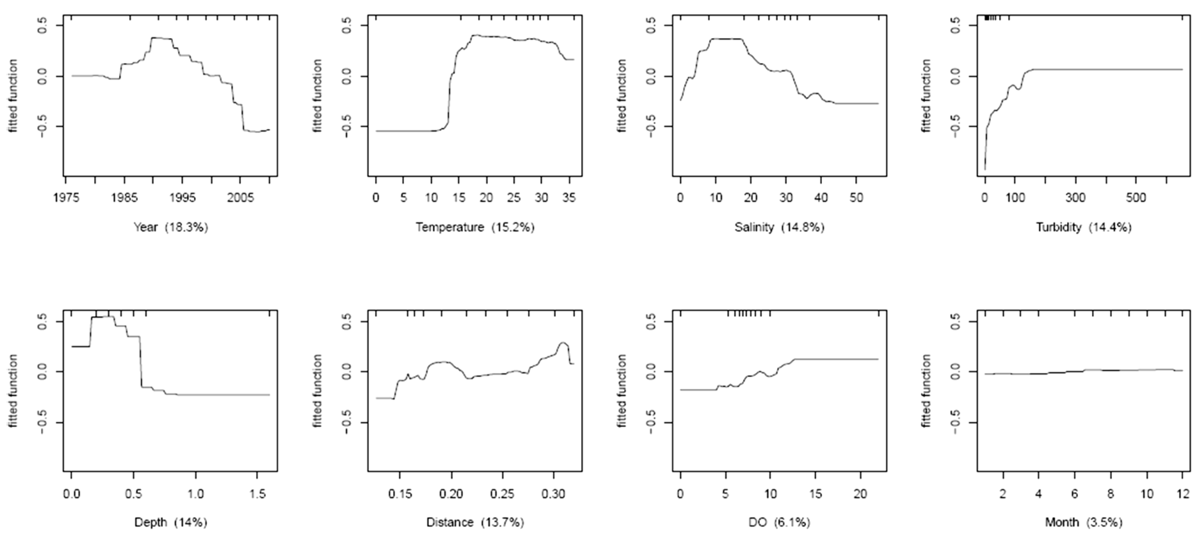


Figure 4.3.11. Functions fitted to the predictor variables by a boosted regression tree (BRT) model relating the probability of occurrence of blue crab to the environment. Y-axes are on the logit scale with mean zero. X-axes parameters: year, temperature (°C), salinity, turbidity (NTU), depth (m), river distance (cost-distance units), dissolved oxygen (DO) (mg O_2 l^{-1}), and month. Percentages indicate proportion of explained deviance attributed to each predictor variable.

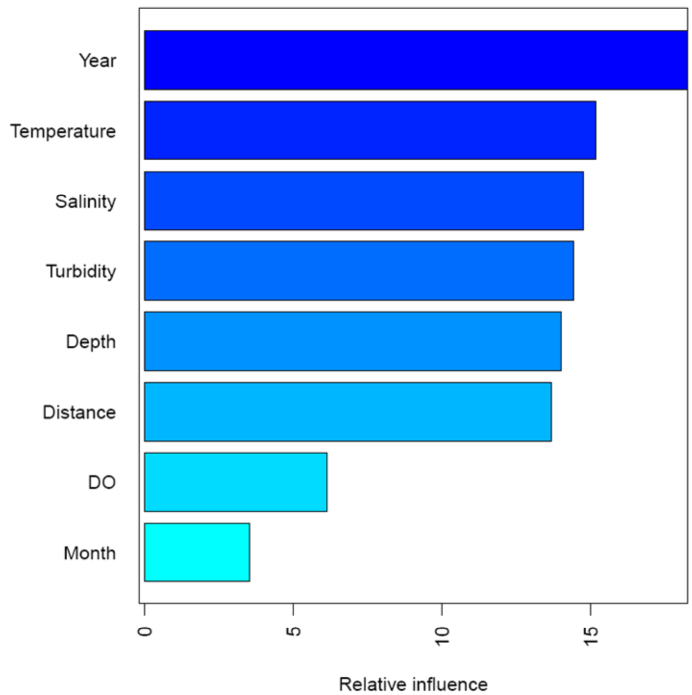


Figure 4.3.12. Average contributions (percent) of environmental variables predicting presence or absence of blue crabs. DO = dissolved oxygen.

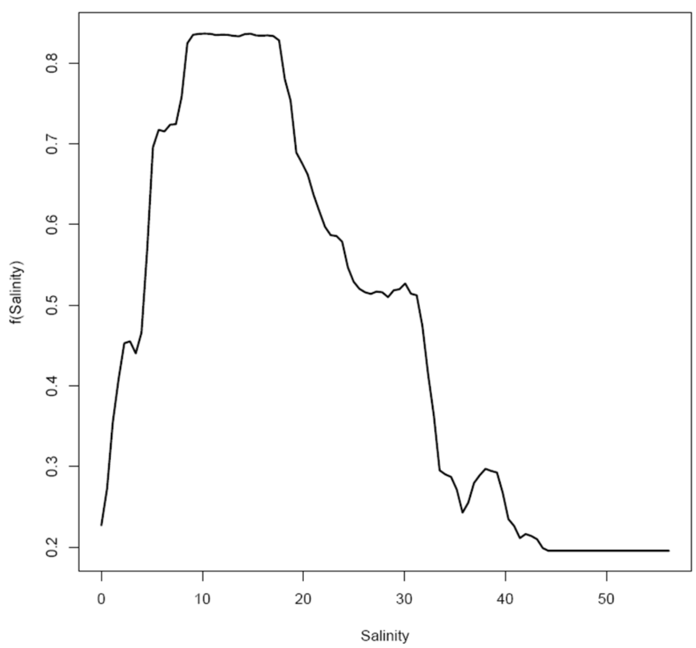


Figure 4.3.13. Functions fitted to salinity by a boosted regression tree (BRT) model relating the probability of occurrence of blue crab to salinity. Y-axis values are on the logit scale with mean zero.

Maps of blue crab probability of occurrence (proxy for abundance) under varying salinity regimes were produced to visually show their distinct freshwater inflow response. Predictions were restricted to the shoreline areas of the bay where samples were collected. Under average salinity conditions at each sampling location, blue crabs are most abundant in the northern and eastern areas of the bay (**Figure 4.3.14**). By reducing salinity (increasing freshwater inflow) by 5 (**Figure 4.3.15A**) and 10 (**Figure 4.3.15B**) from the average there is a higher probability of capture of blue crabs throughout the bay. Increasing salinity (decreasing freshwater inflow) by 5 (**Figure 4.3.15C**) and 10 (**Figure 4.3.15D**) from the average greatly reduces the likelihood of blue crab capture. Similarly, when salinity is decreased 10 from the mean, the abundance of blue crabs will increase up to 10 percent throughout the bay (**Figure 4.3.16A**). However, when the salinity is increased 10 from the mean (**Figure 4.3.16B**) blue crab abundance will decrease up to 5 percent.

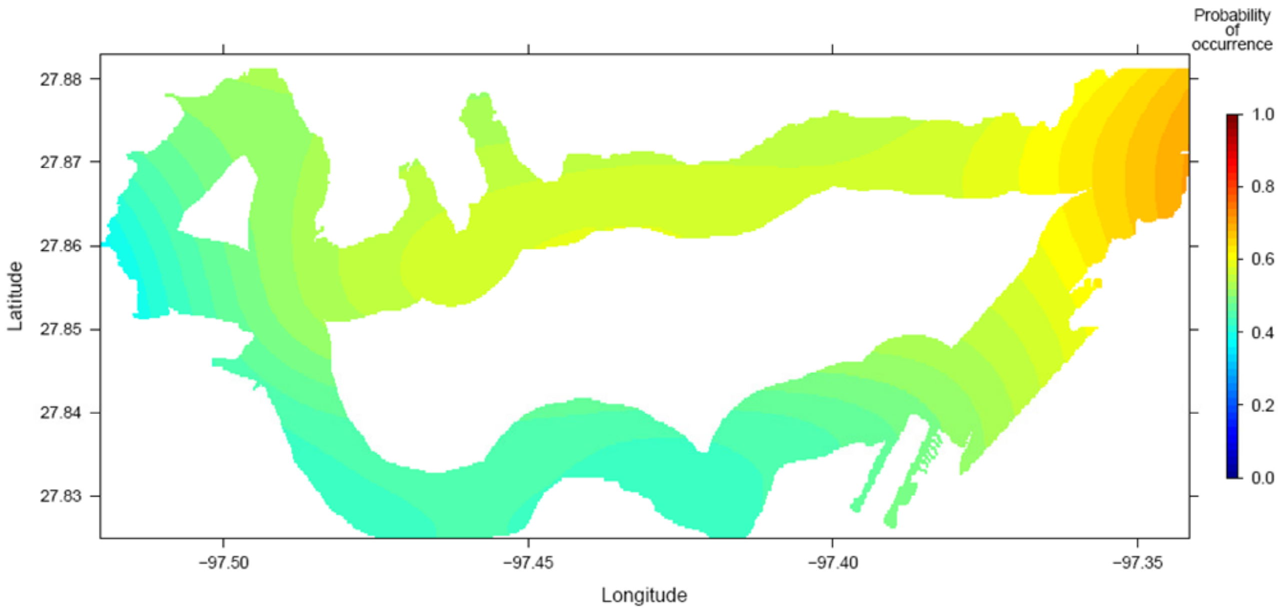


Figure 4.3.14. Probability of occurrence map of blue crab as predicted by a boosted regression tree (BRT) model under average salinity conditions.

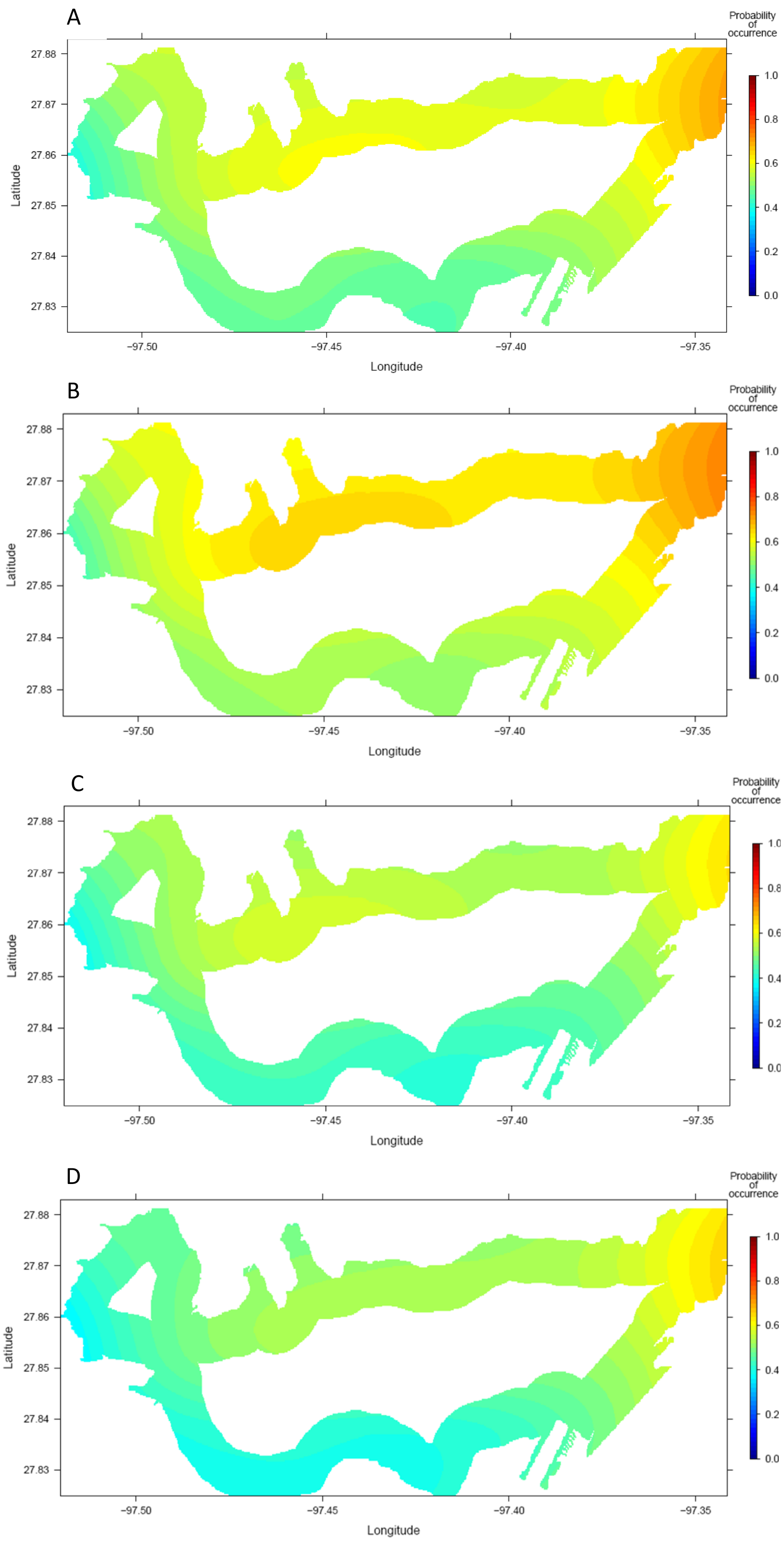


Figure 4.3.15. Blue crab predicted probability of occurrence as predicted by a boosted regression tree (BRT) model when mean salinity is reduced 5 (A), reduced 10 (B), increased 5 (C), and increased 10 (D).

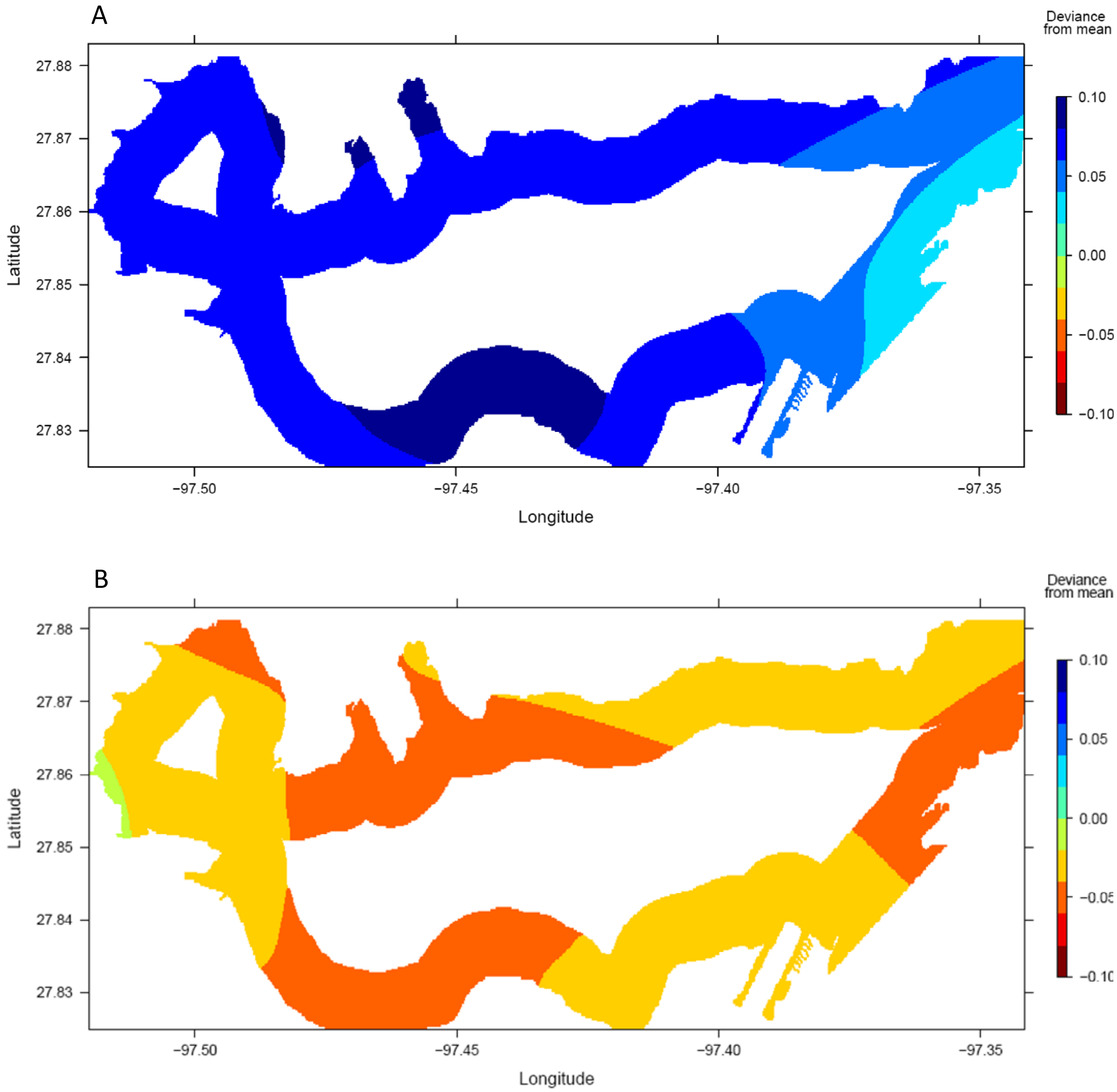


Figure 4.3.16. Blue crab deviance from the mean as predicted by a boosted regression tree (BRT) model when salinity is reduced 10 from the mean (A) and increased 10 from the mean (B).

Atlantic Croaker

Atlantic croaker (*Micropogonias undulatus*) is an estuarine-dependent fish and is an important commercial and recreational fishery in Texas. They are also an important predator of benthic invertebrates (Patillo, et al., 1997). Because of their high abundance and their salinity preferences, they are also good freshwater inflow indicators. Atlantic croaker is euryhaline, but is found in highest abundances in Texas in salinities from 10 to 20 (Patillo, et al., 1997; **Figure 4.3.17**). Adults spawn in the Gulf of Mexico with peak juvenile recruitment into Texas estuaries occurring in November (Petrik, et al., 1999). Therefore, month is a good predictor of their occurrence in the bay (Figure 4.3.17; **Figure 4.3.18**). Salinity is the second best predictor of their abundance in Nueces Bay (Figure 4.3.17; Figure 4.3.18), and outputs from the BRT analysis show that Atlantic croaker have a salinity preference ranging from approximately 8 - 22 (**Figure 4.3.19**). Probability of occurrence maps for Atlantic croaker (similar to the above blue crab maps) can be found in Appendix 4.3.

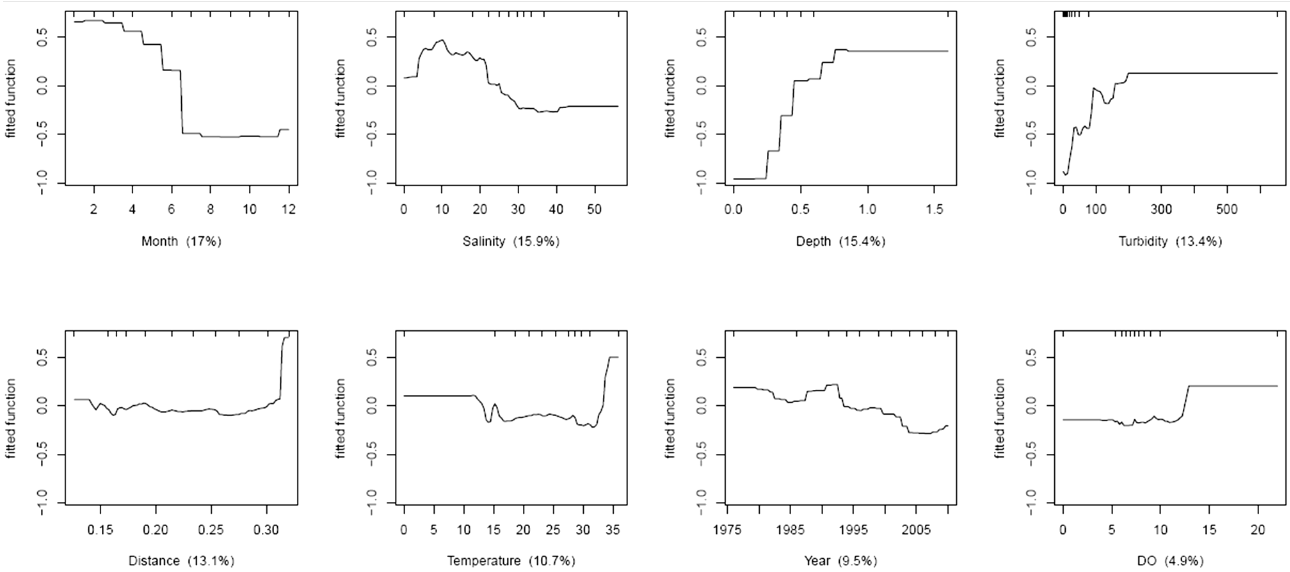


Figure 4.3.17. Functions fitted to the predictor variables by a boosted regression tree (BRT) model relating the probability of occurrence of Atlantic croaker to the environment. Y-axes are on the logit scale with mean zero. X-axes parameters: month, salinity, depth (m), turbidity (NTU), river distance (cost-distance units), temperature (°C), year, and dissolved oxygen (DO) (mg O_2 l^{-1}). Percentages indicate proportion of explained deviance attributed to each predictor variable.

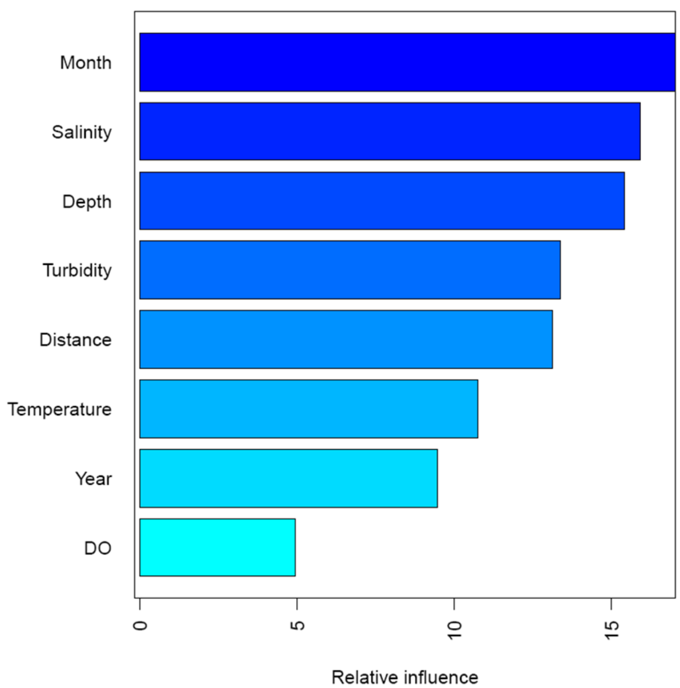


Figure 4.3.18. Average contributions (percent) of environmental variables predicting presence or absence of Atlantic croaker. DO = dissolved oxygen.

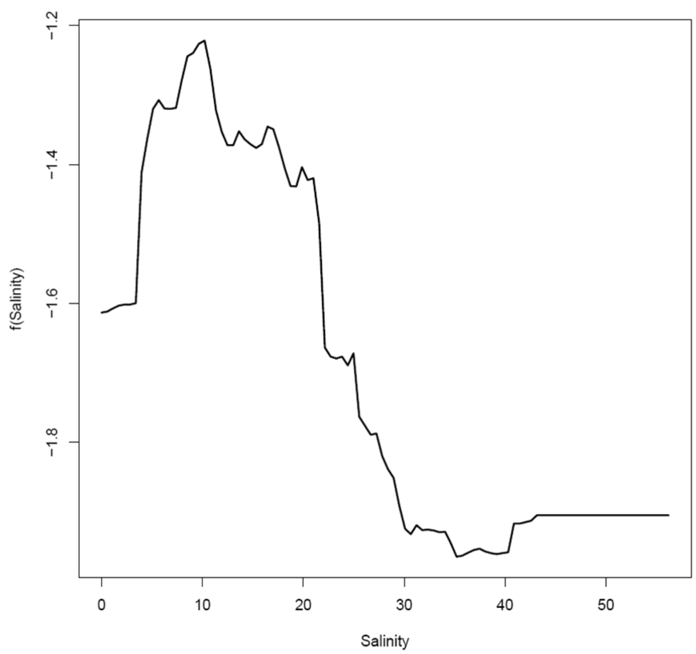


Figure 4.3.19. Functions fitted to salinity by a boosted regression tree (BRT) model relating the probability of occurrence of Atlantic croaker to salinity. Y-axis is on the logit scale with mean zero.

4.4 Drought Criteria Methodology

Water planning in Texas is based in large part on evaluating water resource availability during periods when climatic conditions induce either low-flow or drought of record situations. During such periods river flows are reduced, and therefore freshwater inflow to the estuaries also is reduced leading to elevated salinities and to reductions in sediment and nutrient loads. Several published studies covering the response of Texas bays to drought during the 1950s record the impacts to the estuarine animal communities. However, aside from these isolated studies, the effects of low-flow and drought conditions on the productivity and health of Texas estuaries is poorly understood. In fact, the effect of drought on estuarine ecosystems is relatively poorly understood in other parts of the world as well.

In this study, the effects of droughts on benthic macrofaunal communities in central Texas estuaries were determined. Droughts were defined as being periods at least a year long whose mean inflow to the estuaries is less than 60 percent of the long-term mean inflow. Droughts were classified using mass residual curves of inflow to estuaries along the central Texas coast. Hydrological and macrofaunal characteristics were compared among drought and non-drought periods to determine the impacts of droughts and low flows on estuarine health and productivity.

4.4.1 Methods

<u>Study Area</u>

This study will address the effects of drought and low-inflow conditions on the ecological characteristics of the Nueces Estuary, including Rincon Bayou, Nueces Bay, and Corpus Christi Bay (**Figure 4.4.1**).

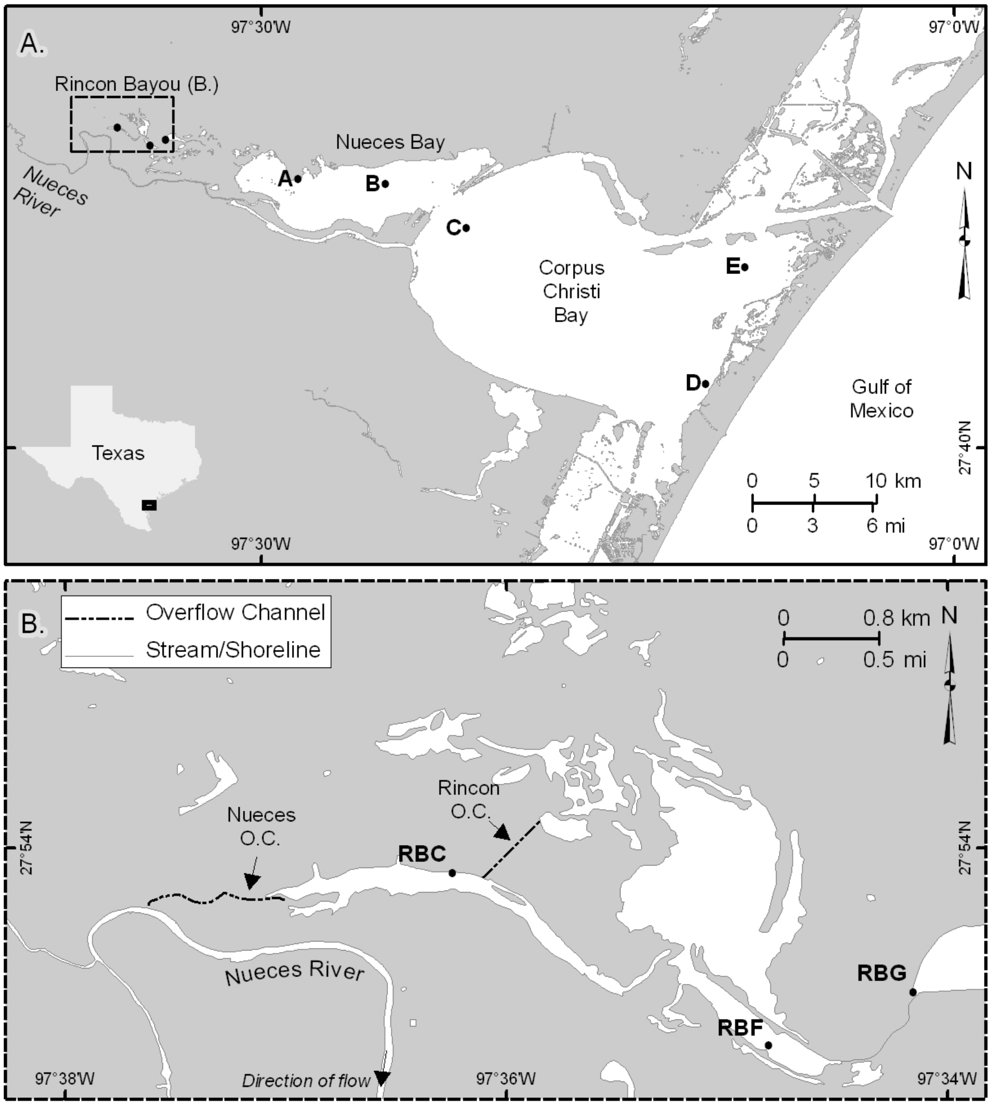


Figure 4.4.1. Map of the sampling stations in Nueces Estuary (A) and Rincon Bayou (B). O.C. = overflow channel.

Defining Droughts

Drought periods were calculated using monthly surface inflow data from the Texas Water Development Board (TWDB, 2011). Surface inflow as calculated by TWDB consists of:

Gaged flow in the estuary watershed (from USGS gages)
\+ Ungaged flow in estuary watershed (modeled flow)
\- Diverted flow
\+ Returned flow.

The period of record for surface inflow data is 1942 to 2009.

In this study, drought periods were determined using a modified method to that of Ward (2011). Droughts were defined as periods that met the following three criteria:

1. The first month of the period must have inflow less than 60% of mean monthly flow ($\bar{Q}$).
2. The first year (12 months) of flow must have on average 60% of mean monthly flow ($\bar{Q}$).

3. All monthly flows after the first year plus the twelve months of the first year must have on average 60% of the mean monthly flow ($\bar{Q}$).

The "60% of average flow" criterion was selected because it 'successfully identifies the historical droughts that have impacted the watershed' (Ward, 2010).

If periods of below average flow met the first two criteria, they were displayed using plots of cumulative-residual-flow. Using the cumulative sum:

$$\sum(Q - \bar{Q})$$

Droughts in the plots were defined as periods of time where the downward segment of a curve is steeper than the straight line

$$y(t) = \sum(Q_0 - \bar{Q})(1 - f)\bar{Q}(t - t_0)$$

where (t_0, $\sum(Q_0 - \bar{Q})$) is the first point of the declining segment and $f = 0.6$ (Ward, 2010).

Estuarine Data Acquisition

The Nueces Estuary has been sampled quarterly for both macrofauna and water quality for at least 15 years (**Table 4.4.1**). Benthic macrofauna were sampled using a 6.7-cm diameter core tube (35.4 cm^2 area) to a depth of 10 cm. Three replicate cores were collected from each station on each sampling date and were preserved with 5 percent buffered formalin. In the laboratory, organisms were extracted on a 0.5 mm sieve, sorted using a stereo microscope, identified to the lowest practical identifiable level (usually species), and enumerated. Biomass was determined after combining individual macrofauna into higher taxa levels (*Crustacea*, *Mollusca*, *Polychaeta*, and others) and drying at 50°C for 24 hours. Mollusc shells were removed with 1 N HCl prior to drying and weighing.

Hydrological measurements including salinity, temperature, dissolved oxygen and pH were taken simultaneously with macrofauna samples using YSI and Hydrolab datasondes.

Table 4.4.1. Summary of hydrology and macrofauna samples taken before 2010. See Figure 4.4.1 for locations of stations.

		Hydrology			**Macrofauna**		
Estuary	**Station**	**First Date**	**Last Date**	**Number of Days**	**First**	**Last**	**Number of Days**
Nueces	A	Oct 1987	Oct 2009	86	Oct 1987	Jul 2002	54
Nueces	B	Oct 1987	Oct 2009	85	Oct 1987	Jul 2002	53
Nueces	C	Oct 1987	Oct 2009	86	Oct 1987	Jul 2002	56
Nueces	D	Oct 1987	Oct 2009	84	Oct 1987	Jul 2002	54
Nueces	E	Apr 1991	Oct 2009	76	Oct 1990	Jul 2002	46
Nueces	RBC	Oct 1994	Dec 2009	129	Oct 1994	Dec 2009	110
Nueces	RBF	Oct 1994	Dec 2009	129	Oct 1994	Dec 2009	109
Nueces	RBG	Apr 1996	Dec 2009	91	Oct 2002	Dec 2009	84

Bi-monthly hydrological data for each estuary were obtained from the Texas Parks and Wildlife Department (TPWD) to determine hydrological characteristics for drought and non-drought periods. TPWD has collected salinity, temperature and dissolved oxygen data throughout Nueces and Corpus Christi Bays using a stratified-random sampling design since the late 1970s. This hydrological sampling is in association with

TPWD's fisheries-independent monitoring program (Martinez-Andrade, 2005). TPWD-derived data from the years 1982 to 2009 were used in the current analysis.

Changes in Estuarine Water Quality

Mean salinity, temperature and dissolved oxygen were determined for combined drought and non-drought periods for each estuary. Differences in hydrology between the primary and secondary bays within each estuary, and between drought and non-drought months were determined using two-way ANOVAs on mean monthly hydrological variables.

Changes in Macrofauna Communities

Mean macrofaunal abundance, biomass and diversity were calculated for the primary and secondary bays within each estuary. Macrofaunal diversity was calculated using Hill's N1 diversity index (Hill, 1973). Hill's N1 was used because it has units of number of dominant species, and is more interpretable than most other diversity indices (Ludwig and Reynolds, 1988). Differences in macrofauna characteristics between the primary and secondary bays within each estuary and between drought and non-drought months were determined using two-way ANOVAs. Macrofaunal community structure was analyzed using non-metric multi-dimensional scaling (MDS) using a Bray-Curtis similarity matrix among stations to create a MDS plot (Clarke, 1993; Clarke and Warwick, 2001). Relationships within each MDS were highlighted using a Cluster Analysis using the group average method. Significant differences between each cluster were tested using the SIMPROF permutation procedure using a significance level of 0.05. Data were $\log_e(x + 1)$ transformed prior to MDS and Cluster analysis in PRIMER to decrease the effect of numerically dominant species on the interpretation of the community composition (Clarke and Gorley, 2006). Significant differences between bays and drought months were determined using a two-way PERMANOVA, a permutational multivariate analysis of variance (Anderson, 2001, McArdle and Anderson, 2001).

Identification of Vulnerable Species

Macrofauna species were deemed vulnerable to drought if they decreased in abundance in drought periods relative to non-drought periods. These drought-vulnerable species were identified using the similarity percentages (SIMPER) procedure (Clarke, 1993) using PRIMER software (Clarke and Gorley, 2006).

4.4.2 Results

Water Quality

The Nueces Estuary experienced drought conditions 75 percent of the time between 1942 and 2009 (**Table 4.4.2**, **Figure 4.4.2**). Eleven of the 16 droughts that have occurred since 1942 have been 1 to 3 years long, however a 10-year long drought occurred from 1992 to 2002.

Salinity in the combined Nueces and Corpus Christi Bays (TPWD data: 1982 to 2009) is significantly higher in drought periods relative to wet periods ($p < 0.001$; **Figure 4.4.3**). The mean salinity in drought periods is 31 and the mean salinity in wet periods is 23. Drought does not cause any significant change to water temperature, dissolved oxygen or turbidity in the combined Nueces and Corpus Christi Bays. Mean turbidity is lower in wet periods than drought periods in the Nueces Estuary.

Rincon Bayou experiences significantly higher salinity in drought periods (mean = 30) relative to wet periods (mean = 8; $p < 0.001$; HRI data: 1994 to 2009). There were no significant differences in temperature, dissolved oxygen, and pH in Rincon Bayou between drought and wet periods.

Table 4.4.2. Nueces Estuary Droughts.

Drought #	Start		End		Duration (Years)
	Year	Month	Year	Month	
1	1942	11	1944	5	1.58
2	1947	8	1949	3	1.67
3	1949	9	1951	8	2.00
4	1951	10	1953	8	1.92
5	1953	12	1957	4	3.42
6	1961	3	1967	8	6.50
7	1968	8	1971	7	3.00
8	1971	12	1973	5	1.50
9	1973	12	1975	5	1.50
10	1977	7	1979	5	1.92
11	1979	7	1980	7	1.08
12	1981	12	1987	6	5.58
13	1987	8	1992	5	4.83
14	1992	7	2002	6	10.00
15	2005	1	2007	6	2.50
16	2007	10	2009	12	2.25
Total Drought					51.25
Total Non-Drought					16.75
Total Years					68.00

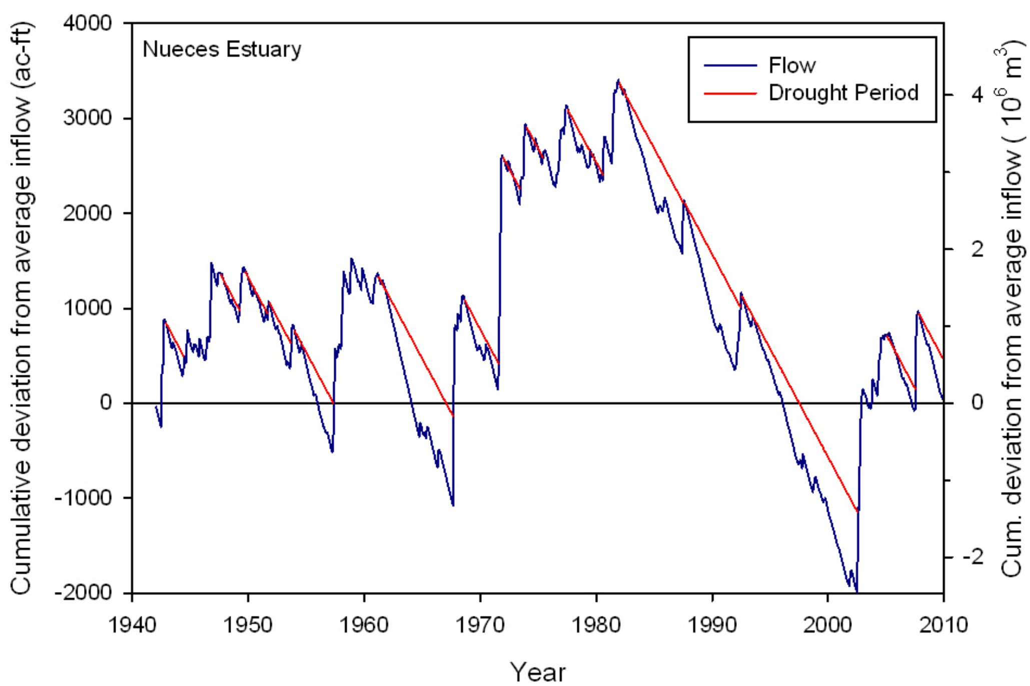


Figure 4.4.2. Cumulative deviation from average monthly inflow to Nueces Estuary and definition of drought periods.

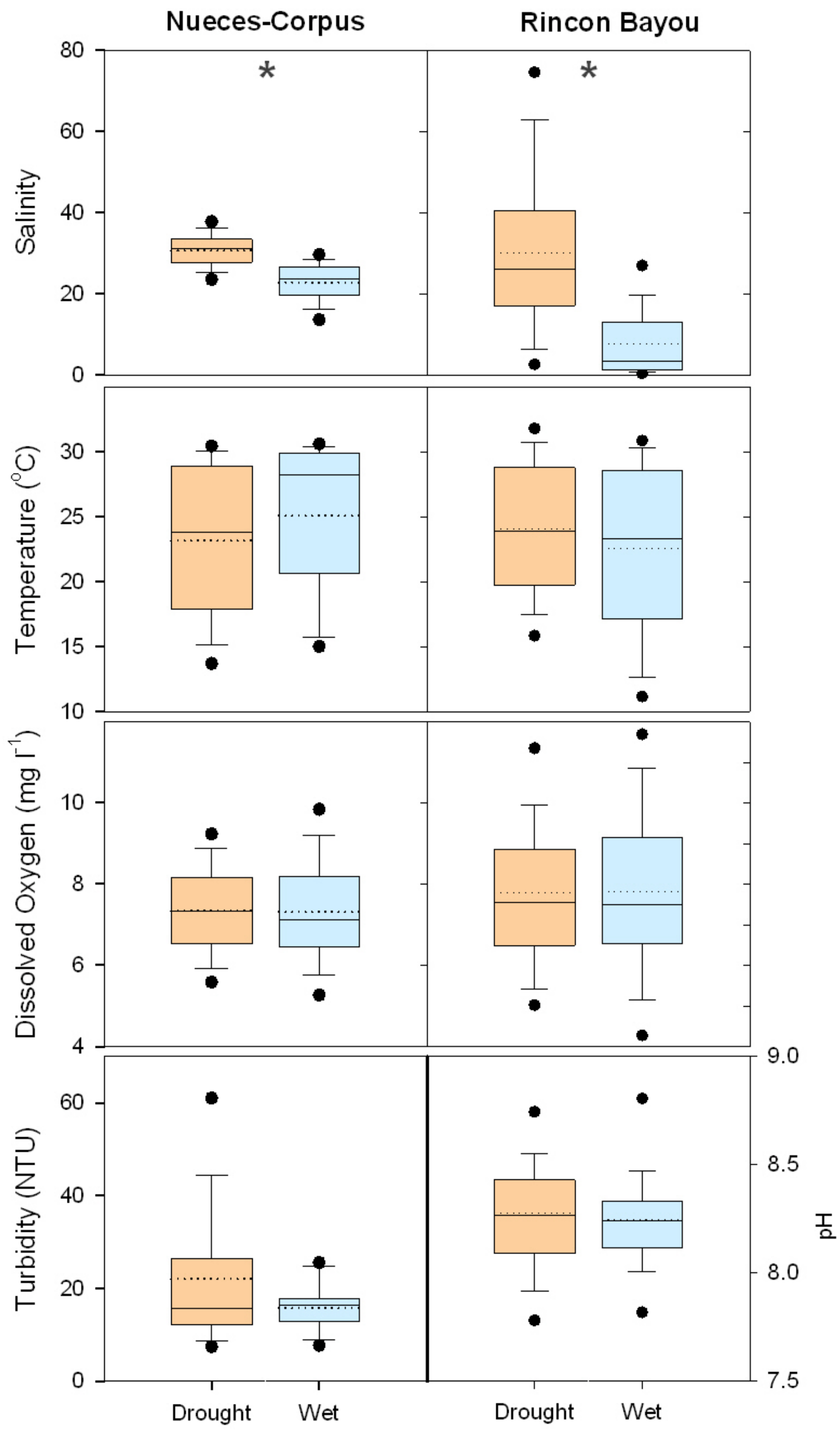


Figure 4.4.3. Comparing drought and wet conditions for four water quality variables in Nueces-Corpus Christi Bays (TPWD data) and Rincon Bayou (HRI data). * indicates significant differences between drought and wet months.

Benthic Macrofauna

Nueces Bay and Corpus Christi Bay macrofauna stations were sampled on 46 to 56 different dates between 1987 and 2002 (Table 4.4.1). However, only one of these dates was during a wet period. Further analyses of macrofauna communities in Nueces and Corpus Christi Bays are severely restricted because of this massive imbalance in samples from drought and wet periods. Rincon Bayou was sampled on 110 different dates, of which 29 were during a wet period. Therefore, the focus of the macrofauna community analysis is located in Rincon Bayou.

Macrofaunal abundance and biomass are significantly lower in wet periods relative to drought periods ($p < 0.001$; **Figure 4.4.4**). N1 Diversity, or the number of dominant species, is significantly higher in wet periods than drought periods in Rincon Bayou ($p < 0.001$). In drought periods, the opportunistic polychaete *Streblospio benedicti*, is on average ten times more abundant than during wet periods (**Table 4.4.3**). *S. benedicti* is an indicator of disturbed environments (Levin, 1984; Palemer, et al., 2002), such as the high salinities of Rincon Bayou during drought conditions. The decrease in number of dominant species (N1 diversity) in wet periods can be partially attributed to the decreased numerical dominance of *S. benedicti*.

Table 4.4.3. Twenty most abundant species in Rincon Bayou.

Species / LPIL taxa	Abundance (n m^{-2})			% of Total	Cum. %
	Drought	Wet	Mean		
Streblospio benedicti	17832	1517	9675	82.51	82.5
Laeonereis culveri	841	252	546	4.66	87.2
Chironomidae (larvae)	340	626	483	4.12	91.3
Mediomastus ambiseta	484	211	348	2.96	94.2
Ostracoda (unidentified)	282	85	183	1.56	95.8
Oligochaeta (unidentified)	326	29	177	1.51	97.3
Nemertea (unidentified)	28	77	52	0.45	97.8
Corophium louisianum	64	34	49	0.42	98.2
Mulinia lateralis	38	44	41	0.35	98.5
Ceratopogonidae (larvae)	19	47	33	0.28	98.8
Paranais grandis	62	0	31	0.27	99.1
Capitella capitata	38	3	20	0.17	99.3
Polydora ligni	17	21	19	0.16	99.4
Hemicyclops sp.	18	1	9	0.08	99.5
Nereididae (unidentified)	9	9	9	0.08	99.6
Hobsonia florida	0	18	9	0.08	99.7
Mysidopsis almyra	4	11	8	0.07	99.7
Rhaphium campestre	8	0	4	0.03	99.8
Macoma mitchelli	7	0	4	0.03	99.8
Pseudeurythoe sp. A	6	0	3	0.03	99.8
Total (all species)	20453	2998	11725	100.00	

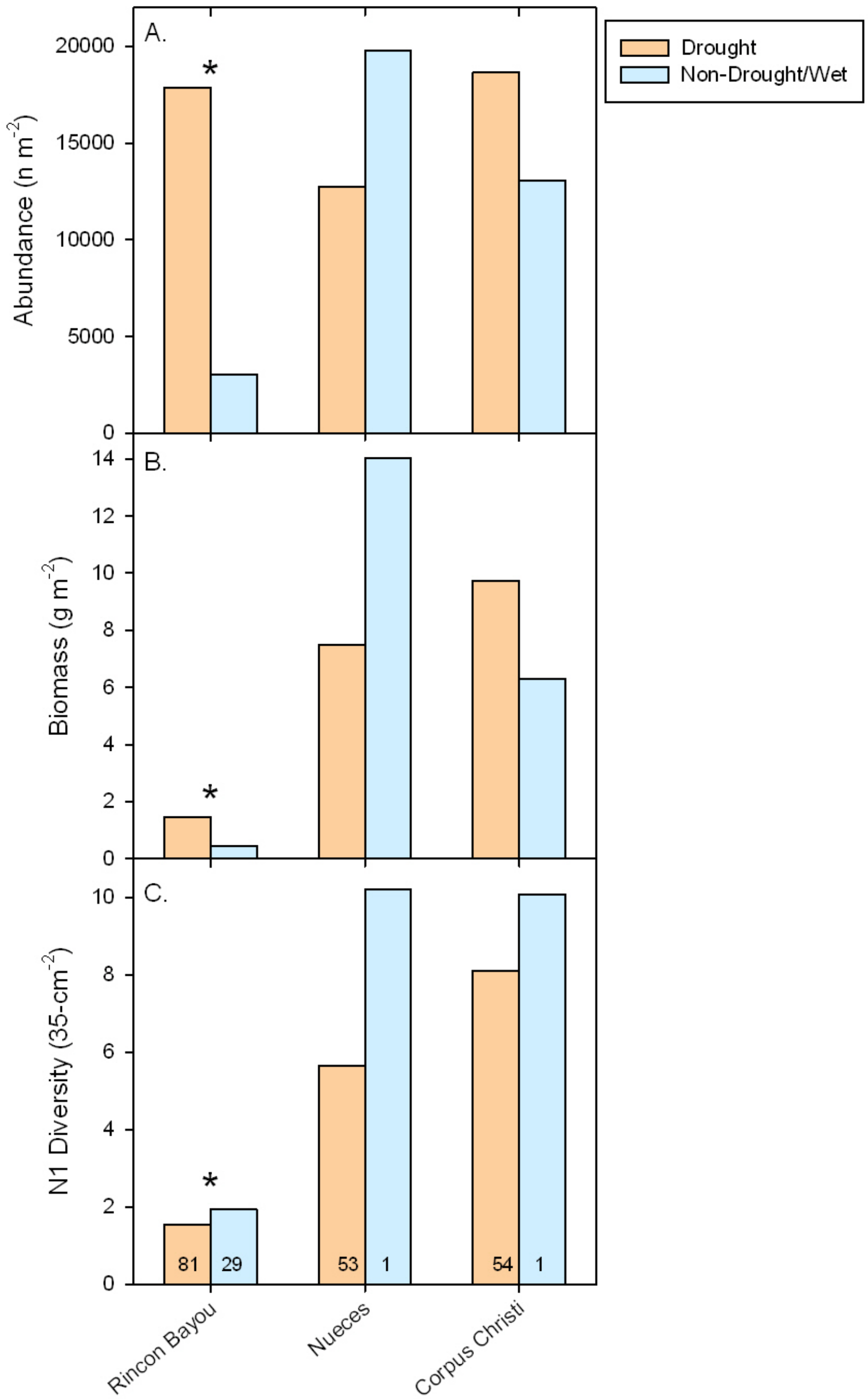


Figure 4.4.4. Mean macrofaunal abundance (A), biomass (B) and diversity (C) for the primary and secondary bays within Nueces Estuary. * indicates significant differences between drought and wet months. Numbers in bars in (C) represent number of dates sampled.

The largest change in abundance of individual species between drought and wet periods occurs with four of the five numerically dominant species (Table 4.4.3 and **Table 4.4.4**). In wet periods, Chironomid larvae and unidentified Nemerteans increase in abundance, while polychaetes *Laeonereis culveri*, *Mediomastus ambiseta*, and *S. benedicti* all decrease in abundance**.** Overall, these individual species changes alter the community composition of Rincon Bayou (**Figure 4.4.5**). The macrofaunal community composition in drought conditions is significantly different to the community composition in wet conditions ($p < 0.001$).

Table 4.4.4. Similarity percentages - species (SIMPER) in Rincon Bayou in drought and wet years. Only top 90 percent of species are included in list. Average dissimilarity between groups is 58.94 percent. Diss = dissimilarity, SD = standard deviation, Contrib = contribution.

Species/LPIL Taxa	Mean log abundance		Mean Diss	Diss/ SD	Contrib (%)	Cum. Contrib (%)
	Drought	Wet				
Streblospio benedicti	8.32	5.53	9.54	0.98	16.18	16.18
Chironomidae (larvae)	2.06	4.24	8.91	1.08	15.11	31.29
Laeonereis culveri	3.27	2.54	7.77	1.08	13.19	44.48
Mediomastus ambiseta	2.7	2.39	6.7	0.92	11.37	55.86
Nemertea (unidentified)	0.98	2.14	5.48	0.84	9.3	65.16
Ceratopogonidae (larvae)	0.39	1.12	2.91	0.57	4.94	70.09
Ostracoda (unidentified)	0.45	1.03	2.61	0.53	4.42	74.51
Mulinia lateralis	0.91	0.64	2.58	0.52	4.38	78.89
Oligochaeta (unidentified)	1.03	0.5	2.42	0.5	4.1	82.99
Hobsonia florida	0.02	0.54	1.18	0.32	1.99	84.99
Polydora ligni	0.28	0.33	0.96	0.3	1.62	86.61
Corophium louisianum	0.26	0.4	0.92	0.32	1.56	88.17
Nereididae (unidentified)	0.13	0.25	0.87	0.26	1.48	89.64
Capitella capitata	0.26	0.12	0.76	0.26	1.29	90.93

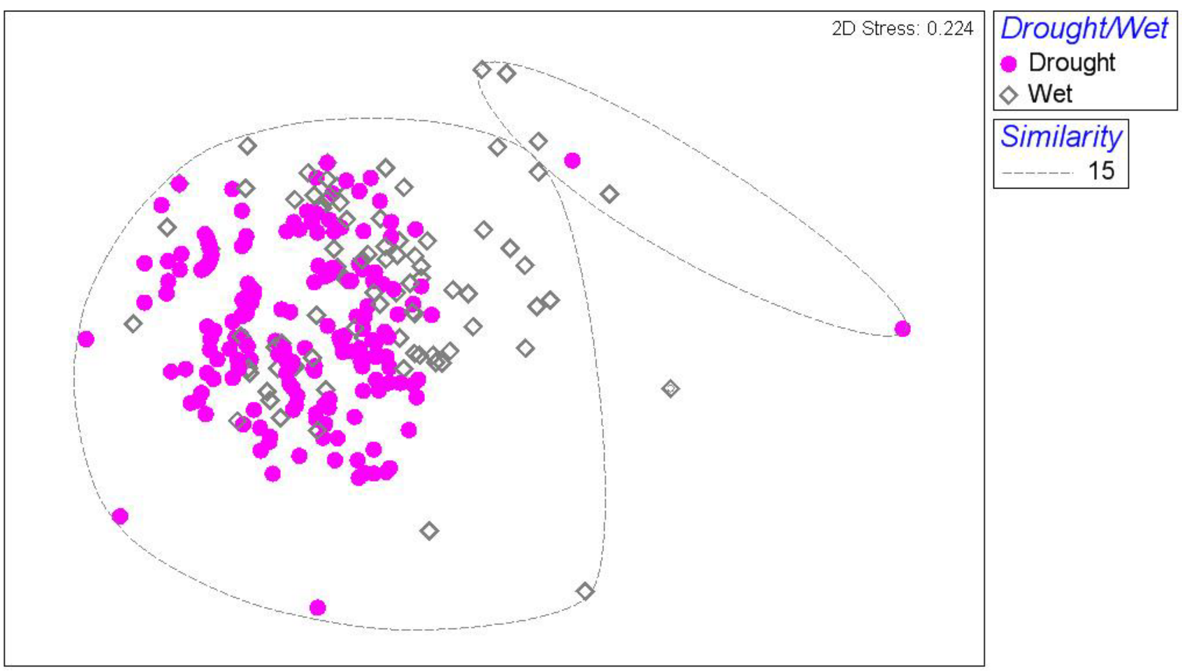


Figure 4.4.5. Quarterly Macrofauna Community Structure in Rincon Bayou (Nueces Estuary) labeled by the bay/region of the estuary and whether the communities are in drought or wet conditions.

Species that are considered vulnerable to drought in Rincon Bayou are those that decrease in abundance in drought relative to wet conditions. The most common vulnerable group of species in Rincon Bayou were the insects. Chironomid and Ceratopogonidae larvae (both midges) commonly occur in wet periods but are rarer during droughts (Table 4.4.4). Ostracods (seed shrimp) and Nemerteans (proboscis worms) are also taxa groups that are vulnerable to droughts. The polychaete *Hobsonia florida* is also vulnerable to droughts but occurs in low abundances even in wet periods.

It must be noted the macrofauna communities are different in each of the three systems (Nueces, Corpus Christi, and Rincon Bayou) regardless of whether they are in drought or wet conditions. Macrofauna communities in Rincon Bayou are significantly different to those occurring in Corpus Christi Bay ($p \leq 0.037$), but not significantly different to those occurring in Nueces Bay ($p \leq 0.098$). The communities in Corpus Christi and Nueces Bays are similar to each other ($p \leq 0.214$). The effect of droughts on macrofauna communities in Nueces and Corpus Christi Bays are speculative using this existing macrofauna data because only one date was sampled during a wet period and the community composition in Nueces and Corpus Christi Bays is dissimilar to that of Rincon Bayou (**Figure 4.4.6**). Diversity, biomass and abundance all increase in the 1 wet date relative to 53 drought dates sampled in Nueces Bay (Figure 4.4.4). In Corpus Christi Bay, macrofauna abundance and biomass decrease but diversity increases in the 1 wet date relative to 54 drought dates sampled.

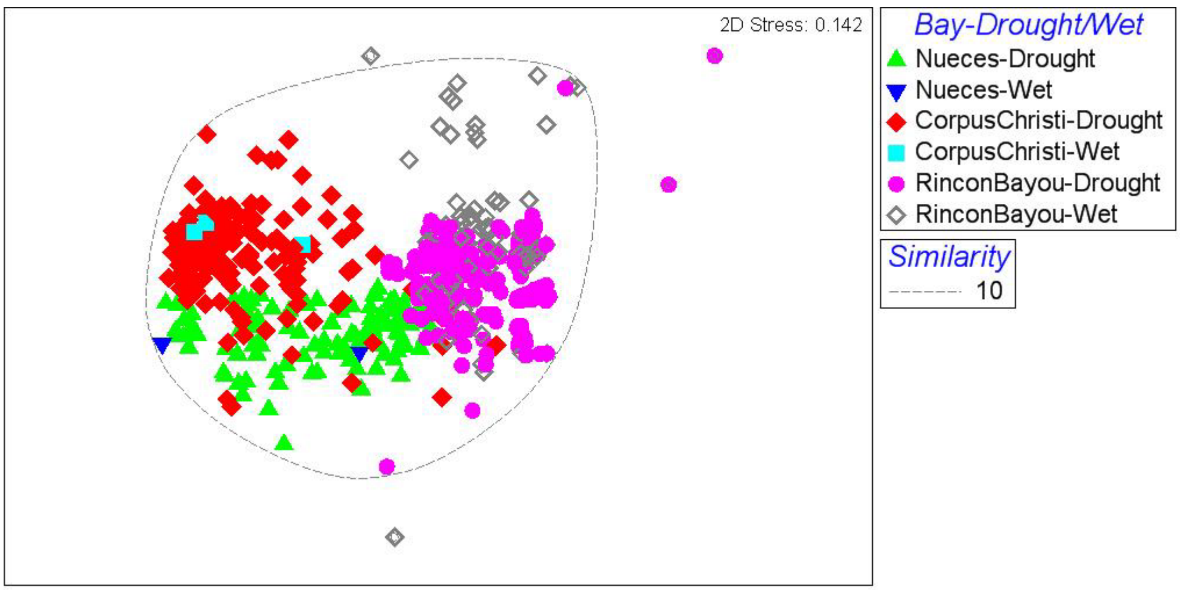


Figure 4.4.6. Quarterly Macrofauna Community Structure in Nueces Estuary labeled by the bay/region of the estuary and whether the communities are in drought or wet conditions.

Although thorough analysis of the effects of droughts on the Nueces Estuary is restricted to Rincon Bayou, the results of the analysis are clear. Drought conditions (low inflows) in the Nueces Estuary caused a loss in ecological integrity in Rincon Bayou by decreasing the number of dominant macrofauna species (N1 diversity) and increasing the dominance by the disturbance-indicating polychaete *Streblospio benedicti*.

4.5 Freshwater Inflow Needs

The table below shows the freshwater inflow regime recommendations for Nueces Bay and Delta based on the above analyses. These volumes were developed through robust predictive models relating the freshwater inflows and salinity that were needed to produce desired salinity ranges in addition to the seasonal delivery of freshwater into the bay and delta for the indicator species. These recommendations are grounded in the historical patterns of water availability on a seasonal basis.

Table 4.5.1. Nueces Bay and Delta Inflow Regime Recommendation Table[1].

Condition (Target Salinity)	Nueces Bay Freshwater Inflow Regime (Attainment)			Recommendations		Historical Attainment		
	one overbanking event per year of 39,000 acft; maximum discharge of 3,600 cfs			Annual Total	Attainment	1941-2009	1941-1982	1983-2009
High (10)	125,000 acft (20%)	250,000 acft (25%)	375,000 acft (20%)	750,000	25%	22%	26%	15%
Base (18)	22,000 acft (60%)	88,000 acft (60%)	56,000 acft (75%)	166,000	80%	67%	81%	44%
Subsistence (34)	5,000 acft (95%)	10,000 acft (95%)	15,000 acft (95%)	30,000	95%	94%	100%	85%
	Nov, Dec, Jan, Feb	Mar, Apr, May, Jun	Jul, Aug, Sept, Oct					
	Winter	Spring	Summer, Fall					

[1] Note: The management goal for a sound environment is the base condition, and subsistence should not be a target level, but only occur rarely during drought conditions. We recommend one overbanking event each year with a peak flow of 3,600 cfs measured at the USGS streamflow gaging station at Calallen Dam with a central tendency volume of 39,000 acft. The overbanking event is intended to count only toward the seasonal attainment. Thus, the water volume entering the bay/delta in one season is independent of the volume entering the bay/delta in the preceding or subsequent season. For example, if a season has twice the inflow recommended by the BBEST, the extra inflow will not count towards the inflow needs for the subsequent season. Moreover, the volume of water entering the bay/delta in a year is independent of the volume entering the bay/delta in the preceding year.

To calculate the regime schedule, it was first determined that a salinity requirement of 18 was essential for maintenance of the indicator species. A base flow regime was calculated that would produce and maintain salinities for a sound ecological environment. The base inflow regime includes freshwater inflows that provide salinities near 18 during critical seasonal time periods. An annual overbank flow that floods the Nueces Delta was also recommended. We used TxBLEND modeled salinities in dry and wet years to determine salinities under drought and wet conditions (Figure 4.1.5). The high and subsistence inflow regimes allow inter-annual variability in freshwater inflow while providing areas in the bay with adequate salinity to ensure a long term sound ecological environment. Nueces Bay inflow (a combination of gaged and ungaged flow) and SALT03 station salinities were analyzed to develop a mathematical relationship between salinity and inflow for the western part of the bay near the SALT03 station. This mathematical relationship was used to calculate freshwater inflow that would generate target salinities (Figure 4.2.1) for high and base flow.

These calculations indicate that an annual inflow of 160,000 acft would provide salinities of approximately 18 during base flow conditions. However, marsh plants in the delta need an annual inflow of 166,000 acft in order to maintain porewater salinity of 25, which allows marsh plants to grow and remain healthy (Table 4.3.1). Thus, the calculated inflows of 160,000 acft to the bay were increased by an additional 6,000 acft to provide base flows and a sound environment for the marsh plants. We also examined TWDB calculated freshwater inflow near Calallen from 1990 to 2009 and determined that annual inflow exceeded 30,000 acft in 95 percent of the years. Therefore, we used 30,000 acft as the basis for the annual recommendation for subsistence conditions. Inflows were distributed between seasons based on historical patterns of seasonal inflow and biological needs of all indicator species (Figure 4.1.1). For example, seasonal amounts for base flow are determined from the needs of marsh plants while, during subsistence flow, the amounts are based on historical monthly patterns (see Figure 4.1.2).

Annual attainment recommendations were based on meeting the biological needs of all indicator species, while accounting for historical patterns of water availability during those months/seasons (Figure 4.1.1 and Figure 4.1.2). To produce and sustain a sound environment, the base flow recommendations should be met or exceeded in 80 percent of the years; the subsistence flow recommendations should be exceeded in 95 percent of the years; and the high flow recommendations should be met or exceeded in about 1of every 4 years. The subsistence flow regime should not be artificially extended. Seasonal attainment frequencies are based on how often (percentage of time) the recommended seasonal inflow volumes were met or exceeded historically on the basis of natural (without dams) Nueces Bay inflow estimates from 1934-1996. Natural Nueces Bay inflow estimates were obtained from the TCEQ Nueces River Basin Water Availability Model (Nueces WAM) on September 16, 2010 (http://www.tceq.texas.gov/permitting/water_supply/water_rights/wam.html).

Clearly, overbanking events are important to estuarine health (for details see Section 1.3 and Section 4.1). For example, the annual overbanking event recommended herein will have numerous ecological benefits to the estuary such as sediment delivery, nutrient improvements, reducing parasite loads within oyster reefs allowing for recovery, and general flushing of the systems. To calculate the number of overbanking events and duration, we examined previous inflow studies by Cunningham (1999), Bureau of Reclamation (2000), Irlbeck and Ward (2000, Appendix C), and determined the amount of flow needed to crest the Nueces River banks and inundate the nearby delta and bay. To generate an overbanking event based on these calculations, there needs to be flow in the Nueces River at the Calallen streamflow gaging station with a magnitude of at least 3,600 cfs and a total volume of 39,000 acft. IHA/HEFR results for the Nueces River near Mathis indicate that 3,600 cfs has occurred at a frequency of twice a year over the period from 1940 to 2009.

Although not specifically addressed in this recommendation, the Nueces BBEST is concerned about the effects of periods without flow into the delta. The Nueces River at Mathis has not had any days without flow from 1940 through 2009. At the Calallen saltwater barrier, only one of the 23 years from 1989 to present did not have days without flow. In some years, there was no flow to the bay over 20 percent of the year. Some periods without flow have exceeded two months. The Nueces BBEST has included a task in Section 7 (Adaptive Management) to determine the effects of no-flow periods on bay and delta health. The absence of specific recommendations at this time regarding no-flow periods should not be interpreted as an indication from the Nueces BBEST that no-flow periods do not affect bay or delta environmental health.

Section 5. Integration of Instream Flow and Freshwater Inflow Regimes

5.1 Comparison of Estuarine Inflow to Instream Flow Regimes

The instream environmental flow regime for the river providing most of a bay's freshwater should be comparable to the freshwater inflow regime needed to keep the bay healthy. The Nueces BBEST calculated a freshwater inflow regime for Nueces Bay/delta independently of its flow regime calculations for the Nueces River between Lake Corpus Christi and the bay/delta complex. The Nueces River at Mathis flow regime applies to the river between Lake Corpus Christi and the saltwater barrier and diversion dam at Calallen. The Nueces estuary begins at the downstream side of this barrier/dam at Calallen where the river flows into the tidal reach of the Nueces River.

Flow at Mathis is determined almost entirely by Lake Corpus Christi releases. Lake Corpus Christi releases with flows lower than pulse flows provide water for municipal, industrial, and agricultural uses. There are four major diversions from the Nueces River within the last river mile before it flows over the Calallen saltwater barrier. Under base flows, these diversions remove a substantial part of the flow before it enters the estuary. Thus, Nueces River at Mathis flows are substantially larger than volumes of water actually reaching the bay. As a result, it is not appropriate to compare the Nueces River at Mathis environmental flow regime to the freshwater inflow recommendations for Nueces Bay.

Despite these conditions, and unlike Nueces Bay, the BBEST agreed that the Nueces River near Mathis is an acceptable sound environment even though daily and seasonal flow patterns are not natural. Although flow in this reach is highly regulated, the BBEST accepted this designation because there is substantial perennial flow in the river from Lake Corpus Christi to near the Calallen saltwater barrier. The BBEST also recognized this is a relatively short reach of river, less than 50 river miles.

When flooding occurs upstream of Lake Corpus Christi and the reservoir is full, flood flows pass through the reservoir and much of those flood flows reaches the bay. The environmental flow regime for the Nueces River at Mathis is based on a period of record from 1940 to 2009. Floods with over 100,000 acft of water passing the Mathis site in a month occurred about once a year prior to 1985 when Choke Canyon Reservoir was still filling. From 1985 through 2010, floods greater than 100,000 acft in a month occurred half as frequently, only about every other year.

Comparison of river flow at Mathis to that at the Calallen saltwater barrier reveals how much flow at Mathis may be reaching the bay and delta. The U.S. Geological Survey has measured flow at the Calallen gage since 1998. From January 1998 through September 2010, the lowest monthly average river flow at the Mathis gage was 38.2 cfs. During the same thirteen years, the lowest monthly average river flow at Calallen was 0.4 cfs. Over a third of monthly average flows at Calallen were less than the lowest monthly average flow at Mathis. The median monthly average flow at Calallen was 60 cfs. At Mathis, the median monthly average flows were over twice as large (146 cfs).

Figure 5.1.1 illustrates flows every 15 minutes from July 1 to October 5, 2011 in the Nueces River at Mathis and Calallen and in Rincon Bayou. The horizontal blue line at 100 cfs represents the summer low base flow regime value for the Nueces River at Mathis. This allows comparison of actual flows to flow regime values.

The Mathis flow pattern reflects effects of reservoir releases for diversions. During a long, hot, dry summer like that from July through September 2011, most rivers would have flows near the dry base or subsistence flow levels. However at the Mathis gage, day-to-day flow increased from mid-July through August as water supply demand rose. Most rivers with natural flow regimes would reflect declining flows during the summer. Most days at this site, flows varied from 10 to 20 cfs during the day.

A pulse of 541 cfs occurred in September at the Mathis gage. This pulse exceeded the 1/season summer pulse regime value of 370 cfs. However, the pulse duration was only 3 days. In most natural rivers, the pulse would decline more gradually over days. The very steep decline of the pulse may be a reflection of a reservoir managed pulse.

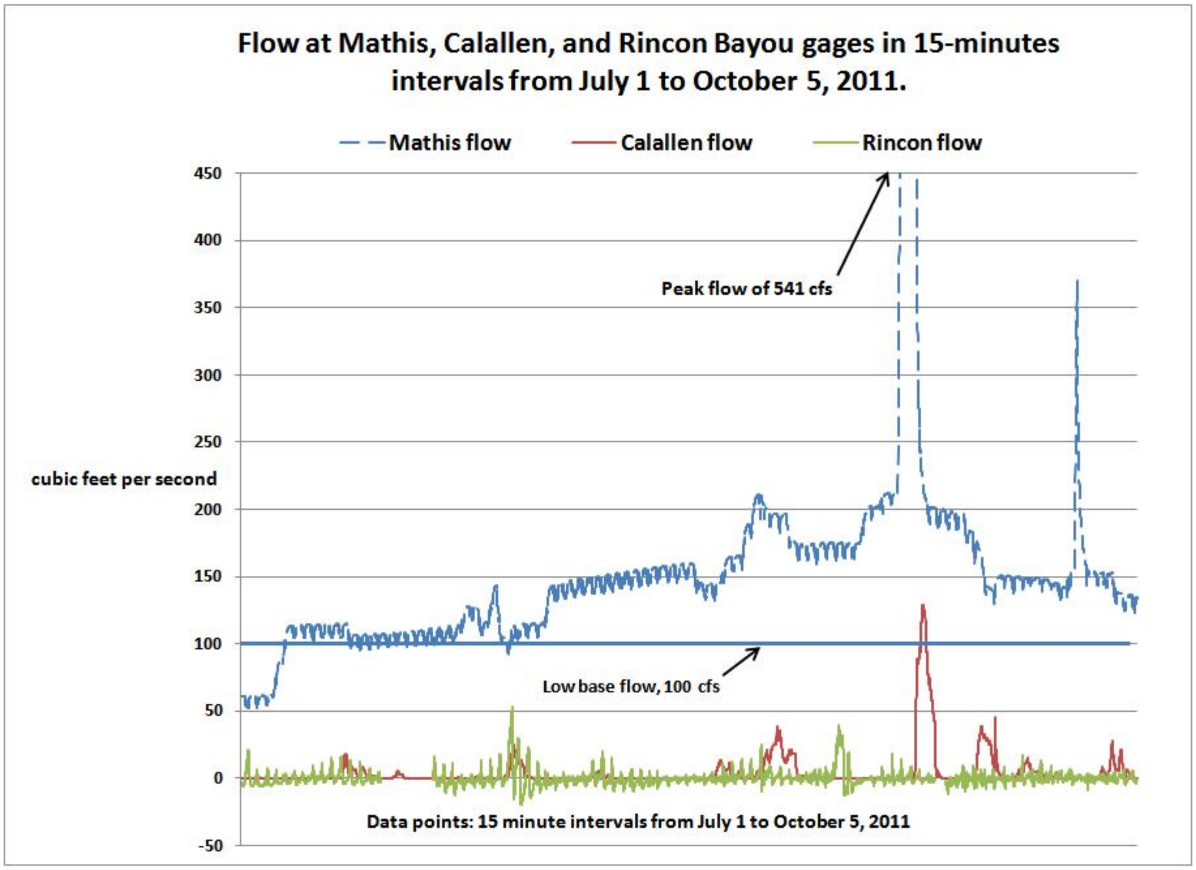


Figure 5.1.1. 15-Minute instantaneous flow measurements of the Nueces River at Mathis and Calallen and Rincon Bayou from July 1 to October 5, 2011.

The red, solid line reflects Nueces flows past the Calallen saltwater dam at the same time that Nueces flows were measured at Mathis. For most of the summer there was no river flow at the Calallen gage even though flows at the Mathis gage were typically over 100 cfs. A pulse occurred at the Calallen gage in September a day after the pulse of 541 cfs was recorded at Mathis. However, the pulse at Calallen was only 129 cfs.

The green line moving up and down around the zero flow line represents Rincon Bayou flow at its gage. These flows reflect tidal fluctuations at this site. When the green line is below the zero flow line, the tide is incoming and pushing water up Rincon Bayou towards the Nueces River. Conversely, when the green line is above the zero flow line the tide is outgoing and water is draining from Rincon Bayou towards Nueces Bay. There is no apparent relation between the pulse flows at Calallen and flow in Rincon Bayou.

Our recommendations are based on TWDB calculated freshwater inflow to Nueces Bay and delta from 1941 through 2009 (TWDB, 2011). These calculations are based on measured inflows to the bay combined with output from the TWDB's Rainfall Runoff model which calculates inflow from rainfall onto watersheds without flow gages. **Table 5.1.1** compares the recommended percent attainments for both seasons and years to recent actual attainment percentages using TWDB calculated freshwater inflows from 1990 through 2008. The difference is particularly pronounced for the base inflow regime for spring, an ecologically important time of the year, which was only exceeded 3 of the 19 years. The base inflow regime annual total was only achieved 47 percent of the years compared to the 80 percent attainment recommendation. Table 5.1.1 illustrates that neither the recommended volumes or frequencies of recommended inflows have reached Nueces Bay despite substantial volumes in the river passing the gage at Mathis.

Table 5.1.1. Comparison of percent attainment recommendations for seasonal freshwater inflows to actual attainment from 1990 through 2008. Inflows were compared to the BBEST regime recommendations (see Section 4.5 for detailed inflow regime). Recommended percent attainments are in parentheses. Spring includes March through June; summer/fall includes July through October; and winter includes November through February of the following year.

	Spring Percent Attainment	**Summer/Fall Percent Attainment**	**Winter Percent Attainment**	**Annual Total Percent Attainment**
High inflow regime	11% (25%)	11% (20%)	21% (20%)	11% (25%)
Base inflow regime	11% (60%)	42% (75%)	32% (60%)	47% (80%)
Subsistence inflow regime	84% (95%)	95% (95%)	89% (95%)	95% (95%)

Clearly, as illustrated by analysis of historical data and recent flows shown in Figure 5.1.1 and Table 5.1.1, Nueces River at Mathis flows are substantially larger than volumes of water reaching the bay. As a result, it is not appropriate to compare the Nueces River at Mathis environmental flow regime to the freshwater inflow recommendations for Nueces Bay.

5.2 Nutrient Considerations

The Science Advisory Committee in the "Methodology for Establishing Freshwater Inflow Regime for Texas Estuaries" (Science Advisory Committee - 2009-03) charged the BBEST to conduct a nutrient overlay. Below is a summary of the relationship between freshwater inflow and nutrients in the Nueces Bay region.

Methods

Fourteen stations have been consistently sampled (mostly monthly) since 2001 or earlier by researchers from the University of Texas Marine Science Institute and Texas A&M University-Corpus Christi (see Montagna, et al., 2009; Dunton, et al., 2011; **Figure 5.2.1**). Physical parameters such as salinity and temperature were measured with a YSI 6920 multiprobe sonde although nutrients and chlorophyll were also sampled. The majority of the nutrient samples were taken by hand and put on ice (< 4.0°C). Water for chlorophyll-*a* analysis was filtered onto Whatman GF/F 25 mm glass 157 fiber filters and placed on ice. Nutrient samples were filtered to remove biological activity (0.45 µm polycarbonate filters). Chlorophyll-*a* was extracted overnight and read on a Turner Model 10-AU fluorometer using a non-acidification technique (USEPA, 1997; Welschmeyer, 1994). Nutrient analysis was conducted using a LaChat QC 8000 ion analyzer with computer controlled sample selection and peak processing. Nutrients measured were (Quikchem method) nitrate+nitrate (31-107-04-1-A), silicate (31-114-27-1-B), ammonium (31-107-06-5-A) and phosphate (31-115-01-3-A).

Station means (± standard error) of each parameter were compared both spatially and versus salinity, a proxy for inflow effects, to determine effects of inflow spatially. Nueces River flow (USGS station 08211500, Nueces River at Calallen, TX) was compared with nutrient concentrations in the Nueces River below the salt-water dam/weir (station 168H) to determine changes in nutrients over different flow volumes.

Results

As expected, salinity increases down the Nueces River, although reverse estuary conditions occur within Rincon Bayou due to lack of freshwater flows that flow into upper Rincon Bayou (**Figure 5.2.1A**). Upper Rincon Bayou experiences high concentrations of ammonium (Figure 5.2.1, **Figure 5.2.3** and **Figure 5.2.5**) and chlorophyll (**Figure 5.2.2**, **Figure 5.2.4,** and **Figure 5.2.6**), which can partially be attributed to the low flow rates that occur there. Low flows in the Nueces River also cause stagnation and phytoplankton blooms (high chlorophyll-*a* concentrations, Figure 5.2.6).

High phosphate concentrations occur in the Nueces River, downstream of the Allison Wastewater Treatment Plant discharge point. Nitrate plus nitrite (Figure 5.2.2, Figure 5.2.4 and Figure 5.2.6), and phosphates (Figure 5.2.1, Figure 5.2.3 and Figure 5.2.5) are higher in Nueces Bay than Rincon Bayou, despite having similar salinities.

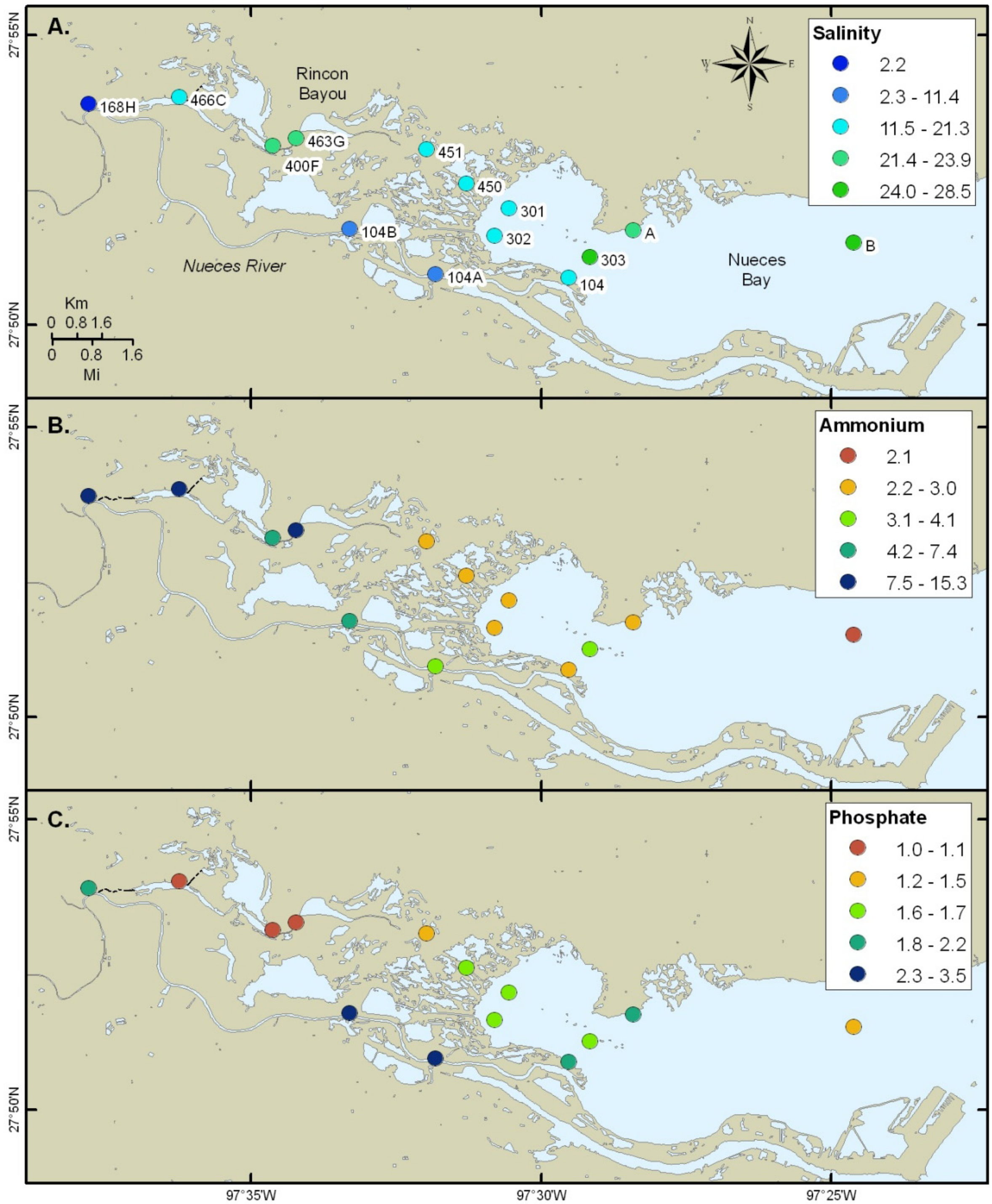


Figure 5.2.1. Mean salinity (A), ammonium (B) and phosphate (C) concentrations at sampling stations in the upper Nueces Estuary. Except for salinity, all parameters are measured in µM.

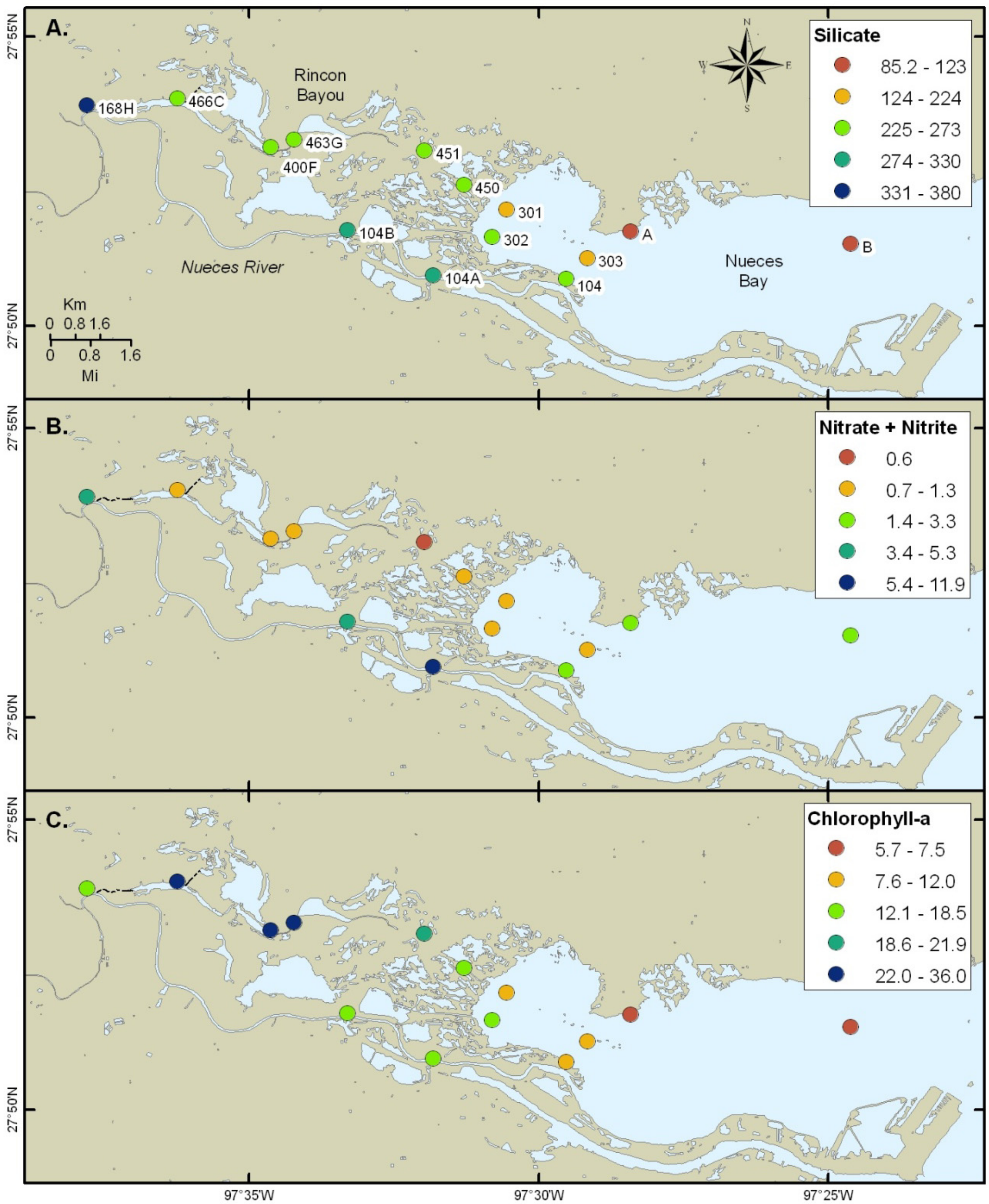


Figure 5.2.2. Mean silicate (A), nitrate plus nitrite (B) and chlorophyll (C) at sampling stations in the upper Nueces Estuary. All parameters are measured in µM.

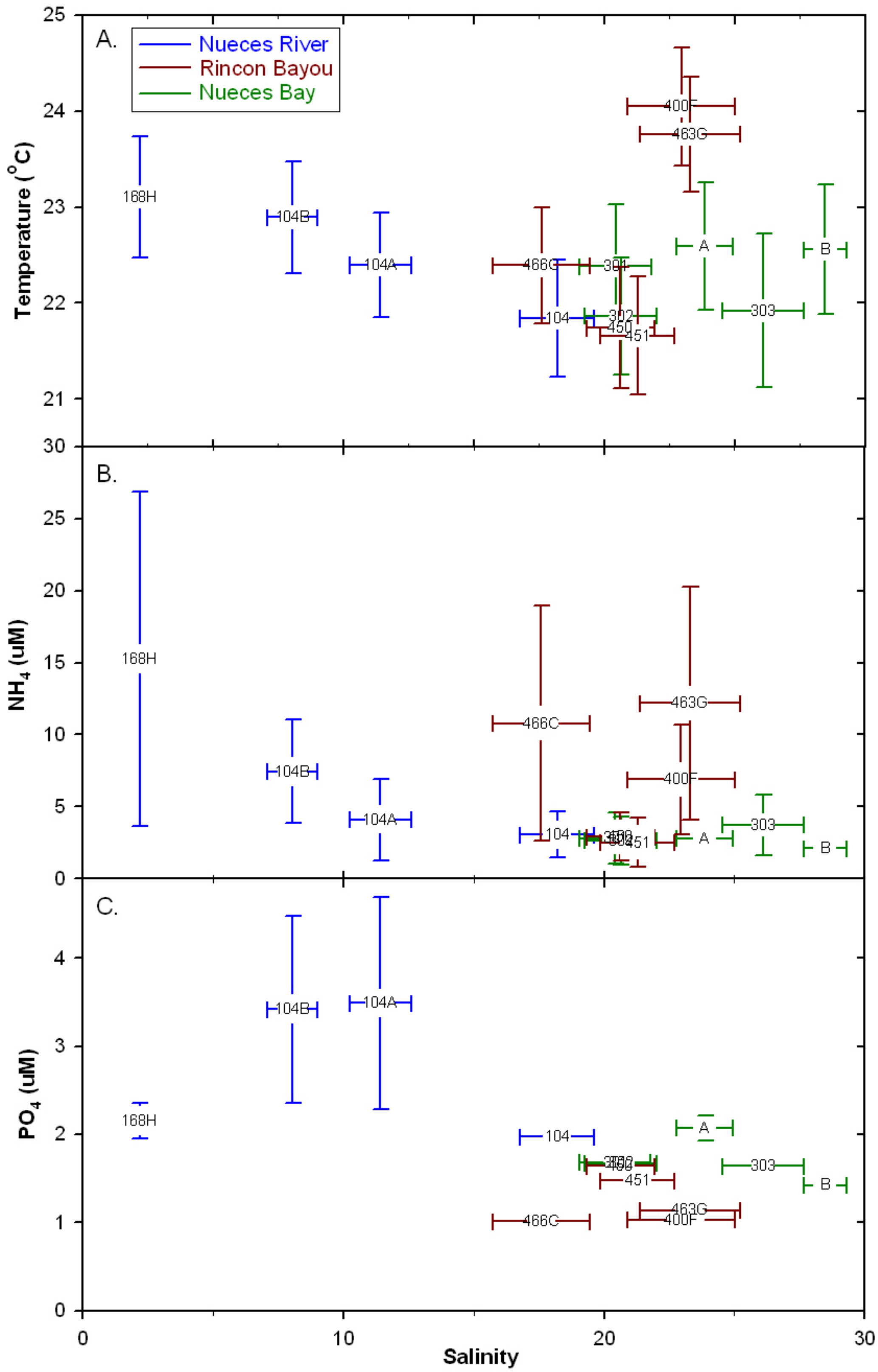


Figure 5.2.3. Temperature (A), ammonium (B) and phosphate (C) concentrations versus salinity in the upper Nueces Estuary. Each plotted point is the mean and standard error (error bars) of a station. Locations of each station are shown in Figure 5.2.1 and Figure 5.2.2.

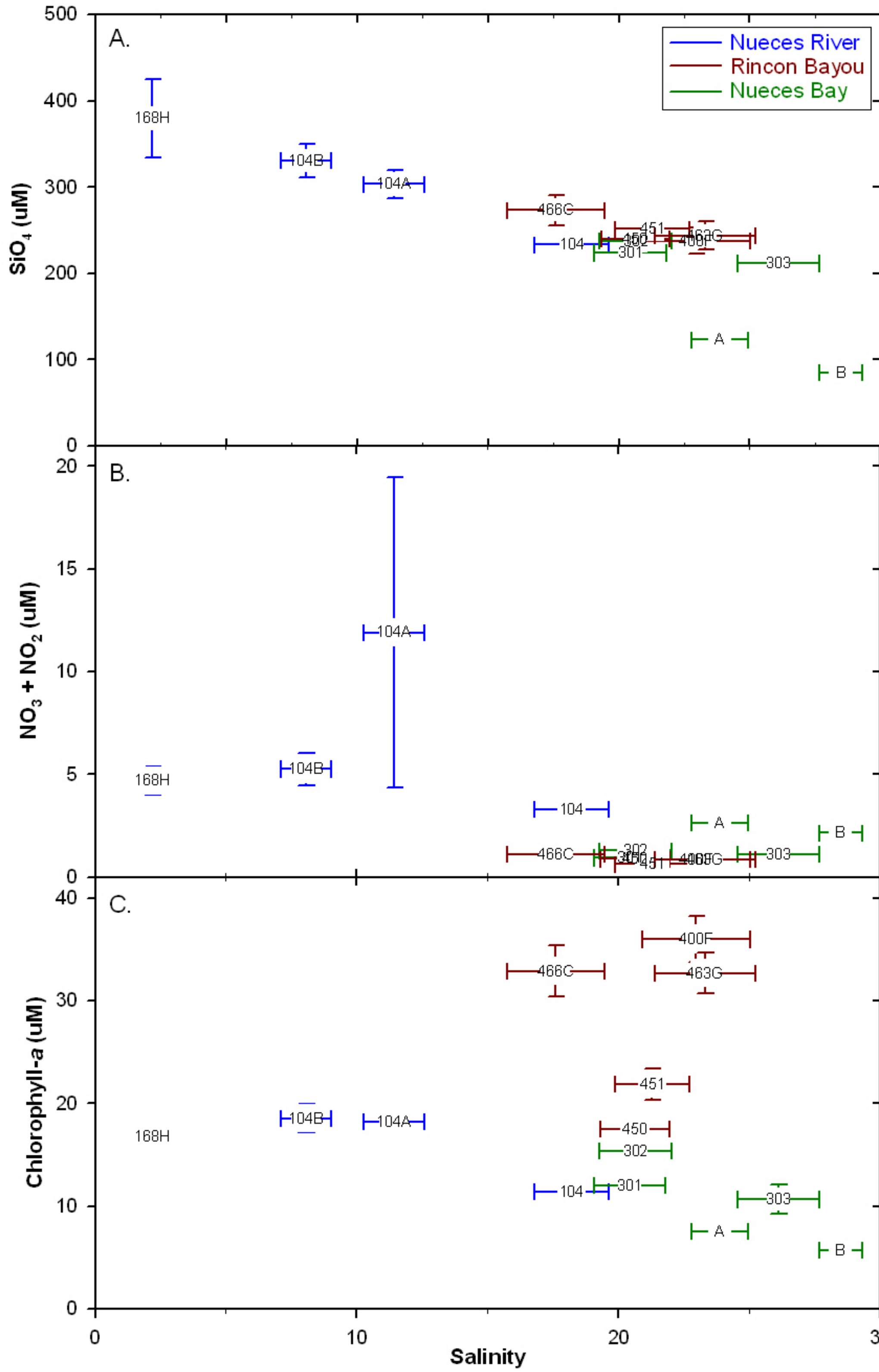


Figure 5.2.4. Silicate (A), nitrate plus nitrite (B), and chlorophyll (C) concentrations versus salinity in the upper Nueces Estuary. Each plotted point is the mean and standard error (error bars) of a station. Locations of each station are shown in Figure 5.2.1 and Figure 5.2.2.

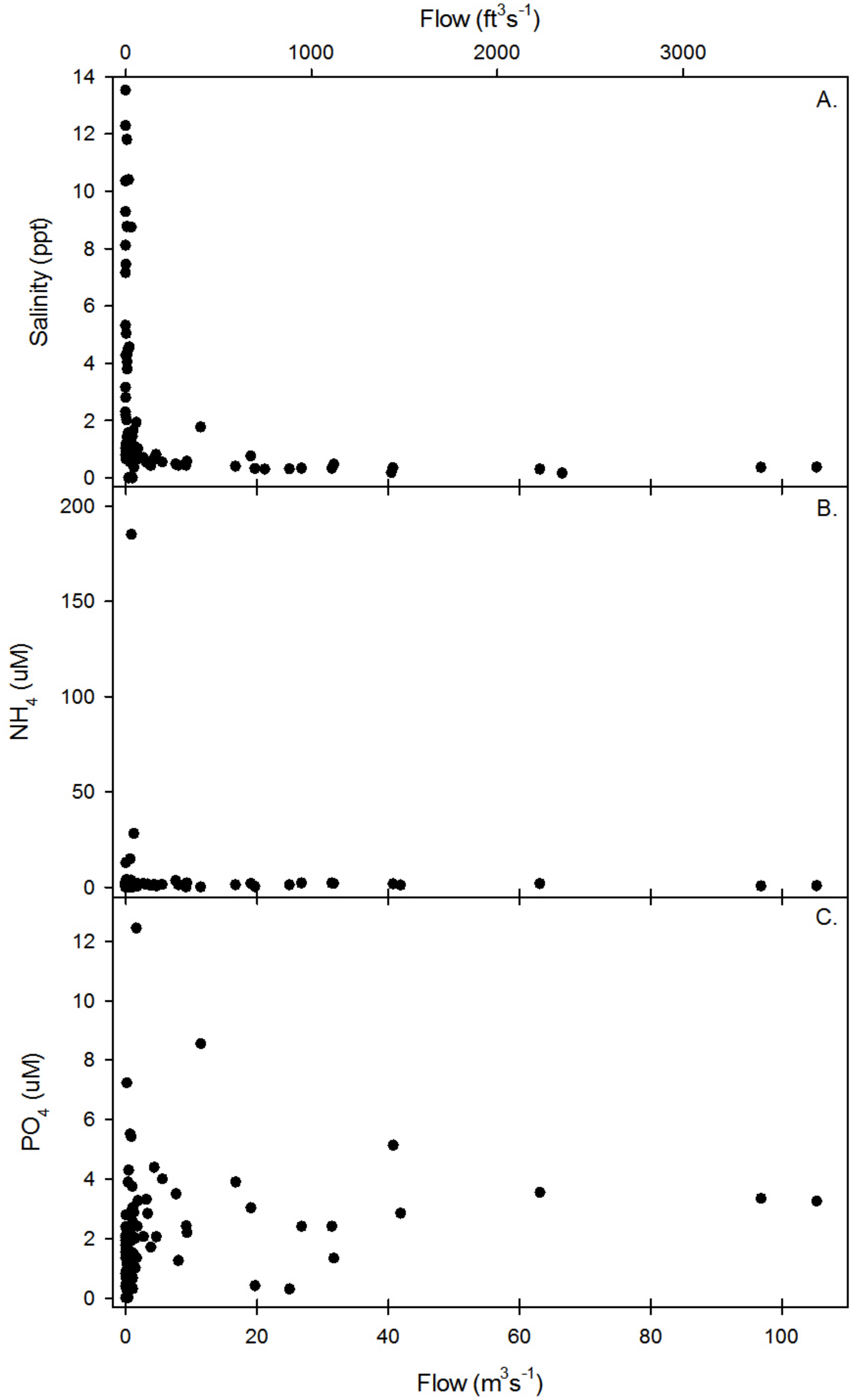


Figure 5.2.5. Salinity (A), ammonium (B) and phosphate (C) in the Nueces River (station 168H) versus Nueces River flow (Calallen gage).

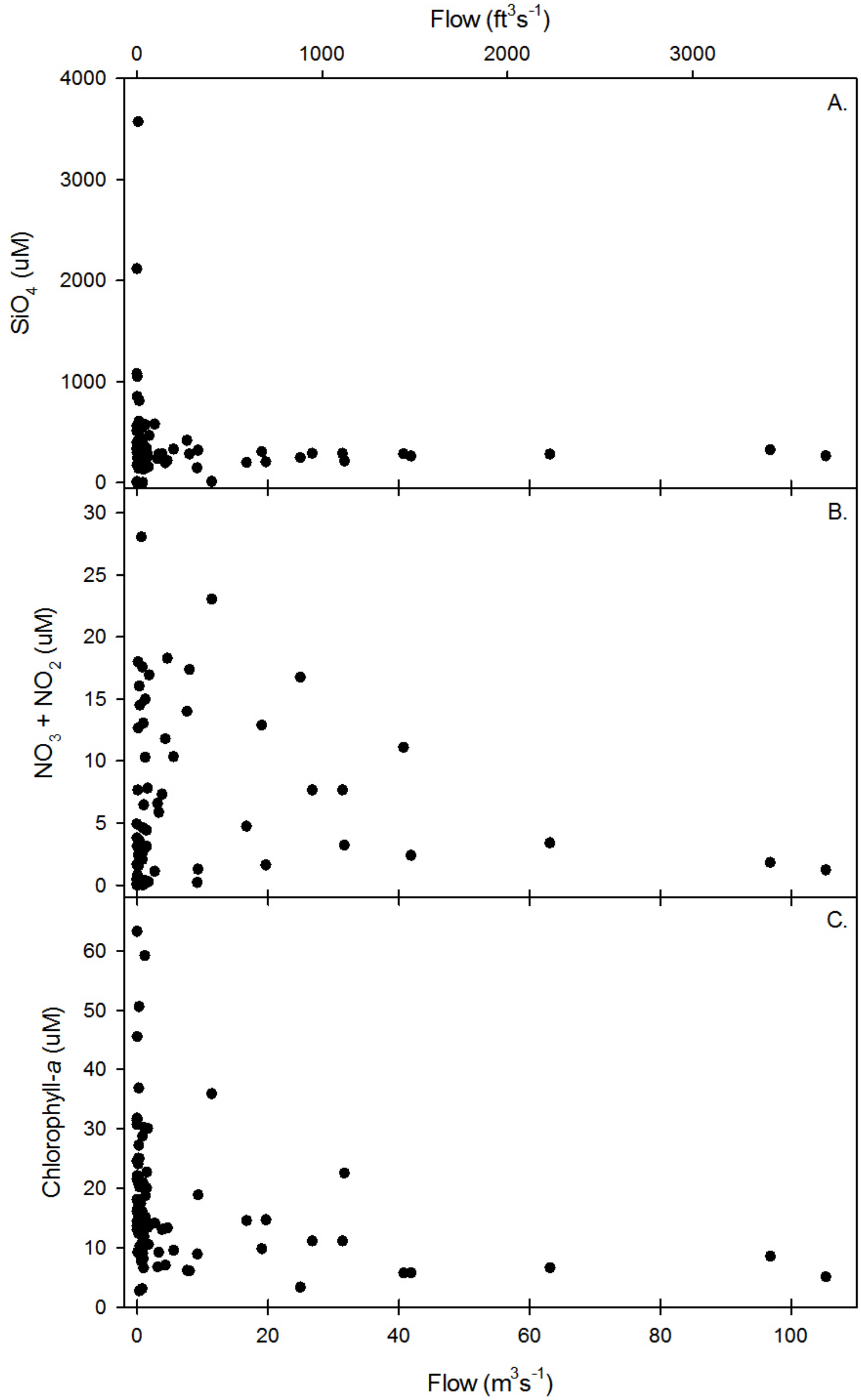


Figure 5.2.6. Silicate (A), nitrate plus nitrite (B) and chlorophyll (C) in the Nueces River (station 168H) versus Nueces River flow (at Calallen gauge site).

Conclusions

Low flows at the Calallen streamflow gaging station allow water stagnation and phytoplankton blooms to occur within the Nueces River downstream of the saltwater barrier dam. The historical low flows to Rincon Bayou allow ammonium concentrations to increase in Rincon Bayou. The current flow volume that enters the Nueces Estuary from the Nueces River is now so small that the addition of nutrients from the river minimally affects Corpus Christi Bay. Increased flows would increase phosphates in Nueces Bay. Thus, our freshwater inflow recommendations (see Section 4.5) will improve nutrient regulation for the Nueces Bay and Delta.

5.3 Sediment Considerations

5.3.1 Sediment Loading to the Nueces Estuary

Freshwater inflows play an important purpose in the physical characteristics of bays and estuaries by providing vital functions such as sediment transport. The sediment delivered to the estuary during times of floods is the source of new material for creating new habitat. In the Nueces Estuary there are two major reservoirs that have had an impact on sediment loading to the bay, Lake Corpus Christi (constructed in 1958) and Choke Canyon Reservoir (constructed in 1982). Since the construction of these reservoirs and the subsequent drought from 1983-1996, freshwater inflows to Nueces Bay were decreased by 55 percent (Asquith, et al., 1997) and by 99.6 percent into the Nueces Delta (BOR, 2000). The lower Nueces River used to overflow its banks (overbank) almost 3 times per year before reservoir construction and now the river only overbanks once every 3 years (BOR, 2000). These freshwater inflow reductions have had a significant impact on sediment transport and loading to these systems. Rasser (2009) estimated a 2.5 meter per year loss of the Nueces Delta at the interface with the bay between the years of 1997 to 2005. These studies suggest that along with wind and wave action and relative sea level rise, that there is a lack of sediment loading in order to keep up with these other erosion processes.

Other studies have shown that more than 95 percent of the Nueces River Basin is upstream of Lake Corpus Christi (Longley, 1994), and Leibbrand (1987) demonstrated that Lake Corpus Christi is an effective sediment sink, retaining 97 percent of the sediment entering the lake between 1977 and 1985. There have been various other studies conducted addressing the problems associated with the reduction in sediment loads to the system, including Morton and Paine (1984), White and Calnan (1990), White and Morton (1996), White, et al. (2002), Yeager, et al. (2006), USACE (2010), and Ockerman and Heitmuller (2010).

The latest study completed in 2010 by Ockerman and Heitmuller developed a Hydrological Simulation Program–FORTRAN (HSPF) watershed model to reproduce streamflow and suspended-sediment concentrations and loads during 1958 to 2008 in the lower Nueces River watershed, downstream from Lake Corpus Christi to the Nueces Estuary. They found through the model simulations that during 1958 to 2008, on average, an estimated 307 tons per day of suspended sediment were delivered to the lower Nueces River and an estimated 297 tons per day were delivered to the estuary. As would be expected, the annual suspended-sediment load was greatly variable, depending on the occurrence of storm events and high streamflows. During the study period, the annual total sediment loads to the estuary varied from an estimated 3.8 to 2,490 tons per day (**Figure 5.3.1**). The study looked at sediment sources and found that on average, 117 tons per day, or about 38 percent of the estimated annual suspended-sediment contribution, originated from cropland. Releases from Lake Corpus Christi delivered an estimated 98 tons per day of suspended sediment or about 32 percent of the 307 tons per day estimated to have been delivered to the lower Nueces River. Erosion of stream-channel bed and banks accounted for 55 tons per day or about 18 percent of the estimated total suspended-sediment load. All other land categories, except cropland, accounted for an estimated 37 tons per day, or about 12 percent of the total. An estimated 9.6 tons per day of suspended sediment or about 3 percent of the suspended-sediment load delivered to the lower Nueces River were removed by water withdrawals before reaching the Nueces Estuary.

Ockerman and Heitmuller's simulation results indicate that the largest sediment loads transported to the Nueces Estuary as a result of stream-channel bed and bank erosion occurred during years with relatively large annual mean streamflows, such as in 1958, 1967, and 1971. During low-flow years, relatively large percentages of the total suspended sediment transported to the Nueces River were removed by water withdrawals. For example, the annual mean streamflow of the Nueces River to the Nueces Estuary was 64 cfs in 2008 (a low flow year) compared with annual median streamflow of 507 cfs measured during 1958 to 2008, and about 50 percent of the total suspended-sediment load was removed in 2008 by water withdrawals.

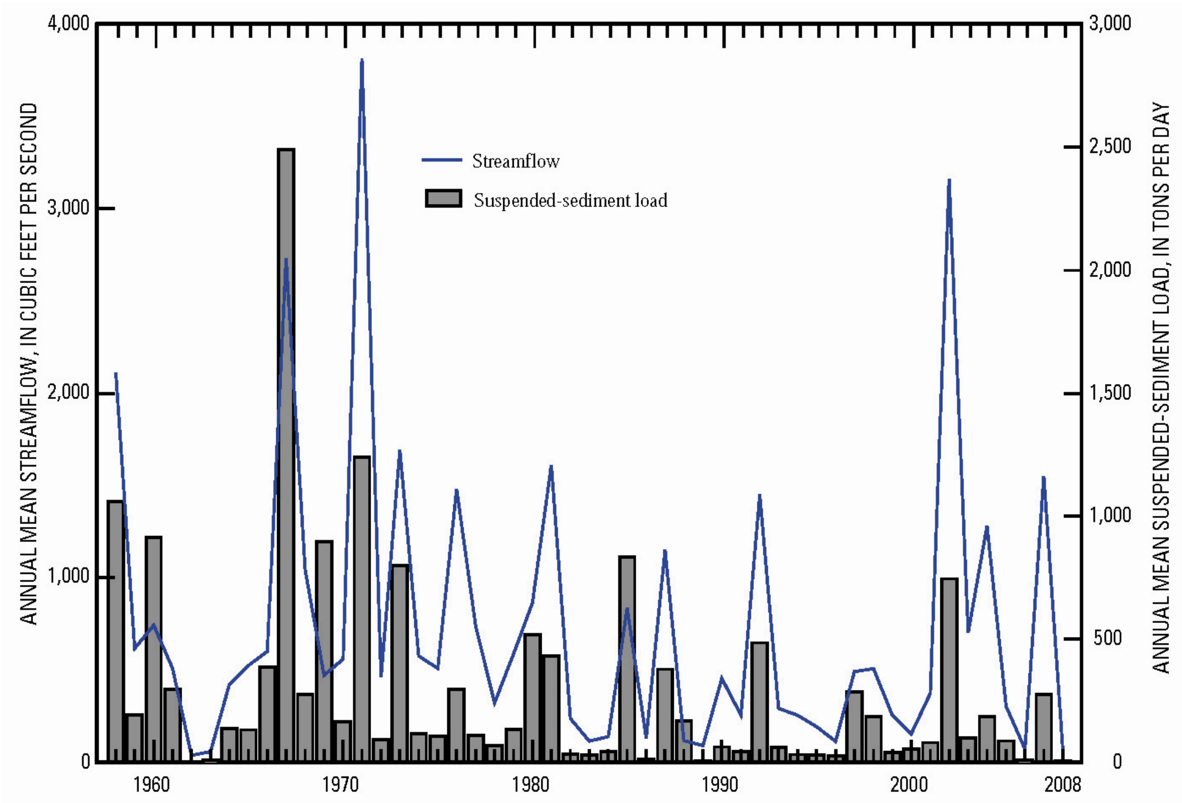


Figure 5.3.1. Estimated annual streamflow and suspended sediment loads to the Nueces Estuary, South Texas, 1958-2008. Source: modified from Ockerman and Heitmuller 2010.

This study also analyzed pre vs. post Lake Corpus Christi (pre-1958 vs. post-1958) between annual suspended sediment loads and annual mean streamflow (**Figure 5.3.2**). As an indication of the sediment retention capacity of the dam, for comparable annual mean discharges, annual suspended-sediment loads after completion of the reservoir have been consistently lower compared with annual suspended-sediment loads before completion of the reservoir.

In a subsequent study by Ockerman in 2010, he modeled sediment sources and quantities being delivered to the estuary pre vs. post Lake Corpus Christi. The study found that when comparing pre and post loads that there was over a 62% decrease in sediment loading to the Nueces Estuary since the construction of Lake Corpus Christi (**Figure 5.3.3**).

The reduction in sediment loads to the Nueces Estuary is the result of sedimentation in large impoundments, notably Lake Corpus Christi, a reservoir whose storage volume was greatly enlarged in 1958 compared to its original (1935) impoundment capacity (**Figure 5.3.4**, **Figure 5.3.5** and **Figure 5.3.6**). The loss of sediment loading is an important ecological problem in the Nueces River watershed, and ensuring ample pulsed freshwater inflows as a conduit for the transportation of this sediment to maintain and create new habitat is an essential part of this system.

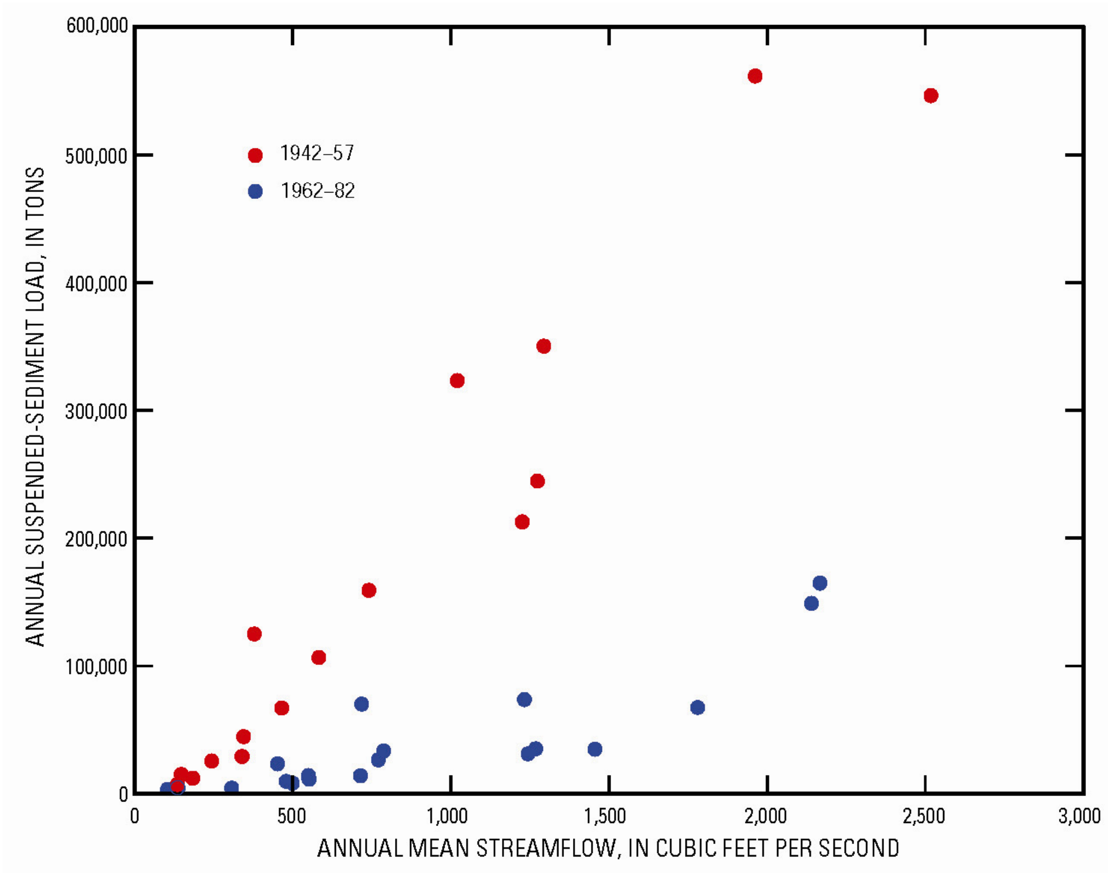


Figure 5.3.2. Annual suspended sediment loads for the Nueces River near Mathis, Texas, 1942-57 and 1962-82. Source: modified from Ockerman and Heitmuller, 2010.

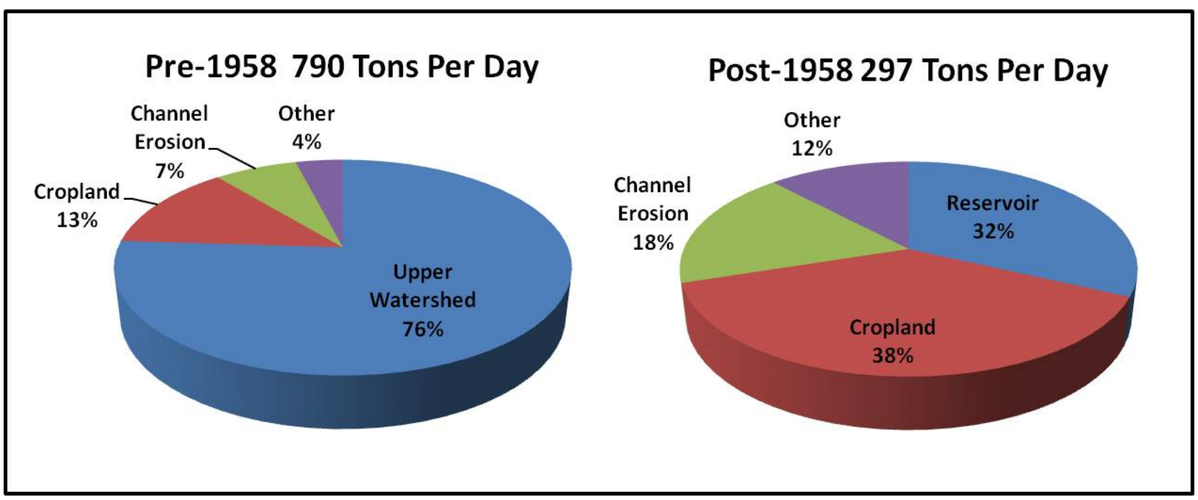


Figure 5.3.3. Sources and quantities of sediment to the Nueces Estuary pre and post-Lake Corpus Christi construction. Loads modeled from data collected at Nueces River near Calallen Dam. Source: modified from Ockerman, 2010.

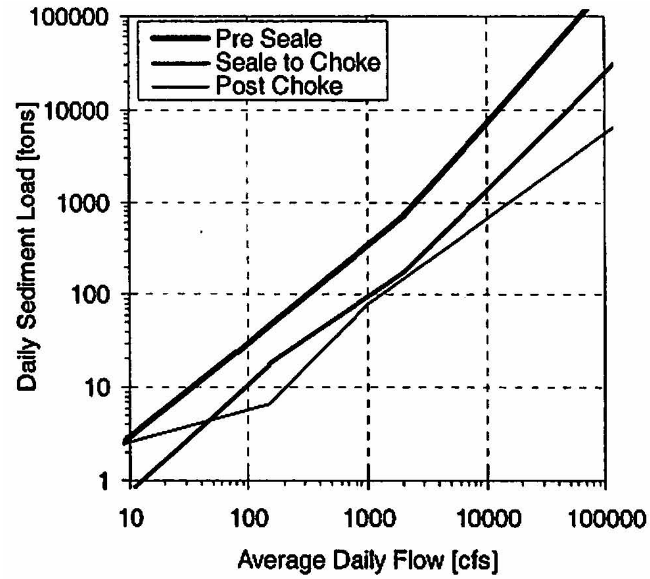


Figure 5.3.4. Modeled sediment load for Nueces River at Mathis. Source: Pulich, et al., 2002.

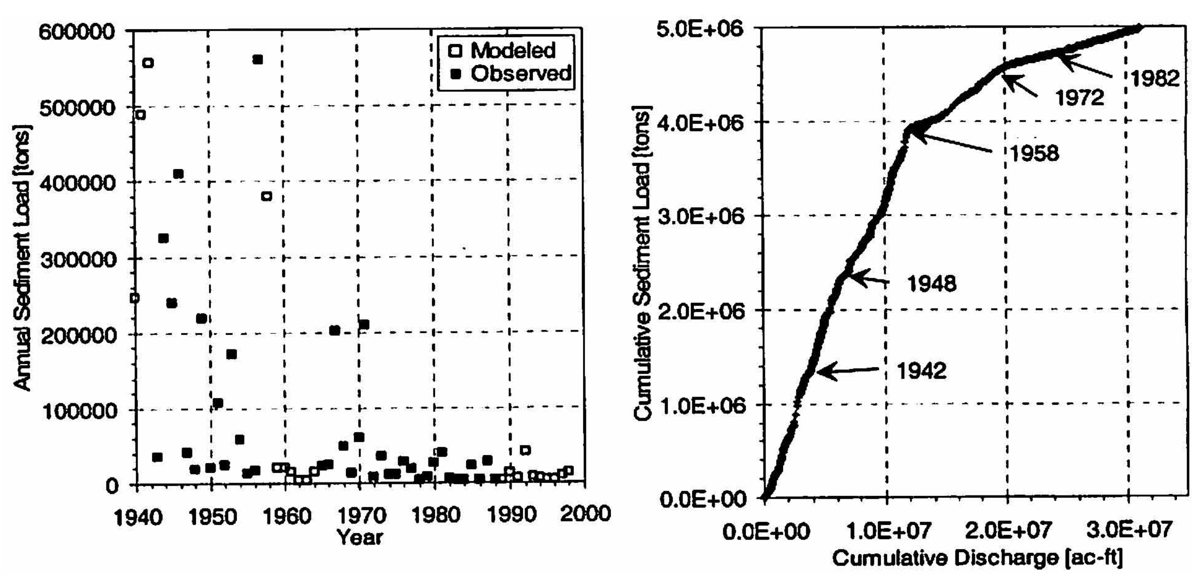


Figure 5.3.5 and **Figure 5.3.6**. Annual sediment load for Nueces River at Mathis (left). Double-Mass Curve for Nueces River at Mathis (right). Source: Pulich, et al., 2002.

A study completed in 2002 by Pulich, et al., titled “Freshwater Inflow Recommendation for the Nueces Estuary” looked at creating a freshwater inflow regime that took into account water quantity and quality by use of a model (TxEMP) developed by the State Bays and Estuaries Research Program. Pulich, et al., recommended a flow regime that causes river overbanking and delta inundation in order to provide needed processes to the bay and delta marsh systems. They suggest that creating higher rate pulsed flow events one or two times a year during the months of April through July is critical to sustaining the Nueces River Delta estuarine nursery and refugium functions, as well as creating a salinity gradient within Nueces Bay. They further state that this sensitive region can only be enhanced by overbanking flows that provide flushing to the system and functional transport of nutrients and sediment to the Nueces Estuary. Their recommendations include the delivery of 89,200 acft of water to the estuary between the months of April through July in one or two pulsed events. They also recommend that if the spring/summer inflows do not occur, then in the fall (September through November) 27,500 acft should be delivered to the estuary.

The Nueces BBEST is recommending a similar approach like Pulich, et al. (2002), with at least one overbanking event per year to allow for flushing of the system and transport of important constituents into the Nueces Delta and Bay. However, the Nueces BBEST did not attempt to quantify the sediment loadings necessary to maintain current bay and delta conditions. This will be a major item of study included in the adaptive management section of this report.

Regional water supply needs, water management strategies, modified landscapes, and natural variability have created a condition that inhibits quantities of sediment needed for creating sustainable habitat within the Nueces Estuary. While sediment load downstream of Lake Corpus Christi has appeared to decrease, detailed impacts, benefits, deficiencies or needs associated with these reduced sediment loads have not been clearly defined by existing studies. Future considerations might include investigations that address spatial extent or location of impact (e.g., in the vicinity of the dam, along the Nueces River between the dam and the estuary, near the City of Corpus Christi water supply intake, and/or within the Nueces Delta) and should also address magnitude and character of sediment needs (i.e. daily or annual volumes of particular sediment grain size classes). Other studies may relate sediment loads to ecological needs, which may be species-specific and may include marsh maintenance, in-stream turbidity/clarity, and in-stream habitat including channel bed characteristics.

5.3.2 Sediment Loading Related to Instream Pulse Flows

The Nueces River is the most significant source of sediment to Nueces Bay (Santschi, 2004). Studies show that Lake Corpus Christi is trapping 97 percent of the sediment transported by the Nueces River, the major source of flows and sediments into Nueces Bay (Leibbrand, 1987). This is sediment that, before the construction of Wesley E. Seale Dam and impoundment of water in Lake Corpus Christi, would have reached the Nueces Estuary. Studies by Ockerman and Heitmuller (2010) also suggest that current suspended sediment supply to the Nueces Bay has been significantly reduced. Because Lake Corpus Christi is located less than 50 miles from the mouth of Nueces Bay and effectively traps most of the sediment being transported by the Nueces River, instream flow recommendations made in the geomorphic overlay for upland river reaches are not likely to provide the necessary sediment inflows to maintain existing river deltas and tidal channels in the tidal marshes and subtidal environments.

5.4 Relationships between Instream Flows and Freshwater Inflows

Analyses summarized in Section 4, Section 5.1, Section 5.2, and Section 5.3 indicate that, under current conditions the Nueces River flows at Mathis will not provide salinity regimes, nutrients or sediments necessary to restore and maintain a sound ecological environment in Nueces Bay in the near future. The BBEST recommends that the Nueces BBASC include additional work to refine understanding of bay and delta health and its relationship to freshwater inflows in its work plan for adaptive management. The current flow patterns create opportunities for the BBASC to explore strategies to either increase freshwater inflows to the estuary or to seek alternative ways to restore and/or enhance estuarine ecological structure and function in the absence of quantities of water recommended by the BBEST.

Section 6. Environmental Flow Regime Recommendations

The environmental flow regime recommendations of the Nueces BBEST for the Nueces River Basin and the Nueces – Rio Grande Coastal Basin, and the associated bays and estuaries are summarized in the following pages for the review and consideration of the Environmental Flows Advisory Group, the Nueces BBASC, and the TCEQ. The environmental flow regime recommendations of the Nueces BBEST include both schedules of flow quantities and descriptions of how these flow quantities are to be applied in the context of environmental flow standards. It is the general expectation of the Nueces 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 Nueces BBEST that the TCEQ will consider direct translation of seasonal ranges of freshwater inflows and associated attainment frequencies into environmental flow standards and, ultimately, apply such standards in the evaluation of applications for new surface water appropriations. With these expectations, the Nueces 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 instream environmental flow regime recommendations (Section 6.3).

6.1 Environmental Flow Regime Summaries

The recommended environmental flow regimes for 18 stream locations throughout the Nueces River Basin are summarized in **Tables 6.1.1** through **6.1.18** in upstream to downstream order (Figure 3.1.1). The recommended environmental flow regimes for two instream locations in the Nueces – Rio Grande Coastal Basin are summarized in **Table 6.1.19** and **Table 6.1.20**. Recommendations regarding hydrologic conditions are included in Section 6.1.1 followed by recommendations regarding each instream flow component in Sections 6.1.2 through 6.1.5. Examples of application of instream flow regimes are included in Section 6.3. The recommended environmental flow regime for freshwater inflows to Nueces Bay is found in Section 6.1.6 and summarized in **Table 6.1.21**.

Table 6.1.1. Environmental Flow Regime Recommendation, Nueces River at Laguna

<table>
<tr><td>Overbank Events</td><td colspan="4">Qp: 15,600 cfs with Average Frequency 1 per 5 years
Regressed Volume is 124,000
Duration Bound is 107</td></tr>
<tr><td rowspan="6">High Flow Pulses</td><td colspan="4">Qp: 4,750 cfs with Average Frequency 1 per 2 years
Regressed Volume is 38,600
Duration Bound is 64</td></tr>
<tr><td colspan="4">Qp: 2,220 cfs with Average Frequency 1 per year
Regressed Volume is 18,400
Duration Bound is 46</td></tr>
<tr><td colspan="4">Qp: 590 cfs with Average Frequency 2 per year
Volume Bound is 11,300
Duration Bound is 26</td></tr>
<tr><td>Qp: 48 cfs with Average Frequency 1 per season
Volume Bound is 1,000
Duration Bound is 7</td><td>Qp: 390 cfs with Average Frequency 1 per season
Volume Bound is 6,070
Duration Bound is 17</td><td>Qp: 170 cfs with Average Frequency 1 per season
Volume Bound is 3,100
Duration Bound is 14</td><td>Qp: 50 cfs with Average Frequency 1 per season
Volume Bound is 800
Duration Bound is 5</td></tr>
<tr><td></td><td>Qp: 99 cfs with Average Frequency 2 per season
Volume Bound is 1,560
Duration Bound is 9</td><td></td><td></td></tr>
<tr><td colspan="4"></td></tr>
<tr><td rowspan="3">Base Flows (cfs)</td><td colspan="2">92</td><td>76</td><td>92</td></tr>
<tr><td colspan="2">65</td><td>48</td><td>65</td></tr>
<tr><td>51</td><td>44</td><td>32</td><td>41</td></tr>
<tr><td>Subsistence Flows (cfs)</td><td>14</td><td>18</td><td>16</td><td>14</td></tr>
<tr><td></td><td>Dec Jan Feb Mar</td><td>Apr May Jun</td><td>Jul Aug Sep</td><td>Oct Nov</td></tr>
<tr><td></td><td>Winter</td><td>Spring</td><td>Summer</td><td>Fall</td></tr>
</table>

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

Pulse volumes are in units of acre-feet and durations are in days.
Period of Record used : 1/1/1924 to 12/31/2009.

Table 6.1.2. Environmental Flow Regime Recommendations, West Nueces River near Brackettville

	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
High Flow Pulses	Qp: 11,200 cfs with Average Frequency 1 per 5 years Regressed Volume is 39,200 Duration Bound is 48											
High Flow Pulses	Qp: 4,090 cfs with Average Frequency 1 per 2 years Regressed Volume is 16,200 Duration Bound is 40											
High Flow Pulses	Qp: 1,020 cfs with Average Frequency 1 per year Regressed Volume is 4,810 Duration Bound is 31											
High Flow Pulses	Qp: 25 cfs with Average Frequency 2 per year Volume Bound is 360 Duration Bound is 16											
High Flow Pulses					Qp: 5 cfs with Average Frequency 1 per season Volume Bound is 76 Duration Bound is 10			Qp: 5 cfs with Average Frequency 1 per season Volume Bound is 84 Duration Bound is 13				
Base Flows (cfs) – High	2				1			2				
Base Flows (cfs) – Medium	1											
Base Flows (cfs) – Low	1											
Subsistence Flows (cfs)	1											
	Winter				Spring			Summer			Fall	

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

Pulse volumes are in units of acre-feet and durations are in days.
Period of Record used : 1/1/1946 to 12/31/2009.
1939-1950 measured data shifted to become 1945-1956 to close gap in data record.

Table 6.1.3. Environmental Flow Regime Recommendation, Nueces River below Uvalde

	Winter (Nov, Dec, Jan, Feb, Mar)	Spring (Apr, May, Jun)	Summer (Jul, Aug)	Fall (Sep, Oct)
Overbank Events	Qp: 18,700 cfs with Average Frequency 1 per 5 years Regressed Volume is 166,000 Duration Bound is 108			
High Flow Pulses	Qp: 6,920 cfs with Average Frequency 1 per 2 years Regressed Volume is 57,100 Duration Bound is 73			
High Flow Pulses	Qp: 2,550 cfs with Average Frequency 1 per year Regressed Volume is 19,500 Duration Bound is 49			
High Flow Pulses	Qp: 510 cfs with Average Frequency 2 per year Volume Bound is 8,240 Duration Bound is 26			
High Flow Pulses	Qp: 13 cfs with Average Frequency 1 per season Volume Bound is 100 Duration Bound is 5	Qp: 110 cfs with Average Frequency 1 per season Volume Bound is 1,280 Duration Bound is 11	Qp: 15 cfs with Average Frequency 1 per season Volume Bound is 100 Duration Bound is 4	Qp: 50 cfs with Average Frequency 1 per season Volume Bound is 690 Duration Bound is 11
High Flow Pulses		Qp: 20 cfs with Average Frequency 2 per season Volume Bound is 200 Duration Bound is 6		
Base Flows (cfs) – High	37		32	37
Base Flows (cfs) – Medium	21		17	19
Base Flows (cfs) – Low	12		9	
Subsistence Flows (cfs)	1			

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

Pulse volumes are in units of acre-feet and durations are in days.
Period of Record used : 1/1/1940 to 12/31/2009.

Table 6.1.4. Environmental Flow Regime Recommendation, Nueces River at Cotulla

	Winter (Nov, Dec, Jan, Feb, Mar)	Spring (Apr, May, Jun)	Summer (Jul, Aug)	Fall (Sep, Oct)
Overbank Events	Qp: 15,100 cfs with Average Frequency 1 per 5 years Regressed Volume is 151,000 Duration Bound is 42			
Overbank Events	Qp: 8,410 cfs with Average Frequency 1 per 2 years Regressed Volume is 80,700 Duration Bound is 38			
Overbank Events	Qp: 4,460 cfs with Average Frequency 1 per year Regressed Volume is 41,100 Duration Bound is 34			
Overbank Events	Qp: 1,560 cfs with Average Frequency 2 per year Volume Bound is 24,200 Duration Bound is 28			
High Flow Pulses	Qp: 96 cfs with Average Frequency 1 per season Volume Bound is 1,570 Duration Bound is 20	Qp: 1,180 cfs with Average Frequency 1 per season Volume Bound is 17,200 Duration Bound is 24	Qp: 100 cfs with Average Frequency 1 per season Volume Bound is 1,030 Duration Bound is 16	Qp: 640 cfs with Average Frequency 1 per season Volume Bound is 8,610 Duration Bound is 26
High Flow Pulses	Qp: 8 cfs with Average Frequency 2 per season Volume Bound is 100 Duration Bound is 13	Qp: 190 cfs with Average Frequency 2 per season Volume Bound is 2,370 Duration Bound is 17		Qp: 35 cfs with Average Frequency 2 per season Volume Bound is 360 Duration Bound is 14
High Flow Pulses		Qp: 15 cfs with Average Frequency 3 per season Volume Bound is 150 Duration Bound is 11		
Base Flows (cfs) – High	38	31	31	42
Base Flows (cfs) – Medium	6	10	7	15
Base Flows (cfs) – Low	1			
Subsistence Flows (cfs)	1			

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

Pulse volumes are in units of acre-feet and durations are in days.
Period of Record used : 1/1/1927 to 12/31/2009.

Table 6.1.5. Environmental Flow Regime Recommendation, Nueces River near Tilden

	Winter (Nov, Dec, Jan, Feb, Mar)	Spring (Apr, May, Jun)	Summer (Jul, Aug)	Fall (Sep, Oct)
Overbank Events	Qp: 24,500 cfs with Average Frequency 1 per 5 years Regressed Volume is 261,000 Duration Bound is 44			
Overbank Events	Qp: 10,700 cfs with Average Frequency 1 per 2 years Regressed Volume is 107,000 Duration Bound is 38			
Overbank Events	Qp: 4,610 cfs with Average Frequency 1 per year Regressed Volume is 43,200 Duration Bound is 33			
Overbank Events	Qp: 1,640 cfs with Average Frequency 2 per year Volume Bound is 25,300 Duration Bound is 27			
High Flow Pulses	Qp: 300 cfs with Average Frequency 1 per season Volume Bound is 4,610 Duration Bound is 22	Qp: 880 cfs with Average Frequency 1 per season Volume Bound is 12,200 Duration Bound is 22	Qp: 320 cfs with Average Frequency 1 per season Volume Bound is 4,390 Duration Bound is 21	Qp: 840 cfs with Average Frequency 1 per season Volume Bound is 10,900 Duration Bound is 23
High Flow Pulses	Qp: 87 cfs with Average Frequency 2 per season Volume Bound is 1,260 Duration Bound is 18	Qp: 280 cfs with Average Frequency 2 per season Volume Bound is 3,360 Duration Bound is 18	Qp: 11 cfs with Average Frequency 2 per season Volume Bound is 96 Duration Bound is 10	Qp: 220 cfs with Average Frequency 2 per season Volume Bound is 2,390 Duration Bound is 16
High Flow Pulses	Qp: 9 cfs with Average Frequency 3 per season Volume Bound is 110 Duration Bound is 12	Qp: 89 cfs with Average Frequency 3 per season Volume Bound is 930 Duration Bound is 14		Qp: 29 cfs with Average Frequency 3 per season Volume Bound is 250 Duration Bound is 10
High Flow Pulses		Qp: 8 cfs with Average Frequency 4 per season Volume Bound is 60 Duration Bound is 8		
Base Flows (cfs) – High	42	25	14	42
Base Flows (cfs) – Medium	1	3	1	12
Base Flows (cfs) – Low	1			
Subsistence Flows (cfs)	1			

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

Pulse volumes are in units of acre-feet and durations are in days.
Period of Record used : 1/1/1943 to 12/31/2009.

Table 6.1.6. Environmental Flow Regime Recommendation, Frio River at Concan

	Winter (Dec, Jan, Feb, Mar)	Spring (Apr, May, Jun)	Summer (Jul, Aug, Sep)	Fall (Oct, Nov)
High Flow Pulses	Qp: 8,860 cfs with Average Frequency 1 per 5 years Regressed Volume is 79,000 Duration Bound is 104			
High Flow Pulses	Qp: 4,870 cfs with Average Frequency 1 per 2 years Regressed Volume is 41,700 Duration Bound is 76			
High Flow Pulses	Qp: 1,780 cfs with Average Frequency 1 per year Regressed Volume is 14,300 Duration Bound is 45			
High Flow Pulses	Qp: 540 cfs with Average Frequency 2 per year Volume Bound is 9,430 Duration Bound is 24			
High Flow Pulses	Qp: 89 cfs with Average Frequency 1 per season Volume Bound is 2,100 Duration Bound is 12	Qp: 300 cfs with Average Frequency 1 per season Volume Bound is 3,550 Duration Bound is 12	Qp: 240 cfs with Average Frequency 1 per season Volume Bound is 2,990 Duration Bound is 13	Qp: 79 cfs with Average Frequency 1 per season Volume Bound is 900 Duration Bound is 5
High Flow Pulses		Qp: 120 cfs with Average Frequency 2 per season Volume Bound is 1,320 Duration Bound is 8	Qp: 43 cfs with Average Frequency 2 per season Volume Bound is 400 Duration Bound is 4	
Base Flows (cfs) – High	79			
Base Flows (cfs) – Medium	61		47	55
Base Flows (cfs) – Low	46	40	33	
Subsistence Flows (cfs)	11	10		

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

Pulse volumes are in units of acre-feet and durations are in days.
Period of Record used : 1/1/1931 to 12/31/2009.

Table 6.1.7. Environmental Flow Regime Recommendation, Dry Frio River near Reagan Wells

	Winter (Dec, Jan, Feb, Mar)	Spring (Apr, May, Jun)	Summer (Jul, Aug, Sep)	Fall (Oct, Nov)
High Flow Pulses	Qp: 2,970 cfs with Average Frequency 1 per 5 years Regressed Volume is 27,200 Duration Bound is 82			
High Flow Pulses	Qp: 1,700 cfs with Average Frequency 1 per 2 years Regressed Volume is 15,300 Duration Bound is 64			
High Flow Pulses	Qp: 540 cfs with Average Frequency 1 per year Regressed Volume is 4,660 Duration Bound is 38			
High Flow Pulses	Qp: 210 cfs with Average Frequency 2 per year Volume Bound is 3,500 Duration Bound is 26			
High Flow Pulses	Qp: 32 cfs with Average Frequency 1 per season Volume Bound is 650 Duration Bound is 13	Qp: 120 cfs with Average Frequency 1 per season Volume Bound is 1,470 Duration Bound is 16	Qp: 81 cfs with Average Frequency 1 per season Volume Bound is 1,100 Duration Bound is 15	Qp: 35 cfs with Average Frequency 1 per season Volume Bound is 620 Duration Bound is 13
High Flow Pulses	Qp: 7 cfs with Average Frequency 2 per season Volume Bound is 98 Duration Bound is 5	Qp: 30 cfs with Average Frequency 2 per season Volume Bound is 370 Duration Bound is 9	Qp: 12 cfs with Average Frequency 2 per season Volume Bound is 160 Duration Bound is 7	
Base Flows (cfs) – High	17		14	17
Base Flows (cfs) – Medium	12	9	8	12
Base Flows (cfs) – Low	7	5	4	7
Subsistence Flows (cfs)	1			

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

Pulse volumes are in units of acre-feet and durations are in days.
Period of Record used : 1/1/1953 to 12/31/2009.

Table 6.1.8. Environmental Flow Regime Recommendation, Sabinal River near Sabinal

	Winter (Dec, Jan, Feb, Mar)	Spring (Apr, May, Jun)	Summer (Jul, Aug, Sep)	Fall (Oct, Nov)
High Flow Pulses	Qp: 5,200 cfs with Average Frequency 1 per 5 years Regressed Volume is 46,200 Duration Bound is 75			
	Qp: 2,350 cfs with Average Frequency 1 per 2 years Regressed Volume is 20,000 Duration Bound is 54			
	Qp: 1,020 cfs with Average Frequency 1 per year Regressed Volume is 8,290 Duration Bound is 38			
	Qp: 330 cfs with Average Frequency 2 per year Volume Bound is 5,420 Duration Bound is 24			
	Qp: 62 cfs with Average Frequency 1 per season Volume Bound is 1,530 Duration Bound is 17	Qp: 180 cfs with Average Frequency 1 per season Volume Bound is 2,210 Duration Bound is 15	Qp: 100 cfs with Average Frequency 1 per season Volume Bound is 1,180 Duration Bound is 12	Qp: 53 cfs with Average Frequency 1 per season Volume Bound is 840 Duration Bound is 12
		Qp: 64 cfs with Average Frequency 2 per season Volume Bound is 750 Duration Bound is 10	Qp: 11 cfs with Average Frequency 2 per season Volume Bound is 130 Duration Bound is 5	
		Qp: 22 cfs with Average Frequency 3 per season Volume Bound is 240 Duration Bound is 6		
Base Flows (cfs) – High	35		29	35
Base Flows (cfs) – Medium	21		13	21
Base Flows (cfs) – Low	11	8	3	10
Subsistence Flows (cfs)	1			

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

Pulse volumes are in units of acre-feet and durations are in days.
Period of Record used : 1/1/1943 to 12/31/2009.

Table 6.1.9. Environmental Flow Regime Recommendation, Sabinal River at Sabinal (below Edwards Outcrop)

	Winter (Nov, Dec, Jan, Feb, Mar)	Spring (Apr, May, Jun)	Summer (Jul, Aug)	Fall (Sep, Oct)
Overbank Events	Qp: 5,040 cfs with Average Frequency 1 per 5 years Regressed Volume is 35,500 Duration Bound is 50			
	Qp: 2,210 cfs with Average Frequency 1 per 2 years Regressed Volume is 14,600 Duration Bound is 37			
High Flow Pulses	Qp: 1,070 cfs with Average Frequency 1 per year Regressed Volume is 6,690 Duration Bound is 29			
	Qp: 230 cfs with Average Frequency 2 per year Volume Bound is 2,680 Duration Bound is 17			
	Qp: 21 cfs with Average Frequency 1 per season Volume Bound is 310 Duration Bound is 11	Qp: 56 cfs with Average Frequency 1 per season Volume Bound is 430 Duration Bound is 9	Qp: 3 cfs with Average Frequency 1 per season Volume Bound is 27 Duration Bound is 5	Qp: 20 cfs with Average Frequency 1 per season Volume Bound is 150 Duration Bound is 6
		Qp: 3 cfs with Average Frequency 2 per season Volume Bound is 18 Duration Bound is 3		
Base Flows (cfs) — High	3	3	3	3
Base Flows (cfs) — Medium	2	1	1	2
Base Flows (cfs) — Low	1	1	1	1
Subsistence Flows (cfs)	1	1	1	1

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

Pulse volumes are in units of acre-feet and durations are in days.
Period of Record used : 1/1/1953 to 12/31/2009.

Table 6.1.10. Environmental Flow Regime Recommendation, Hondo Creek near Tarpley

	Winter (Dec, Jan, Feb, Mar)	Spring (Apr, May, Jun)	Summer (Jul, Aug, Sep)	Fall (Oct, Nov)
High Flow Pulses	Qp: 3,340 cfs with Average Frequency 1 per 5 years Regressed Volume is 30,400 Duration Bound is 51			
High Flow Pulses	Qp: 1,470 cfs with Average Frequency 1 per 2 years Regressed Volume is 12,200 Duration Bound is 38			
High Flow Pulses	Qp: 790 cfs with Average Frequency 1 per year Regressed Volume is 6,200 Duration Bound is 30			
High Flow Pulses	Qp: 330 cfs with Average Frequency 2 per year Volume Bound is 4,530 Duration Bound is 22			
High Flow Pulses	Qp: 61 cfs with Average Frequency 1 per season Volume Bound is 1,020 Duration Bound is 15	Qp: 290 cfs with Average Frequency 1 per season Volume Bound is 3,360 Duration Bound is 18	Qp: 90 cfs with Average Frequency 1 per season Volume Bound is 890 Duration Bound is 12	Qp: 50 cfs with Average Frequency 1 per season Volume Bound is 580 Duration Bound is 11
High Flow Pulses	Qp: 16 cfs with Average Frequency 2 per season Volume Bound is 200 Duration Bound is 8	Qp: 91 cfs with Average Frequency 2 per season Volume Bound is 950 Duration Bound is 12	Qp: 24 cfs with Average Frequency 2 per season Volume Bound is 220 Duration Bound is 7	Qp: 13 cfs with Average Frequency 2 per season Volume Bound is 120 Duration Bound is 6
High Flow Pulses	Qp: 6 cfs with Average Frequency 3 per season Volume Bound is 54 Duration Bound is 5	Qp: 36 cfs with Average Frequency 3 per season Volume Bound is 340 Duration Bound is 9	Qp: 4 cfs with Average Frequency 3 per season Volume Bound is 34 Duration Bound is 4	
High Flow Pulses		Qp: 6 cfs with Average Frequency 4 per season Volume Bound is 52 Duration Bound is 5		
Base Flows (cfs) – High	15	17		15
Base Flows (cfs) – Medium	6	5	9	8
Base Flows (cfs) – Low	3	1	2	3
Subsistence Flows (cfs)	1			

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

Pulse volumes are in units of acre-feet and durations are in days.
Period of Record used : 1/1/1953 to 12/31/2009.

Table 6.1.11. Environmental Flow Regime Recommendation, Seco Creek at Miller Ranch near Utopia

	Winter (Dec, Jan, Feb, Mar)	Spring (Apr, May, Jun)	Summer (Jul, Aug, Sep)	Fall (Oct, Nov)
High Flow Pulses	Qp: 1,600 cfs with Average Frequency 1 per 5 years Regressed Volume is 17,500 Duration Bound is 62			
High Flow Pulses	Qp: 700 cfs with Average Frequency 1 per 2 years Regressed Volume is 6,790 Duration Bound is 44			
High Flow Pulses	Qp: 310 cfs with Average Frequency 1 per year Regressed Volume is 2,720 Duration Bound is 31			
High Flow Pulses	Qp: 120 cfs with Average Frequency 2 per year Volume Bound is 1,710 Duration Bound is 21			
High Flow Pulses	Qp: 21 cfs with Average Frequency 1 per season Volume Bound is 290 Duration Bound is 12	Qp: 91 cfs with Average Frequency 1 per season Volume Bound is 1,140 Duration Bound is 17	Qp: 38 cfs with Average Frequency 1 per season Volume Bound is 360 Duration Bound is 11	Qp: 23 cfs with Average Frequency 1 per season Volume Bound is 270 Duration Bound is 11
High Flow Pulses	Qp: 9 cfs with Average Frequency 2 per season Volume Bound is 100 Duration Bound is 8	Qp: 33 cfs with Average Frequency 2 per season Volume Bound is 360 Duration Bound is 12	Qp: 11 cfs with Average Frequency 2 per season Volume Bound is 93 Duration Bound is 7	Qp: 7 cfs with Average Frequency 2 per season Volume Bound is 65 Duration Bound is 6
Base Flows (cfs) – High	7			
Base Flows (cfs) – Medium	4	3		4
Base Flows (cfs) – Low	2	1		
Subsistence Flows (cfs)	1			

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

Pulse volumes are in units of acre-feet and durations are in days.
Period of Record used : 1/1/1962 to 12/31/2009.

Table 6.1.12. Environmental Flow Regime Recommendation, Leona Springs near Uvalde

<table>
<tr><td rowspan="3">Base Flows (cfs)</td><td colspan="12">33</td></tr>
<tr><td colspan="4">25</td><td colspan="3">20</td><td colspan="3">18</td><td colspan="2">22</td></tr>
<tr><td colspan="4">11</td><td colspan="3">10</td><td colspan="5">11</td></tr>
<tr><td>Subsistence Flows (cfs)</td><td colspan="12">1</td></tr>
<tr><td></td><td>Dec</td><td>Jan</td><td>Feb</td><td>Mar</td><td>Apr</td><td>May</td><td>Jun</td><td>Jul</td><td>Aug</td><td>Sep</td><td>Oct</td><td>Nov</td></tr>
<tr><td></td><td colspan="4">Winter</td><td colspan="3">Spring</td><td colspan="3">Summer</td><td colspan="2">Fall</td></tr>
</table>

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

Period of Record used : 1/1/1930 to 12/31/2009.

Spring discharges during this Period of Record are computed using a regression equation based on water levels in the Uvalde County Edwards Aquifer Monitoring Well (J-27). Insufficient data are avaiable for development of high flow pulse recommendations at this location.

Table 6.1.13. Environmental Flow Regime Recommendation, Frio River near Derby

	Winter (Nov, Dec, Jan, Feb, Mar)	Spring (Apr, May, Jun)	Summer (Jul, Aug)	Fall (Sep, Oct)
Overbank Events	Qp: 16,400 cfs with Average Frequency 1 per 5 years Regressed Volume is 96,400 Duration Bound is 36			
Overbank Events	Qp: 7,200 cfs with Average Frequency 1 per 2 years Regressed Volume is 42,600 Duration Bound is 31			
Overbank Events	Qp: 4,010 cfs with Average Frequency 1 per year Regressed Volume is 23,900 Duration Bound is 29			
High Flow Pulses	Qp: 1,670 cfs with Average Frequency 2 per year Volume Bound is 18,800 Duration Bound is 25			
High Flow Pulses	Qp: 87 cfs with Average Frequency 1 per season Volume Bound is 1,450 Duration Bound is 20	Qp: 900 cfs with Average Frequency 1 per season Volume Bound is 7,940 Duration Bound is 17	Qp: 58 cfs with Average Frequency 1 per season Volume Bound is 510 Duration Bound is 13	Qp: 350 cfs with Average Frequency 1 per season Volume Bound is 4,340 Duration Bound is 24
High Flow Pulses	Qp: 12 cfs with Average Frequency 2 per season Volume Bound is 190 Duration Bound is 15	Qp: 210 cfs with Average Frequency 2 per season Volume Bound is 1,810 Duration Bound is 14		Qp: 7 cfs with Average Frequency 2 per season Volume Bound is 97 Duration Bound is 12
High Flow Pulses		Qp: 49 cfs with Average Frequency 3 per season Volume Bound is 420 Duration Bound is 11		
High Flow Pulses		Qp: 5 cfs with Average Frequency 4 per season Volume Bound is 41 Duration Bound is 8		
Base Flows (cfs) – High	25	22	16	25
Base Flows (cfs) – Medium	17	11	7	12
Base Flows (cfs) – Low	8	3	2	5
Subsistence Flows (cfs)	1			

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

Pulse volumes are in units of acre-feet and durations are in days.
Period of Record used : 1/1/1916 to 12/31/2009.

Table 6.1.14. Environmental Flow Regime Recommendation, Frio River at Tilden

	Winter (Nov–Mar)	Spring (Apr–Jun)	Summer (Jul–Aug)	Fall (Sep–Oct)
Overbank Events	Qp: 12,600 cfs with Average Frequency 1 per 5 years Regressed Volume is 99,000 Duration Bound is 34			
Overbank Events	Qp: 7,320 cfs with Average Frequency 1 per 2 years Regressed Volume is 55,600 Duration Bound is 31			
Overbank Events	Qp: 4,140 cfs with Average Frequency 1 per year Regressed Volume is 30,400 Duration Bound is 27			
Overbank Events	Qp: 2,050 cfs with Average Frequency 2 per year Volume Bound is 24,400 Duration Bound is 23			
High Flow Pulses	Qp: 390 cfs with Average Frequency 1 per season Volume Bound is 5,320 Duration Bound is 20	Qp: 1,490 cfs with Average Frequency 1 per season Volume Bound is 15,700 Duration Bound is 18	Qp: 270 cfs with Average Frequency 1 per season Volume Bound is 2,440 Duration Bound is 14	Qp: 960 cfs with Average Frequency 1 per season Volume Bound is 10,400 Duration Bound is 20
High Flow Pulses	Qp: 86 cfs with Average Frequency 2 per season Volume Bound is 1,070 Duration Bound is 13	Qp: 460 cfs with Average Frequency 2 per season Volume Bound is 4,470 Duration Bound is 14	Qp: 36 cfs with Average Frequency 2 per season Volume Bound is 280 Duration Bound is 9	Qp: 120 cfs with Average Frequency 2 per season Volume Bound is 1,080 Duration Bound is 12
High Flow Pulses	Qp: 25 cfs with Average Frequency 3 per season Volume Bound is 290 Duration Bound is 9	Qp: 190 cfs with Average Frequency 3 per season Volume Bound is 1,790 Duration Bound is 12		Qp: 13 cfs with Average Frequency 3 per season Volume Bound is 100 Duration Bound is 7
High Flow Pulses	Qp: 6 cfs with Average Frequency 4 per season Volume Bound is 63 Duration Bound is 6	Qp: 83 cfs with Average Frequency 4 per season Volume Bound is 730 Duration Bound is 10		
Base Flows (cfs) – High	29	25	14	21
Base Flows (cfs) – Medium	12	7	2	3
Base Flows (cfs) – Low	1			
Subsistence Flows (cfs)	1			
	Nov, Dec, Jan, Feb, Mar	Apr, May, Jun	Jul, Aug	Sep, Oct
	Winter	Spring	Summer	Fall

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

Pulse volumes are in units of acre-feet and durations are in days.
Period of Record used : 1/1/1933 to 12/31/2009.
This Period of Record includes approximately 45 years of data estimated by intervening drainage area ratio using records for the Frio River near Derby and at Calliham.

Table 6.1.15. Environmental Flow Regime Recommendation, San Miguel Creek near Tilden

	Winter (Nov–Mar)	Spring (Apr–Jun)	Summer (Jul–Aug)	Fall (Sep–Oct)
Overbank Events	Qp: 8,180 cfs with Average Frequency 1 per 5 years Regressed Volume is 33,300 Duration Bound is 23			
Overbank Events	Qp: 3,970 cfs with Average Frequency 1 per 2 years Regressed Volume is 16,600 Duration Bound is 21			
Overbank Events	Qp: 2,210 cfs with Average Frequency 1 per year Regressed Volume is 9,450 Duration Bound is 20			
High Flow Pulses	Qp: 990 cfs with Average Frequency 2 per year Volume Bound is 7,310 Duration Bound is 18			
High Flow Pulses	Qp: 160 cfs with Average Frequency 1 per season Volume Bound is 1,580 Duration Bound is 19	Qp: 690 cfs with Average Frequency 1 per season Volume Bound is 4,940 Duration Bound is 16	Qp: 160 cfs with Average Frequency 1 per season Volume Bound is 1,040 Duration Bound is 13	Qp: 300 cfs with Average Frequency 1 per season Volume Bound is 2,010 Duration Bound is 15
High Flow Pulses	Qp: 45 cfs with Average Frequency 2 per season Volume Bound is 470 Duration Bound is 16	Qp: 220 cfs with Average Frequency 2 per season Volume Bound is 1,560 Duration Bound is 14	Qp: 16 cfs with Average Frequency 2 per season Volume Bound is 110 Duration Bound is 10	Qp: 44 cfs with Average Frequency 2 per season Volume Bound is 310 Duration Bound is 12
High Flow Pulses	Qp: 14 cfs with Average Frequency 3 per season Volume Bound is 160 Duration Bound is 14	Qp: 100 cfs with Average Frequency 3 per season Volume Bound is 740 Duration Bound is 13		Qp: 5 cfs with Average Frequency 3 per season Volume Bound is 35 Duration Bound is 8
High Flow Pulses	Qp: 7 cfs with Average Frequency 4 per season Volume Bound is 86 Duration Bound is 13	Qp: 47 cfs with Average Frequency 4 per season Volume Bound is 340 Duration Bound is 12		
Base Flows (cfs) – High	4	4	3	4
Base Flows (cfs) – Medium	2	2	1	2
Base Flows (cfs) – Low	1	1	1	1
Subsistence Flows (cfs)	1	1	1	1
Months	Nov, Dec, Jan, Feb, Mar	Apr, May, Jun	Jul, Aug	Sep, Oct

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

Pulse volumes are in units of acre-feet and durations are in days.
Period of Record used : 1/1/1965 to 12/31/2009.

Table 6.1.16. Environmental Flow Regime Recommendation, Atascosa River at Whitsett

	Winter (Nov, Dec, Jan, Feb, Mar)	Spring (Apr, May, Jun)	Summer (Jul, Aug)	Fall (Sep, Oct)
Overbank Events	Qp: 13,100 cfs with Average Frequency 1 per 5 years Regressed Volume is 61,400 Duration Bound is 29			
	Qp: 8,220 cfs with Average Frequency 1 per 2 years Regressed Volume is 38,900 Duration Bound is 26			
	Qp: 3,880 cfs with Average Frequency 1 per year Regressed Volume is 18,700 Duration Bound is 22			
High Flow Pulses	Qp: 1,990 cfs with Average Frequency 2 per year Volume Bound is 14,800 Duration Bound is 19			
	Qp: 730 cfs with Average Frequency 1 per season Volume Bound is 5,720 Duration Bound is 18	Qp: 1,770 cfs with Average Frequency 1 per season Volume Bound is 12,500 Duration Bound is 16	Qp: 250 cfs with Average Frequency 1 per season Volume Bound is 1,960 Duration Bound is 12	Qp: 620 cfs with Average Frequency 1 per season Volume Bound is 4,320 Duration Bound is 14
	Qp: 230 cfs with Average Frequency 2 per season Volume Bound is 1,960 Duration Bound is 14	Qp: 600 cfs with Average Frequency 2 per season Volume Bound is 4,280 Duration Bound is 13	Qp: 37 cfs with Average Frequency 2 per season Volume Bound is 280 Duration Bound is 7	Qp: 100 cfs with Average Frequency 2 per season Volume Bound is 720 Duration Bound is 9
	Qp: 74 cfs with Average Frequency 3 per season Volume Bound is 690 Duration Bound is 11	Qp: 220 cfs with Average Frequency 3 per season Volume Bound is 1,550 Duration Bound is 11	Qp: 5 cfs with Average Frequency 3 per season Volume Bound is 34 Duration Bound is 4	Qp: 21 cfs with Average Frequency 3 per season Volume Bound is 150 Duration Bound is 6
	Qp: 28 cfs with Average Frequency 4 per season Volume Bound is 280 Duration Bound is 9	Qp: 80 cfs with Average Frequency 4 per season Volume Bound is 580 Duration Bound is 9		
Base Flows (cfs)	14	10	8	
	9	5	4	
	5	2	1	2
Subsistence Flows (cfs)	1			

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

Pulse volumes are in units of acre-feet and durations are in days.
Period of Record used : 1/1/1933 to 12/31/2009.

Table 6.1.17. Environmental Flow Regime Recommendation, Nueces River near Three Rivers

	Winter (Nov, Dec, Jan, Feb, Mar)	Spring (Apr, May, Jun)	Summer (Jul, Aug)	Fall (Sep, Oct)
Overbank Events	Qp: 28,300 cfs with Average Frequency 1 per 5 years Regressed Volume is 362,000 Duration Bound is 41			
	Qp: 16,400 cfs with Average Frequency 1 per 2 years Regressed Volume is 192,000 Duration Bound is 34			
	Qp: 9,130 cfs with Average Frequency 1 per year Regressed Volume is 97,000 Duration Bound is 28			
	Qp: 5,420 cfs with Average Frequency 2 per year Volume Bound is 88,300 Duration Bound is 24			
High Flow Pulses	Qp: 2,050 cfs with Average Frequency 1 per season Volume Bound is 26,800 Duration Bound is 18	Qp: 4,090 cfs with Average Frequency 1 per season Volume Bound is 64,600 Duration Bound is 22	Qp: 1,100 cfs with Average Frequency 1 per season Volume Bound is 13,600 Duration Bound is 15	Qp: 2,420 cfs with Average Frequency 1 per season Volume Bound is 34,200 Duration Bound is 19
	Qp: 720 cfs with Average Frequency 2 per season Volume Bound is 8,460 Duration Bound is 13	Qp: 1,660 cfs with Average Frequency 2 per season Volume Bound is 22,200 Duration Bound is 16	Qp: 280 cfs with Average Frequency 2 per season Volume Bound is 2,520 Duration Bound is 9	Qp: 710 cfs with Average Frequency 2 per season Volume Bound is 7,920 Duration Bound is 13
	Qp: 320 cfs with Average Frequency 3 per season Volume Bound is 3,430 Duration Bound is 11	Qp: 690 cfs with Average Frequency 3 per season Volume Bound is 7,830 Duration Bound is 12	Qp: 34 cfs with Average Frequency 3 per season Volume Bound is 200 Duration Bound is 4	Qp: 160 cfs with Average Frequency 3 per season Volume Bound is 1,340 Duration Bound is 8
	Qp: 140 cfs with Average Frequency 4 per season Volume Bound is 1,410 Duration Bound is 8	Qp: 320 cfs with Average Frequency 4 per season Volume Bound is 3,190 Duration Bound is 10		Qp: 15 cfs with Average Frequency 4 per season Volume Bound is 82 Duration Bound is 4
Base Flows (cfs)	100	83	57	68
	37		30	37
	12	10	6	9
Subsistence Flows (cfs)	1			

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

Pulse volumes are in units of acre-feet and durations are in days.
Period of Record used : 1/1/1916 to 12/31/2009.

Table 6.1.18. Environmental Flow Regime Recommendation, Nueces River near Mathis

		Winter (Nov, Dec, Jan, Feb, Mar)	Spring (Apr, May, Jun)	Summer (Jul, Aug)	Fall (Sep, Oct)
Overbank Events		Qp: 22,700 cfs with Average Frequency 1 per 5 years Regressed Volume is 400,000 Duration Bound is 51			
Overbank Events		Qp: 12,900 cfs with Average Frequency 1 per 2 years Regressed Volume is 196,000 Duration Bound is 40			
Overbank Events		Qp: 7,690 cfs with Average Frequency 1 per year Regressed Volume is 102,000 Duration Bound is 31			
Overbank Events		Qp: 4,090 cfs with Average Frequency 2 per year Volume Bound is 83,000 Duration Bound is 23			
High Flow Pulses		Qp: 1,120 cfs with Average Frequency 1 per season Volume Bound is 14,200 Duration Bound is 12	Qp: 2,540 cfs with Average Frequency 1 per season Volume Bound is 49,400 Duration Bound is 19	Qp: 370 cfs with Average Frequency 1 per season Volume Bound is 4,970 Duration Bound is 10	Qp: 1,550 cfs with Average Frequency 1 per season Volume Bound is 24,700 Duration Bound is 15
High Flow Pulses		Qp: 590 cfs with Average Frequency 2 per season Volume Bound is 6,270 Duration Bound is 9	Qp: 420 cfs with Average Frequency 2 per season Volume Bound is 5,090 Duration Bound is 9	Qp: 150 cfs with Average Frequency 2 per season Volume Bound is 1,650 Duration Bound is 6	Qp: 240 cfs with Average Frequency 2 per season Volume Bound is 2,670 Duration Bound is 7
Base Flows (cfs)	High (75th %ile)	120	150	170	140
Base Flows (cfs)	Medium (50th %ile)	96	120	140	110
Base Flows (cfs)	Low (25th %ile)	70	89	100	88
Subsistence Flows (cfs)	Subsistence	37			

Flow Levels

- High (75th %ile)
- Medium (50th %ile)
- Low (25th %ile)
- Subsistence

Pulse volumes are in units of acre-feet and durations are in days.
Period of Record used : 1/1/1940 to 12/31/2009.

Table 6.1.19. Environmental Flow Regime Recommendation, Oso Creek at Corpus Christi

	Winter (Nov, Dec, Jan, Feb, Mar)	Spring (Apr, May, Jun)	Summer (Jul, Aug)	Fall (Sep, Oct)
Overbank Events	Qp: 3,550 cfs with Average Frequency 1 per 5 years Regressed Volume is 15,700 Duration Bound is 28			
	Qp: 2,500 cfs with Average Frequency 1 per 2 years Regressed Volume is 11,100 Duration Bound is 26			
	Qp: 1,320 cfs with Average Frequency 1 per year Regressed Volume is 5,960 Duration Bound is 23			
	Qp: 660 cfs with Average Frequency 2 per year Volume Bound is 4,590 Duration Bound is 19			
High Flow Pulses	Qp: 220 cfs with Average Frequency 1 per season Volume Bound is 1,600 Duration Bound is 17	Qp: 230 cfs with Average Frequency 1 per season Volume Bound is 1,480 Duration Bound is 13	Qp: 21 cfs with Average Frequency 1 per season Volume Bound is 160 Duration Bound is 8	Qp: 360 cfs with Average Frequency 1 per season Volume Bound is 2,450 Duration Bound is 15
	Qp: 59 cfs with Average Frequency 2 per season Volume Bound is 450 Duration Bound is 13	Qp: 48 cfs with Average Frequency 2 per season Volume Bound is 330 Duration Bound is 9	Qp: 6 cfs with Average Frequency 2 per season Volume Bound is 39 Duration Bound is 6	Qp: 64 cfs with Average Frequency 2 per season Volume Bound is 450 Duration Bound is 11
Base Flows (cfs)	2			
	2			
	1			
Subsistence Flows (cfs)	1			

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

Pulse volumes are in units of acre-feet and durations are in days.
Period of Record used : 1/1/1973 to 12/31/2009.

Table 6.1.20. Environmental Flow Regime Recommendation, San Fernando Creek near Alice

	Winter (Nov, Dec, Jan, Feb, Mar)	Spring (Apr, May, Jun)	Summer (Jul, Aug)	Fall (Sep, Oct)
Overbank Events	Qp: 3,990 cfs with Average Frequency 1 per 5 years Regressed Volume is 17,700 Duration Bound is 38			
Overbank Events	Qp: 1,380 cfs with Average Frequency 1 per 2 years Regressed Volume is 6,260 Duration Bound is 29			
Overbank Events	Qp: 610 cfs with Average Frequency 1 per year Regressed Volume is 2,790 Duration Bound is 23			
High Flow Pulses	Qp: 170 cfs with Average Frequency 2 per year Volume Bound is 1,490 Duration Bound is 17			
High Flow Pulses	Qp: 14 cfs with Average Frequency 1 per season Volume Bound is 170 Duration Bound is 12	Qp: 65 cfs with Average Frequency 1 per season Volume Bound is 470 Duration Bound is 11	Qp: 17 cfs with Average Frequency 1 per season Volume Bound is 140 Duration Bound is 9	Qp: 28 cfs with Average Frequency 1 per season Volume Bound is 240 Duration Bound is 10
High Flow Pulses	Qp: 7 cfs with Average Frequency 2 per season Volume Bound is 78 Duration Bound is 9	Qp: 14 cfs with Average Frequency 2 per season Volume Bound is 100 Duration Bound is 7	Qp: 4 cfs with Average Frequency 2 per season Volume Bound is 37 Duration Bound is 6	Qp: 8 cfs with Average Frequency 2 per season Volume Bound is 69 Duration Bound is 8
Base Flows (cfs) – High	2			
Base Flows (cfs) – Medium	2		1	
Base Flows (cfs) – Low	1			
Subsistence Flows (cfs)	1			

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

Pulse volumes are in units of acre-feet and durations are in days.
Period of Record used : 1/1/1965 to 12/31/1996.
1996 is a synthetic date created by removing a 13 year gap in the Period of Record.

6.1.1 Hydrologic Conditions (Wet/Average/Dry/Subsistence)

The Nueces BBEST recommends that seasonal hydrologic condition at any specific location be determined on the basis of the 12-month cumulative antecedent flow volume near that location as compared to trigger volumes selected such that dry, average, and wet conditions will apply 25 percent, 50 percent, and 25 percent of the time, respectively. The subsistence hydrologic condition is a sub-category of the dry hydrologic condition with a trigger volume set such that subsistence conditions apply only 10 percent of the time. Use of 12-month cumulative flow volumes provides adequate recognition of the persistence of drought and avoids more complex antecedent seasonal computations associated with shorter durations. It is recommended that the applicable hydrologic condition for the entire season be determined on the basis of an assessment of hydrologic condition at the beginning of the first day of the season, thereby recognizing practical operations. 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.

6.1.2 Subsistence Flows

Available hydrologic, biological, 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. More than a single observed violation of stream standards for dissolved oxygen has not occurred at flows less than 50 cfs near 11 of the 20 streamflow gages for which flow regime recommendations are provided, even at the statistically-derived subsistence flow values. Among the nine gage locations with observed violations of dissolved oxygen standards, six are classified as intermittent (i.e. reporting zero flow more than five percent of the time), two are perennial with low flows sustained by the discharge of treated wastewater, and one is perennial with at least 10 percent of gaged streamflows less than 1 cfs. Subsistence flow recommendations of no less than 1 cfs by the Nueces BBEST for intermittent gage locations ensures that ecological functions associated with subsistence flow will be supported no less frequently than they have been historically. Active data collection and monitoring under subsistence and zero flow conditions is recommended to more quantitatively assess the potential effects of extended periods of such flows on aquatic species in flowing stream segments or isolated pools.

It is the consensus of the Nueces 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 Nueces BBEST further recommends that all inflow[1] be passed when inflows are between the specified seasonal base and subsistence values under dry hydrologic conditions. Only under subsistence hydrologic conditions, a sub-category of dry hydrologic conditions, which occur up to 10 percent of the time, may inflow passage be reduced to seasonal subsistence values.

6.1.3 Base Flows

Available hydrologic, biological, 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 and proximate riparian vegetation for extended periods. Results of habitat modeling at two locations on the Nueces River (Laguna and Three Rivers) and one location on the Frio River (Concan) indicate that the statistically-derived base flows may maintain suitable habitat for all of the species 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 Nueces BBEST that translation of seasonal base flows into environmental flow standards and permit conditions may result in more frequent occurrence of flows within the range of recommended seasonal base values as a result of the issuance of new surface water appropriations or amendments. The Nueces BBEST finds some degree of reduction in frequency below historical levels to be an acceptable ecological risk. Habitat attainment frequency tables in Section 3.3 suggest that there may not be drastic reductions in frequency of attainment of our 75 percent of maximum threshold under our flow recommendations. However, tables and figures showing percentages of maximum habitat versus discharge for selected species included in Section 3.3 and Appendix 3.3.1 indicate that any substantial reduction in flows below our base flow recommendations may quickly reduce available instream habitat.

6.1.4 High Flow Pulses

Available hydrologic, biological, geomorphologic, 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 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 four per season, three per season, two per season, one per season, two per year, 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. Recognizing the ecological importance of seasonal and two per year pulses, particularly for intermittently flowing stream locations, the Nueces BBEST recommendations include upper confidence bound (rather than central tendency) pulse volumes and durations for all seasonal and two per year events.

It is the understanding of the Nueces BBEST that translation of pulse flows of specified frequencies into environmental flow standards and permit conditions may result in reduced magnitude or less frequent occurrence of high flow pulses as a result of the issuance of new surface water appropriations or amendments. The Nueces BBEST finds some degree of reduction in pulse magnitude or frequency to be an acceptable

[1] 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.

ecological risk. However, the geomorphological analysis in Section 3.5 indicates that the minimum flows protected by the recommendation (i.e., “infinite infrastructure”) scenario could result in sediment transport being reduced by as much as 80 percent. In order to provide greater certainty that the ecological functions of high flow pulses will be maintained, the Nueces BBEST recommends up to eight levels of pulse flow events based on the HEFR analyses. Because the high pulse flows are episodic events, the Nueces BBEST has 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 flow pulse requirement and the criteria for allowing higher-level pulse flow events to satisfy the yet unmet annual or seasonal pulse flow events with lower pulse peak flow trigger levels. Application of the adopted criteria is demonstrated in Section 6.3 (**Table 6.3.1**).

A qualifying flow pulse or overbank event is identified when flow exceeds the prescribed trigger (i.e. peak) flow magnitude. It continues (which means flows are passed up to that trigger magnitude) until the prescribed volume or duration has passed. If, during a qualifying event at one magnitude, flows increase to a magnitude that exceeds a greater magnitude event trigger, the trigger magnitude, volume, and duration of the higher qualifying pulse controls inflow passage. In this case, the higher magnitude events are considered to satisfy the lower magnitude events in the same season (e.g., one 2 per year event also counts for one per season event, one two per season, one three per season event, and one four per season event).

6.1.5 Overbank Flows

Available hydrologic, biological, geomorphologic, 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 ranging from two per year to one per five years.

6.1.6 Estuarine Inflow Regime Summary

The freshwater inflow regime recommendation of the Nueces BBEST for Nueces Bay is summarized in **Table 6.1.21**. In this table, recommended annual and seasonal freshwater inflow volumes for Nueces Bay are presented along with recommended attainment frequencies for subsistence, base, and high flow conditions. The Nueces BBEST recommends that compliance with these recommended freshwater inflow volumes can be assessed by accounting for all freshwater inflows to Nueces Bay including gaged streamflow at Calallen (UGGS# 08211500), runoff that is not measured by the streamflow gaging station at Calallen, diversions into Rincon Bayou and the Nueces Delta bypassing the Calallen gage, and/or discharges of treated wastewater.

Recognizing the ecological importance of periodic inundation of the Nueces Delta, the Nueces BBEST also recommends one Nueces River overbanking event per year. Nueces BBEST research and calculations indicate that such an overbanking event occurs when gaged streamflow at Calallen (USGS# 08211500) equals or exceeds 3,600 cfs and the volume passing this gage during the high flow pulse event equals or exceeds 39,000 acft. Freshwater inflow volume associated with this overbanking event may count only towards the recommended seasonal inflow volumes in Table 6.1.21 for the season in which the overbanking event occurs.

For reasons discussed in Sections 1, 2 and 4 of this report, the Nueces BBEST has chosen not to provide freshwater inflow regime recommendations for Corpus Christi, Oso, and Baffin Bays or the upper Laguna Madre.

Table 6.1.21. Environmental Flow Regime Recommendation, Nueces Bay

Condition (Target Salinity)	Nueces Bay Freshwater Inflow Regime (Attainment)			Recommendations		Historical Attainment		
	one overbanking event per year of 39,000 acft; maximum discharge of 3,600 cfs			Annual Total	Attainment	1941-2009	1941-1982	1983-2009
High (10)	125,000 acft (20%)	250,000 acft (25%)	375,000 acft (20%)	750,000	25%	22%	26%	15%
Base (18)	22,000 acft (60%)	88,000 acft (60%)	56,000 acft (75%)	166,000	80%	67%	81%	44%
Subsistence (34)	5,000 acft (95%)	10,000 acft (95%)	15,000 acft (95%)	30,000	95%	94%	100%	85%
	Nov, Dec, Jan, Feb	Mar, Apr, May, Jun	Jul, Aug, Sept, Oct					
	Winter	Spring	Summer (Jul, Aug); Fall (Sept, Oct)					

6.2 Comparison to Water Rights Permits and State Methodology

In 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. Immediately following are general comparisons of Nueces BBEST instream flow regime recommendations, which are based on best available science, to the flow restrictions found in existing run-of-river water rights in the Nueces River Basin. In subsequent paragraphs, the Nueces Bay freshwater inflow regime recommendation of the Nueces BBEST is compared to relevant provisions in the Agreed Order governing operations of the Choke Canyon Reservoir / Lake Corpus Christi (CCR/LCC) System.

Review of the current Nueces River Basin Water Availability Model (Nueces WAM) data files available from TCEQ indicates that there are approximately 30 run-of-river water rights with special conditions including streamflow restrictions. Almost all of these rights are located in the headwaters of the Nueces River Basin upstream of the outcrop of the Edwards Aquifer (see Figure 3.1-1) and are used for irrigation purposes. Flow restrictions associated with these water rights are applied uniformly throughout the year and do not include the seasonal variability typical of Nueces BBEST subsistence and base flow recommendations. Flow restrictions for existing water rights on major streams are listed below, along with comparable environmental flow recommendations of the Nueces BBEST for proximate stream locations in parentheses.

Nueces River at Laguna = 38 cfs (seasonal dry base flows = 32 cfs to 51 cfs)

Frio River at Concan = 7.5 cfs to 39 cfs (seasonal dry base flows = 33 cfs to 46 cfs)

Sabinal River near Sabinal = 3.9 cfs to 6 cfs (seasonal dry base flows = 3 cfs to 11 cfs)

Hondo Creek near Tarpley = 5 cfs (seasonal dry base flows = 1 cfs to 3 cfs)

Leona Springs/River near Uvalde = 11 cfs (seasonal dry base flows = 10 cfs to 11 cfs)

It is apparent that flow restrictions in Nueces River Basin water rights are remarkably consistent in magnitude with the dry base flow recommendations of the Nueces BBEST.

Choke Canyon Reservoir and Lake Corpus Christi are major reservoirs within the Nueces River Basin. Choke Canyon Reservoir is a Bureau of Reclamation Project operated by the City of Corpus Christi. The city owns Lake Corpus Christi and operates the two together as the Choke Canyon Reservoir/Lake Corpus Christi (CCR/LCC) System to meet municipal and industrial water demands. The city operates the CCR/LCC System in compliance with a TCEQ Agreed Order, a legal imperative. The Agreed Order, last amended and issued April 4, 2001, established an operating procedure pertaining to Special Condition 5.B., Certificate of Adjudication No. 21-3214 (the water right for Choke Canyon Reservoir), held by the City of Corpus Christi, the Nueces River Authority (NRA), and the City of Three Rivers. This order specifies monthly inflow targets for Nueces Bay that must be met by allowing inflows to pass through the reservoirs to the Nueces Bay and Estuary. These monthly inflow targets are based on total system storage of the reservoirs.

The monthly targets were developed by the TWDB and the TPWD to maximize biological benefits for species inhabiting the estuary. Specifically, the model used to come up with the inflow numbers was the Estuarine Mathematical Programming Model (TxEMP), a non-linear optimization model. This optimization model was used in conjunction with the hydrodynamic circulation model (TxBLEND) to evaluate freshwater inflows needed to maintain salinity gradients and fisheries harvest in Texas bays and estuaries.

From the TxEMP Model, the 2001 Agreed Order established a monthly schedule of desired freshwater inflows to Nueces Bay to be satisfied by reservoir spills, return flows, runoff below Lake Corpus Christi, and/or pass-throughs of system inflows. In simplest terms, the amount of water that flows into the reservoir system, up to a target amount, must be "passed through" to the bays and estuaries. Inflows above the target amount, which varies by month, can be captured for future use. The maximum required pass-through amount for any given year is 138,000 acft. When the reservoir system is greater than or equal to 70 percent of full (**Table 6.2.1**), the annual Nueces Bay inflow target is 138,000 acft. Under the current 2001 Agreed Order, pass-throughs can be reduced based on excess inflow from the previous month for up to one half of the following month's inflow requirement or low monthly salinity variation in the upper Nueces Bay (**Table 6.2.2**). When reservoir system storage is below 70 percent of capacity, but above 40 percent, the annual Nueces Bay inflow target is 97,000 acft. If system storage drops below 40 percent, but is above 30 percent, the City automatically enacts drought contingency measures and the pass-through requirements drop to 1,200 acft per month (the monthly median inflow to Lake Corpus Christi during the drought of record). If the system storage drops below 30 percent, the City automatically enacts more stringent drought contingency measures and pass-throughs from the reservoir system are suspended.

There are two main issues with TxEMP. First, flow results higher than the historical monthly medians are not allowed by model constraints, such that the maximum harvest (MaxH) flow can only be equal to or less than the historical monthly median inflows. Any need for inflows higher than monthly medians in any month for biological purposes cannot be directly evaluated from the model results. Second, TxEMP outputs for MaxH and MinQ (minimum inflows necessary to meet biological targets) are computed on a monthly basis according to pre-set historical bounds. Estuarine scientists now postulate that seasonal pulses could be more beneficial and critical for the biota than the strictly-defined monthly inflows currently in place for the Nueces Estuary. The Nueces BBEST is recommending a seasonally-based freshwater inflow regime that incorporates this concept of pulsed inflows.

Table 6.2.1. 2001 Agreed Order established monthly "pass-through" targets for freshwater inflows to the Nueces Estuary. Capacity refers to the percent of the combined storage capacity of Choke Canyon Reservoir and Lake Corpus Christi.

2001 Agreed Order Pass-Through Targets (acft)				
Month	**Capacity ≥ 70%**	**40% ≤ Capacity < 70%**	**30% ≤ Capacity < 40%**	**Capacity < 30%**
Jan	2,500	2,500	1,200	0
Feb	2,500	2,500	1,200	0
Mar	3,500	3,500	1,200	0
Apr	3,500	3,500	1,200	0
May	25,500	23,500	1,200	0
June	25,500	23,000	1,200	0
July	6,500	4,500	1,200	0
Aug	6,500	5,000	1,200	0
Sept	28,500	11,500	1,200	0
Oct	20,000	9,000	1,200	0
Nov	9,000	4,000	1,200	0
Dec	4,500	4,500	1,200	0
Total	138,000	97,000	14,400	0

Table 6.2.2. 2001 Agreed Order established salinity relief credit structure to reduce pass-through amount to Nueces Bay. Credits can be obtained in two ways: 1) In any given month, if the average salinity during the week of the 15th through the 21st, is at or below the Salinity Lower Bound (SLB) for the following month at Salt03 salinity station in Nueces Bay, then the target amount for the following month will be completely suspended. 2) In any given month, if the average daily salinity is X practical salinity units (psu) below the Salinity Upper Bound (SUB) for 10 consecutive days, then the target is reduced by Y%.

Month	**Salinity Lower Bounds**	**Salinity Upper Bounds**	**Reduction for Average Salinity**		
			5 psu below SUB	**10 psu below SUB**	**15 psu below SUB**
Jan	5	30	25%	50%	75%
Feb	5	30	25%	50%	75%
Mar	5	30	25%	50%	75%
Apr	5	30	25%	50%	75%
May	1	20	0%	25%	75%
June	1	20	0%	25%	75%
July	2	25	25%	50%	75%
Aug	2	25	25%	50%	75%
Sept	5	20	0%	25%	75%
Oct	5	30	0%	25%	75%
Nov	5	30	25%	50%	75%
Dec	5	30	25%	50%	75%

This complicates the task of comparing what is currently in place under the 2001 Agreed Order and what the Nueces BBEST is recommending. Comparing the cumulative monthly freshwater inflow amounts for a particular season (e.g., March through June or July through August) to the corresponding seasonal inflow recommendations from the Nueces BBEST analyses, a comparison can be illustrated (**Table 6.2.3**). Another concern with comparing these two freshwater inflow regimes is that the current 2001 Agreed Order bases pass-through amounts on monthly combined storage capacity in the CCR/LCC System, whereas the Nueces BBEST is recommending a freshwater inflow regime based on high flow, base flow, and subsistence flow that also includes attainment frequencies. For comparison purposes, we have matched up the >70 percent (MaxH) capacity with the Nueces BBEST "high flow" periods, the 70 percent to 40 percent (MinQ) capacity to the "base flow" level, and 40 percent to 30 percent reservoir capacity to the "subsistence flow" level (Table 6.2.3).

Table 6.2.3. Comparison of current 2001 Agreed Order pass-through requirements to the Nueces BBEST freshwater inflow recommendations for Nueces Bay.

Nueces BBEST Seasons	Month	2001 Agreed Order Targets (acft) **>70% Capacity**	Nueces BBEST Recommen-dations (acft) **High Flow**	2001 Agreed Order Targets (acft) **70% to 40% Capacity**	Nueces BBEST Recommen-dations (acft) **Base Flow**	2001 Agreed Order Targets (acft) **40% to 30% Capacity**	Nueces BBEST Recommen-dations (acft) **Subsistence Flow**
Spring	Mar	58,000	250,000 at 25% of time	53,500	88,000 at 60% of time	4,800	10,000 at 95% of time
	Apr						
	May						
	June						
Summer - Fall	July	61,500	375,000 at 20% of time	30,000	56,000 at 75% of time	4,800	15,000 at 95% of time
	Aug						
	Sept						
	Oct						
Winter	Nov	18,500	125,000 at 20% of time	13,500	22,000 at 60% of time	4,800	5,000 at 95% of time
	Dec						
	Jan						
	Feb						

As an example, when CCR/LCC System percent combined capacity is greater than 70 percent full ("high flow period"), the cumulative March through June (spring season) inflows into Nueces Bay under the current 2001 Agreed Order would be set at a target of 58,000 acft, so long as there is sufficient inflow available to pass-through to the estuary. Under this same season, the Nueces BBEST is recommending a seasonal high flow of 250,000 acft with an attainment frequency of 25 percent of the time.

Another easy to read illustration for comparing the 2001 Agreed Order FWI regime to the Nueces BBEST recommendations is to overlay each of the annual FWI quantities to Nueces Bay for the period of record (1941 to 2009). **Figure 6.2.1** shows the current 2001 Agreed Order FWI regime of 138,000 acft, 97,000 acft, and 14,400 acft overlaid on a chart of FWI to Nueces Bay. **Figure 6.2.2** shows the Nueces BBEST recommendations of 750,000 acft, 166,000 acft, and 30,000 acft overlaid on a chart of FWI to Nueces Bay.

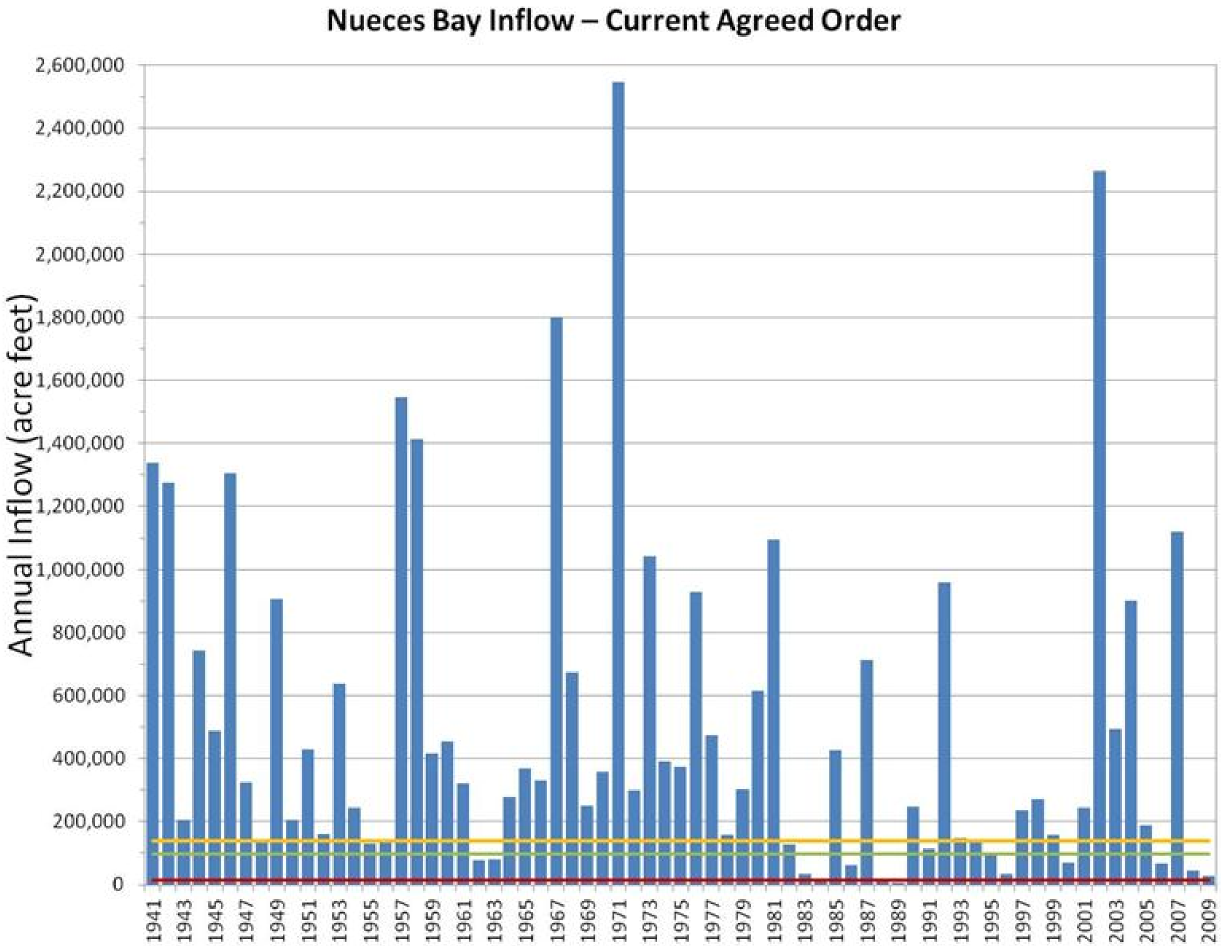


Figure 6.2.1. Comparison chart of the current 2001 Agreed Order FWI regime of 138,000 acft (yellow line), 97,000 acft (green line), and 14,400 acft (red line) overlaid on the annual FWIs to Nueces Bay from 1941 to 2009.

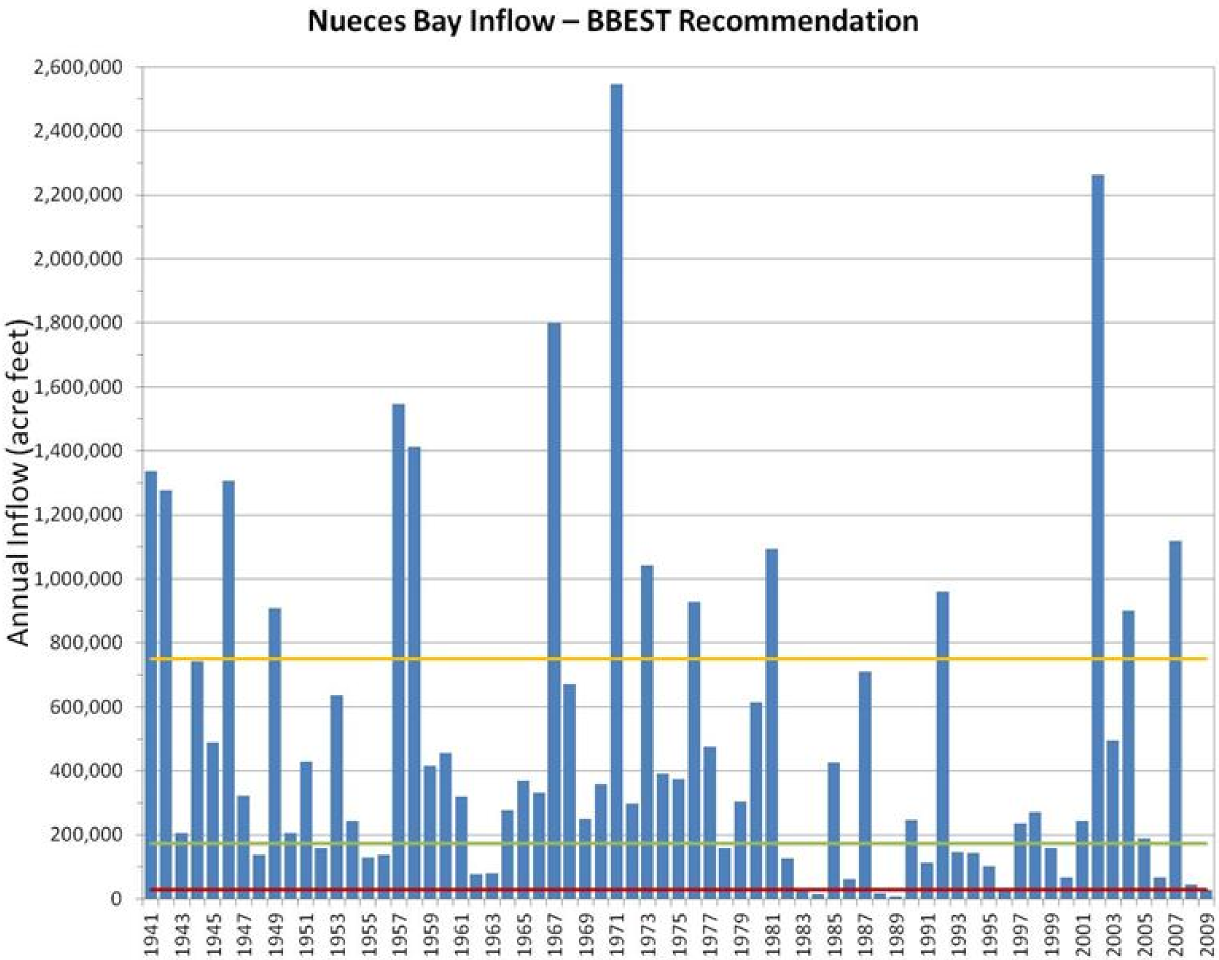


Figure 6.2.2. Comparison chart of the Nueces BBEST recommendations of 750,000 acft (yellow line), 166,000 acft (green line), and 30,000 acft (red line) overlaid on the annual FWIs to Nueces Bay from 1941 to 2009.

6.3 Example Application(s) of Flow Regime Recommendations

An important consideration of the Nueces BBEST in providing its instream environmental flow regime recommendations in the form of Table 6.1.1 through Table 6.1.20 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 Nueces River at Laguna. Guiding principles for flow regime application are summarized in **Table 6.3.1** 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 6.3.1 in the following sub-sections are made by line number in the table.

6.3.1 Subsistence Flows

1) If inflow is less than the seasonal subsistence flow, then all inflow must be passed and none impounded or diverted (Line 1). Hydrologic conditions are not a factor.

6.3.2 Base Flows

1) Hydrologic conditions as defined in Section 6.1.1 are applicable when inflow is less than the lowest applicable pulse peak flow in the same season or all pulse recommendations have been satisfied.
2) Under subsistence hydrologic conditions, if inflow is less than the seasonal base flow and greater than the seasonal subsistence flow, the seasonal subsistence flow must be passed and the balance may be impounded or diverted to the extent available, subject to senior water rights (Line 2)
3) Under dry hydrologic conditions, if inflow is less than the seasonal base flow and greater than the seasonal subsistence flow, then all inflow must be passed (Line 2a).
4) Under average and wet hydrologic conditions, if inflow is less than the seasonal base flow, then all inflow must be passed and none impounded or diverted (Lines 10 and 13).
5) If inflow is less than the lowest applicable pulse trigger flow (Qp) and greater than the seasonal base flow for the current hydrologic condition, then that seasonal base flow must be passed, and the balance may be impounded or diverted to the extent available, subject to senior water rights (Lines 3, 3a, 11 and 14).

6.3.3 High Flow Pulses

1) If inflow is greater than a specified pulse trigger flow (Qp) and less than the next greatest specified pulse trigger flow, and all applicable pulse recommendations have not been satisfied, then all inflow up to the lower of the two trigger flows 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, 4c, 5a, 5b, 6a, 6b, 7a, 7b, 8a, 8b, 9a, 9b, 12, and 15).
2) If all applicable pulse recommendations have been satisfied and inflow is greater than the seasonal base flow for the current hydrologic condition, then that seasonal base flow must be passed, and the balance may be impounded or diverted to the extent available, subject to senior water rights (Lines 4b, 4d, 5c, 6c, 7c, 8c, and 9c).
3) Pulse events are identified upon occurrence of specified trigger flow (Qp), 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. Once a pulse event has been identified, volumes passed during the event, including those prior to exceeding the specified trigger flow, may be credited towards the specified volume requirement.
4) One large pulse counts as one pulse in each of the smaller categories subject to reset at season or return period end.
5) Each return period (i.e., 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.

Table 6.3.1. Instream Flow Regime Recommendation Example, Nueces River at Laguna

Instream Flow Regime Application Example
Nueces River @ Laguna

Line #	Season	Hydrologic Condition	Incoming Streamflow (cfs)	99 cfs 2/Season Pulse Count	390 cfs 1/Season Pulse Count	590 cfs 2/Year Pulse Count	2,220 cfs 1/Year Pulse Count	4,750 cfs 1/2Years Pulse Count	15,600 cfs 1/5Years Pulse Count	Passing Streamflow (cfs)	Impound or Divert (cfs)	Line Notes
1	Spring	Subsistence	10							10	0	Pass all inflow.
2	Spring	Subsistence	20							18	2	Pass seasonal Subsistence flow (18 cfs).
3	Spring	Subsistence	50							44	6	Pass Dry Base flow (44 cfs).
4a	Spring	n/a	110	0 or 1						99	11	2/Season Pulse applies. Pass inflow up to 99 cfs until 1,560 acft or 9 days have passed. Add 1 to 2/Season & smaller pulse count.
4b	Spring	Subsistence	110	2						44	66	2/Season Pulses met. No larger pulses engaged. Pass Dry Base flow (44 cfs).
2a	Spring	Dry	20							20	0	Pass all inflow.
3a	Spring	Dry	50							44	6	Pass Dry Base flow (44 cfs).
4c	Spring	n/a	110	0 or 1						99	11	2/Season Pulse applies. Pass inflow up to 99 cfs until 1,560 acft or 9 days have passed. Add 1 to 2/Season pulse count.
4d	Spring	Dry	110	2						44	66	2/Season Pulses met. No larger pulses engaged. Pass Dry Base flow (44 cfs).
5a	Spring	n/a	400	0, 1, or 2	0					390	10	1/Season Pulse applies. Pass inflow up to 390 cfs until 6,070 acft or 17 days have passed. Add 1 to 1/season & smaller pulse count.
5b	Spring	n/a	400	1	1					99	301	2/Season Pulse applies. Pass inflow up to 99 cfs until 1,560 acft or 9 days have passed. Add 1 to 2/Season pulse count.
5c	Spring	Dry	400	2	1					44	356	2/Season & 1/Season Pulses met. No larger pulses engaged. Pass Dry Base flow (44 cfs).
6a	Spring	n/a	600	0, 1, or 2	0 or 1	0 or 1				590	10	2/Year Pulse applies. Pass inflow up to 590 cfs until 11,300 acft or 26 days have passed. Add 1 to 2/Year & smaller pulse counts.
6b	Spring	n/a	600	1	1	1				590	10	2/Year Pulse applies. Pass inflow up to 590 cfs until 11,300 acft or 26 days have passed. Add 1 to 2/Year & smaller pulse counts.
6c	Spring	Dry	600	2	2	2				44	546	2/Season, 1/Season, and 2/Year Pulses met. No larger pulses engaged. Pass Dry Base flow (44 cfs).
7a	Spring	n/a	2,300	0, 1, or 2	0 or 1	0 or 1	0			2,220	80	1/Year Pulse applies. Pass inflow up to 2,220 cfs until 18,400 acft or 46 days have passed. Add 1 to 1/Year & smaller pulse counts.
7b	Spring	n/a	2,300	1	1	1	1			590	1,710	2/Year Pulse applies. Pass inflow up to 590 cfs until 11,300 acft or 26 days have passed. Add 1 to 2/Year & smaller pulse counts.
7c	Spring	Dry	2,300	2	2	2	1			44	2,256	2/Season, 1/Season, 2/Year, & 1/Year Pulses met. No larger pulses engaged. Pass Dry Base flow (44 cfs).
8a	Spring	n/a	5,000	0, 1, or 2	0 or 1	0 or 1	0 or 1	0		4,750	250	1/2Year Pulse applies. Pass inflow up to 4,750 cfs until 38,600 acft or 64 days have passed. Add 1 to 1/2Year & smaller pulse counts.
8b	Spring	n/a	5,000	1	1	1	1	1		590	4,410	2/Year Pulse applies. Pass inflow up to 590 cfs until 11,300 acft or 26 days have passed. Add 1 to 2/Year & smaller pulse counts.
8c	Spring	Dry	5,000	2	2	2	1	1		44	4,956	2/Season, 1/Season, 2/Year, 1/Year, & 1/2Year Pulses met. No larger pulses engaged. Pass Dry Base flow (44 cfs).
9a	Spring	n/a	16,000	0, 1, or 2	0 or 1	0 or 1	0 or 1	0 or 1	0	15,600	400	1/5Year Pulse applies. Pass inflow up to 15,600 cfs until 124,000 acft or 107 days have passed. Add 1 to 1/5Year & smaller pulse counts.
9b	Spring	n/a	16,000	1	1	1	1	1	1	590	23,450	2/Year Pulse applies. Pass inflow up to 590 cfs until 11,300 acft or 26 days have passed. Add 1 to 2/Year & smaller pulse counts.
9c	Spring	Dry	16,000	2	2	2	1	1	1	44	15,956	2/Season, 1/Season, 2/Year, 1/Year, 1/2Year, & 1/5Year Pulses met. Pass Dry Base flow (44 cfs).
10	Spring	Average	50							50	0	Pass all inflow.
11	Spring	Average	80							65	15	Pass Average Base flow (65 cfs).
12	Spring	n/a	110	0 or 1						99	11	2/Season Pulse applies. Pass inflow up to 99 cfs until 1,560 acft or 9 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 9c above noting that the minimum of Average Base flow or inflow must be passed.**									
13	Spring	Wet	80							80	0	Pass all inflow.
14	Spring	Wet	95							92	3	Pass Wet Base flow (92 cfs).
15	Spring	n/a	110	0 or 1						99	11	2/Season Pulse applies. Pass inflow up to 99 cfs until 1,560 acft or 9 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 9c 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 smallest seasonal 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., 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 (e.g., 1/Year, 1/2Year, & 1/5Year) are often classified as Overbank events at flow regime recommendation locations selected by the Nueces BBEST.
7) Pulse events are identified upon occurrence of specified trigger flow (Qp), 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) Once a pulse event has been identified, volumes passed during the event, including those prior to exceeding the specified trigger flow, may be credited towards the specified volume requirement.
9) Pulse criteria are not engaged in shaded cells because incoming streamflow does not exceed the prescribed trigger flow magnitude.

6.3.4 General Considerations

Under all hydrologic conditions, the Nueces BBEST recommends that flows passed for senior water rights count towards satisfaction of any specified subsistence, base, and pulse flow rates and volumes.

6.3.5 Example Instream Flow Regime Applications and Verification

To the extent that the Nueces River Basin and the Nueces - Rio Grande Coastal Basin have exhibited characteristics of sound ecological environments throughout the last century, the Nueces BBEST is cognizant of 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 the minimums needed to continue to support a sound ecological environment as available water resources are being developed. The Nueces BBEST recognizes that some lesser quantities of flow and/or lesser frequencies of occurrence than observed historically may also be adequate at some instream locations. Nueces Bay, on the other hand, has not exhibited characteristics of a sound ecological environment throughout the last century. Hence, the Nueces BBEST freshwater inflow regime recommendation for Nueces Bay inflow quantities and frequencies of occurrence is greater than observed in the most recent decades.

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 instream 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. An attainment frequency approach is part of the Nueces BBEST Nueces Bay recommendations.

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 in east Texas river basins, either with full use of existing water rights or with new project development. Hence, the Nueces BBEST has considered finite, but very large scale, example infrastructure projects including a major reservoir on the Nueces River at Cotulla and a major run-of-river diversion from the Nueces River at Laguna. Neither of these example projects is a recommended or alternative water management strategy for implementation within the next 50 years in any of the approved 2011 regional water plans. Without regard to the practicality of “infinite infrastructure”, the BBEST also comments on the ability of the flow recommendations in and of themselves to maintain key components of a sound ecological environment (e.g., instream habitat in Section 3.3 and sediment transport in Section 3.5). In support of the Nueces BBEST, TPWD staff performed hydrologic time series analyses of these example infrastructure projects using the Flow Regime Application Tool (FRAT) and developed flow frequency curves representative of scenarios ranging from historical to "infinite infrastructure." Results obtained using FRAT are included as Appendix 6.3.1.

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 or exceed 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 Nueces 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 Nueces BBEST has simulated long-term operations of a major reservoir on the Nueces River at Cotulla. For the purposes of this illustrative example, it is assumed that this reservoir would be located at the reference gage location on the Nueces River at Cotulla, have a conservation storage capacity of 527,600 acft, and be operated with direct diversions of the firm yield subject to application of the Nueces BBEST flow regime recommendation (Table 6.1.4) in the form of permit conditions described herein. The simulation period used is 1934 through 1996 and seasonal hydrologic conditions are determined as described in Section 6.1.1.

Figure 6.3.1 shows historical and regulated frequencies of streamflow passing the Nueces River at the Cotulla reference gage location with and without the example reservoir project. Historical streamflows are simply obtained from the USGS gage records. Baseline and the other regulated flow curves reflect full consumptive uses of existing water rights upstream of Cotulla. Reservoir Example regulated flows reflect firm yield operations of a large on-channel reservoir subject to the instream environmental flow regime recommendations of the Nueces BBEST. For perspective, Figure 6.3.1 also shows regulated streamflow frequencies assuming "infinite infrastructure" with only the minimum flows specified in the Nueces BBEST flow regime recommendation remaining in the river. This flow frequency curve is identified in Figure 6.3.1 as the "Minimum Flow Protected by Recommendation." Flow frequency curves similar to those in Figure 6.3.1 were originally developed by TPWD staff (Appendix 6.3.1) with both the Reservoir Example and the Minimum Flow Protected by Recommendation results being based on initial draft flow regime proposals including from two to seven tiers of high flow pulses with alternative volumes and durations based on central tendency and upper bound values derived using HEFR. Sediment transport analyses performed by the TWDB at the request of the Nueces BBEST as part of the geomorphology overlay provided technical support for including up to eight tiers of high flow pulses in the Nueces BBEST flow regime recommendations.

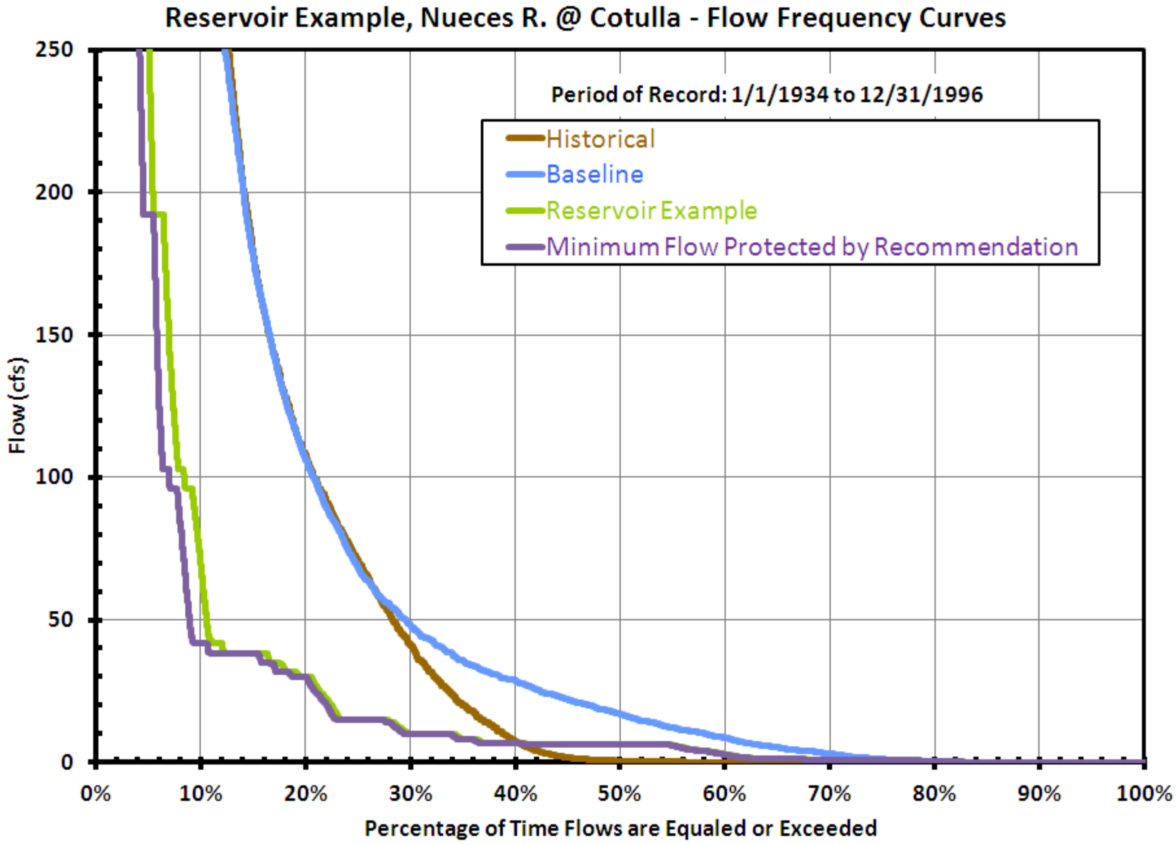


Figure 6.3.1. Reservoir Example, Nueces River at Cotulla Flow Frequency Curves.

Key observations upon review of Figure 6.3.1 include the following:

1) For the purposes of this illustrative example only, the reader should focus on the regulated streamflow frequency curves (i.e. Baseline, Reservoir Example, and Minimum Flow Protected by Recommendation) and the relative differences between them. The apparent difference between the Historical and Baseline curves at streamflows below about 60 cfs is not "real" and is a result of insufficient available historical data necessitating simplifying assumptions in the computation of natural streamflows used in the Nueces WAM.

2) Leveling of the regulated streamflow frequency curves for the Reservoir Example and Minimum Flow Protected by Recommendation is apparent at specified flow values (potential permit conditions) within the recommended flow regime. Flows passing this example project and shown in Figure 6.3.1 were computed using HEFR results (Appendix 3.2.2) prior to rounding and simplification of seasonal base flows for the final flow regime recommendation as presented in Table 6.1.4.

3) Flows at the seasonal subsistence and dry base levels (less than 1 cfs) occur no more frequently with the Reservoir Example project than in the Baseline scenario. Ecological significance of flows at these low levels should be considered in the context of the facts that zero flow is reported by the USGS for this location more than 40 percent of the time and that the average duration of zero flow periods is 49 days. Water quality monitoring data (Figure 3.4.2 and Appendix 3.4.1) may provide additional insights.

4) Flows within the range of seasonal base levels (between 1 cfs and 42 cfs) occur more frequently with the Reservoir Example project than in the Baseline scenario. Ecological significance of this change may be assessed, in part, by consideration of information regarding perennial pools (Section 3.6.4.1). Additional relevant information might include evaporation, evapotranspiration, and infiltration rates as well as water quality data for perennial pools. Flows exceeding the range of seasonal base levels

occur <u>less</u> frequently with the Reservoir Example project than in the Baseline scenario. These flows are addressed as pulse flows in the following paragraph.

5) Flows within the range of seasonal pulse (greater than 15 cfs) and overbank levels (greater than 1,560 cfs) occur much less frequently with the Reservoir Example project than they did historically, but incrementally 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 computations (Table 3.5.2), comparison to sustainability boundaries (Appendix 6.3.2), and consideration of riparian ecological functions (Figure 3.6.8).

6) Streamflow frequency information, as presented in Figure 6.3.1 and considered in the context of relevant information in this report, may be particularly useful to the Nueces BBASC as it considers many factors in preparing its recommendations on environmental flow standards and strategies. For example, the reductions in pulse and overbank flows associated with simulated operations of a large on-channel reservoir at Cotulla result in simulated 50 percent reductions in annual sediment yield as compared to the Baseline scenario, even with operations of the example project being subject to the environmental flow regime recommendations of the Nueces BBEST (Table 3.5.2). The Nueces BBEST recognizes that a reduction in annual sediment yield of this magnitude could modify channel shape and aquatic and riparian habitats that have provided for a sound ecological environment at this location.

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 Nueces BBEST has considered construction and long-term operation of a theoretical large-scale run-of-river diversion project with off-channel storage. For the purposes of this illustrative example, it is assumed that facilities capable of diverting 400 cfs would be located at the reference gage location on the Nueces River at Laguna, and operated subject to application of the recommended flow regime (Table 6.1.1) in the form of permit conditions described herein. In this example, water diverted from the Nueces River would be delivered to a nearby off-channel reservoir having a conservation storage capacity of about 44,000 acft 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 1996, and seasonal hydrologic conditions are defined as described in Section 6.1.1. **Figure 6.3.2** shows historical and regulated frequencies of streamflow passing the Nueces River at Laguna reference gage location including the Minimum Flow Protected by Recommendation.

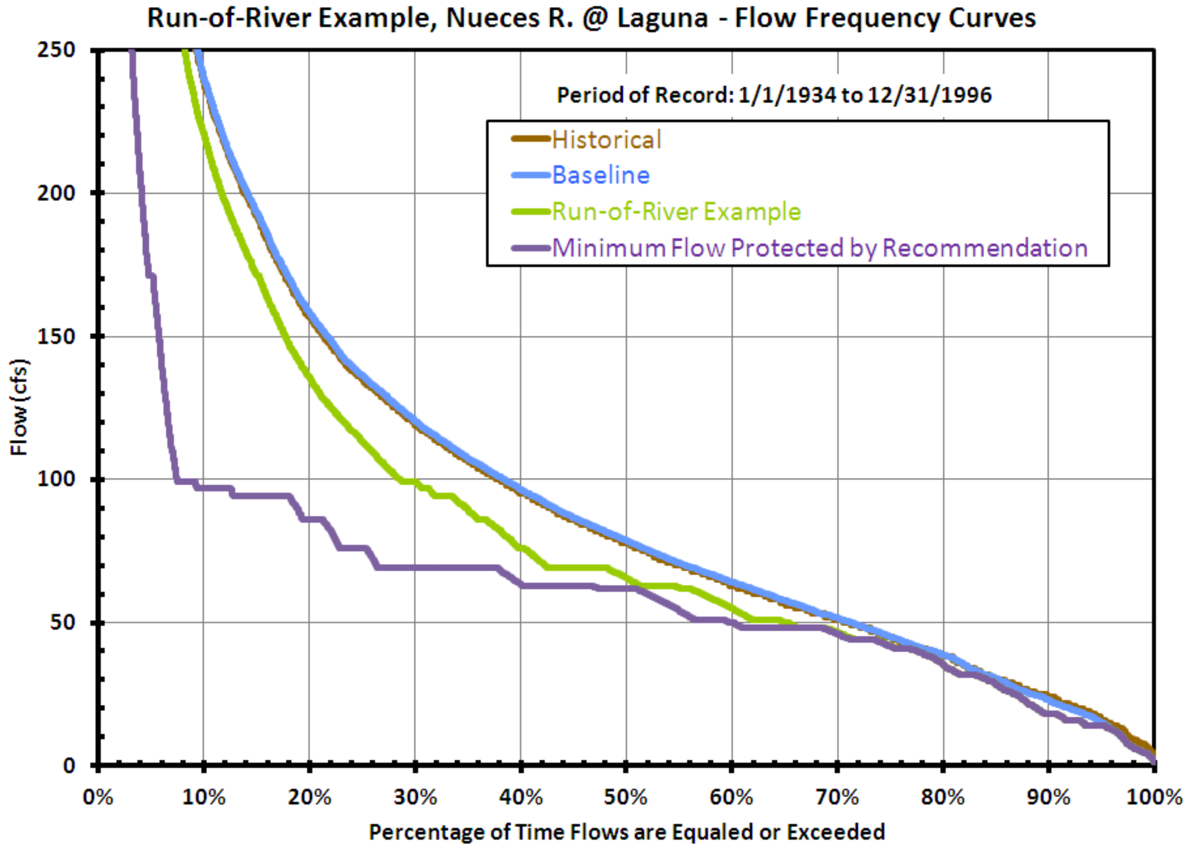


Figure 6.3.2. Run-of-River Example, Nueces River at Laguna Flow Frequency Curves.

Key observations upon review of Figure 6.3.2 include the following:

1) Leveling of the regulated streamflow frequency curves for the Run-of-River Example and Minimum Flow Protected by Recommendation is apparent at specified flow values (potential permit conditions) within the recommended flow regime. Flows passing this example project and shown in Figure 6.3.2 were computed using HEFR results (Appendix 3.2.2) prior to rounding and simplification of seasonal base flows for the final flow regime recommendation as presented in Table 6.1.1.

2) Flows at, but not below, the seasonal subsistence levels (ranging from 14 cfs to 18 cfs) occur slightly more frequently with the Run-of-River Example project than they did under the Baseline and Historical scenarios although the differences are not readily discernable in Figure 6.3.2. Ecological significance of this change may be assessed, in part, by review of water quality monitoring data (Appendix 3.4.1) and curves relating streamflow, aquatic habitat, and frequency of aquatic habitat availability by species (Figure 3.3.3, Figures 3.3.4 through 3.3.6, and Appendix 3.3.1). Flows exceeding the range of seasonal subsistence levels occur slightly less frequently with the Run-of-River Example project than in the Baseline and Historical scenarios. These flows are addressed as base and pulse flows in the following paragraphs.

3) Flows within the range of seasonal base levels (between 32 cfs and 92 cfs) occur more frequently with the Run-of-River Example project than they did under the Baseline and Historical scenarios. Ecological significance of this change may be assessed, in part, by review of curves relating streamflow, aquatic habitat, and frequency of aquatic habitat availability by species (Figure 3.3.3, Figures 3.3.4 through 3.3.6, and Appendix 3.3.1). Flows exceeding the range of seasonal base levels occur less frequently with the Run-of-River Example project than in the Baseline scenario. These flows are addressed as pulse flows in the following paragraph.

4) Flows within the range of seasonal pulse (greater than 48 cfs) and overbank levels (greater than 15,600 cfs) occur somewhat less frequently with the Run-of-River Example project than they did historically. Under the Minimum Flow Protected by Recommendations scenario, this difference is much more pronounced. Ecological significance of this change may be assessed, in part, by review of sediment yield computations (Table 3.5.1), comparison to sustainability boundaries (Appendix 6.3.2), and consideration of riparian ecological functions (Section 3.6.2).

5) Streamflow frequency information, as presented in Figure 6.3.2 and considered in the context of relevant information in this report, may be particularly useful to Nueces 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 Laguna result in less than 6 percent reductions in annual sediment yield with such operations being subject to the environmental flow regime recommendations of the Nueces BBEST (Table 3.5.1). The Nueces BBEST recognizes that a reduction in annual sediment yield of this magnitude is unlikely to significantly affect the channel shape and aquatic and riparian habitats that have provided for a sound ecological environment at this location. Lacking significant storage on the river like the Reservoir Example at Cotulla, operations of this Run-of-River Example under the Nueces BBEST flow regime recommendation might limit streamflow changes sufficiently to retain a stable channel in dynamic equilibrium, thereby posing significantly less ecological risk with respect to geomorphology and riparian vegetation. Subject to the Minimum Flow Protected by Recommendations scenario (i.e., "infinite infrastructure") sediment transport at the Laguna site could be reduced by 80 percent (Table 3.5.1).

The Nueces BBEST clearly understands that consideration of two examples of potential flow regime application does not address all potential ecological concerns at all locations throughout the Nueces River Basin and the Nueces - Rio Grande Coastal Basin. These examples are, however, indicative that flow regime application in accordance with the recommendations presented herein can support sound ecological environments, even though frequencies of attainment for various flows may be less than observed historically. These examples and corresponding habitat and sediment transport analyses do illustrate concerns for maintenance of at least some components of a sound ecological environment under implementation of flow regimes for large on-channel reservoirs or in an "infinite infrastructure" scenario, however unlikely such a scenario may be. In particular, these scenarios are likely to significantly impact high flow pulses and sediment transport. These two examples also highlight the very significant differences between perennial and intermittent streams and between the relative ecological risks associated with on-channel reservoirs as compared to run-of-river diversions with (or without) off-channel storage. Regarding the latter point, ***the Nueces BBEST recommends regulatory consideration of site-specific geomorphology and aquatic and riparian habitat studies in the permitting of any large, on-channel reservoirs in the Nueces River Basin***. This recommendation is supported, in part, by the supplemental sustainability boundaries assessments included in Appendix 6.3.2.

Section 7. Adaptive Management

7.1 Purpose

The Nueces BBASC is charged with identifying research and monitoring to guide future changes in environmental flows analysis, environmental flows standards, and strategies to provide environmental flows. Future work will be conducted within the context of the work plan the stakeholders are responsible for preparing. This section of the Nueces BBEST report:

- Identifies future research and monitoring;
- Proposes a structure for the work plan; and
- Identifies information that may be needed by stakeholders to develop their work plan.

Senate Bill 3 specifies the goals of the work plan:

> *Section 11.02362 (p) In recognition of the importance of adaptive management, after submitting its recommendations regarding environmental flow standards and strategies to meet the environmental flow standards to the commission, each basin and bay area stakeholders committee, with the assistance of the pertinent basin and bay expert science team, shall prepare and submit for approval by the advisory group a work plan. The work plan must:*
>
> 1. *establish a periodic review of the basin and bay environmental flow analyses and environmental flow regime recommendations, environmental flow standards, and strategies, to occur at least once every 10 years;*
> 2. *prescribe specific monitoring, studies, and activities; and*
> 3. *establish a schedule for continuing the validation or refinement of the basin and bay environmental flow analyses and environmental flow regime recommendations, the environmental flow standards adopted by the commission, and the strategies to achieve those standards.*
>
> *Section 11.1471 (f) An environmental flow standard or environmental flow set-aside adopted under Subsection (a) may be altered by the commission in a rulemaking process undertaken in accordance with a schedule established by the commission. In establishing a schedule, the commission shall consider the applicable work plan approved by the advisory group under Section 11.02362 (p).*

7.2 Future Research and Monitoring Needs

A table of information needs identified by the BBEST follows. The following paragraphs describe the general sections of the table. Beginning on page 7-12, a Sample Detailed Task is provided as an example of how tasks in this work plan may be conducted in a holistic fashion for streams.

<u>Number</u>

This column assigns a number to each research or monitoring need for ease of identification and future reference.

<u>Priority</u>

Priority (whether high, medium, or low) refers to the importance of the information needed as decided by the BBASC at the time their work plan is produced. The BBASC understands priorities can change for many reasons and will modify their work plan, including priorities, when appropriate.

<u>Description of the Information Needed</u>

This column identifies the question that needs to be answered to achieve the work plan's purpose.

<u>Monitoring, Special Study, Research, or Modeling</u>

Some work may require monitoring which usually involves collecting the same types of data at a site over several seasons and years. Other questions may be addressed with a special study involving one or a few sampling trips to some sites to answer a specific question. Research may involve literature review, data compilation, and analysis to answer a question without additional field data collection. Modeling is the specialized analysis of relationships, usually with the use of sophisticated computer models of parts of the ecosystem. There are not always clear distinctions between special studies, research, and modeling. In many cases, these approaches will be combined to address future information needs.

<u>Schedule</u>

Schedule is to be determined on the basis of prioritization of work plan activities by the Nueces BBASC, hence, any dates specified in this section are for illustrative purposes only. The schedule may change based on availability of resources and revised needs for information. Most projects are scheduled to be completed by 2021 to allow review and revision of reports, and development of BBASC recommendations to the TCEQ. By 2021, the BBASC may provide the TCEQ and the Environmental Flows Advisory Group a report, summarizing:

1) Validation and refinement of the basin and bay environmental flow analyses and environmental flow regime recommendations, the environmental flow standards adopted by the commission, and the strategies to achieve those standards; and
2) Suggestions for future monitoring, studies, and activities.

In some cases, monitoring, research and modeling activities may continue past 2021.

A long-term work plan schedule compatible with Senate Bill 1, regional water planning effort's 5-year schedule may be desirable. The BBASC may decide to merge the work plan schedule with the Senate Bill 1 schedule after 2021. The BBASC may wish to stay informed of and coordinate with the Senate Bill 1 process in the interim.

<u>Organizations Involved</u>

Organizations expected to contribute to the work described here include state agencies: principally TWDB, TCEQ, and TPWD, with possible support by the Texas General Land Office, Texas State Soil and Water Conservation Board, and the Texas Department of State Health Services, particularly its Seafood Safety Division. Federal agencies which may help include the U.S. Geological Survey, U.S. Environmental Protection Agency, U.S. Fish and Wildlife Service, Natural Resource Conservation Service, National Oceanic and Atmospheric Administration, and the U.S. Army Corps of Engineers. River authorities, water providers, and water users may be involved. Some nonprofit organizations including Texas Stream Team conduct water monitoring. Others that may collect data relating flow to environmental health include the Nature Conservancy, a variety of land trusts, local chapters of the Audubon Society, local chapters of Texas Master Naturalists, and others. Colleges and universities across the state engage in research and monitoring that may produce the types of information sought in the work plan. In this basin, particularly important universities include the University of Texas at San Antonio, Texas State University, Harte Research Institute, University of Texas Marine Science Institute, and Texas A & M University - Corpus Christi. This is a preliminary list of organizations that may be involved and could be updated as responsibilities, key personnel, and funding priorities of different organizations change with time.

Funding

Funding is expected to limit implementation of the work plan. Three approaches may provide funding for tasks:

1) Collaboratively incorporate work plan tasks into existing, funded, monitoring programs with related objectives. Several BBASC members represent organizations conducting monitoring and they could take leadership roles in guiding this merger of monitoring efforts.
2) Seek new sources of funding for tasks, including legislatively allocated funds, and state and federal grants.
3) Modify tasks as possible and appropriate to access existing funding sources not necessarily intended to support the Senate Bill 3 process. Although information needs are expected to be prioritized, the order of implementation may be modified as necessary to improve access to existing funding sources. Additionally, many tasks have closely related objectives. If necessary, objectives can be partially modified to obtain existing funding.

The BBASC could focus on identification of funding sources as it initiates its work plan. University researchers are aware of different funding sources, particularly research grants, which may facilitate work to address work plan tasks. Considerable local, state, and federal funding is currently allocated to monitoring flow and water chemistry. Comparatively little funding is spent collecting biological data. Less funding is spent interpreting relationships between sound environment, flow, and other factors. Success of the work plan may rest, in large part, on efforts of BBASC members to integrate information needs described below with existing monitoring and analysis programs.

Complicating Factors

A number of conditions could obscure sound understandings of the relationships between flow and the ecological health of streams and bays. Long-term variability in climate is a universal complicating factor. We continue to learn more about the effects of conditions in the equatorial Pacific Ocean on wetter and dryer than normal seasons and years in Texas. Recent analysis of tree rings suggests "megadroughts" lasting 20 to 30 years may have occurred in the past. Long-term climate variability means some monitoring and special studies may collect data over too short a span of time to completely understand the effects of these long-term patterns. Other complicating factors include:

- The relatively long life spans of some species that will be analyzed. Some mussel and riparian tree species may live over one hundred years.
- Changes in agricultural, industrial, and municipal use of surface and ground water.
- Changes in waste loading from municipal, agricultural, industrial, and nonpoint sources of pollution.
- Noxious species like giant cane outcompete native species, modify groundwater conditions, and impact healthy sediment transport.
- Changes in land cover/land use by cities, industries, or agricultural which modify drainage and aquifer recharge patterns.

Identification of complicating factors relevant to specific tasks would be a critical early step prior to initiating any monitoring, special studies, or research for the work plan.

Responsible Party

The BBASC is responsible for developing the work plan with assistance as desired from the BBEST. Perhaps the most important question not addressed by Senate Bill 3 is who will ultimately guide accomplishment of work plan tasks. This question asks who will be responsible for ensuring monitoring, research, and special studies are funded, conducted, and reports produced. The TWDB is expected to have a prominent role because of its responsibilities for managing water supplies and its funding of water-related research. The TCEQ and TPWD, because of their extensive roles and experience in maintaining ecological health of streams and estuaries, also may share responsibility for ensuring the projects in this work plan are carried out.

Table 7.2.1. Future Research and Monitoring Needs.

<table>
<tr><th>Number</th><th>Priority</th><th></th></tr>
<tr><td colspan="3">Rivers and Streams</td></tr>
<tr><td>1</td><td></td><td>Describe relationships between flow and physical, chemical, and biological structure and function of the streams and how these relationships support ecological health.
There has been practically no study of the interrelationships between environmental flow regime components and stream health in the Nueces basin. It would be valuable to analyze the results of future studies and monitoring described in the work plan in a holistic manner to improve understanding of flow and environmental health in Nueces basin streams.
Describe the role of flow in the ecological health of the stream. This is an overarching goal that could be accomplished by combining information collected from 2011 through 2020 with earlier data. A 2021 work plan report could summarize results of monitoring and studies conducted in the basins for this adaptive management process and obtained from other sources. The focus of the report would be on relationships between flows and ecological health in a minimum of two representative streams in each of the Edwards Plateau, South Texas Brush Country, and Coastal Bend reaches. One stream in each reach would be perennial and the other intermittent with perennial pools. The analysis in this task is particularly suited to the biennial state-wide water quality assessment based primarily on TCEQ's Surface Water Quality Monitoring (SWQM) and Clean Rivers Program data. TCEQ's SWQM Information System database would be an excellent starting point for this task.
In addition to site-specific studies, another potential approach to develop relationships between flow and ecology would be to utilize regional ecological datasets. By analyzing information such as biological monitoring data from streams with a range of hydrologic alteration, it is possible to develop relationships between flow alteration metrics and ecological metrics. For example, relationships have been developed between base flow alteration and temperature, fish biomass, and benthic macroinvertebrate community indices. This can be a useful approach in regions where detailed site-specific studies are not available, but less intensive information is available across a basin, region, or state. Availability of ecological data for such analyses in the Nueces basin should be assessed and flow-ecology relationships developed using either stream gage data or flow alteration metrics derived from WAMs.</td></tr>
<tr><td>2</td><td></td><td>Identify stream locations and estuaries not included in the BBEST environmental flow regime report that should be analyzed for relationships between flow and environmental health.
This would be a desk-top study based in part on review of expected water demands and availability identified by regional water planning. This review would help identify water bodies that may have future water rights applications for diversions. Review and identification of additional locations for environmental flow analysis could be summarized in 2013 and 2018.</td></tr>
</table>

Number	Priority	
Rivers and Streams		
3		**Conduct additional modeling of relationships between in-stream habitat and flow.** The BBEST and its contractors made considerable progress in understanding relationships between instream habitat suitability, however the work was based on fish habitat relationships from streams outside the basin, was only conducted at three sites, and was only conducted under one flow condition at two of the sites. Factors possibly complicating this analysis include human alterations to physical habitat not associated with flow like channel clearing and shaping for flood control, invasion of noxious plants (giant cane) or animals (armored catfish) that alter physical habitat. Specific tasks may include: ▪ Suitable habitat may be in small, disconnected patches and higher or lower flows might be needed to connect or increase size of suitable habitat patches. In order to address this, a habitat mapping approach such as a 2-dimensional model (e.g., River2D) or MesoHabSim that produces a spatially explicit, continuous map of habitat at the site at multiple flow levels would be necessary to evaluate how patches of habitat are connected at different flows. ▪ Develop habitat suitability models for non-native species. Such models would help evaluate potential interactions between modified flow regimes and likelihood of establishment of non-native species (most of which are adapted to relatively stable deep water habitats). ▪ Collect basin-specific information about the instream habitats utilized by different species of fish and their different life stages. ▪ Collect more habitat utilization data from different streams and at different flows. ▪ Model hydraulic conditions under several different flows. ▪ Sample the cross-sections measured at these three sites to obtain at least one additional set of hydraulics measurements near the middle or upper end of the base flow recommendations. This would allow evaluation of another source of uncertainty, the stage-discharge rating curves used at each site.
4		**Describe ecological services provided by perennial pools.** There are a number of streams in the Nueces basin which stop flowing at times. Little is known about the ecological structure and function of these pools and particularly the relation of their environmental health to flow. It is important to study how the different flow regime components support environmental health in these perennial pools. This could be a special study conducted on at least one stream in each of the Edwards Plateau, South Texas Brush Country, and Coastal Bend reaches with a report summarizing results produced by 2021. Some monitoring programs do not collect information from perennial pools when there is no flow. In some cases there may be questions about how to access streams for sampling when there is no flow and the perennial pool is not near the established monitoring site. Existing monitoring programs could be asked to monitor physical, chemical, and biological conditions when streams stop flowing and form perennial pools. This sampling would focus on fish, benthic macroinvertebrates, mussels, riparian plants, and as resources permit, wildlife using the riparian zone. It would also focus on seasons when perennial pools are most likely to occur. Water chemistry would be monitored in conjunction with biological monitoring and, preferably, continuous recording water quality meters would be installed.
5		**Identify flow regime components and quantities necessary to sustain mussels and compare to flow regimes identified necessary to sustain fish communities.** Some streams in the Nueces basin have diverse mussel communities with at least 11 species, including the state-listed threatened golden orb, found at sites on the Nueces River between Cotulla and Lake Corpus Christi. Some species found by the BBEST and the BBEST's contractors may live over 100 years. Very little is known about the distribution of mussels, their life stages, life cycles, and relationships to flow. Some species depend on certain species of fish to complete the parasitic life stage of the mussel. This could be a special study including a special survey to identify where mussels are living in the basin, with greater emphasis initially on threatened species. Special studies would then be conducted on at least two streams to describe the life histories of the mussels and their relationships to different environmental flow regime components. An interim report would be produced in 2019, including specific recommendations for future study. Since TPWD has listed 15 species of mussels as threatened and the U.S. Fish and Wildlife Service is considering listing some of those same species as federally threatened species, it is possible there may be funding readily available for this work, particularly through the U.S. Fish and Wildlife Service's State Wildlife Grant program than for other monitoring described here.

Number	Priority	
		Rivers and Streams
6		**Describe how surface flow patterns and quantities are changing compared to the period of record patterns. Include consideration of possible future flows and diversions.** Flow patterns vary naturally over time. Some flow patterns may be relatively long and influenced by several different global climate drivers, e.g., Southern Pacific Oscillation, North Atlantic Oscillation, etc. Some streams in the basin have very limited records of flow, in some cases only back to the early 1970s. It will be important in considering whether there should be changes to environmental flow standards to understand if, and how flow patterns have changed from the patterns used to develop the flow recommendations in this report. This would be a 10-year review of flow monitoring data collected principally by the USGS and summarized in a 2021 report. Preliminary flow data review would be conducted every three years and recommendations would be issued regarding the continuation of monitoring at gages and the addition of flow monitoring at new sites.
7		**Describe groundwater flow into streams and how is it changing.** Aerial photography and anecdotal reports of landowners indicate there are perennial pools that have not dried up in recent history. These pools are being sustained by groundwater input. Groundwater and surface water interchange may be much more important in this relatively arid part of Texas. This may require creation of long-term groundwater monitoring locations combined with special studies analyzing relationships between groundwater levels, stream flows, groundwater withdrawals, land cover/use patterns, and meteorological conditions for specific streams. Monitoring could be designed to last past 2022 and perhaps until at least 2072 to capture long-term patterns in groundwater-surface water interchange. Special studies analyzing relationships between groundwater levels, stream flows, and groundwater withdrawals, combined with a review of monitoring data could be conducted every 10 years.
8		**Describe relationships between benthic macroinvertebrates and flow.** Very little is known about benthic macroinvertebrates in Nueces basin streams. Stream macroinvertebrates are periodically decimated by natural disturbances, such as floods and droughts (Resh, et al., 1988). Flow regime plays a major role in structuring habitat conditions for stream macroinvertebrates through direct effects, as well as interaction with substrate, food supply and physico-chemical parameters (Ward, 1992). Benthic macroinvertebrates are reliable indicators of localized alterations in streams (Rosenberg and Resh, 1992) and are being increasingly used in evaluating effects of hydrology and habitat changes. Rapid bioassessment protocols have been developed for benthic macroinvertebrates and additional quarterly monitoring of benthic macroinvertebrates in conjunction with water quality monitoring would help clarify relationships between benthic macroinvertebrates and flow.
9		**Identify water development activities planned for the future, and how they might influence groundwater, river flows, and physical and hydrologic connections between the two.** Human population is predicted to double and there will be changing demands for surface water and groundwater as there are changes in industrial, agricultural, and oil and gas exploration water uses. Water development possibilities identified in the regional water plans and from other sources should be evaluated. These studies would start as desk-top studies involving the prioritization of possible water development activities to evaluate. Desk-top studies would then compile and review available information about groundwater, stream flow, and possible links between the two in the area of the planned water development. As necessary, field studies would be conducted to provide needed information. Possible water development activities are likely to occur distant from the sites for which environmental flow regimes have been identified. Groundwater/surface water linkages between the location of the possible water development and the site where environmental flow standards have been set should be understood.

Number	Priority	
		Rivers and Streams
10		**Describe changes in geomorphology, i.e. trends in channel elevation, longitudinal profile, width, floodplain width, stream form, bed sediment size, and the role the flow regime contributes to those changes.** The relatively short amount of time which the BBEST had to develop environmental flow recommendations did not permit in-depth analysis of the relationships between channel shape and flow. Channels move and change, but maintain a dynamic equilibrium within the range of historic flows. A substantial change in the historic flow patterns used to develop the flow recommendations may cause the channel shape to change beyond its dynamic equilibrium. If the channel shape changes substantially, it alters the relationships between flow and aquatic habitat and the riparian community. This would be a desk-top study utilizing available data and aerial photography for at least two representative streams in each of the three reaches. Review of available literature review would guide identification of additional field data and/or aerial photography that should be collected. Indicators of change in channel morphology and their levels useful in identifying ecologically harmful changes in channel morphology would be identified. The cumulative impacts of multiple, relatively small, diversions on channel morphology would be evaluated in this analysis. Limited availability and resolution of Light Detection and Ranging (LIDAR) data that measures ground surface elevation along with the dynamic nature of stable channels could complicate this analysis.
11		**Identify the best period of record to use in deciding which hydrologic condition and hydrologic triggers should be used.** If the TCEQ establishes environmental flow standards with multiple base flows, the TCEQ will identify a hydrological condition and triggers which direct how water diversions to different levels of base flow are made. This will be a desk-top study of flows and climate for a minimum of two sites in each of the Edwards Plateau, South Texas Brush Country, and Coastal Bend. Consideration will be given to how well the hydrologic condition represents the actual flow regime, the ability of the hydrologic condition and triggers to represent the natural variability of flows, and the ease with which the hydrologic triggers can be used by the regulated community.
12		**Identify key flow-dependent ecosystem functional (create ecological structure) processes associated with a sound ecological environment.** Riverine ecosystems are complex systems of interacting abiotic and biotic components. To manage these systems effectively, a basic understanding of these interactions (such as food web dynamics, reproductive cues, species recruitment, and colonization) is required. Attempting to manage a riverine ecosystem without adequate understanding of such processes can be problematic. This should be a desk top study at this time given the substantial lack of information on the ecological structure of the streams and riparian zones of the Nueces River Basin. The work plan should identify and evaluate key ecosystem processes and services, such as elemental cycling and the productivity of important plant and animal populations in a minimum of two representative streams in each of the Edwards Plateau, South Texas Brush Country, and Coastal Bend reaches. Examples include primary production (periphyton, macrophytes), secondary production, organic matter dynamics (coarse particulate organic matter, fine particulate organic matter), trophic level dynamics and food webs, resistance and resilience of stream communities to drought and floods, invasive species impacts to water quantity and quality (giant cane, salt cedar), invasive species effects on interspecific competition (e.g., giant cane and historical riparian community, zebra mussels and native mussels).

Number	Priority	
Rivers and Streams		
13		**Develop sustainability boundary analysis.** The primary tasks that need to be addressed in further development of the sustainability boundaries analysis are evaluation of other measures of flow to build boundaries around and to evaluate the best alteration thresholds to define sustainability. The Nueces BBEST experimented with mean monthly flow in this analysis to define normal conditions, but the work plan should evaluate other potential measures of normal flow conditions. These might include simple measures of flow variability such as median daily or monthly flows across the period of record. They could also be flow components such as base dry flows by month or high flow pulses. Our initial analysis utilized the 10% and 20% thresholds suggested by Richter et al. 2011, but more extensive use of this method should not be made without evaluating and potentially modifying these thresholds or considering other bases (e.g., standard deviation) for defining thresholds. One way thresholds might be evaluated is through flow-ecology relationships built from ecology data from a suite of streams with a range of levels of flow alteration across the Nueces River Basin, central Texas, or all of Texas. The work plan might also involve application of the sustainability boundaries approach to other locations in the Nueces River Basin. This would involve using FRAT or other tools to develop time series of flow for other locations to evaluate flow recommendation implementation scenarios.
Bays		
14		**Describe relationships between freshwater inflow to bays and physical, chemical, and biological structure and function of the estuaries and how these relationships support ecological health.** It would be valuable to analyze the results of future studies and monitoring in a holistic manner to improve understanding of flow and environmental health in Nueces basin estuaries. This is an overarching goal that would be accomplished by combining information collected from 2011 through 2020 with earlier data. The 2021 work plan report would summarize results of monitoring and studies conducted for this adaptive management process and obtained from other sources. The BBEST report focused on relationships between inflow and ecological health in Nueces Bay where most freshwater impact occurs. However, the BBEST did not conduct in-depth analysis of freshwater inflows and environmental health in other related bays systems. For future studies, assessment would be conducted on the importance of freshwater inflow to Corpus Christi and Oso bays. Planning would begin for freshwater inflow studies for the hypersaline areas Baffin Bay and the upper Laguna Madre as well.
15		**Describe and design studies to address relationships between abundance of fish and shellfish in the bay and bay salinities.** The BBEST's initial study relied heavily on TPWD's substantial database that includes species and abundance of fish and shellfish as well as salinity when samples were collected. This is certainly one of the best coastal fisheries monitoring programs in the world. However, it is not designed to address some site specific fine-scale questions like those dealing with salinity and fisheries abundance. Monitoring should continue, but this program should expanded to address specific regional questions are not readily possible with the current design of the TPWD monitoring program. Synoptic surveys should be designed specifically to describe relationships between abundance of important estuarine fish and shellfish and salinity. These directed studies would greatly enhance our understanding of freshwater inflows on fish and shellfish in this region.
16		**Identify improvements made in methods for determining environmental flow regimes for estuaries.** Intensive literature review combined with expert meetings and consultation would be conducted to stay abreast of latest developments in this field of science, particularly as it relates to freshwater inflows from arid watersheds into estuaries. New techniques would be evaluated and applied to Nueces Bay, as appropriate.

<table>
<tr><th>Number</th><th>Priority</th><th></th></tr>
<tr><th colspan="3">Bays</th></tr>
<tr><td>17</td><td></td><td>Describe the relationship between freshwater inflow and location and area of oyster reefs, and health and abundance of oysters in Nueces Bay.
Historical information indicates oysters were much more abundant in Nueces Bay 70-100 years ago. Recent information is lacking for this important estuarine indicator due to lack of monitoring and studies on this species in the region.
Oysters should be mapped every 5 years with side-scan sonar (this may be done by TPWD since it has acquired side-scan sonar capability), and related to inflow. Dermo monitoring by the Oyster Sentinel program would be continued. Water quality monitoring (temperature, salinity, oxygen, and pH) would be conducted with continuously recording meters placed on the reefs in the locations where Oyster Sentinel samples would be collected. Oyster reef mapping would help understand oyster response to freshwater inflow to the bay. It would also create a baseline which would help evaluate any strategies to improve conditions for oysters in the bay.</td></tr>
<tr><td>18</td><td></td><td>Evaluate potential for Allison wastewater effluent with its nutrients and other return flows (e.g., Oso Bay returns) to improve environmental health of the Rincon Bayou delta.
Assessing alternative sources of water such as treated effluent from the Allison wastewater treatment plant that is discharged into the Rincon Bayou delta could be important in the future. The wastewater discharge permit requires some ammonia-nitrogen removal from the effluent before it can be discharged into the delta. Moving the discharge to the delta may eliminate the need for ammonia-nitrogen removal from the effluent.
Analysis should be conducted to determine the volume of wastewater and nitrogen that could be added to the Rincon Bayou delta from the Allison wastewater treatment plant and other areas such as those being release to Oso Bay. This analysis should also involve an assessment of the regulatory changes necessary to maximize the contribution of the wastewater treatment plant to the delta's environmental health.</td></tr>
<tr><td>19</td><td></td><td>Identify vegetation/marsh changes occurring in the Rincon Bayou delta and relationship of those changes to freshwater inflow.
Health of the marsh plant community in the Rincon Bayou delta has been used to demonstrate effects of changes in freshwater inflow. Continue field studies in the Rincon Bayou delta to track changes in vegetation and marsh condition and relate those changes to freshwater inflow patterns.</td></tr>
<tr><td>20</td><td></td><td>Define ecological effects of zero flow event duration, intervals between periods of zero flow, and long-term frequency of zero flow occurrence.
From 1989 to October 2011, 18 percent of the days have had no flow from the Nueces River into Nueces Bay. Only one of 23 years during this period has had flow every day. Some no flow periods have lasted for two consecutive months.
Monitoring, research, and studies are on-going and planned for Nueces Bay and the Nueces delta. Attention should be placed in these studies and future studies to ensure information collected can also be used to evaluate how periods of no flow are affecting ecological health of the bay and delta.</td></tr>
<tr><td>21</td><td></td><td>Continued monitoring of Vegetative Indicators
Two marsh plant species proved to be useful indicators of the timing and quantity of freshwater inflows. Smooth cordgrass (Spartina alterniflora) abundance was strongly correlated with freshwater inflows because it is found adjacent to tidal creeks where it is directly impacted by the salinity of tidal creek water. Borrichia frutescens, the primary competitor of S. alterniflora, is found at higher elevations where salts concentrate in dry well drained sediments. Freshwater inflows are important because they flush accumulated salts from sediment porewaters and maintain adequate soil moisture. Future monitoring should assess whether decreased freshwater inflows are altering the competitive balance among plant species or impacting their distributions.
Detailed investigations on the spatial and temporal variability of environmental variables such as porewater salinity are necessary in order to predict the response of vegetation communities to changes in freshwater inflow. Future monitoring of environmental conditions in the Nueces Delta should include porewater measurements taken over a variety of spatial and temporal scales. Previous studies have collected data from selected sites on a quarterly or monthly basis. In contrast to quarterly or monthly monitoring schemes, continuous monitoring can resolve the impact of individual freshwater inflow events. Low cost continuous monitoring of porewater conditions via remotely deployed sensors would enable researchers to investigate the importance of freshwater inflow to vegetation health.</td></tr>
</table>

Number	Priority	
Basin-wide		
22		**Implement a program to evaluate effectiveness of strategies used in areas where there may be inadequate amounts of water for an environmentally sound stream or estuary.** Part of this program would involve the design of desk-top or field studies to determine strategy effectiveness in: 1) restoring or providing ecological structure and function provided by a sound flow regime; or 2) restoring environmentally sound flow regimes.
23		**Implement a program to evaluate future alternative water sources and response to increased demand as climate changes.** Clearly, with increasing demand for water from a variety of current and future users, water supply for bay ecological health has the potential to be compromised. Moreover, the BBEST report did not address any changes in supply due to climate change-water availability relationships. Studies should be performed to assess future water supply and its impact on the environment in terms of conservation, alternative water supplies such as pipelines, relationships between groundwater and surface waters, desalination potential, and other methods to maintain supply of freshwater inflow to the estuary.

7.3 Adaptive Management/Work Plan Process

An organization and process is needed to implement the work plan which will carry out the research and monitoring described above. The following steps suggest an organization and process which stakeholders may consider:

1. Four months following submittal of its report to the TCEQ and the Environmental Flows Advisory Group, the BBASC would convene a meeting with the BBEST to initiate the work plan. This meeting would identify steps to be taken, individuals responsible, funding sources, and deadlines.
    a. BBASC and the BBEST would continue to identify potential sources for funding, monitoring, special studies, and research. Individuals may be invited to describe local, state, and federal grant opportunities. Invitations would be extended to organizations/individuals that are doing monitoring not included in the Coordinated Monitoring Schedule (the Coordinated Monitoring Schedule is developed annually by monitoring organizations in each basin and outlines where, when, and what type of monitoring will be done in the basin), i.e. industries or municipalities required to monitor, Nueces River Authority, City of Corpus Christi, Texas Stream Team volunteer monitors, Texas Mussel Watch volunteers, Harte Research Institute, University of Texas Marine Science Institute, Texas A&M University-Corpus Christi, Texas Master Naturalists, etc. Opportunities would be sought to adjust existing monitoring, particularly Clean Rivers Program work, to address multiple needs including those of the BBASC.
    b. The BBASC would convene a work group that would:
        1) Identify baseline sound environment conditions
        2) Compile information collected for the work plan
        3) Analyze information and prepare the initial work plan for BBASC approval and submittal in 2013.
    c. The BBASC would finalize a process and schedule for describing work plan results by 2021.
    d. The BBASC would schedule annual or more frequent adaptive management meetings to be informed of work plan progress, discuss needs and opportunities for funding and collaboration, and modify the plan as necessary.
2. Each basin has an annual Clean Rivers Program Coordinated Monitoring meeting to discuss monitoring needs for the upcoming monitoring year. A member of the BBASC or BBEST would attend that meeting. The BBASC/BBEST representative would discuss inclusion of work plan monitoring in the basin's Coordinated Monitoring Schedule with the goal of incorporating as much of the work plan monitoring as reasonable.

7.4 Work Plan Product

The product of the work plan would be a report to the TCEQ and Environmental Flows Advisory Group on or before the 10th anniversary of TCEQ's adoption of environmental flow standards for the Nueces basin. The report would:

- Summarize relevant monitoring, special studies, and research done;
- Validate or suggest refinement of the BBEST's environmental flows analyses and recommendations;
- Describe environmental flow regimes for sites not included in the original BBEST and BBASC recommendations as appropriate;
- Validate TCEQ's environmental flows standards and where appropriate, suggest refinements to those standards; and
- Validate strategies implemented to provide environmental flows and where appropriate, propose new strategies or refinements to existing strategies.

The overall goal of this report would be to:

- Summarize results of the studies recommended in this work plan with particular emphasis on the inclusion/analysis of information collected after 2011 when the BBEST's environmental flow recommendations were published.
- Revise as appropriate, environmental flow regime recommendations published by the BBEST.
- Revise the work plan to ensure future information adequately supports development of environmental flow regimes and environmental flow standards.

This report will be published in 2021. This should be the first in what will be considered a long term process with reviews of work plan implementation conducted at least once every five years and reevaluation of environmental flow regime recommendations at least once every 10 years until 2082.

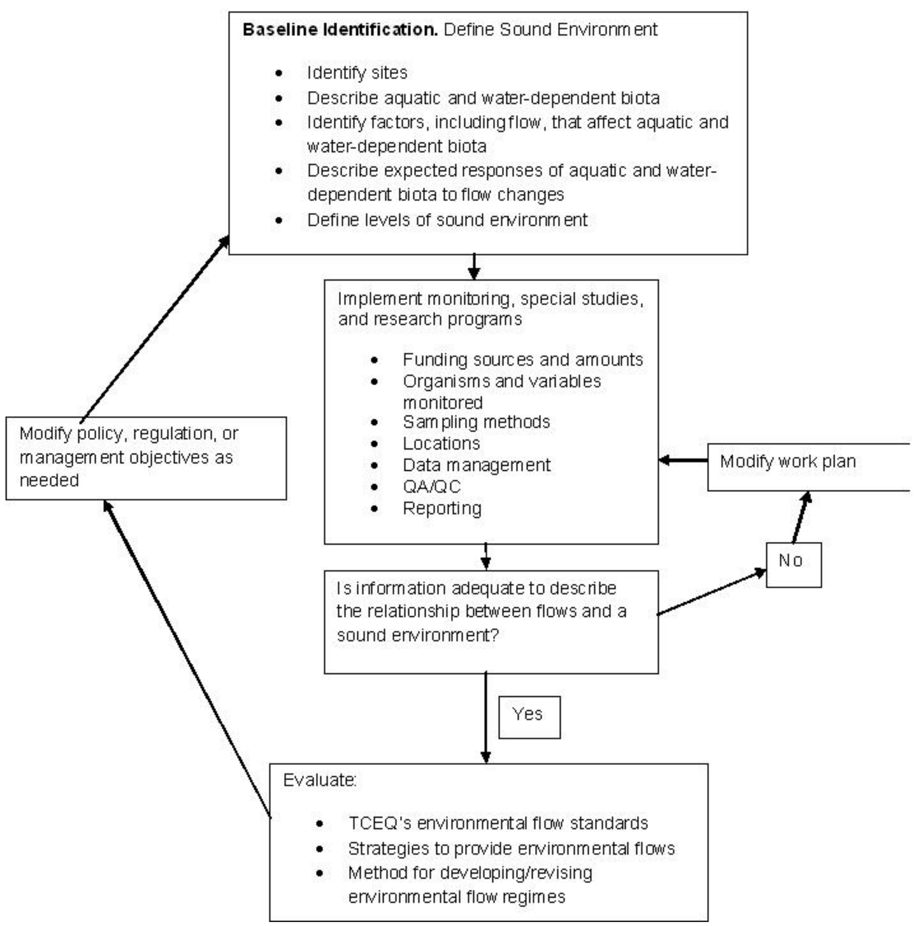
7.5 Baseline Identification

The BBASC would create a work group to describe ecological baseline conditions that represent a sound environment for each site included in the BBEST's environmental regime report and for sites added later. The group could include representatives of the BBASC and the BBEST as well as local, state, and federal experts, university researchers, and others. Measurable ecological components and their values which represent a sound environment would be described for each water body.

Achievement of baseline values would be used to assess whether or not flow regimes are maintaining a sound environment. Ecological components may include lists of aquatic species (e.g., fish, benthic macroinvertebrates including mussels, aquatic and riparian vegetation), expected relative abundance, food web composition, reproductive behavior, area of water-dependent wetlands like marshes, habitat availability, etc.

The sound environment baselines for each water body would be completed by 2016. The sound environment descriptions will be dynamic and modified as more information is obtained. The diagram below illustrates this process and is based on the U.S. Environmental Protection Agency report (2005), "Use of Biological Information to Better Define Designated Aquatic Life Uses in State and Tribal Water Quality Standards: Tiered Aquatic Life Uses."

Adaptive Management Plan Flow Chart



Sample Detailed Task

Instream Flow: Relationships between flow regime components and physical, chemical, and biological ecosystem components.

This section describes an example holistic approach to sampling instream sites intended to help understand relationships between flows and sound environment in streams and rivers.

1. Sampling Period

Annual monitoring should be conducted during the late summer or early fall at each site. The goal is to minimize variation due to flows during the sampling period, maximize sampling gear efficiencies, and permit comparative evaluations of the aquatic, riparian, water quality, and physical conditions. It is suggested that intensive Texas Instream Flow Program (Senate Bill 2-style) studies not be initiated at this time. We believe that it would be more practical to implement intensive surveys based on the 5 year monitoring results if monitoring results show that alternative flow regimes may be warranted or the status of the system is trending toward an unsound ecological environment.

2. Establishment of Monitoring Reaches

At each site, a monitoring reach should be established of sufficient length (~150 mean active channel widths) provided site access and logistics allow, near enough to the USGS flow gage to allow an accurate understanding of flows and flow changes.

3. Data Collected

a. Flows

The work plan should track plans to maintain flow gaging at all sites of interest in order to ensure flow continues to be monitored by USGS at all necessary sites. At each site, it is recommended that the daily gage data be analyzed in terms of attainment frequencies of the various environmental flow regime components such as:

- percent of time flows were observed in each of the base flow levels;
- number, timing, and duration of pulse flow events;
- number, timing, and duration of overbank flow events; and
- amount and timing of all diversions.

As much attention as possible should be placed on quantifying flows contributed by groundwater, whether from springs, alluvial aquifers, or bank storage. Some of these flows derived from groundwater which contribute to stream flow are typically referred to as "base flow". This should be done for main-stem river channels as well as tributaries in areas where groundwater outflows to surface waters are anticipated. Quantification of groundwater flows and how they are changing should be focused in areas where groundwater withdrawals have affected stream flow or where they may affect stream flows in the future.

b. Water Quality and Temperature

Available data from all existing water quality monitoring activities should be assimilated and analyzed for trends and potential limiting values for target aquatic biota. It is recommended that during the initial 5 year monitoring activities that meters be placed within the monitoring reach to accumulate daily oxygen and temperature data that would permit calibration of a water quality model such as QualTx. Modeling oxygen levels and temperature with flow will permit an evaluation of subsistence flows and water quality conditions that may impact the aquatic biota.

c. Aquatic Biota Monitoring

Sampling should be conducted using a variety of gear types (i.e. electrofishing, seining, hoop nets, etc.) in three replicates of all available mesohabitat types within each established monitoring reach. Examples of different mesohabitats are shallow pools or deep pools, riffles, and shallow or deep runs. This sampling will permit assessment of the community structure and distribution by habitat types. All fish should be identified to species, total lengths and wet weights measured, and qualitative data on overall condition such as emaciation, external parasites, etc, recorded. It is not prudent to focus on only a few indicator species given how little quantitative data exists on community structure and population dynamics. Selection of indicator species should be evaluated at year 5 based on the analysis of the holistic sampling results.

It is also recommended that 3 replicate samples of both invertebrate drift and benthic invertebrates be collected from a randomly selected riffle habitat at the monitoring site. All available mesohabitats should be surveyed for mussels within each monitoring reach to assess their distribution and abundance within the monitoring reach. Data should be collected on spawning condition. These data should be analyzed in terms of species composition, relative abundance, and relation to flow, etc.

d. Habitat Monitoring

Mesohabitat mapping should be conducted with the aquatic biota sampling. This mapping should delineate the area of each mesohabitat and its characteristics like maximum depth, current velocity, substrate, and cover for fish (i.e. vegetation, woody debris). Mesohabitat maps will relate aquatic biota to habitats at each monitoring site. Linking habitat availability with biological community composition and relative abundance will help understand how changes in habitat availability with flow can impact species distributions and abundance. These data will also be valuable in assessing potential trends in habitat availability over time.

e. Channel Geometry and Riparian Community

The shape of the cross-sections across the river should be measured from where the riparian vegetation meets the upland vegetation from one side of the river to the other side where the riparian and upland vegetation meet. The shape of cross-sections across the river should be measured at approximately 20 points along the channel on an annual basis. Riparian plants, their ages, and locations should be measured along each of these cross sections. These data should be analyzed to examine changes in native and non-native plants and their recruitment into the riparian zone. At each cross section, Wolman Pebble counts (a technique for measuring the size of particles on the river bottom) should be conducted to describe the sizes of particles on the river bottom. These data will show if large changes in bottom sediment movement are affecting river channel characteristics.

f. Land Use/Land Cover

Changes in land use and land cover should be examined every 5 years within the contributing watershed and used to assess trends that can affect flow regimes and changes in water quality. The contributing watershed is the portion of the watershed where rainfall runoff will enter into a stream and flow through the watershed. Non-contributing areas are the portions of the watershed where rainfall will not runoff into a stream. This should identify for example changes in impervious layer area, changes in native and non-native vegetation, agricultural crop patterns, etc.

g. Funding Sources

Funding by the U.S. Environmental Protection Agency supports monitoring by TCEQ. The CRP is a state fee-funded program and the monitoring is conducted by partner agencies — primarily river authorities. Different private, state (e.g., State Wildlife Grants), and federal grant programs occasionally make funding available for this type of data collection and analysis. A work group of BBASC and BBEST members should be established in each basin by 2012 for the purpose of pursuing alternative funding sources.

h. Potential Confounding Variables

Relationships between flow regime and environmental health may be confounded by:

- Episodes (fish die-offs and spills) that negatively impact biota and affect biological monitoring results;
- Point and nonpoint source pollutants;
- Invasive species;
- Urban development in the watershed that increases impervious cover;
- Changes in land use and/or land cover; and
- Changes in ground water use.

i. Schedule and Reports

Data collection and analysis should be reviewed by 2017 and a report should be produced that summarizes information collected, identifies changes that need to be made in monitoring, and identifies potential aspects of environmental flow regime that may need to be modified in the future.

A summary report should be produced by 2021, summarizing data collected from present into 2021 and making recommendations for environmental flow regime components. This report will also identify water bodies that should be studied in the future.

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