Environmental Flows Recommendations Reports by the Rio Grande, Rio Grande estuary, and Lower Laguna Madre Basin and Bay Expert Science Teams (BBESTs)

July 27, 2012

INTRODUCTION

Section 11.02362(b)(3) of Senate Bill 3 (SB3) as enacted by the 80th Texas Legislature in 2007 identifies the river basin and bay system consisting of the Texas portions of the Rio Grande, the Rio Grande estuary, and the Lower Laguna Madre (collectively the Texas Rio Grande system) as a priority system for the purpose of developing environmental flow regime recommendations and adopting environmental flow standards. This report presents the findings and recommendations of the SB3 Rio Grande Basin and Bay Expert Science Team (BBEST) regarding these environmental flow requirements. Because of distinct differences in the aquatic environments across the Texas Rio Grande system, the associated different needs with regard to protecting environmental flows, and the unique water rights, water availability and institutional aspects of this system, this SB3 work has been conducted by two subgroups of the BBEST, a Lower Rio Grande BBEST and an Upper Rio Grande BBEST.

The Texas Rio Grande system as defined by SB3 covers a large geographical area characterized by extremely varied climatic and hydrologic conditions and correspondingly varied aquatic biological resources extending from the humid subtropical coastal environment on the lower end to the semi-arid middle basin and finally to the upper basin Big Bend desert region. In total, this system covers approximately 70,000 square miles within Texas, and the Rio Grande itself extends over 1,200 river miles along the international border between the United States and Mexico from near El Paso, Texas to the Gulf of Mexico. On this segment of the river, there are two major international reservoirs, Amistad Reservoir just upstream of Del Rio, Texas, and Falcon Reservoir downstream of Laredo, Texas, both of which are jointly operated by the United States and Mexico Sections of the International Boundary and Water Commission (IBWC). Water users in Texas are the sole beneficiaries of the United States share of water from these two reservoirs, and releases are made for Texas users at the request of the Texas Rio Grande Watermaster under the Texas Commission on Environmental Quality (TCEQ).

Downstream of Fort Quitman, Texas, to the mouth of the Rio Grande at the Gulf of Mexico, the flows in the Rio Grande are divided between the United States and Mexico by the provisions of the 1944 Treaty between the two countries, with portions of the inflows from some of Mexico's tributaries assigned to the United States. The IBWC performs daily accounting of inflows and ownership of the waters flowing in the Rio Grande for this segment of the river. Upstream of Fort Quitman, the Convention of 1906 defines the ownership of flows in the Rio Grande between the United States and Mexico. The Rio Grande Compact between the Texas, New Mexico and Colorado divides the inflows to the upper portion of the Rio Grande among these states. These multiple institutional arrangements and the various agencies and entities involved in their implementation can complicate the management of the flows in the river for purposes of environmental protection. For example, as noted in Section 11.02362(m) of SB3, it is specifically acknowledged that "For the Rio Grande below Fort Quitman, any uses attributable to Mexican water flows must be excluded from environmental flow regime recommendations".

There are over 1,500 surface water rights within the Texas Rio Grande system that authorize the diversion of about 3.5 million acre-feet of water per year for a variety of uses including domestic, municipal, industrial, mining and irrigation. Water rights on the middle and lower portions of the Rio Grande below Amistad Reservoir are supplied with stored water from Amistad and Falcon Reservoirs, to the extent it is available, and these water rights are subject to a class-based system of water rights administration that prioritizes the available supplies for these water rights based on their type of use, with domestic, municipal and industrial uses assigned the highest priority. Currently, the combined authorized annual diversion from Amistad and Falcon Reservoirs for these middle and lower Rio Grande water rights is about 2.15 million acre-feet per year, whereas the combined firm annual yield of these reservoirs is only about 1.05 million acre-feet per year, which creates a situation of substantial over-appropriation and periodic shortages for many of the lower-priority water rights, i.e., irrigation and mining. Other water rights in the Texas Rio Grande system that do not rely on Amistad and Falcon Reservoirs for their supplies are subject to the prior appropriation doctrine for the allocation of available streamflows during dry periods. Under this doctrine, the older water rights are allocated available streamflows first before the more junior priority rights, which again results in significant supply shortages for many water rights.

Because of the significant over-appropriation of available surface water supplies in the Texas Rio Grande system, the TCEQ, which is the water rights regulatory agency for Texas, generally considers that no unappropriated water is available within the system for the issuance of new water rights permits. Since the environmental flow standards adopted by the TCEQ under authority of SB3 apply only to new permits or certain water rights amendments issued by the TCEQ on or after September 1, 2007, there appears to be little or no need for specific environmental flow regime recommendations from the BBEST or environmental flow standards from the TCEQ solely for new appropriations of water within the Texas Rio Grande system.

Still, there is need to understand the aquatic biological resources that exist and have existed within key portions of the Texas Rio Grande system and their relationships to streamflows. For example, in the upper Big Bend portion of the Rio Grande basin, efforts are underway to acquire existing water rights that then can be dedicated to protecting environmental flows – the question is how much water is needed. The timing and magnitude of releases from Luis L. Leon Reservoir on the Rio Conchos near Presidio to meet treaty delivery requirements to the United States also could potentially be adjusted to maximize the beneficial effects of various flow patterns on maintaining channel features and biological integrity downstream along the Rio Grande, but more information on the flow patterns needed to accomplish these purposes is needed. In the lower basin, studies are underway to assess the role of marsh grasses in the Laguna Madre for supporting a wide variety of marine organisms and processes, and one of the key aspects of this research is the importance of freshwater inflows from the Arroyo Colorado for maintaining conditions conducive to these marsh grasses.

Recognizing: (1) that no new water rights permits would likely be issued by the TCEQ within the Texas Rio Grande system, (2) that there are specific needs in some portions of the Texas Rio Grande system for pursuing SB3 environmental flow studies to investigate environmental flow requirements, and (3) the fact that initial funding for the BBEST's work was limited and of short duration, the Basin and Bay Area Stakeholders Committee (BBASC) for the Texas Rio Grande system determined at the outset of the Rio Grande SB3 process that the scope of activities of the BBEST should be limited to a manageable portion or portions of the system area so that this work could reasonably be accomplished within the given timeframe and funding. To this end, the BBASC, through consensus action, identified the Rio Grande basin upstream of Amistad Reservoir and below Fort Quitman, including the Pecos and Devils river basins, as the Upper Rio Grande BBEST Study Area, and the segment of the Rio Grande below Falcon Dam, the Rio Grande estuary, the Arroyo Colorado and the Lower Laguna Madre as the Lower Rio Grande BBEST Study Area.

The work of these two BBEST subgroups is reported in this document as separate sections with separate recommendations.

Environmental Flows Recommendations Report

Final Submission to the Environmental Flows Advisor Group, Rio Grande Estuary and Lower Laguna Madre Basin and Bay Area Stakeholders Committee, and Texas Commission on Environmental Quality

Texas Commission on Environmental Quality

Texas Parks & Wildlife

Texas Water Development Board

Rio Grande, Rio Grande Estuary, and Lower Laguna Madre Basin and Bay Expert Science Team

July 2012

Rio Grande, Rio Grande Estuary, and Lower Laguna Madre Basin and Bay Expert Science Team

July 25, 2012

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

Tony Reisinger, Chair
Rio Grande, Rio Grande Estuary, and Lower Laguna Madre Basin and Bay Stakeholder Committee

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

The Rio Grande, Rio Grande Estuary, and Lower Laguna Madre Basin and Bay Expert Science Team (Lower Rio Grande BBEST) submits it final report as charged under Senate Bill 3 (89th R, 2007). This final report includes environmental flow recommendations and the rationales used to determine them. The Lower Rio Grande BBEST members have reached consensus on these recommendations.

Respectfully submitted,

______________________________ .... ______________________________
Hudson DeYoe, Ph. D., Chair ....Robert Edwards, Ph. D.

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David Buzan, Vice Chair .... Carlos Marin, Ph. D.

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Jude Benavides, Ph. D. .... Warren Pulich Jr., Ph. D.

Rio Grande BBEST Acknowledgements

The members of the Rio Grande Basin and Bay Expert Science Team respectfully and gratefully acknowledge the invaluable technical and logistical support provided by the following organizations and very capable individuals:

- Texas Water Development Board – Carla Guthrie, Caimee Schoenbaechler, Junji Matsumoto, Nolan Raphelt, Ruben Solis, and Gayla Ray

- Texas Parks and Wildlife Department – Mark Lingo, Lynne Hamlin, and James Tolan

- Texas Commission on Environmental Quality – Cory Horan, Chris Loft, and Erasmo Yarritos, Jr.

- Texas Sea Grant – Tony Reisinger

This report may be cited as follows:

Rio Grande, Rio Grande Estuary, and Lower Laguna Madre Basin and Bay Expert Science Team for the Lower Rio Grande Basin. 2012. Environmental Flows Recommendations Report. Final Submission to the Environmental Flows Advisory Group, Rio Grande, Rio Grande Estuary, and Lower Laguna Madre Basin and Bay Stakeholders Committee, and Texas Commission on Environmental Quality.

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Common Abbreviations

ac-ft	acre-feet (volume of water equal to one acre covered to a depth of 1 foot)
BBASC	Rio Grande Basin and Bay stakeholder committee
BBEST	Lower Rio Grande Basin and Bay expert science team
cfs	cubic feet per second
ENSO	El Nino/Southern Oscillation
EPA	Environmental Protection Agency
fps	feet per second
GIWW	Gulf Intracoastal Water Way
HECRAS	Hydrologic Engineering Centers River Analysis System
HEFR	Hydrology-Based Environmental Flow Regime
HSC	Habitat Suitability Criteria
NRCS	Natural Resources Conservation Service
PDO	Pacific Decadal Oscillation
ppt	parts per thousand, a measure of salinity. For example, 1 ppt means 1 part salt in 1,000 parts water
PSU	practical salinity unit; approximately equal to 1 part per thousand (ppt) unit
SAC	Texas Environmental Flows Science Advisory Committee
SB 2	Senate Bill 2
SB 3	Senate Bill 3
TESCP	Texas Ecological Systems Classification Program (Section 3.8)
TIFP	Texas Instream Flow Program
TPWD	Texas Parks and Wildlife Department
TWDB	Texas Water Development Board
TxRR	Texas Rainfall-Runoff model
US and USA	United States of America
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey

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. The process (**Figure 1.1.1**) began with selection of the Environmental Flows Advisory Group (EFAG) and reaches an interim conclusion for each river basin and associated estuarine system when the Texas Commission on Environmental Quality (TCEQ) adopts rules implementing environmental flow standards. This Environmental Flows Recommendations Report is the primary deliverable of the Rio Grande Basin and Bay Expert Science Team (Rio Grande BBEST) and is provided to help stakeholders and the TCEQ in their deliberations and development of environmental flow standards.

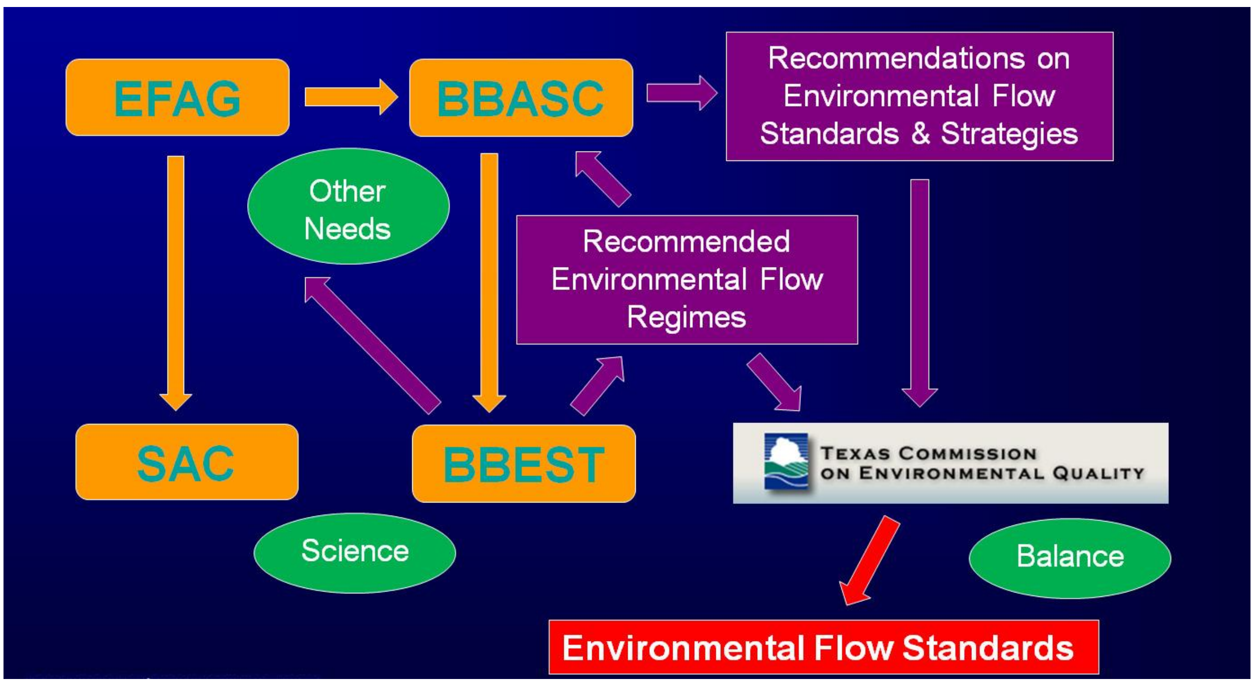

Figure 1.1.1. SB3 Environmental Flow Process (chart developed by Sam Vaugh, Nueces BBEST).

1.1.1. Environmental Flows Advisory Group (EFAG)

The EFAG has 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 Rio Grande Basin and Bay Area Stakeholder Committee (BBASC). The EFAG also provides a technical review of the adequacy of BBEST reports.

1.1.2. Science Advisory Committee (SAC)

The SAC has nine technical experts in diverse areas relevant to environmental flows and has provided documented guidance to both BBESTs and BBASCs regarding development of environmental flow recommendations. 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 interrelationships between environmental flow regimes and water supply projects, and consideration of attainment frequencies and hydrologic conditions. This guidance has been relied upon by the Lower Rio Grande BBEST in execution of its charge although not to the extent of its use by other BBESTs. The highly modified and regulated hydrology of the Rio Grande, resacas, and the Arroyo Colorado creates different circumstances for which some of the guidance is less applicable.

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, electricity generation, commercial fishing, public interests, regional water planning, river authorities, and environmental groups. BBASCs appoint BBESTs comprised of technical experts with knowledge of particular river basin and bay systems and/or development of environmental flow regimes.

The Rio Grande BBASC is comprised of 19 members. On February 28, 2011, the Rio Grande BBASC appointed 12 scientists as members of the Rio Grande BBEST. The Rio Grande BBASC at this time also divided the BBEST into Upper Rio Grande and Lower Rio Grande BBESTs with 6 scientists assigned to each BBEST. The Upper Rio Grande BBEST was charged with identifying environmental flow recommendations for the reach of the Rio Grande from Presidio downstream to Lake Amistad and including the Pecos and Devil River watersheds. The Lower Rio Grande BBEST was charged with focusing its development of environmental flow recommendations to freshwater inflow needs of the estuaries. This report provides the recommendations of the Lower Rio Grande BBEST.

Information regarding the Lower Rio Grande BBEST is summarized in **Section 1.2**. Once a BBEST issues its recommendations report, the appointing BBASC will consider 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.

<u>Justification for Upper and Lower Basin BBESTs</u>

Section 11.02362(b)(3) of Senate Bill 3 (SB3) as enacted by the 80th Texas Legislature in 2007 identifies the river basin and bay system consisting of the Texas portions of the Rio Grande, the Rio Grande estuary, and the Lower Laguna Madre (collectively the Texas Rio Grande system) as a priority system for the purpose of developing environmental flow regime recommendations and adopting environmental flow standards. Because of distinct differences in the aquatic environments across the Texas Rio Grande system, the associated different needs with regard to protecting environmental flows, and the unique water rights, water availability and institutional aspects of this system, this SB3 work has been conducted by two subgroups of the BBEST, a Lower Rio Grande BBEST and an Upper Rio Grande BBEST. This report presents the findings and recommendations of the Lower Rio Grande BBEST.

The Texas Rio Grande system as defined by SB3 covers a large geographical area characterized by extremely varied climatic and hydrologic conditions and correspondingly varied aquatic biological resources extending from the humid subtropical coastal environment on the lower end to the semi-arid middle basin and finally to the upper basin Big Bend desert region. In total, this system covers approximately 70,000 square miles within Texas, and the Rio Grande itself extends over 1,200 river miles along the international border between the United States and Mexico from near El Paso, Texas to the Gulf of Mexico. On this segment of the river, there are two major international reservoirs, Amistad Reservoir just upstream of Del Rio, Texas, and Falcon Reservoir downstream of Laredo, Texas, both of which are jointly operated by the United States and Mexico Sections of the International Boundary and Water Commission (IBWC). Water users in Texas are the sole beneficiaries of the United States' share of water from these two reservoirs, and releases are made for Texas users at the request of the Texas Rio Grande Watermaster under the Texas Commission on Environmental Quality (TCEQ).

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Because of the significant over-appropriation of available surface water supplies in the Texas Rio Grande system, the TCEQ, which is the water rights regulatory agency for Texas, generally considers that no unappropriated water is available within the system for the issuance of new water rights permits. Since the environmental flow standards adopted by the TCEQ under authority of SB3 apply only to new permits or certain water rights amendments issued by the TCEQ on or after September 1, 2007, there appears to be little or no need for specific environmental flow regime recommendations from the BBEST or environmental flow standards from the TCEQ solely for new appropriations of water within the Texas Rio Grande system.

Still, there is a need to understand the aquatic ecosystems that exist and have existed within key portions of the Texas Rio Grande system and their relationships to stream flows. In the lower basin, studies are underway to assess relationships between seagrass abundance and composition in the Lower Laguna Madre and freshwater inflows to the Laguna Madre. One of the key aspects of this research is the effect of freshwater inflows from the Arroyo Colorado on Laguna Madre seagrasses.

Recognizing: (1) that no new water rights permits would likely be issued by the TCEQ within the Texas Rio Grande system, (2) that there are specific needs in some portions of the Texas Rio Grande system for pursuing SB3 environmental flow studies to investigate environmental flow requirements, and (3) initial funding for the BBEST's work was limited and of short duration, the Basin and Bay Area Stakeholders Committee (BBASC) for the Texas Rio Grande system determined at the outset of the Rio Grande SB3 process that the scope of activities of the BBEST should be limited to a manageable portion or portions of the system area allowing that this work could reasonably be accomplished within the given timeframe and funding. The BBASC, through consensus action, identified the Rio Grande basin below Falcon Dam, the Rio Grande estuary, the Arroyo Colorado and the Lower Laguna Madre as the Lower Rio Grande BBEST Study Area.

1.2. Lower Rio Grande Basin and Bay Expert Science Team (Lower Rio Grande BBEST)

1.2.1. Membership

The Lower Rio Grande BBEST is comprised of 6 members appointed by the Rio Grande BBASC. Active membership of the Lower Rio Grande BBEST is summarized below along with assignments.

Hudson DeYoe	Chair, Lower Laguna Madre Co-lead	University of Texas-Pan American, Edinburg, TX
Dave Buzan	Vice-chair, Resaca and Arroyo Colorado Lead	Atkins Global, Inc., Austin, TX
Jude Benavides	Hydrology Co-lead	University of Texas at Brownsville, Brownsville, TX
Carlos Marin	Hydrology Co-lead	Ambiotec, Inc., Brownsville, TX
Robert Edwards	Rio Grande Lead	University of Texas-Pan American, Edinburg, TX
Warren Pulich Jr.	Lower Laguna Madre Co-lead	Texas State University, San Marcos, TX

1.2.2. Lower Rio Grande 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.*

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

Since its first meeting on April 20, 2011, the Lower Rio Grande BBEST has worked to its charge. As a result of regular meetings of the full BBEST, focused subcommittee meetings, and the individual and collective efforts of BBEST members, we believe that we have met that charge. Agendas and minutes of the Lower Rio Grande 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, and Tony Reisinger, the chair of the BBASC. The University of Texas - Pan American and the University of Texas at Brownsville graciously provided meeting space.

1.3. Sound Ecological Environment

The BBEST charge is to develop flow regimes "adequate to support a 'sound ecological environment' and to maintain the productivity, extent and persistence of key aquatic habitats in and along the affected water bodies." The Lower Rio Grande BBEST adopted the definition of sound ecological environment described by the Science Advisory Committee for Environmental Flows (SAC 2006) as follows:

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.

We note that these points refer broadly to attributes or status of an environment (e.g. species composition and habitats) and ecological functions and processes. The 2006 SAC, in subsequent discussion, also highlighted a key point, for which we agree with, that the adjective "sound" may be interpreted differently when viewing different aquatic systems and through the lens of various stakeholders or others. In the view of this science team, "sound" does not equate to "natural" or "pristine". Thus, evidence of some level of alteration still allows for a determination of "soundness."

We believe, given the 2006 SAC concepts and recognition of the scope of the word "sound," that a comprehensive definition can be offered. The BBEST used the following modification of the SAC's characterization of sound environment. A sound environment:

- Maintains native species,
- Is sustainable, and
- Is a current condition. Current condition represents the condition from some year to present identified by the BBEST. The period of current condition may be defined differently for each body of water.

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

The BBEST applied this definition of a "sound ecological environment" to the following six geographical regions of the Lower Rio Grande study area:

- Lower Laguna Madre (LLM)
- Tidal portion of the Rio Grande
- Above-tidal portion of the Rio Grande up to Anzalduas Dam
- Arroyo Colorado
- Resacas; and
- Coastal basins between the LLM and the Rio Grande tidal.

Evaluation of the criteria for a sound ecological environment was then conducted for each of these regions.

1.3.1. Riverine

Rio Grande Above Tidal

The Rio Grande in its above tidal and tidal reaches should not be considered sound ecological environments when compared to their historical condition prior to the early 1900s. The hydrology has been substantially altered since dams and flood control structures have eliminated flooding from the Rio Grande. Flows in the river have also been reduced since the initiation of gravity irrigation which has removed a substantial portion of the original water flow. This is most pronounced in the tidal portion of the Rio Grande which has periodically ceased flow during extreme periods of drought, but most recently in a non-severe drought period in 2001. Water quality issues have also arisen with the growth of population and from various irrigation practices. However, the Rio Grande BBEST agreed to consider a definition of sound environment that focused on the current condition and whether it supported sustainable populations of native species.

Application of this definition to the above tidal portion of the Rio Grande from above the Anzalduas flood control structure downstream to the El Jardin weir indicates that an ecologically sound environment would:

- Sustain a riparian plant community dominated by a diverse group of native riparian plants;
- Have an absence of invasive, exotic aquatic plants like water hyacinth, water lettuce, and Hydrilla, and
- Provide sufficient freshwater inputs to support an aquatic community including:
- One or more threatened amphibians, for example the Rio Grande siren (*Siren intermedia texana*), black-spotted newt (*Notophthalmus meridionalis*), or Mexican white-lipped frog (*Leptodactylus fragilis*)
- Two or more species of native turtles
- A mixed community of native fishes, including approximately two-thirds to three-quarters of the species being primary freshwater species (also native species with a range of feeding habits including top predators), which is not dominated

by exotic fish species and approximately one-quarter to a third of the species being secondary freshwater or estuarine species.

Arroyo Colorado

Little is known about the ecological condition of the Arroyo Colorado prior to the 1950s and its dredging to accommodate barge traffic. Prior to that time, it was described as one of two perennial streams, along with the Rio Grande, in Cameron County; and as a ditch that frequently was filled with salt water from its connection to the hypersaline Laguna Madre. As freshwater flow has increased to the Arroyo Colorado over the past 60 years, a more typical estuarine condition has been created between the freshwater flow of the Arroyo (treated wastewater and irrigation return flow periods without rainfall) and the Laguna Madre which is no longer typically hypersaline. The lower 10 river miles of the Arroyo is currently utilized as nursery habitat by a variety of native estuarine and marine species, such as white shrimp (*Penaeus setiferus*), spotted sea trout (*Cynoscion nebulosis*), and red drum (*Sciaenops ocellatus*).

However, the sound ecological condition of the Arroyo Colorado is inseparably linked to its shape and the quality of freshwater entering it. The relatively deep, dredged channel, allows a stable salt water wedge to intrude far up the Arroyo. During the summer this salt water layer combined with the nutrient-rich freshwater inflow from wastewater treatment plants and irrigated fields, creates stable anoxic conditions in the layer of the Arroyo Colorado below 5 feet deep from the Port of Harlingen downstream over 15 stream miles. These anoxic conditions have led to frequent fish kills in past years, although the upper layer of water has continued to provide estuarine conditions in much of the upper reach.

The Rio Grande BBEST does not consider the Arroyo Colorado a sound environment in regard to flow because the current flow does not support a healthy, diverse, sustainable community of native fish and shellfish along its entire length and because the sources of flow degrade water quality in the upper 15 river miles of the Arroyo.

Brownsville/Resaca Watershed

Resacas should not be considered sound ecological environments when compared to their historical condition before the early 1800s. Their hydrology has been substantially altered since dams and flood control structures have eliminated flooding from the Rio Grande which historically was one of their primary sources of water. This pattern of flooding connected the hydrology, chemistry, and biology of the Rio Grande and resacas.

Despite the changes over the past 200 years, resacas provide valuable ecological services. Resacas provide valuable habitat for a variety of amphibians like the state-threatened Rio Grande siren and fish. Dense riparian vegetation surrounding some resacas provide habitat for migratory songbirds and semitropical birds found primarily in this subtropical region of Texas.

The hydrological control of the lower Rio Grande suggests the river will cease migrating back and forth over its lower flood plain between McAllen, Texas, and the Gulf of Mexico.

With the loss of this river migration, resacas will no longer be formed. Without human intervention to protect existing resacas they can be expected to gradually fill with sediment and stop functioning ecologically as perennial water bodies.

1.3.2. Estuarine

<u>Lower Laguna Madre</u>

The BBEST considers estuarine and wetland ecosystems of the LLM “relatively sound” with qualified exceptions. We must acknowledge that its characteristic ecosystems have exhibited adaptive responses over the past 60+ years, as the lagoon has transitioned from the historical natural conditions of the late 1950s to present. Geomorphological alterations in the 1950s (viz., dredging of channels and passes) have changed the lagoon environment and its characteristic species and habitats. Therefore, the current time frame for evaluation of ecological health of the LLM extends from only ca 1960 to present. Conditions observed now can be considered adaptive responses to a more stable, lower-salinity environment, as a result of the absence of the extremely high salinity regimes formerly seen in the pre-1960s era (Carpelan 1967, Quammen and Onuf 1993, Onuf 2007), as well as recent evidence of climate changes (Tolan and Fisher 2009).

Several lines of evidence support the BBEST’s determination that the Lower Laguna Madre Estuary environment has been “sound” from the early 1960s, but that it appears to be undergoing detrimental changes over the last 15-20 years. Measures of the status of some native species and habitats indicate that impairment of estuarine biologic and chemical processes may be occurring. As one of only 5 historically hypersaline lagoonal estuaries in the world (Tunnell 2001), this unique system is exhibiting recent symptoms of ecological disturbance that are indicative of impacts to its ecological “soundness”.

1. The LLM is famous for its lush seagrass beds, which accounted for approx. half of the total seagrass acreage in Texas as of 1996. However, this highly productive habitat actually decreased overall from its peak of 59,153 ha in the 1960s, to 46,558 ha in mid-1970s, and then to 46,624 ha in 1988, as documented by Quammen & Onuf (1993). Seagrass acreage and species composition changed because of dredging the Gulf Intracoastal Waterway (GIWW) and Mansfield Pass, hypersalinity amelioration, and species successional processes in a shallow high-salinity lagoon (this seems to contradict the second factor). These changes in quantity of seagrasses were accompanied by large changes in species composition, with the hypersalinity-tolerant species, shoal grass (*Halodule*), being reduced by over 60% and displaced by manatee grass (*Syringodium*) and turtle grass (*Thalassia*). An updated survey in 1998-2000 [Seagrass Status and Trends for the Laguna Madre, (Onuf 2007)] assessed the total acreage in 2000 at 46,174 ha, very similar to the 1988 level. However, Onuf (2007) concluded that the Lower Laguna Madre seagrasses were still showing effects from water clarity degradation probably from maintenance dredging on the GIWW and nutrient loading from unknown sources. As we will show later in this report, seagrass acreage has undergone further decline over the last decade, as much as 24% in the region from Port Mansfield south to around Stover Point. Species composition has also changed significantly for this region, as indicated by almost complete loss of *Thalassia* and *Syringodium*.

An equally unique feature of LLM is its extensive wind-tidal flats covered with cyanobacterial (‘blue-green algal’) mats. Such wind-tidal flats, occurring in the intertidal zone, basically replace the characteristic intertidal salt marsh habitat existing on the middle and upper Texas coast which is largely absent in LLM. These semi-aquatic algal mat systems are well-known for their high primary production and nitrogen fixation which helps support the LLM food webs (Pulich and Rabalais1986). Since the 1980s (White et al. 1986), the integrity of these unique intertidal areas has been degraded by heavy impacts from off-road vehicular traffic and development activities on South Padre Island.

2. Long-term maintenance of normal estuarine fishery populations would appear to be possible only within the context of a generally sound estuarine environment. At the request of the BBEST, James Tolan of the Corpus Christi Regional Office of Texas Parks and Wildlife Department compiled a status and trends assessment based upon the 25 years of fishery samples data collected by the TPWD Coastal Fisheries Resource Monitoring Program for the LLM. The results of this analysis, covering the ten species that numerically comprised > 95% of the individuals collected in all samples from 1982-2010, showing routine fluctuations in catch rates, except for blue crab (*Callinectes sapidus*) (see TPWD Resource Monitoring data in Appendix).Thus, most fisheries communities in the LLM are considered stable and intact, characteristic of the estuarine species of this subtropical area of the lower Texas coast (Mark Lingo,TPWD, pers. comm.). With the exception of blue crabs and southern flounder (*Paralichthys lethostigma*), no significant decreases in the abundance of native species or overall changes in their trophic structure have been observed over the recent past. It is noteworthy, however, that a tropical species, gray snapper (*Lutjanus griseus*), has increased significantly in recent years in the LLM (Tolan and Fisher 2009). Additionally, some prized tropical game fish species, notably snook (*Centropomus spp*.) and tarpon (*Megalops atlanticus*), were also encountered more frequently. Tropical macroalgae (e.g. *Penicillus*) recently have also been observed after many years of absence (Kowalski et al. 2007). These documented increases in tropical flora and fauna are thought to be related to increasing wintertime water temperatures, which have shown an upward trend from the early 1990s until 2009 (ca. 1 ºC rise over this period). Taken together, these observations would all appear to reflect a change to a warmer environment beginning to dominate the LLM (Tolan and Fisher 2009).

The well-documented decline in blue crab abundance is a broad-scale phenomenon, encompassing the entire Gulf coast and Atlantic seaboard. A relationship between declines in blue crab and freshwater inflow alterations has not been identified. Recent fluctuations in southern flounder have been noted by sports fishermen, who report fewer numbers caught (Tony Reisinger, pers. comm.). This decline has been observed coast-wide, similar to the blue crab. Possible causes may include overfishing, habitat degradation, limited recruitment, or warming temperatures interfering with reproduction (J. Tolan, pers. comm.).

3. With respect to hydrologic conditions, there has undeniably been a fundamental change since the late 1950s from the dredging of the GIWW (completed in 1952) and the opening of Mansfield Pass to the Gulf in 1958. Although these anthropogenic alterations have ameliorated water conditions from regularly hypersaline (up to 70 – 80 psu), the system still frequently displays arid, high-salinity regimes (above 50 psu). Thus, it is more correct to refer to the earlier extreme salinity conditions as being “tolerated” rather than “required” by the native species. Once salinities were ameliorated from 70 or higher psu to more moderate 30 – 50 psu (as they have been over the last 40 years or so), growth, reproduction, and species diversity of many of the characteristic estuarine flora and fauna have increased dramatically (Carpelan 1967, Gunter 1967, Tunnell 2001).

4. Anthropogenic hydrologic alterations, accompanied by increased freshwater drainage from the Arroyo Colorado and other sources, provide for increased hydrodynamic circulation in the open LLM system. These dynamics have allowed for more rapid dispersion of both salinity and suspended sediments from dredging and also increased inputs of other water quality components, such as dissolved nutrients and contaminants. Regardantly, the biotic and abiotic indicator assessment conducted by NOAA’s National Estuarine Eutrophication Survey of Gulf of Mexico estuaries in 1997 is relevant (NOAA 1996). This report compared current (as of the mid 1990s) conditions over those of the previous 50 years (based on limited data availability). The 1997 report considered that “….chl a [chlorophyll a], turbidity and nutrient concentrations, as well as nuisance algal blooms and hypoxia events, [had] increased. SAV [submerged aquatic vegetation] coverage [had] decreased….toxic bloom events remained unchanged, [but] are observed episodically.”

Recent data on Harmful Algal Blooms (HABs) suggests a significant increase in red tides over the last 20 years (Meridith Byrd, TPWD, Coastal Fisheries Division) for the entire Texas coast, including the LLM. The Texas Brown tide impacted the LLM in the early 1990s (Whitledge and Stockwell 1995) and other algal blooms are also regularly encountered (DeYoe, pers. observ.). These indicators put the LLM in the higher range of estuaries with increasing trends in water quality/nutrient enrichment problems. More recently, NOAA’s Estuarine Eutrophication Assessment Survey Update Report (2007), essentially an “estuarine report card”, stated that the condition of the LLM estuary may have generally improved over the last ten years. However, it concluded that more definitive data were needed to clarify the status of nutrient conditions, phytoplankton blooms (nuisance and HABs), and epiphyte and macroalgal accumulations. Moreover, recent observations by DeYoe (2000s, pers. observ.) and Dunton et al. (unpubl. data from 2011 survey) suggests that epiphytes and macroalgae are still a problem in some LLM locations.

5. In summary, the Lower Rio Grande BBEST has concluded that the evidence presented above supports a determination that a sound ecological environment existed in the Lower Laguna Madre since the late 1950s to early 1990s, but that currently, conditions are tending toward a more unsound (or disturbed) environmental condition. We caution that water quality issues especially warrant consideration because of the potential for causing impacts on LLM seagrass and algal populations, resulting from the direct effects of nutrient/contaminant loading and salinity regimes, and the indirect effects from nuisance phytoplankton and macroalgal blooms. Particularly, reduced water clarity and salinity reduction affecting submerged vegetation compared to 20 – 30 years ago appears problematic. These stressors may be exacerbated by the increasing trend in LLM water temperatures documented by Tolan and Fisher (2009), an indicator of potential climate change impacts. As will be explained later in this report, further studies and monitoring are needed to demonstrate and quantify the connections between these water quality and water quantity (freshwater inflows) dynamics, and their role in contributing to increasing LLM ecological imbalance.

<u>Rio Grande Tidal</u>

Application of this definition to the tidal portion of the Rio Grande from the El Jardin weir downstream to the mouth indicates that an ecologically sound environment would:

- Sustain a riparian plant community dominated by a diverse group of native riparian plants,
- Have an absence of invasive, exotic aquatic plants like water hyacinth, water lettuce, and *Hydrilla*, and
- Provide sufficient freshwater inputs to support a mixed aquatic community including a mixed community of fish including approximately 10-20% of the species being primary freshwater species (including native species with a range of feeding habits including top predators, and continuous flows to the Gulf of Mexico) to allow for all life stages of estuarine and marine species to have access the nursery grounds of the tidal portion throughout the year.

<u>Bahia Grande and San Martin Lake Complex</u>

The Bahia Grande/San Martin Lake region has low relief with very shallow basins interspersed with lomas (clay dunes). Previous to significant anthropogenic development (roads and ship channel) in the 1930s onward, the area was probably periodically flooded by overflows from the Rio Grande and tropical storms bringing torrential rains and/or coastal flooding. Based on this regime, the basins were likely sometimes dry or filled with freshwater or salt water. When filled with water, salinities within the basins probably ranged from zero to hypersaline (>100 psu). It is possible that the basins could have had productive but ephemeral aquatic ecosystems populated by opportunistic, fast-growing species that could tolerate wide salinity fluctuations. It seems unlikely that they ever maintained seagrass-based ecosystems.

One of the first alterations to the region was the construction of a railroad trestle in the 1872 that nearly bisected the Bahia into a northern and a southern basin. This reduced but did not eliminate internal circulation. In 1934-36, the Brownsville Ship Channel was constructed that eliminated communication between the Bahia Grande/San Martin Lake area and the Rio Grande. In the 1953, Highway 48 was constructed that stopped exchange between the Bahia Grande and the ship channel. From 1953 until 2005, the Bahia Grande was essentially a dry basin that may have been intermittently filled with rain water. In 2005, a small pilot channel was constructed that connected the Bahia to the Brownsville Ship Channel.

As there is little data on the condition of the Bahia Grande prior to 2005, we propose to base our definition of a sound ecological environment on the current condition of the Bahia. From 2005 to 2009, a baseline study was performed to document the “recovery” of the Bahia Grande (Hicks et al. 2010) following connection to the ship channel. The main water quality issue was/is hypersalinity. The pilot channel does not provide enough exchange with the ship channel water to keep the waters from becoming hypersaline during summers (excluding the effect of large rainfall events). During the study, salinity ranged from 25 to 120 psu with salinities being usually higher in the more isolated north subbasin. Average basin salinity was >60 psu for 16 of 49 months of the study. Otherwise, nutrients in the Bahia Grande are generally low with ammonium levels less than 8 μM, nitrate-nitrite levels generally less than 4 μM, and dissolved phosphate levels less than 2 μM. Despite low nutrients, water column phytoplankton biomass was considerable at times with chlorophyll values exceeding 40 μg L^{-1} (winter and spring 2008) but these chlorophyll levels may have been due to suspended benthic (bottom) microalgae. Benthic microalgal production (mostly diatoms and cyanobacteria) likely supplies a large portion of the energy for the ecosystem, but further research is needed.

The benthic animal community was dominated by annelid worms (16 polychaete and 1 oligochaete species) with capitellids and spionids being the dominant taxa. Benthic community species richness reached its highest level during January 2008 and 2009 as salinity declined from maximum values. During periods of extreme hypersalinity diversity was generally low. Species richness was generally higher in the southern sub-basin that had more moderate salinities.

Bag seine and gill net sampling methods were utilized to monitor the nekton community. Bag seine samples were dominated by a single species, *Cyprinodon variegates* (sheepshead minnow), accounting for 91% of the total abundance among 24 fish species. Using gill nets, the most common species of the 12 species captured was *Mugil cephalus* (striped mullet) representing 39.5% of total abundance.

The Bahia Grande is a moderately productive ecosystem with an ephemeral faunal community having low to moderate diversity due to periodic changes in salinity. Whether it is a sound ecological environment depends on ecosystem haven been (pre-1930s) naturally variable due to basin characteristics and geography (shallowness, large surface area, poor circulation and sensitivity to hydrologic events). However, since construction of the pilot channel in 2005, this aquatic ecosystem is probably less variable but still stressed by high salinities. Construction of a larger channel has been proposed and funded, however this construction will only substantially affect the southern sub-basin. The northern subbasin will likely still have poor circulation and resulting variable salinities. Currently, the Bahia Grande is not a sound ecological environment, but may become more so with the construction of a new wider channel.

San Martin Lake system consists of three interconnected basins (east, middle and west) the last of which is the largest. The west basin has the best circulation from two features, a wide and deep channel at the south end connecting it to the Brownsville Ship Channel, and the input of freshwater near its northern end. The freshwater actually enters the system at the middle basin which is connected to the western basin. The freshwater comes from the Rancho Viejo Floodway, Loma Alta Lake and the city of Brownsville. The freshwater moderates the salinity of the basin and also adds nutrients to the system as one of the Brownsville waste water treatment plant contributes its effluent to the inflow.

There is no state water quality or fisheries data available for San Martin Lake, however the eastern basin does have well-developed oyster beds in its southern half and is heavily fished (but this may be due more to easy access than a good fishery) (DeYoe, pers. observ.). The oysters may be benefiting from a phytoplankton community whose growth is stimulated by the nutrients coming from the freshwater input. Contrarily, the basin is suspected of being a red tide "incubator" due to the history of red tide occurrences in that area and its environmental features (DeYoe, pers. comm.). A study of San Martin Lake is about to commence to describe its water quality and phytoplankton community.

Because there is little data available, we offer no opinion about whether San Martin Lake is a sound ecological environment.

1.4. Geographic Scope

1.4.1. Water Bodies

The BBEST was initially directed to develop environmental flow recommendations for the Lower Laguna Madre. However, the BBEST, in discussion with the chair of the BBASC, agreed to expand the geographic scope of the BBEST's analysis. The BBEST focused its efforts on important water bodies in the USA portion of the Rio Grande basin downstream of Falcon Dam. Those water bodies included:

- Rio Grande above tidal. This includes the Rio Grande from Falcon Dam downstream to a point about 7 river miles downstream of the International Bridge in Brownsville, where a rock weir prevents tidal movement upstream in the Rio Grande. This reach corresponds to TCEQ water quality segment 2302 and is included in Zapata, Starr, Hidalgo, and Cameron counties.
- Rio Grande tidal. This reach includes the tidally influenced reach of the Rio Grande from a point about 7 river miles downstream of the International Bridge in Brownsville where a rock weir prevents tidal movement upstream in the Rio Grande, and extends 48 miles downstream to the river's mouth with the Gulf of Mexico. This weir is locally referred to as El Jardin. The tidal reach is located entirely within Cameron County.
- Resacas. Resacas are former portions of the Rio Grande channel left behind as the Rio Grande has moved back and forth over thousands of years. Hundreds of miles of resacas provide ecological, recreational, and economic benefits in Hidalgo and Cameron counties. Resacas are found in Hidalgo and Cameron counties.
- Arroyo Colorado. The Arroyo Colorado extends approximately 80 river miles through the lower Rio Grande Valley to its mouth with the Lower Laguna Madre. The upper 63 river miles are upstream of tidal influence (TCEQ water quality segment 2202) while the lower 26 river miles are channelized for navigation and are tidally influenced (TCEQ water quality segment 2201). The Arroyo Colorado watershed includes Hidalgo, Cameron and Willacy counties.
- Lower Laguna Madre. The Lower Laguna Madre extends north from Brazos Santiago Pass to the Land Cut north of Port Mansfield and Mansfield Pass and passes through Cameron, Willacy, and Kennedy counties.

- Bahia Grande and San Martin Lakes. The Bahia Grande and San Martin Lakes receive drainage from the coastal basin north of the Rio Grande and South of the Arroyo Colorado. Both are tidally influenced ecosystems. This area is part of Cameron County.

The BBEST provides quantitative environmental flow recommendations for the Lower Laguna Madre and the Rio Grande tidal in this report. The role of environmental flows for the Brownsville/Resaca watershed, the Rio Grande above tidal, the Arroyo Colorado, and the Bahia Grande and San Martin Lakes are described, but quantitative environmental flow recommendations are not made by the BBEST for those ecosystems.

1.4.2 Geology

The area encompassed by the BBEST's analysis is referred to as the Lower Rio Grande Valley. It includes the northern portion of the historical Rio Grande delta plain created over tens of thousands of years (ACWP 2007). The southern portion of the valley and the deltaic plain is in Mexico, south of the Rio Grande which forms the border between the USA and Mexico. This deltaic plain is relatively flat with an average slope less than 1.5 feet per mile. The upper two-thirds of the basin has soils dominated by clay and silt loams deposited by the Rio Grande while the lower third of the basin is predominantly sand with some silt and clay. Soils are generally loosely consolidated. Groundwater typically can be found from 1 to 30 feet below ground and ranges from fresh to brackish (total dissolved solids up to 10,000 mg/l).

1.4.3. Climate

The Lower Rio Grande Valley has a subtropical/subhumid climate characterized by hot summers and dry winters (Larkin and Bomer 1983). It is considered a "modified marine environment" where weather is dominated by tropical air flowing from the Gulf onshore most of the year. Prevailing winds are from the southeast with an average velocity of 10.5 miles per hour (Texas Coastal Ocean Observation Network [TCOON] 2011, based on measurements every 12 hours from 2000 through 2011).

The US Global Change Research Program coordinates research on changes in the environment including climate changes. Texas is in the southeast USA study region which has a typical climate described as, "…warm and wet, with mild winters and high humidity, compared with the rest of the continental United States" (US Global Change Research Program 2009). The average annual temperature in the southeast region has risen about 2 degrees Fahrenheit (°F) since 1970 with most of the increased temperatures occurring during the winter. Increased winter temperatures are reflected in reductions in the number of freezing days with 1 to 4 fewer freezing days each winter. General weather patterns are influenced considerably by the El Niño Southern Oscillation. El Niño periods produce colder and wetter than normal winters while La Niña periods produce warmer and dryer winters.

Climate models indicate temperatures will continue to increase in the southeast region of the USA during all seasons, with greatest increases occurring during summers. By 2080, average temperatures in the region are expected to be between 4.5 and 9.0°F higher. Climate changes are predicted to increase hurricane peak wind speeds, rainfall intensity, and storm surge height and strength (US Global Change Research Program 2009).

July and August are typically the hottest months of the year while December and January are the coldest months (National Oceanic and Atmospheric Administration [NOAA] 2011). The wettest months of the year are September and October with heavy rains associated with tropical storms. The average annual rainfall is about 26 inches. The highest temperature of 106°F was recorded in March 1984 while the lowest temperature of 12°F was measured in February 1899.

This part of Texas has been affected by 28 tropical storms and hurricanes during the period from 1874 through 2010 (HurricaneCity.com 2011). Impacts from these storms have usually occurred in early September. Although the majority of these storms arrive from the Gulf, some are Pacific storms that cross northern Mexico from west to east to affect the area. The longest period between storms impacting this area is 12 years and the average period between storms has been 5 years.

1.4.4. Terrestrial Biota

The Lower Rio Grande Valley is within the subtropical, semi-arid Tamaulipan Biotic Province (Blair 1950). According to Blair (1950), the Tamaulipan Biotic Province supports three salamander species, only one of which, the Texas black-spotted newt (*Notophthalmus meridionalis meridionalis*) is endemic to the region. The other two species are the barred tiger salamander (*Ambystoma tigrinum mavortium*) and the western lesser siren (*Siren intermedia nettingi*). Nineteen frog and toad species occur or have occurred in the Tamaulipan Biotic Province, along with at least 19 lizard species and 36 snake species (Blair 1950). The region supports many different species of birds. At least 61 mammal species occur or have occurred within recent times in the Tamaulipan Biotic Province (Blair 1950).

1.4.5. Terrestrial Habitat

Thornscrub forest and brush habitat is typically characterized by thorny brush and forest, and mesquite savannahs that occur on upland sites like fluvial riparian zones of resacas and the Rio Grande, and on lomas throughout the study area. A remnant of the sabal palm forest occurs in the Brownsville area (Sabal Palm Grove). Remnants of the impenetrable thornscrub vegetation along the Rio Grande and tributaries provide habitat for rare species of plants and animals (Jahrsdoerfer and Leslie 1998). Importantly, impenetrable brush with a relatively closed canopy can serve as travel corridors for the federally-listed ocelot (*Leopardus pardalis*) and jaguarundi (*Herpailurus yaguarondi*) (USFWS 2012). Many birds only found in the LRGV use thornscrub forest and brushland as habitat (Jahrsdoerfer and Leslie 1998). Within the study area, thornscrub forest occurs along resacas within and near the city of Brownsville. Thornscrub brush exhibits a patchy occurrence, found mainly on high depositional ridges and lomas throughout the Rio Grande Delta.

Clay lomas are brush-covered clay dunes situated within tidal and wind-tidal flats. Because lomas are dunes situated within tidal zones, the abrupt topographic relief creates a unique habitat. The clay lomas were formed through sediment deposition by the Rio Grande River within tidal flats. When these tidal flats are dry, wind-blown particles build the dune. Lomas can reach a height of 30 ft above surrounding flats (Jahrsdoerfer and Leslie 1988). Texas fiddlewood, Texas ebony and other woody brush typically colonize the dune. Dune base vegetation usually consists of sea ox-eye daisy and glassworts (Jahrsdoerfer and Leslie 1998), which are common high salt marsh plants.

Tidal flats provide important habitat for a variety of coastal wildlife from migratory waterfowl, shorebirds (like the federally-listed piping plover, (*Charadrius melodius*), wading birds, and other estuarine-dependent species like shrimp and various finfish. Texas contains more tidal flats than any other state (23 percent of the nation's total, approximately 14 percent of which are located around the Laguna Madre) (Tunnell and Judd 2001). Some portions of study area tidal flats called wind flats are unique in that wind and storm events dictate inundation, as opposed to typical, astronomically-driven, tidal regimes (Tunnel and Judd 2002). Often these areas are dry, or consist of hypersaline, warm shallow water. Regional conditions that create the wind-tidal systems include hypersalinity, flat topography, winds and a lack of freshwater inflow (Tunnel and Judd 2001).

Conditions on wind-tidal flats are not conducive to marsh vegetation, and consequently these features are usually barren except for large areas colonized by cyanobacteria (blue-green algae) mats called algal flats. Algal flats are large, flat areas occurring at sea level to less than 3.3 feet (1 meter) above sea level that are inundated only during extreme tidal events, storms, and floods. Despite their barren appearance, studies show that these semi-aquatic algal mat systems are capable of very high primary production and nitrogen fixation under wet conditions, thus providing organic matter and fixed nitrogen to LLM food webs (Pulich and Rabalais 1986, Pulich and Scalan 1989). The low surface gradient of algal flats in the study area prevents drainage during flood events from the Laguna Madre (and promotes evaporation), resulting in interlaminated sand, mud, marine shells, algal mats, and evaporates (Morton and Holmes, 2009). The unique processes that result in algal flat formations only exist in several locations worldwide, including the Persian Sea, Red Sea, and eastern Mediterranean Sea (Morton and Holmes, 2009). Within the study area, wind-tidal flats (including algal flats) mostly occur on the north end of Bahia Grande, within the San Martin Lake complex, and on the eastern portions of South Bay.

Section 2 Hydrology

2.1 Study Area and Basic Hydrography

The hydrography of the study area for this report consists of four major groups of watersheds, three of which drain into the Lower Laguna Madre and one that flows directly to the Gulf of Mexico. Three of the four groups of watersheds were studied in detail in this report. They include:

- The Rio Grande River watershed (downstream of Anzalduas Dam)
- The Arroyo Colorado watershed (gaged and ungaged portion)
- The Brownsville / Resaca watersheds.

A fourth group of watersheds located north of the Arroyo watershed also drains into the Lower Laguna Madre and was included in the TWDB Coastal Hydrology Technical Report., but was not included in water balance calculations completed in this chapter. **Figure 2.1.1** shows the watersheds included in this study. The same figure also illustrates major stream components of each watershed, as well as important hydraulic structures and gauging locations throughout the study area.

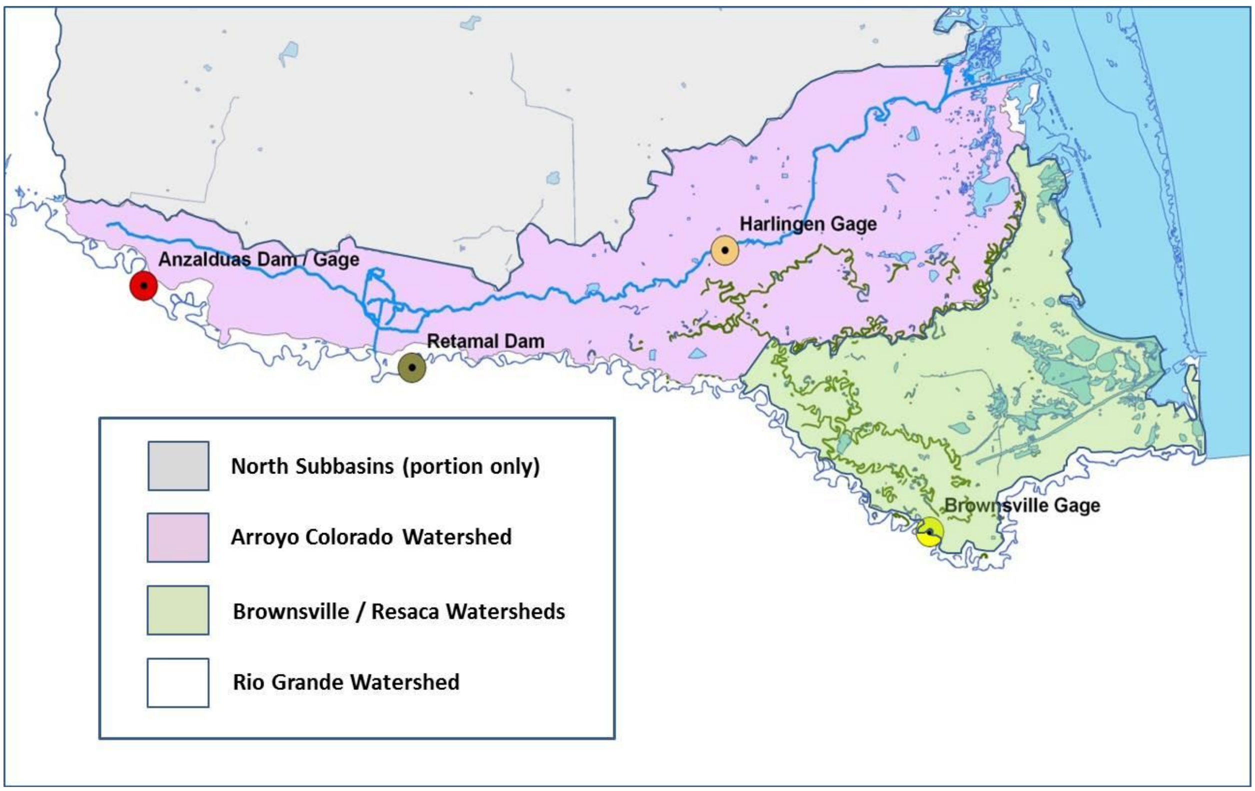


Figure 2.1.1 Study area map showing the three watersheds included in the water balance / flow analysis discussed in this chapter. The Rio Grande watershed is the narrow, white boundary along the Rio Grande River from Anzalduas Dam to the mouth of the river at its confluence with the Gulf of Mexico. (Note: Only a portion of the north subbasins is included in this figure. Additional detail for this section can be seen in **Figure 2.1.3.**)

2.1.1. Historical Changes to Area Hydrography

Activities related to both agriculture and urbanization have led to significant changes to the study area's hydrography over the last 100 years, shifting it from one dominated by deltaic processes and periodic, wide-area flooding to one dominated by anthropogenic influences. These changes can largely be linked to three factors.

First, in the early part of the 20th century, large scale agriculture began to take root in the Lower Rio Grande Valley. Massive clearing of native plant cover and vegetation was undertaken in order to provide room for crop production and to access the fertile delta soil resulting from years of flood deposition from the Rio Grande River.

Second, additional changes to the landscape and hydrography of the study area were brought about by the need for an irrigation system capable of withdrawing, conveying, and distributing water over many hectares of land. The irrigation system was largely in place by the early 1930s and its extensive network of canals has greatly influenced drainage patterns.

Third and lastly, the combination of flat terrain, rapid population growth and urbanization over the 20th century, and periodic heavy rainfalls and flood flows due to tropical storms led to the need for significant flood control improvements. These improvements came in two parts: the development of a regional flood control project designed to protect the area from the historical flood cycle of the Rio Grande River and an extensive network of drainage ditches designed to move flood waters out of the area. (Arroyo Colorado Watershed Partnership 2007)

2.1.2. Rio Grande Study Area

The portion of the Rio Grande included in the water balance and flow calculations discussed in this chapter includes the reach between Anzalduas Dam and the mouth of the river. The Rio Grande watershed is extremely narrow in this area like many other meandering rivers approaching their base level elevation, with the narrow width resulting from the formation of natural levees from overbank flood deposition of suspended sediment and material. **Figure 2.1.1** shows the meandering nature of the Rio Grande and its narrow watershed.

A set of important hydraulic structures exist on this portion of the river – the Anzalduas Dam, the Retamal Dam, and a system of man-made levees – all part of the Lower Rio Grande Federal Flood Control Project. Anzalduas Dam serves as a flood control and diversion dam during high flow events, diverting some of the design flow northward into the Arroyo Colorado headwater section via the Banker Floodway. Retamal Dam serves a similar purpose; however, it diverts flood flows southward into the Mexican floodway.

The Rio Grande serves as the primary source of water supply for the Lower Rio Grande Valley, with a distant second source being the recent implementation of brackish groundwater desalination plants throughout the region. Heavy withdrawal volumes divert much of the average flow between Anzalduas and the City of Brownsville for agricultural and municipal uses. Most of the return flows associated with these uses are discharged either to the Arroyo Colorado on the west side of the study area or the Brownsville / Resaca watersheds on the southeast side of the study area – with both of these watersheds draining to the Lower Laguna Madre. The result of this use and discharge pattern is a net lowering of flows in the Rio Grande River due to withdrawals and a net increase of average flows in the Arroyo and Brownsville / Resaca watersheds due to sustained agricultural and municipal return flows.

2.1.3. Arroyo Colorado Study Area

The entire Arroyo Colorado watershed is included in the water balance and flow calculations included in this chapter, including both the gaged basin upstream of Harlingen and the ungaged, tidally influenced section located downstream of Harlingen. There are several published and gray literature documents that include specific hydrographic information on this well-studied watershed.

The Arroyo Colorado (or “the Arroyo”) serves many important hydrologic and hydraulic functions in the Lower Rio Grande Valley. These include: flood control as both part of the Federal Flood Control Project and a conveyance for local area drainage ditches, conveyance of return flows from both agricultural and municipal sources downstream to the LLM, navigation to the Port of Harlingen from the LLM, freshwater inflows to the LLM, and the support of riparian habitat. Some limited recreational opportunities are also provided by way of boating and kayaking in some of the downstream reaches.

Figure 2.1.2 shows both the freshwater and tidally influenced sections of the Arroyo as well as its watershed boundaries and the major portions of the flood control project. The Banker Floodway, in the western / upstream portion of the watershed, serves as the primary connection between the Rio Grande and the Arroyo during the infrequent periods of operation of the flood control system. The middle section of the Arroyo then serves as a pilot channel for flood flows until Llano Grande near Weslaco, where the North Floodway diverts the majority of flood flows out of the Arroyo streambed and around Harlingen. The Arroyo then continues to its eventual confluence with the LLM.

Perennial flow in the Arroyo is sustained mostly by municipal wastewater treatment facilities, with seasonal increases in flow resulting from pulsed irrigation return flows strongly tied to the irrigation season. Urban and overland runoff during locally heavy rainfalls also adds to temporary increases in flow–particularly during the tropical season months of June-October.

Historically, the Arroyo may have served as a conduit for rainfall runoff that could not drain to the Rio Grande due to the latter stream’s natural levees, functioning somewhat as a Yazoo stream although not rejoining with the Rio Grande. Conversely, the Arroyo may be an abandoned distributary of the Rio Grande that is now only hydrologically connected to the Rio Grande by the flood control system and through anthropogenic use and return of water.

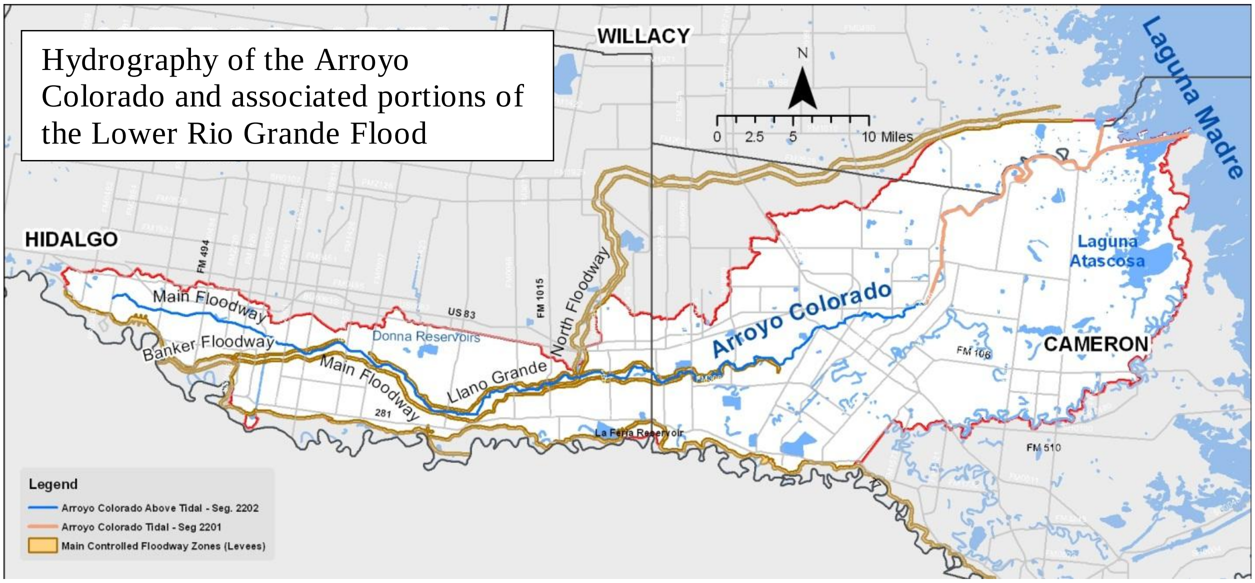


Figure 2.1.2. Detail of the Arroyo Colorado watershed with major stream segments that correspond to the Federal Flood Control Project of the Lower Rio Grande Valley. The tidally influenced segment is shown in light red. Levees that are part of the flood control project are shown in bolded gold lines. (Arroyo Colorado Watershed Partnership, 2007)

Regardless of which of these is historically accurate, the current flow regime in the Arroyo is drastically different than historical flows – with a shift from its low-level flow regime of near zero to one that is maintained at a consistent level due to municipal returns. High-level flood flows are affected by flood control modifications including diversions, dams, levees, and channelization.

2.1.4. Brownsville / Resaca Study Area

The green shaded portion of **Figure 2.1.1.** shows the group of watersheds referred to in this report as the Brownsville / Resaca watersheds. This area is dominated on the west and southern side by a system of old distributaries and ox-bows of the Rio Grande locally referred to as “resacas”. The eastern, more coastal side of this area is dominated by coastal low land features including bays, wind-blown tidal flats and the Brownsville Ship Channel. In contrast to the Rio Grande and Arroyo watersheds, this area has a combination of discharge locations including the Brownsville Ship Channel for the south and eastern portion and a distributed discharge path including small drain paths, resacas and bays for the eastern section.

Figure 2.1.3 shows the collection of subwatersheds in this region used by the TWDB. Subbasins #22902 and #22908 consist of a network of resacas and interstitial drainage ditches that drain stormwater to the Brownsville Ship Channel. Subbasins #22901 and #22907 consists of a similar, lower flow network that drains either directly to the LLM or to bays that later connect with the LLM.

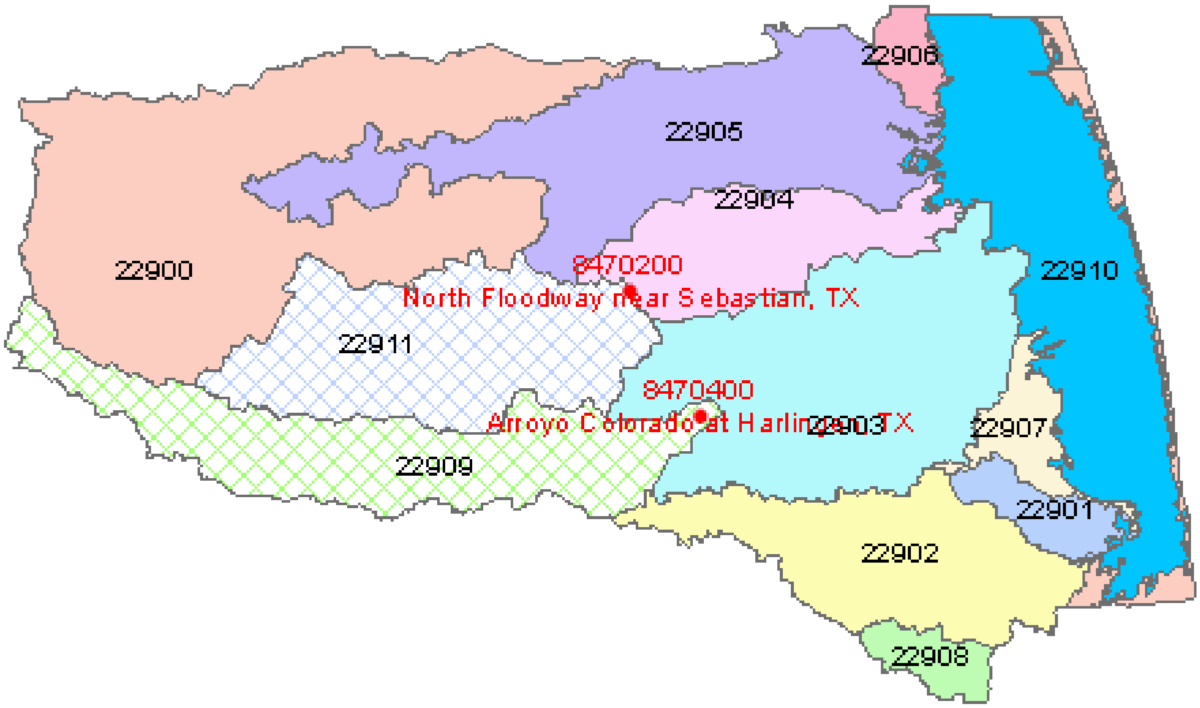


Figure 2.1.3 Study area delineated in subbasins used by the Texas Water Development Board Coastal Hydrology Program (Schoenbaechler et al., 2011)

Resacas are unique hydrologic features in South Texas that serve multiple functions including riparian habitat preservation, local storm water retention, irrigation and municipal water storage, aesthetics and recreation including fishing, kayaking, and birding. Limited environmental monitoring, water quality data, and hydrologic data on resacas has contributed to a lack of appreciation and protective policy formulation for these important local amenities – resulting in the degradation of habitat and natural ecosystem function over time. Unchecked urban runoff and the absence of periodic flows that historically flushed these systems of sediment, has resulted in the accumulation of unconsolidated sediments with a corresponding reduction of storage capacity and water depth. (Whitko 2005) Despite this, the resacas serve a vital role in habitat preservation for the area (Coastal Impact Monitoring Program 1994). The ecological role of resacas is discussed further in Section 7.

2.2. Historic Flows

Historic flows within the Lower Rio Grande and the Arroyo Colorado were examined utilizing available gage data at three locations maintained by the International Boundary and Water Commission (IBWC). The locations of the 3 flow gages are illustrated in Figure _ . Gage #08469200 is located just downstream of Anzalduas dam on the Rio Grande and will be referred to as the Anzalduas gage. Gage #08475000 is located just upstream of the saltwater rock weir in Brownsville and will be referred to as the Brownsville Gage. Gage #08470400 is located in Harlingen near the U.S. Highway 77 crossing of the Arroyo Colorado and will be referred to as the Harlingen Gage.

Data was collected from each of the gages for their available periods of record. The data was evaluated in terms of average daily, average monthly and average annual flow. Additionally, quarterly variations in monthly flow were examined to investigate seasonal variations of flow. Finally, annual average flows before and after the construction of specific dams on the Rio Grande is compared.

2.2.1. Lower Rio Grande Historic Flows

Two streamflow gages along the Rio Grande were used to analyze historic flows in the lower reaches of the Rio Grande downstream of Anzalduas dam – the Anzalduas gage and the Brownsville gage as illustrated in **Figure 2.2.1**. Average daily flow data was collected and plotted from 1952 through 2009 at the Anzalduas gage and from 1934 to 2009 at the Brownsville gage as depicted in **Figures 2.2.2 and 2.2.3**. The reported daily flows were then aggregated into monthly and yearly flows as illustrated in **Figures 2.2.3 – 2.2.7**. On average, flows recorded at the Anzalduas gage were over 30% higher than at the more downstream Brownsville gage. **Table 2.2.1** summarizes the daily, monthly, and annual average and range of flows at each of the two gages along the Lower Rio Grande. **Tables 2.2.2 and 2.2.3** show historic flows at each of the two gages in the Rio Grande by selected percentiles to the maximum available period of record and the common period of record respectively.

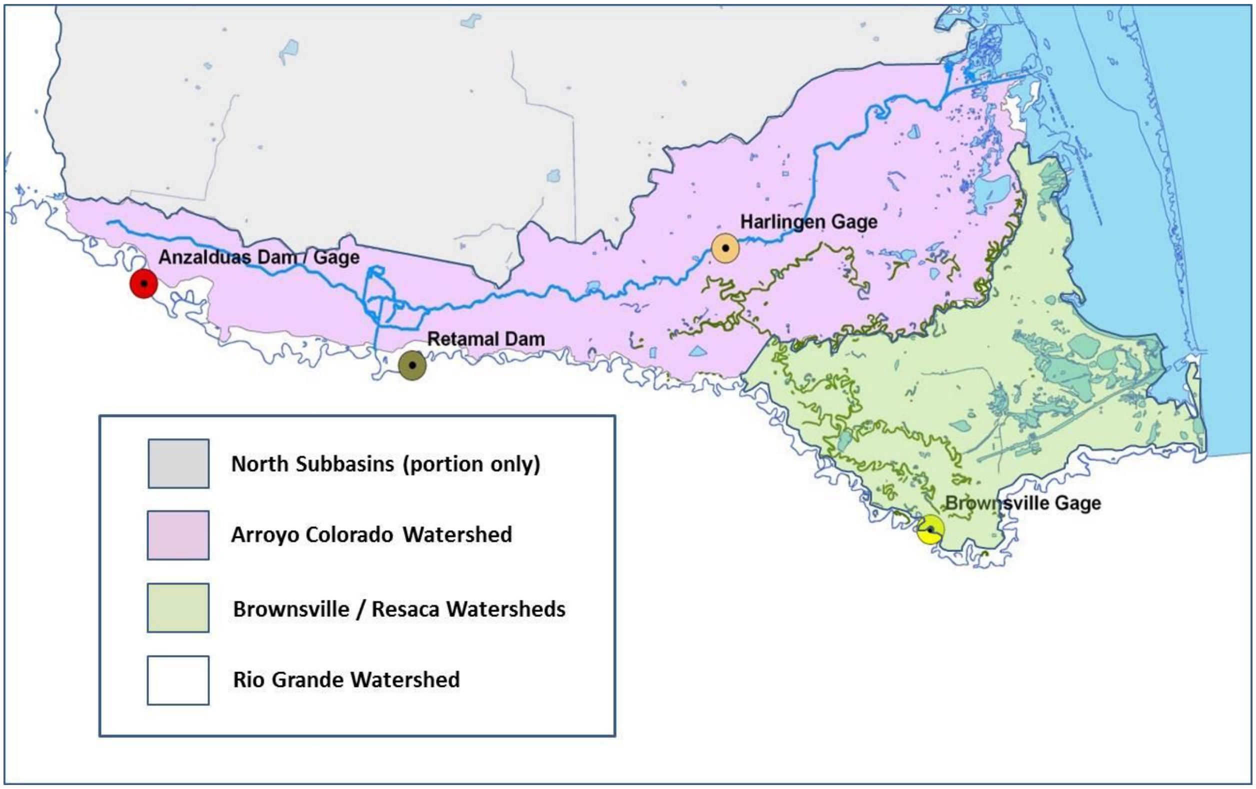


Figure 2.2.1. Map of the Rio Grande and Arroyo Colorado with dam and gage locations.

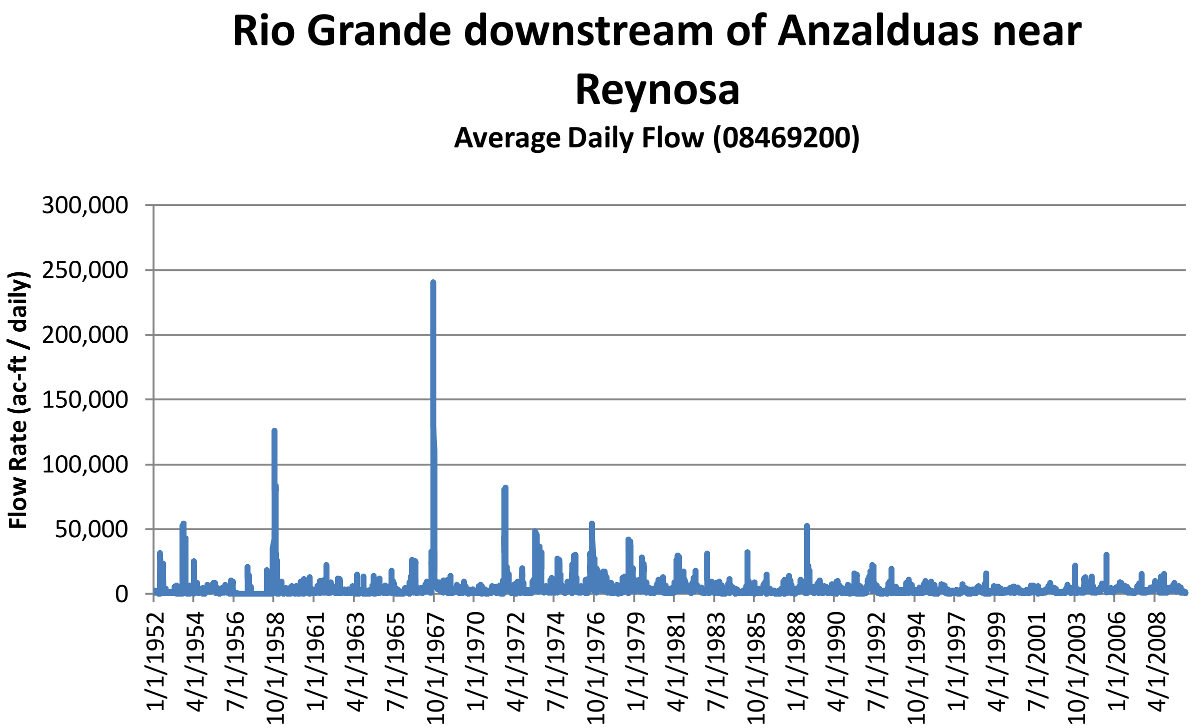


Figure 2.2.2. Average daily flows as recorded by the IBWC gage #08469200 near Mission, TX and Reynosa, Mexico.

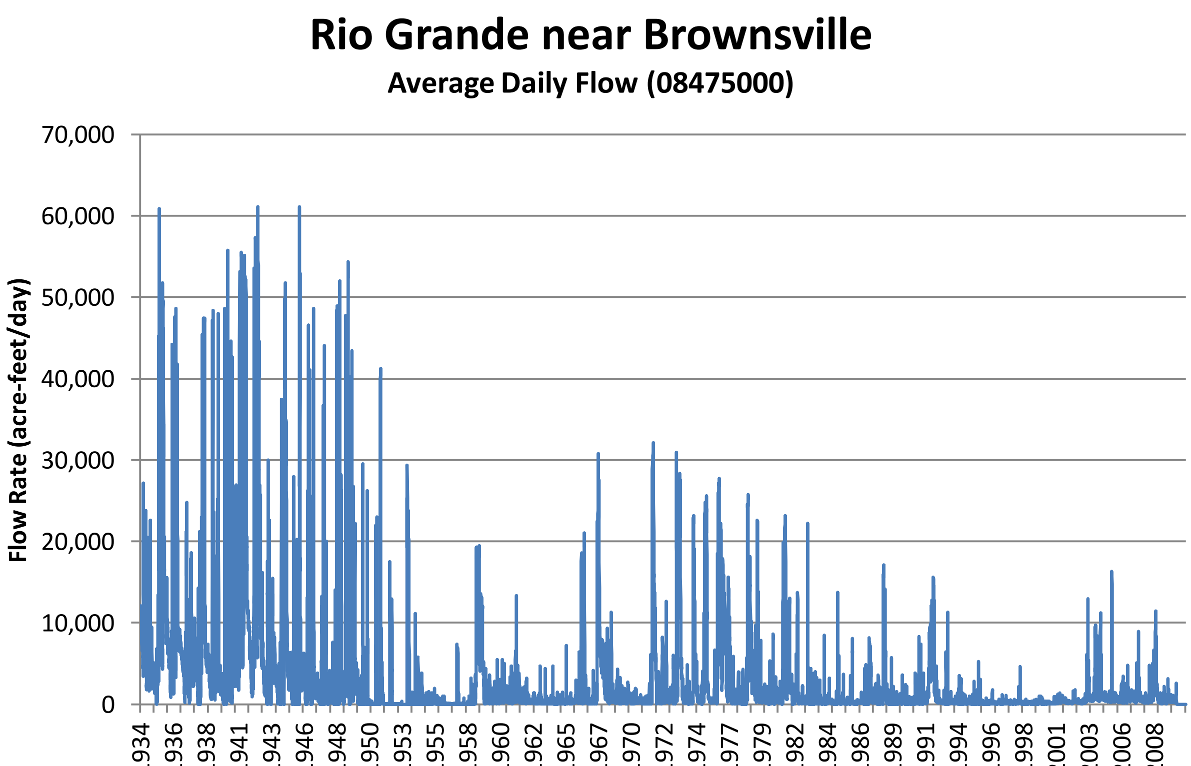


Figure 2.2.3. Average daily flows as recorded by the IBWC gage #08475000 near Brownsville, TX.

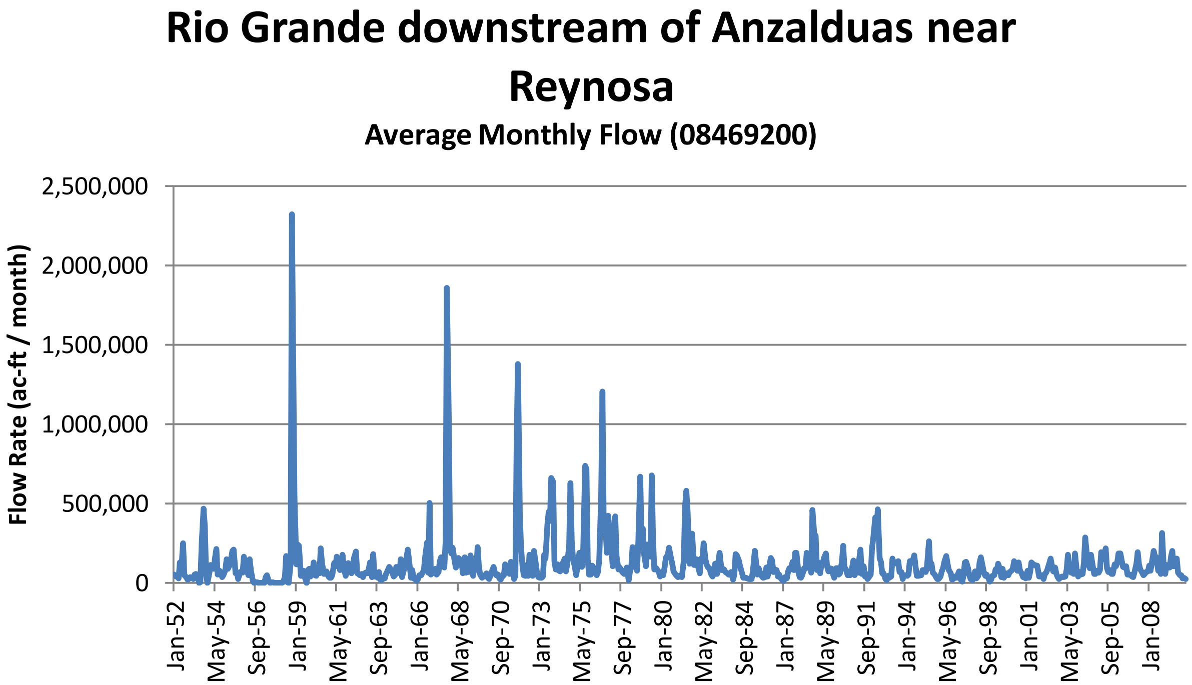


Figure 2.2.4. Average monthly flows as recorded by the IBWC gage #08469200 near Mission, TX and Reynosa, Mexico.

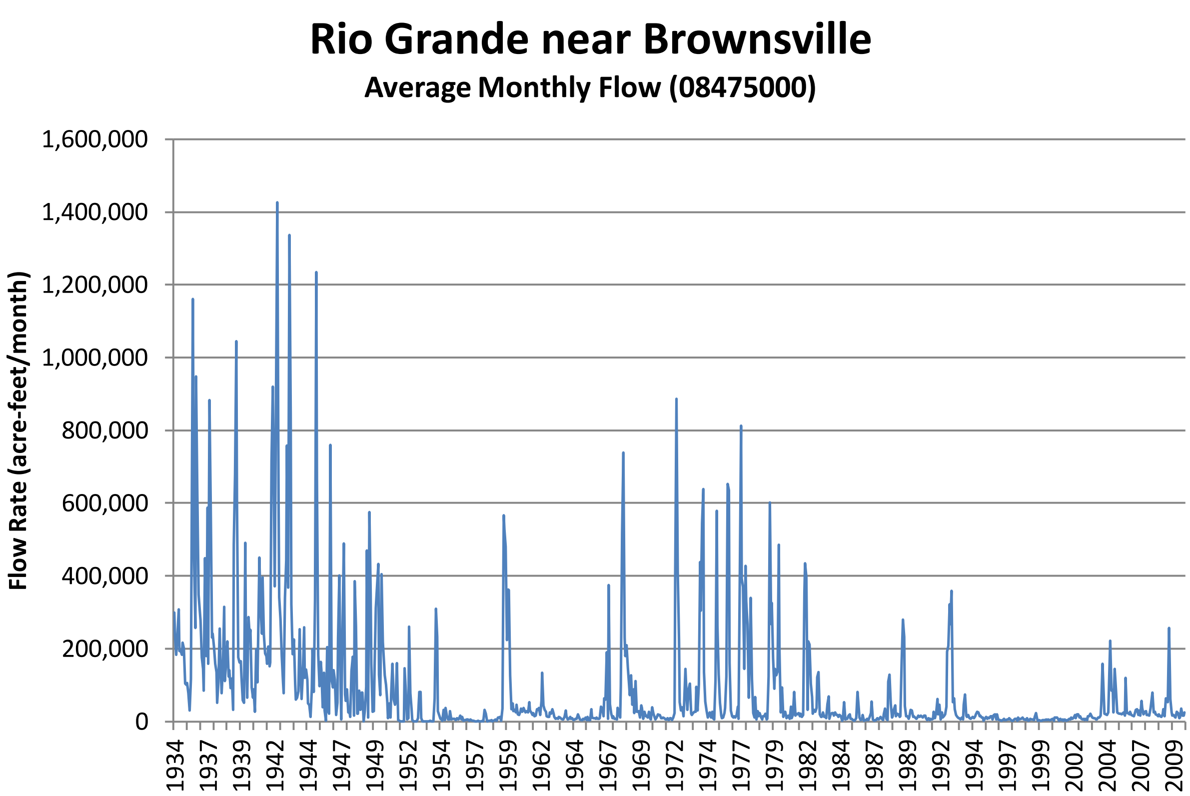


Figure 2.2.5. Average monthly flows as recorded by the IBWC gage #08475000 near Brownsville, TX.

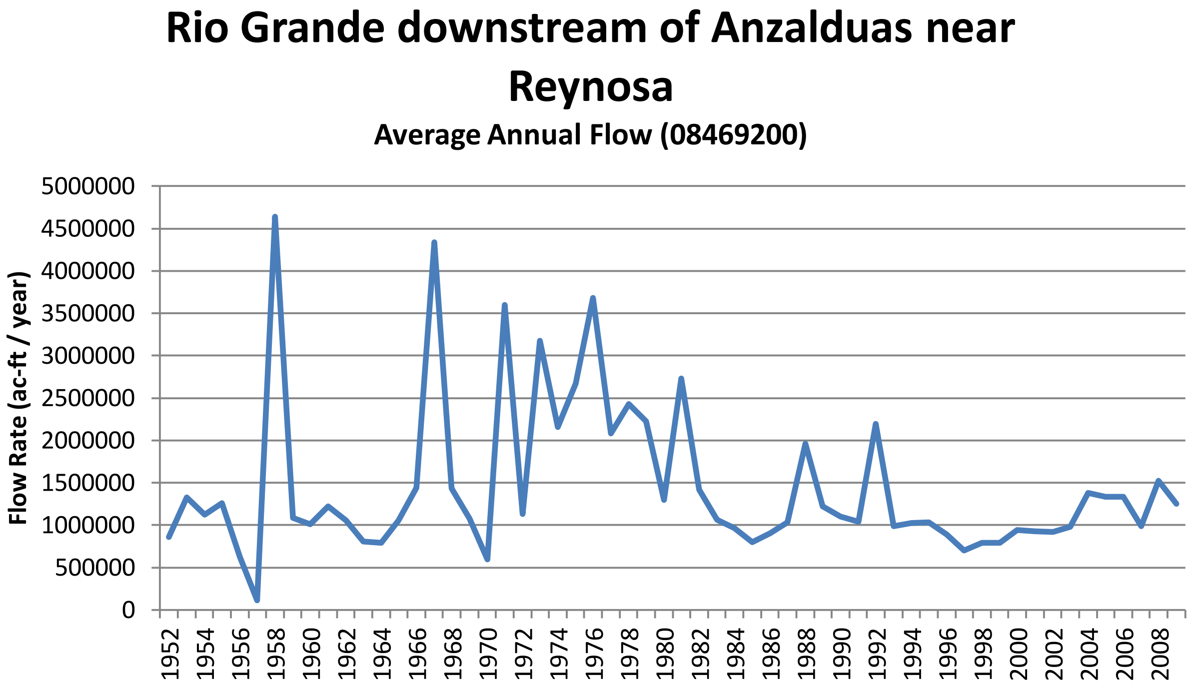


Figure 2.2.6. Average yearly flows as recorded by the IBWC gage #08469200 near Mission, TX and Reynosa, Mexico.

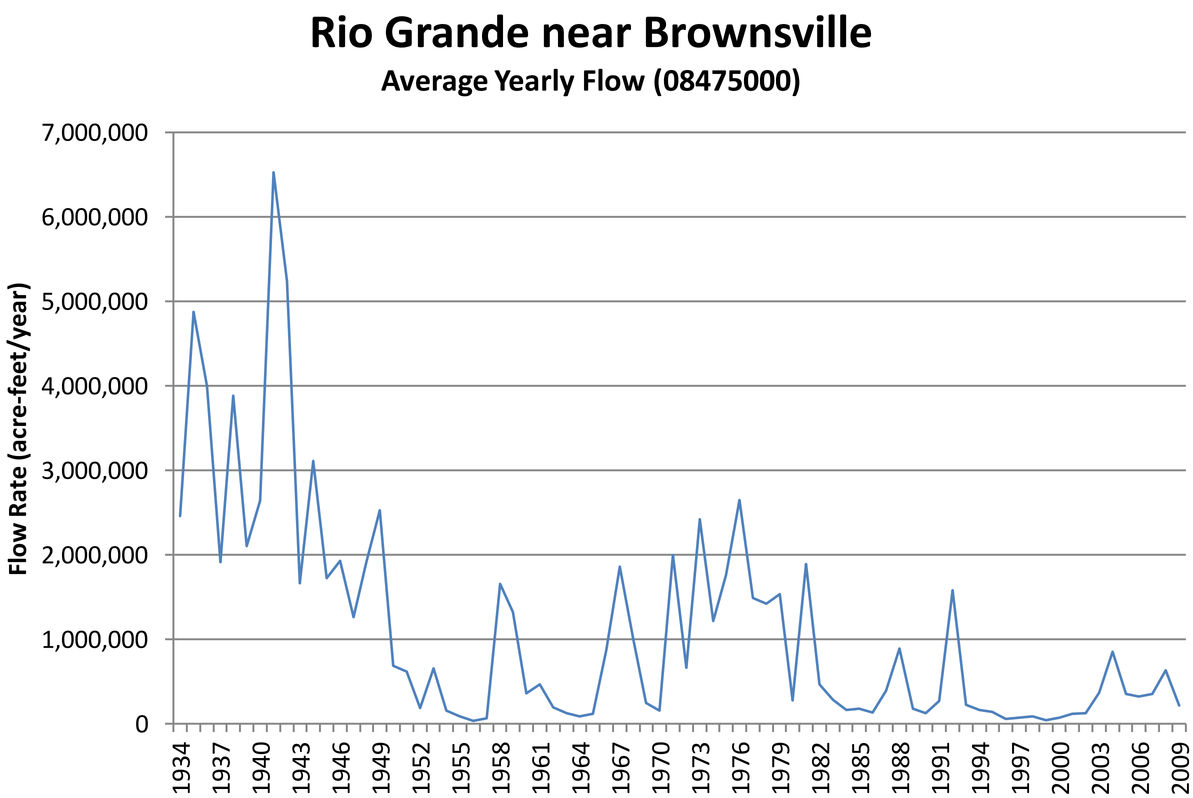


Figure 2.2.7. Average yearly flows as recorded by the IBWC gage #08475000 near Brownsville, TX.

Table 2.2.1. Summary of historic flows in the Rio Grande at the Anzalduas and Brownsville flow gages. Brownsville gage data provided for both available period of record and matched period of record for comparison between gages.

Historic Flows in the Rio Grande					
	Description	**Units**	**Anzalduas Gage** (1952-2009)	**Brownsville Gage** (1934-2009)	**Brownsville Gage** (1952-2009)
Daily Values	Average Daily Flow	(ac-ft/day)	3,992	3,058	1,692
	Max. Daily Flow	(ac-ft/day)	240,272	61,084	32,153
	Min. Daily Flow	(ac-ft/day)	0	0	0
Monthly Values	Average Monthly Flow	(ac-ft/month)	121,249	93,081	51,503
	Max. Monthly Flow	(ac-ft/month)	2,326,080	1,427,409	887,393
	Min. Monthly Flow	(ac-ft/month)	339	0	0
Yearly Values	Average Yearly Flow	(ac-ft/year)	1,457,837	1,116,966	618,035
	Max. Yearly Flow	(ac-ft/year)	4,640,852	6,524,758	2,645,806
	Min. Yearly Flow	(ac-ft/year)	114,748	30,582	30,582

Table 2.2.2. Summary of historic flows by percentile in the Rio Grande at the Anzalduas gage and the Brownsville gage for their entire available periods of record.

Historic Monthly Flows - Rio Grande (ac-ft/month)		
Percentile	**Anzalduas Gage** (1952-2009)	**Brownsville Gage** (1934-2009)
5th	19,306	2,184
10th	30,162	4,148
25th	49,301	8,535
50th	79,199	21,276
75th	132,436	95,612
90th	215,383	267,417
95th	320,408	436,349

Table 2.2-3 Summary of historic flows by percentile in the Rio Grande at the Anzalduas gage and the Brownsville gage for the period of record common to both gages.

Monthly Flows - Rio Grande		
Percentile	**Anzalduas Gage (1952 - 2009)**	**Brownsville Gage (1952 - 2009)**
5th	19,306	1,951
10th	30,162	3,657
25th	49,301	6,816
50th	79,199	14,889
75th	132,436	32,385
90th	215,383	127,71
95th	320,408	271,109

The annual average flow data revealed a substantial variation in flow between the minimum and maximum values. To better understand this variation, annual average flows were grouped into five time categories roughly coinciding with the construction of four dams that have been built on the Rio Grande over the last 60 years. These dams and the year their construction was completed are summarized in **Tables 2.2.4**. Of the four dams two of them, Falcon Dam and Amistad Dam, are storage dams and the other two, Anzalduas Dam and Retamal Dam, are diversion dams. Each of these four dams will be further described below.

Table 2.2-4 Summary of Lower Rio Grande dams and year of construction

Lower Rio Grande Dams	
Dam	**Year Constructed**
Falcon Dam	1954
Anzalduas Dam	1960
Amistad Dam	1969
Retamal Dam	1975

Falcon Dam, constructed in 1954, is the oldest of the four dams and is the lowermost international multipurpose dam and reservoir on the Rio Grande. The dam is located approximately 80 miles southeast of Laredo, Texas and 150 miles above the mouth of the Rio Grande. The dam was designed to control and regulate the flow of international waters and to contribute to the mutual welfare of both Mexico and the United States with respect to irrigation, domestic and flood releases and through the generation of electricity through the dam's hydroelectric generating plant. The storage capacity of the reservoir is approximately 3,978,000 acre-ft including 2,668,000 acre-ft of conservation and silt volume, 509,000 acre-ft of flood control storage volume and 801,000 acre-ft of superstorage (IBWC 2012).

The Anzalduas Dam is a diversion dam located in Hidalgo County between Mission and McAllen, Texas. Construction of the dam was completed in 1960 and was designed to divert the US share of floodwaters to its interior floodway as well as allowing for the diversion of water to Mexico's main irrigation canal.

The Amistad Dam is the other storage dam on the Lower Rio Grande and is the largest of the storage dams and reservoirs built on the international reach of the entire Rio Grande. The dam is located in Del Rio, Texas and was designed for flood control and water conservation storage to benefit both Mexico and the United States. The dam is 6.1 miles long and has sixteen spillway gates capable of releasing 1,500,000 cubic feet per second (CFS) of flow. The total volume of the reservoir impounded by the dam is approximately 3,124,260 acre-ft (IBWC 2012).

The Retamal Dam is a diversion dam located 10 miles south of Donna, Texas. The dam was constructed in 1975 to allow Mexico to divert its share of floodwater to the Mexican interior floodway and to limit flood flows at Brownsville-Matamoros to within the safe capacity of the Rio Grande.

The construction of these four dams has impacted the overall flow dynamics of the Lower Rio Grande by effectively reducing the amount of daily, monthly, and yearly flow reaching the downstream portion of the Rio Grande and entering the Gulf of Mexico. This impact is illustrated in **Figure 2.2.8**, which groups the annual average flows at the Brownsville gage, downstream of all constructed dams, by time periods relative to the construction of each dam. For example, the first bar on the graph represents the annual average flow from 1934 up to 1954 when the Falcon Dam was completed. The next bar on the graph represents the annual average flow from 1934 up to 1960 when the Anzalduas Dam was completed. The third bar represents average annual flow from 1934 up to the construction of the Amistad Dam in 1969 and so on. Overall, a significant reduction is observed in annual average flow coinciding with the construction of each of the four dams. The end result is an average annual flow over the entire time period of just over 1.1 million acre-ft per year versus nearly 2.5 million acre-ft per year during the period of 1934 to 1954 before Falcon Dam was constructed in 1954.

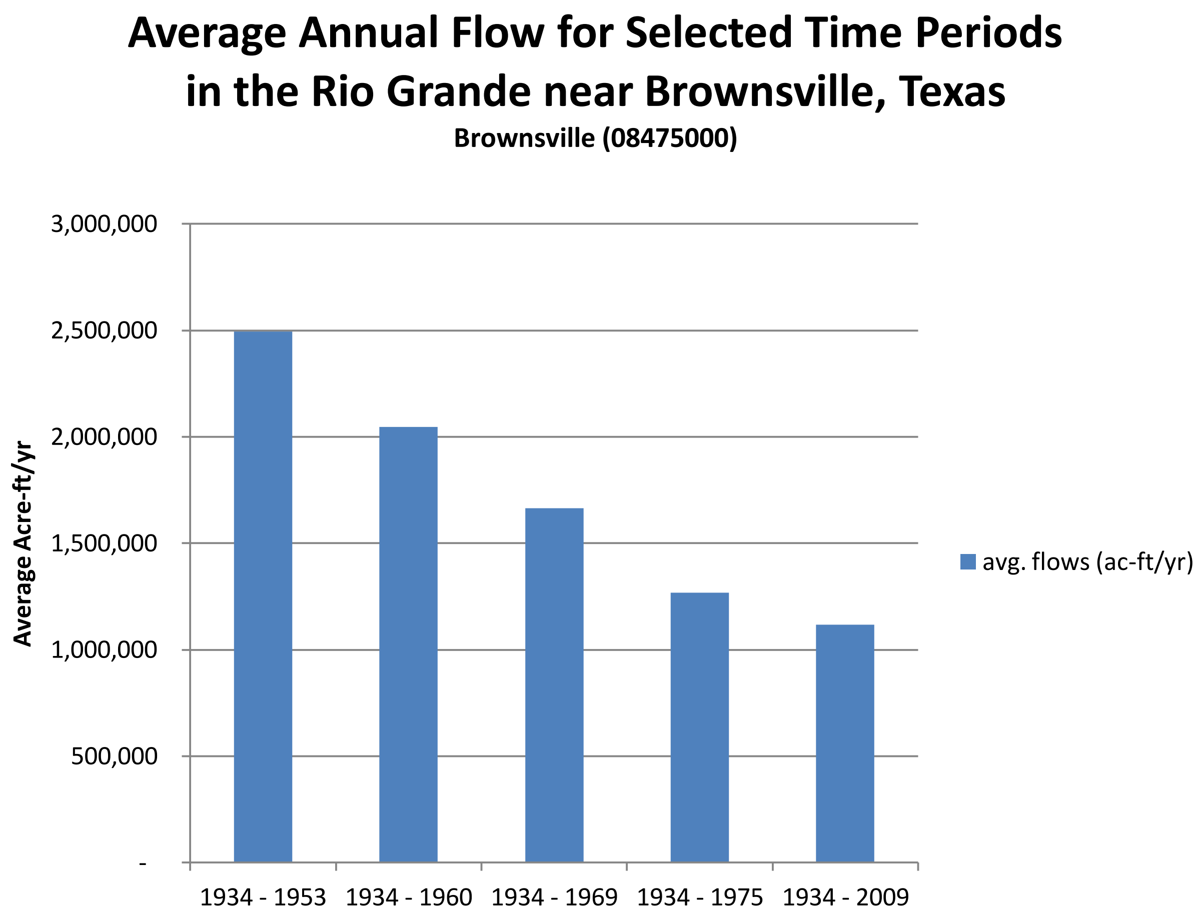


Figure 2.2.8. Average yearly flows grouped cumulatively by time periods coinciding with the construction of the four dams described in Table II.2-4.

In addition to the impact caused by dam construction along the Lower Rio Grande on average flow rates, a seasonal variation of flow may also be observed. Data collected between 1934 and 2009 at the Brownsville gage was aggregated on a quarterly basis as illustrated in **Figure 2.2.9**. In this figure the first quarter represents the months of January – March, the second quarter represents April – June and so on. The result of this analysis reveals the highest monthly flows during the third quarter months of July – September with average monthly flows of nearly 126,000 acre-ft/month. This is followed by the fourth quarter months of October – December where average monthly flows were approximately 113,000 acre-ft/month. In the second quarter, historic flows were over 83,000 acre-ft/month and the lowest quarterly flows were observed in the first quarter with average values just over 50,000 acre-ft/month.

Data for the Brownsville gage was compared over calendar quarters for the period of record before any of the dams (1934-2009) as well as after all dams were in place (1975-2009). While exhibiting a similar trend between quarters as the aggregate 1934-2009 data, the flows are attenuated significantly between the two periods. First and second quarter flows were reduced by approximately 75% when comparing the 1934-1954 data to the 1975-2009 periods. Third and fourth quarter flows were reduced by approximately 80% over the same periods.

The specific reasons for this reduction in flow is beyond the scope of this report to support scientifically; however, it is clear that a combination of flood storage and flood flow diversions (see Rio Grande Flood Control Project at the end of this section) as well as increasing demand and water withdrawals for both agricultural and municipal use have drastically reduced historic flows in the downstream reaches of the Rio Grande. As discussed in **Subsection 2.1** (hydrography section of this chapter), the Rio Grande downstream of Anzalduas Dam and the Arroyo Colorado function as a paired system once withdrawals from the Rio Grande and return flows to the Arroyo Colorado are taken into account. Specific flow values for municipal and agricultural withdrawals (from the Rio Grande) and return values (to the Arroyo Colorado) are provided in **Subsections 2.3 and 2.4** of this Section.

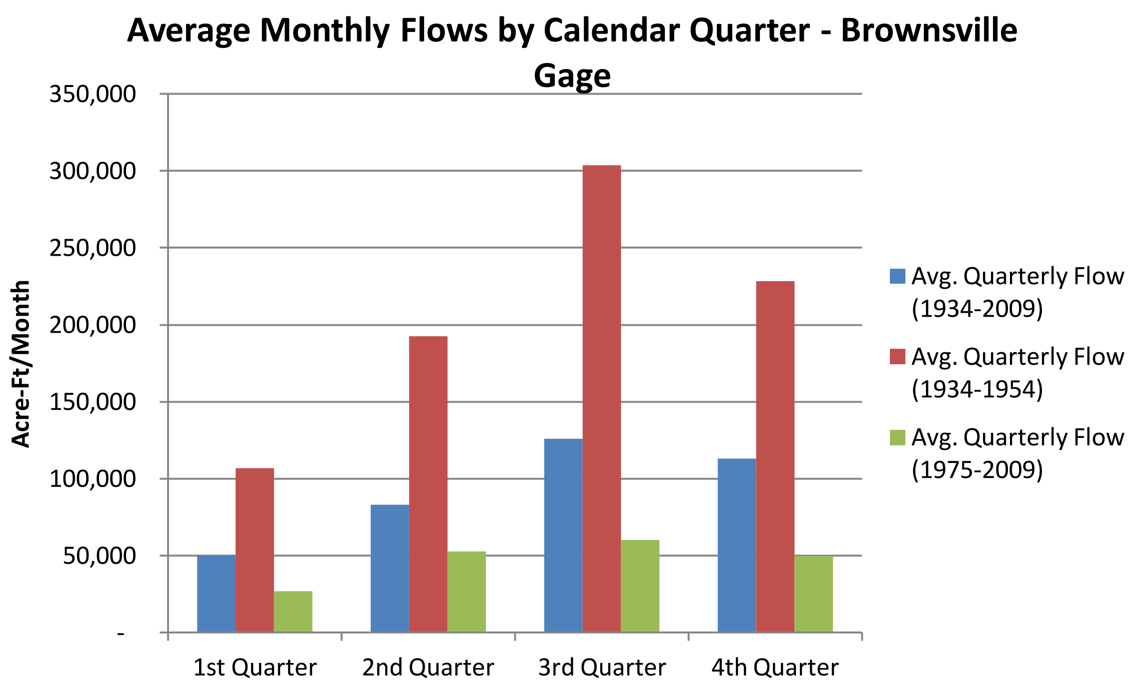


Figure 2.2.9. Average monthly flows at the Brownsville gage grouped quarterly from 1934 to 2009, 1934-1954, and 1975-2009.Arroyo Colorado Historic Flows

Average daily flow data was collected and plotted from 1977 through 2009 as depicted in **Figure 2.2.10** for the Harlingen gage. The reported daily flows were then aggregated into monthly and yearly flows as illustrated in **Figures 2.2.11 and 2.2.12. Table 2.2.5** summarizes the daily, monthly, and annual average and range of flows at the Harlingen gage and **Table 2.2.6** shows historic flows by selected percentiles of flow for comparison between the gages on the Rio Grande and the Arroyo Colorado. The common period of record for the three gages was limited to 1977-2009 by the Arroyo Colorado gage data. It is important to point out that while the downstream gages for the Arroyo Colorado and the Rio Grande have median (50th percentile) flows that are similar (about 14,000 ac-ft / month), the flows in the Rio Grande vary more significantly, particularly at the 10th and 90th percentile ranges. A more detailed discussion on the comparison between flows in the Arroyo and the Rio Grande is provided in **Subsection 2.5** for a more focused period of record of 1999-2008.

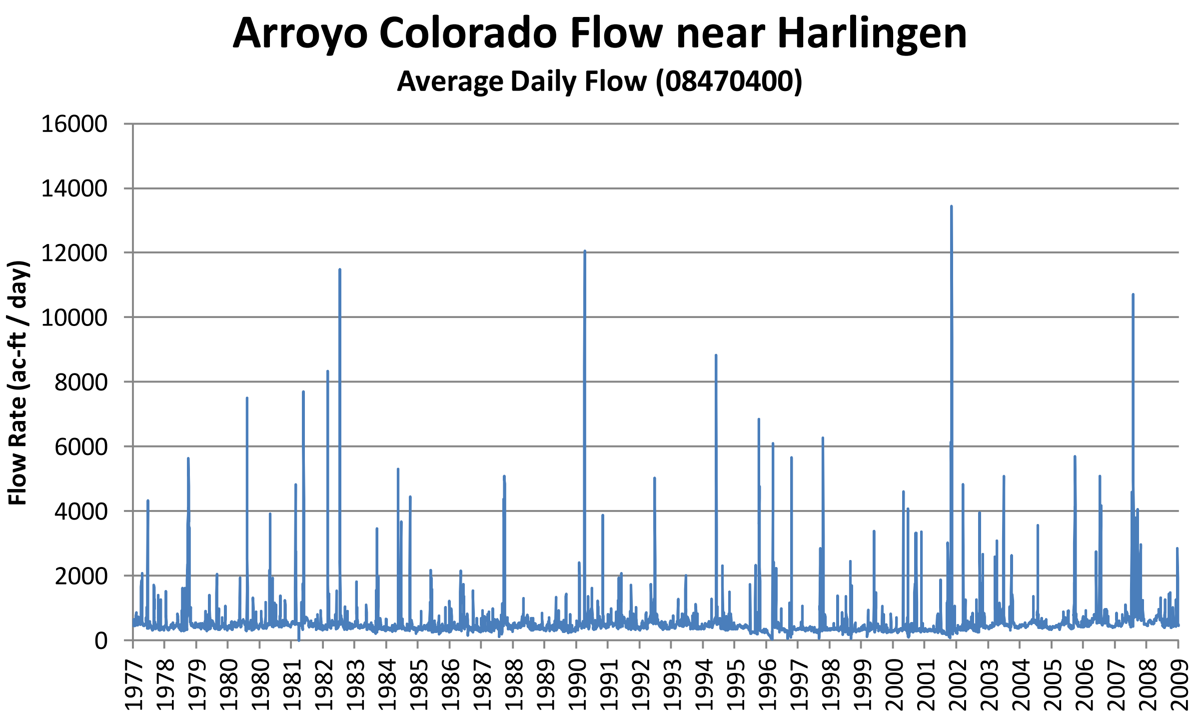


Figure 2.2.10. Average daily flows as recorded by the Harlingen gage in the Arroyo Colorado from 1977 to 2009.

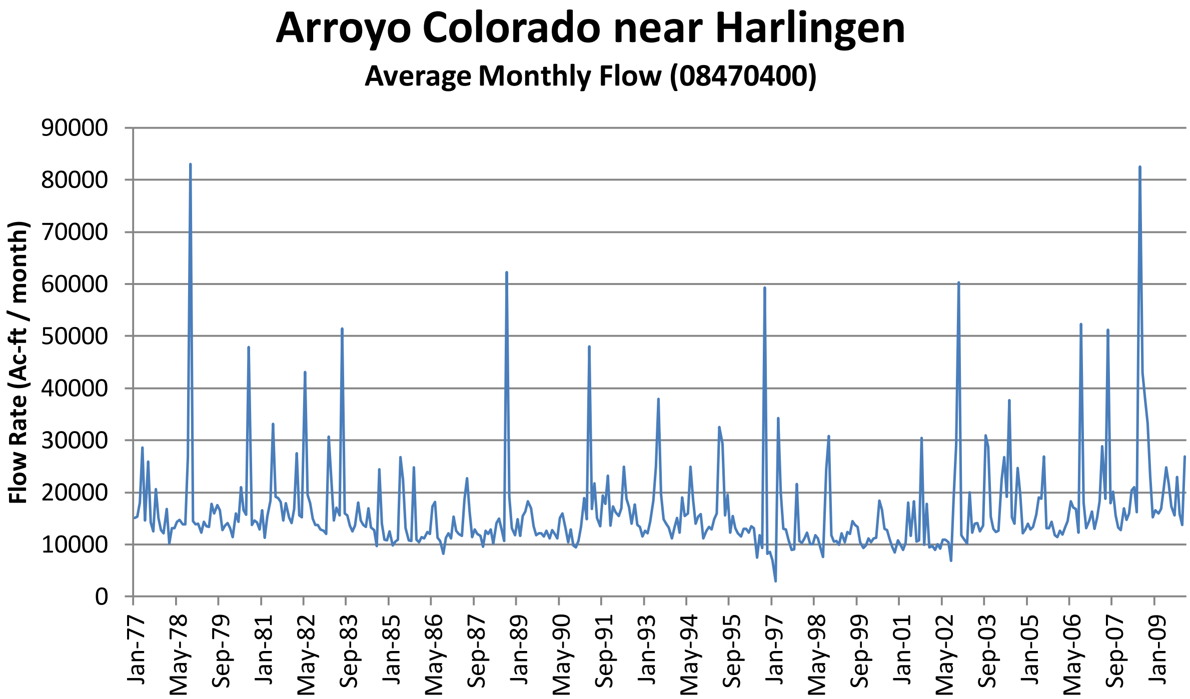


Figure 2.211. Average monthly flows as recorded by the Harlingen Gage in the Arroyo Colorado from 1977 to 2009.

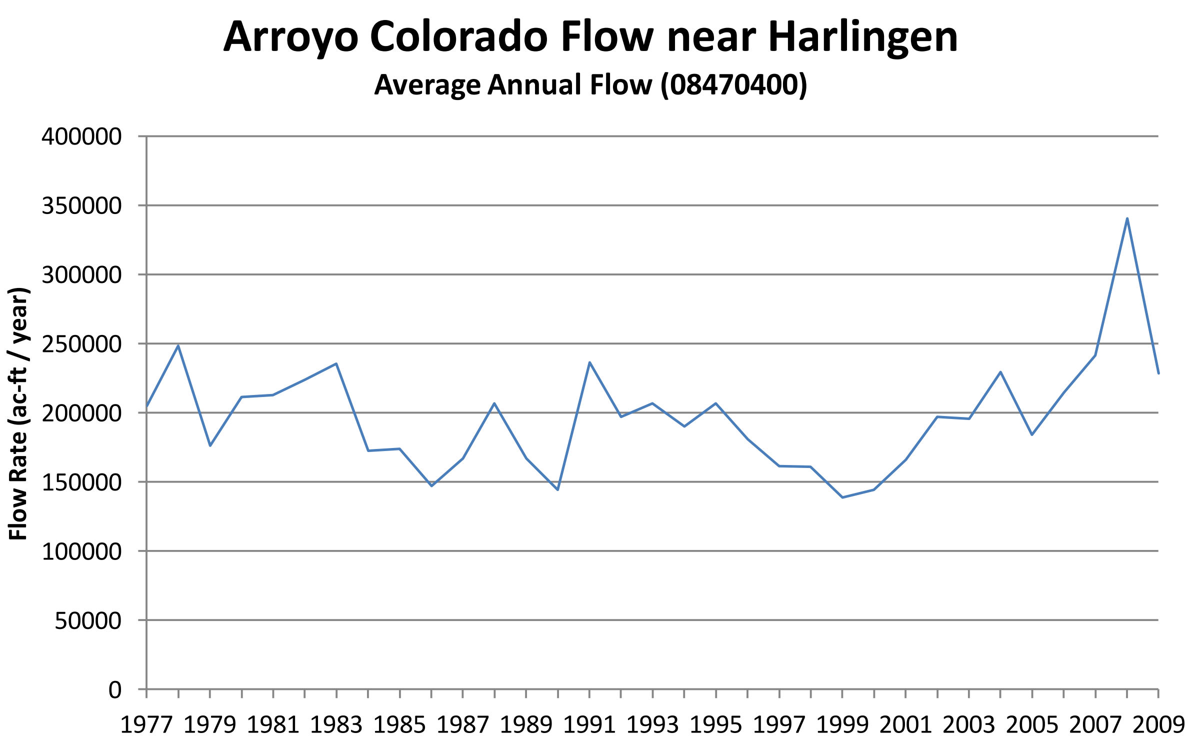


Figure 2.2.12. Average daily flows grouped in the Arroyo Colorado at the Harlingen gage from 1977 to 2009.

Table 2.2.5. Summary of historic flows in the Rio Grande at the Anzalduas gage and the Brownsville gage.

Historic Flows in the Arroyo Colorado		
	Description	**Harlingen Gage**
Daily Values	Average Daily Flow	540
	Max. Daily Flow	13,499
	Min. Daily Flow	0
Monthly Values	Average Monthly Flow	16,450
	Max. Monthly Flow	83,022
	Min. Monthly Flow	2,938
Yearly Values	Average Yearly Flow	197,401
	Max. Yearly Flow	340,377
	Min. Yearly Flow	138,781

Table 2.2.6. Summary of historic flows by percentile in the Arroyo Colorado at the Harlingen gage, compared to percentile flows in the Rio Grande (Anzalduas and Brownsville gages) for the common period of record of 1977-2009.

Monthly Flows - Arroyo Colorado and Rio Grande (1977-2009)			
Percentile	**Harlingen Gage (1977-2009)**	**Anzalduas Gage (1977-2009)**	**Brownsville Gage (1977-2009)**
5th	9,602	26,715	3,179
10th	10,431	34,817	4,177
25th	12,018	51,569	7,131
50th	13,942	81,368	14,533
75th	17,628	129,801	25,550
90th	24,766	191,280	90,403
95th	30,866	283,721	209,117

Seasonal variations in flow are approximated by aggregating the monthly flow values on a quarterly basis. **Figure 2.2.13** shows the average flow for each quarter for the period of 1977 through 2009. The graph indicates that the periods of highest average flow are observed in the 2nd and 3rd quarters (April – September) with average flows about 18,000 acre-ft/month. Flows in the 4th quarter (October – December) from 1977 to 2009 have averaged just below 16,000 acre-ft/month and the 1st quarter average flows were approximately 14,000 acre-ft/month.

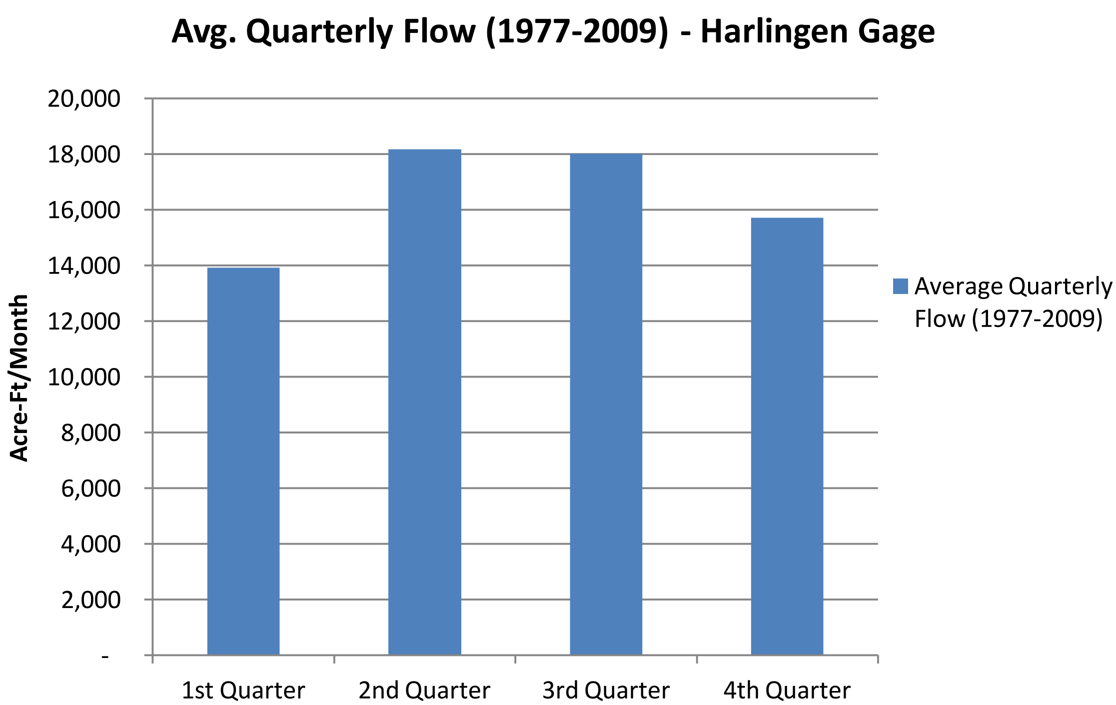


Figure 2.2.13. Average monthly flows grouped quarterly from 1977 to 2009 at the Harlingen Gage

2.2.2. The Rio Grande Valley Federal Flood Control Project

This section presents a brief summary of the Lower Rio Grande Flood Control Project (LRGFCP). The LRGVCP consists of a series of diversion dams, dikes, levees, and interior floodways that serve to protect the Rio Grande Valley from river-related flooding stemming from rainfall over the watershed of the Rio Grande upstream of the Valley. The project is detailed here to highlight the operations of the system during high-flow events and how this standard operation would affect flow patterns in the Rio Grande / Arroyo Colorado system. The systems two diversion dams – Anzalduas and Retamal – function to divert sufficient flood flows so that the design flow past Brownsville / Matamoros is 20,000 cfs, a mere 8% of the design flood flow of 250,000 cfs into Anzalduas dam.

The LRGFCP covers 180 river miles from Penitas, TX to just downstream of Brownsville, Texas. Approximately 270 miles of levees are located along the Rio Grande, the Arroyo Colorado, and interior floodways. Major operational systems include the Banker Floodway, Main Floodway, North Floodway, the Arroyo Colorado, Anzalduas Dam, and Retamal Dam. While levees are an integral part of the system, perhaps the most vital components are the two diversion dams and the systems of interior floodways designed to handle diverted water – preventing this water from travelling downstream and impacting the Brownsville –

Matamoros area. Anzalduas dam is located just south of Mission, Texas and has the primary function of diverting the U.S. share of floodwaters in the U.S. floodways. Retamal dam, located south of Donna, Texas, diverts Mexico’s share of floodwaters into the Mexican floodways. Both diversion dams operate in concert to limit the flows in the Rio Grande downstream of the dams so that flood flows in the Rio Grande remain at safe levels in the Brownsville – Matamoros area.

Figure 2.2.14 shows the location of the diversion dams, interior floodways on both the US and Mexican sides, the component portions of the U.S. interior floodways (Main, Arroyo Colorado, and North floodways) and the location of major cities, notably Brownsville / Matamoros, McAllen and Harlingen.

The system operates under specific design flood flows (100 year flood?) that were updated after Hurricane Beulah in 1967, owing to the devastating floods experienced in the Harlingen area after that storm. The current design flows are as follows:

- 250,000 cubic feet per second (cfs) at Rio Grande City (inflow to Anzalduas Dam);
- 105,000 cfs for diversion by Anzalduas to the U.S. floodway (Main floodway)
- 105,000 cfs for diversion by Retamal to the Mexican floodway
- 84,000 cfs in the North Floodway (diverted from the Arroyo Colorado)
- 21,000 cfs in the Arroyo Colorado at Harlingen
- 20,000 cfs in the Rio Grande at Brownsville / Matamoros.

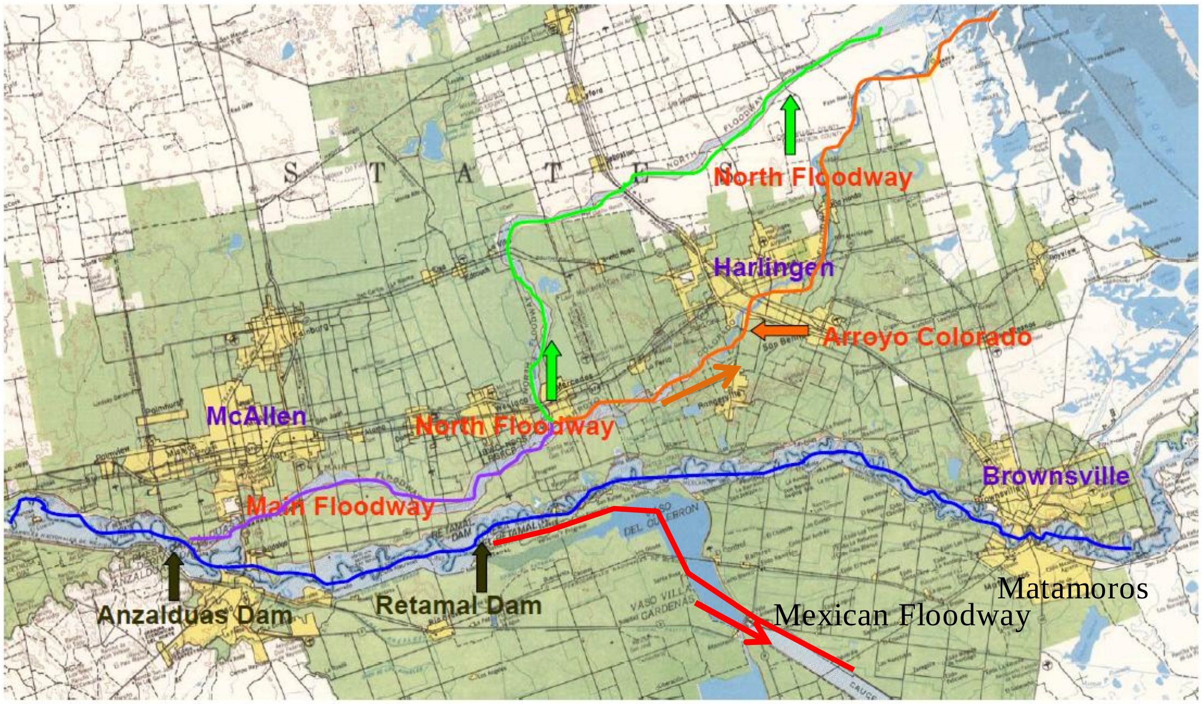


Figure 2.2.14. Generalized schematic of the Lower Rio Grande Flood Control Project showing diversion dams, diversion floodways, and larger cities in the LRGV. (IBWC, 2012 with modifications)

2.3. Rio Grande River - Withdrawal Data

Rio Grande River water withdrawal data for both municipal and agricultural use were collected from a variety of sources, focusing on the reach of the river between Anzalduas Dam and Brownsville, Texas. Assistance with the collection of withdrawal data was obtained via subcontract with the Texas AgriLife, Texas Water Resources Institute/Institute of Renewable Natural Resources (TWRI/IRNR).

Data were collected from each source for their available periods of record. The data were compiled and evaluated in terms of total monthly withdrawal volumes. The BBEST felt that monthly data were sufficient for the purposes of water balance calculations and sufficient to capture any intra-annual / seasonal fluctuations in in-stream flows for both the Arroyo Colorado and Rio Grande.

As discussed in **Section 2.1**, only withdrawals from the Rio Grande were of primary interest. Additionally, withdrawal data were characterized as upstream or downstream within the study area defined in this report. An upstream withdrawal signifies a withdrawal occurring from the Rio Grande between just downstream of Anzalduas Dam and Gage #08473700 (near Los Indios, Texas). A downstream withdrawal signifies a withdrawal occurring between Gage #084734700 near Los Indios, Texas and Gage #08475000 near Brownsville, Texas. This boundary point between upstream and downstream withdrawals was chosen for two reasons: first, it represents the location where the Arroyo Colorado watershed boundary diverges from the Rio Grande watershed boundary (see **Figure II.2-1**); and second, withdrawals upstream of this point are more likely to be associated with uses that discharge to the Arroyo Colorado. Similarly, withdrawals downstream of the Los Indios, Texas location are more likely to be associated with uses that discharge to the Brownsville/Resaca watershed system – eventually draining to the Lower Laguna Madre via a drainage mechanism other than the Arroyo Colorado (e.g. drainage ditch, Resaca, or Brownsville Ship Channel).

2.3.1. Agricultural Withdrawal Data

Three main sources of agricultural withdrawal data were identified by TWRI/IRNR. They included: the Rio Grande Watermaster's Office, the International Boundary and Water Commission's on-line reporting data, and irrigation data associated with the Soil and Water Assessment Tool (SWAT) model generated by Dr. Narayanan Kannan with the Texas AgriLife Blackland Research and Extension Center. The SWAT model irrigation (agricultural withdrawal) data were only available for the upstream withdrawal section as the SWAT model's study area was limited to the Arroyo Colorado watershed (Kannan 2012). (Note: The words "withdrawal" and "diversion" are used interchangeably across the sources of data discussed in this section. As a result, for the purposes of this report, the word "withdrawal" will be used to refer to the removal of water from the Rio Grande for all end uses. This is true regardless of whether the removal of water is intended for consumptive or non-consumptive agricultural and municipal uses.)

Direct communication with several irrigation districts suggested the Rio Grande Watermaster Program was the best and most central source of irrigation withdrawal data; however, after communications with the Watermaster, it was confirmed that their office was not responsible for tracking water use after the point of withdrawal. In other words, an irrigation district may withdraw water from the Rio Grande under an agricultural water right and then later transfer or sell that water to a municipality for municipal use. In fact, this is a common practice in the LRGV. It was beyond the scope of this study to identify and track water transfers after the initial point of withdrawal.

After further communication with personnel from the IBWC, it was confirmed that the on-line IBWC diversion data represented combined municipal and agricultural withdrawals for sections within the study area. Thus, it was determined withdrawal data would have to consist of combined agricultural and municipal withdrawals and that the best source of withdrawal data for the purposes of constructing a water balance and determining water exchanges between the Rio Grande and the Arroyo Colorado was the IBWC withdrawal data.

2.3.2. Municipal Withdrawal Data

Two main sources of municipal withdrawal data were identified by TWRI/IRNR. They included: the Rio Grande Watermaster's Office and the IBWC. After communication with members of the Region M Planning group and with the Watermaster's office, it was determined that the Watermaster's office was the best source of data for municipal withdrawal information. However, as discussed previously, post-withdrawal exchanges of water are not tracked by their office, and despite well-documented withdrawals at point locations up and down the Rio Grande, the end use of the withdrawn water could not be determined by this information. As such, the combined municipal and agricultural withdrawal data recorded by the IBWC was utilized for water balance calculations and in-stream flow discussions completed in this report.

2.4. Return Flow Data

Return flow data for the Arroyo Colorado and Rio Grande were collected for both municipal and agricultural sources. The primary focus for return flows was the Arroyo Colorado and the Brownsville/Resaca watershed drainage system, which principally serve as the conveyance mechanism for discharges from municipal wastewater treatment plants and irrigation drainage. Return flows for the Rio Grande were considered to be negligible with the notable exception of the south wastewater treatment plant in Brownsville, Texas. Assistance with the collection of return flow data was obtained via subcontract with the Texas AgriLife, Texas Water Resources Institute/Institute of Renewable Natural Resources (TWRI/IRNR). As was the case for withdrawal data, return flow data were collected from each source for their available periods of record and compiled in total monthly return volumes.

Agricultural return flows in the study area were assumed to be comprised mostly of irrigation drainage return either through drainage ditch networks or groundwater flow. Municipal return flows within the study area were assumed to consist mostly of wastewater treatment plant discharges. While there are additional sources of return flow to both the Arroyo Colorado and the Rio Grande, these sources were either beyond the scope of this report to estimate or measure (baseflow) or considered minor.

2.4.1. Agricultural Return Flow Data

Agricultural return flow data must be estimated due to the fact that large-scale measurements for this parameter are not feasible. Additionally, irrigation return flows are notoriously difficult to estimate because of the inherent difficulty in estimating the many variables that influence these flows. Rates of consumption, infiltration, evaporation and runoff vary between crop types, soil types, irrigation schedules, and many other factors. One source of irrigation return flow estimates was identified by TWRI/IRNR for the Arroyo Colorado basin – the SWAT model being completed by Dr. Narayanan Kannan with the Teas AgriLife Blackland Research and Extension Center. This data file was used as the return flow agricultural parameter for the upper portion of the water balance in **Section 2.6**. Data for return flow from agricultural sources in the Brownsville/Resaca watershed system was not available. This was due to the fact that the SWAT model used to procure agricultural data for the upper portion did not include the Brownsville/Resaca watershed area. Total return data (combined agricultural and municipal data) were available from the TWDB Coastal Hydrology Technical Report on a subwatershed basis (Schoenbaechler et al. 2011). However, it was necessary to use an estimate for agricultural return flows based on the upstream agricultural return to withdrawal ratio. This ratio was approximately 15 % and was used to estimate downstream agricultural return flows. See a more complete discussion of agricultural return flow estimates in the water balance discussed in **Section 2.6**.

2.4.2. Municipal Return Flow Data

Two main sources of upstream municipal return flow data were identified by TWRI/IRNR. They included the TWDB Coastal Hydrology Technical Report (Schoenbaechler et al., 2011) and the SWAT model previously discussed. The TWDB inflow study obtained their municipal return flow data from a review of permitted outfalls in the study area. The TWDB inflow study data was selected for water balance calculations as the inflow values generated by this work was used for other studies completed as part of this report – namely the impact of freshwater flows on sea grasses in the Lower Laguna Madre. This inflow study was also the only source of municipal return flow data for the downstream portion of the study area and was utilized in the water balance discussed in **Section 2.6**.

One municipal return flow for the Rio Grande was identified by TWRI/IRNR, specifically the south wastewater treatment plant for the City of Brownsville, Texas. Discharge data for this plant was obtained by a review of discharge permits and was extracted from the TWDB inflow study.

2.5. Watershed Runoff and Channel Loss Data

Runoff and channel loss data for the three watersheds in the study area were critical to the formation of a water balance. As before, assistance with the collection of runoff and loss data was obtained via subcontract with TWRI/IRNR. The primary sources of runoff data consisted of existing or recently completed hydrologic models including the SWAT model and the TWDB Coastal Hydrology Technical Report discussed in previous sections.

2.5.1. Watershed Runoff Data

Two sources of watershed runoff data were identified by TWRI/ IRNR for the Arroyo Colorado watershed. Watershed runoff data for the entire Arroyo Colorado watershed (both gaged and ungaged sections) was obtained from the SWAT model generated by Dr. Narayanan Kannan with the Texas AgriLife Blackland Research and Extension Center. Annual and monthly data were provided by this model for the period of record between1999-2008 on a subwatershed basis. Runoff contributions from the subwatersheds upstream of the Harlingen gage (Gage #08470400) were utilized. While this data represented the most up-to-date data available for the Arroyo watershed, the smaller ten year period of record was the limiting period of record for the water balance discussed in **Section 2.6**.

An additional source of runoff data for the ungaged portion of the Arroyo watershed (downstream of the Harlingen gage discussed in Section II_2) was available from the Texas Rainfall-Runoff (TxRR) model (Schoenbaechler et al. 2011). This data was available for the years 1977-2010; however, specific runoff data was estimated by the study for the ungaged portion of the watershed only. Gage flow values were used to estimate total bay inflow directly for the portion of the watershed upstream of Harlingen as the specific constituents of the gaged flow value (e.g., runoff, return flows) were not the focus of that study.

As discussed in **Section 2.1**, the Brownsville/Resaca watershed system has not been studied as extensively as the Arroyo Colorado. Additionally, the Brownsville/Resaca watershed is not monitored by a single streamflow gage. This negatively impacts the availability of data for this watershed, such as runoff and loss data. While some flood hydrology studies were identified for specific, more urbanized subwatersheds (typically in Brownsville), no studies covered the entire Brownsville / Resaca watershed region. As a result, it was necessary to rely on the TWDB Freshwater Inflows study that utilized the Texas Rainfall Runoff (TxRR) model to estimate runoff from ungaged basins. While the TxRR model has been successfully utilized in a variety of coastal ungaged watersheds, the BBEST found it necessary to comment on the surprising fact that a rapidly urbanizing watershed such as the Brownsville/Resaca watershed system was still ungaged – particularly one with such critical water resource challenges. **Section 9** will provide more discussion on this important topic – the need for gaging in the Brownsville/Resaca watershed.

No specific hydrologic models were identified that focused on the narrow Rio Grande watershed between Anzalduas dam and the Gulf of Mexico. As the system is well-gaged, and combined with the fact that the Rio Grande watershed is extremely narrow in extent due to natural and man-made levees, the runoff component of the Rio Grande for this reach was assumed negligible for the purposes of the water balance work in **Section 2.6**. For the same reason, the TWDB Bays and Estuaries Program has not developed a TxRR model for the Rio Grande watershed.

2.5.2. Channel Loss Data

Channel losses are often a critical and sensitive parameter in the calibration and validation of hydrologic models. As the parameter is difficult to estimate with accuracy, it is often left to a range of values and subsequently used in the calibration and final validation of the model through comparison to a known flow value provided by a streamflow gage.

The SWAT model developed for the Arroyo Colorado provided net runoff data for the watershed and thus included loss estimates in the runoff values. As TWDB data was used for flows downstream of the Harlingen gage, an estimate for channel losses of 1% of instream flow was applied to those values in the water balance discussed in the following section.

The Water Availability Model (WAM) for the Rio Grande utilized a channel loss rate of 0.08% per river mile for the Rio Grande reach within our study area (Brandes 2003). This rate was applied to Rio Grande flows in the water balance that follows.

It is likely that Brownsville/Resaca watershed channel loss rates vary greatly by system (e.g., drainage ditch, Resaca system). No loss rate values were identified in any studies or work that encompassed the entire watershed area. A rough estimate of 0.16% per river mile for the Resaca system was utilized based on the fact that seepage and infiltration losses were considered higher in the this watershed as compared to the Rio Grande due to higher residence times and increased wetting/drying of side banks due to greatly varying flow rates.

Section 2.6 General Water Balance for the Study Area Portion of the Rio Grande, Arroyo Colorado, and Brownsville / Resaca Watersheds for the Years 1999-2008

2.6.1 Purpose and Goal

A deterministic, general water balance for the study area discussed in **Section 2.1** was completed for a period of record from 1999-2008. The water balance focused on parameters and data deemed of great interest or importance to the Lower Rio Grande / Lower Laguna Madre BBEST. Parameters and data of interest included:

- The determination of existing flows on a percentile distribution basis in the Rio Grande, Arroyo Colorado, and the Brownsville / Resaca watersheds.
- Estimation of the volume of agricultural and municipal withdrawals from the Rio Grande on a monthly basis and geographically broken up into upper and lower regions.
- Estimation of the volume of agricultural and municipal returns to the Arroyo Colorado, Rio Grande, and Brownsville / Resaca watersheds on a monthly basis.
- Estimation of the percentage of flow in the Arroyo Colorado due to agricultural / municipal return flows and watershed runoff on a monthly or annual basis.
- Comparison of mean, median, and percentile flow volumes under specific conditions for each basin's inflow to the Laguna Madre and Rio Grande estuary as appropriate. Conditions as currently identified included:
- "existing flow" conditions (1999-2008)
- "natural flow" conditions. (1999-2008) Note: "Natural flow" condition signifies no withdrawals or returns associated with municipal and agricultural uses.

Output for each of the above was determined as being needed on a monthly basis. Most output parameters were estimated at this time step; however, percentile flow in the Arroyo Colorado belonging to agricultural, municipal or runoff could not be estimated on a monthly basis due to the lack of residence time and travel time data for agricultural operations and return flow.

The approach and scope of the water balance was initially intended to provide a range of possible values for any general set of "water use and return" scenarios; however, limitations in periods of record for several parameters, lack of specific geographic location data for some withdrawal and return data, and the expected difficulty in obtaining agricultural return flow data forced a switch to a more straightforward, deterministic model under a limited set of flow scenarios – namely "existing" and "natural flow".

Thus, the final dataset and flow values build off of and should complement other studies in the area, including Brandes (2003) and Schoebaechler et al. (2011), by specifically addressing the above identified needs of the BBEST. The dataset should also set the foundation for future water balance work and assist in the identification of water use data management and tracking improvements that will likely assist in the implementation of recommendations and proposed adaptive management strategies.

2.6.2 Limitations of Study

The undertaking of any water balance for an area as complex as the Lower Rio Grande Valley is a task often limited to broad parameter balancing such as rainfall, runoff and flow calculations. Due to time, scope, data availability and budget limitations, the water balance conducted for this study has very specific limitations with respect to its use and application for purposes not expressly listed in the previous section. Additionally, accuracy of the percentile flow values are limited to the accuracy of available data and should be considered applicable only for comparisons of flow between the studied watersheds and inflow to the Lower Laguna Madre and Rio Grande estuary as appropriate.

The study was not intended to account for all parameters traditionally included in a full-scale balance. It should be considered a general balance of runoff, agricultural and municipal withdrawals / returns, and losses where available. Specific parameters that were not investigated included evapotranspiration, infiltration, and groundwater / interflow. Additionally, the study was not designed to provide geographically detailed flow and/or use information at the specific water feature level (i.e., canals, ditches, particular discharge and / or withdrawal points).

Four specific additional limitations of the water balance include:

- No diversions or return data to Mexico were included in the study. This may initially seem like a significant enough of a limitation to question the accuracy of model output data; however, it should be noted that agricultural withdrawal and returns on the Mexican side are generally outside of the study area. Additionally, the presence of a flow gage at the downstream location of Brownsville, Texas and the fact that component flows were not needed for the Rio Grande lessened the importance of this data.
- Water withdrawal and return data were not available for extended periods. Period of record for the water balance was limited by agricultural return data provided by a recently conducted hydrologic study (see **Section 2.4**).
- The balance is limited to volumetric flow comparisons at a monthly time step. Timing differences between return and withdrawal dates are by nature, highly variable, and beyond the scope of this report to estimate with confidence.
- The entire system is part of the Rio Grande Federal Flood Control Project and periodically, albeit infrequently, switches to an entirely different flow pattern, flow regime, and structure as discussed in **Section 2.2**.
- The lack of streamflow gages in the Brownsville / Resaca watershed system prevented an evaluation of the validity of assumptions for agricultural return flows in that portion of the study area.

2.6.3. Water Balance Schematic and Variables

Figure 2.6.1 shows a conceptual schematic illustrating flow paths, diversions / withdrawals, returns, and other variables utilized in the water balance model and calculations. The thick, blue arrows show the principal basins in the study area: Arroyo Colorado (gaged and ungaged sections), Brownsville area resacas and drainage systems, and the Rio Grande between Anzalduas Dam and the Gulf of Mexico. The outfalls of the three basins are also shown to insure that the reader is aware that the Rio Grande discharges directly to the Gulf of Mexico. The Arroyo Colorado and the North Floodway drain to the Lower Laguna Madre directly. Brownsville area resacas and ditches drain to the Brownsville Ship Channel, which connects to the Lower Laguna Madre. A fourth set of subbasins that was not originally included in the water balance, but was later incorporated by utilizing TWDB data, is shown in the figure and labeled as "Subbasins North of Arroyo Colorado."
Other flow patterns and/or uses are illustrated in specific colors as follows:

Green	Diversion / Withdrawals
Black	Returns
Orange	Agriculture / Municipal Consumption and/or Losses
Light Brown	Transmission Losses
Red	Floodway Operational Flow Patterns
Light Blue	Distributed Rainfall Runoff
Darker Blue (broad)	Primary Flow Path for each Basin

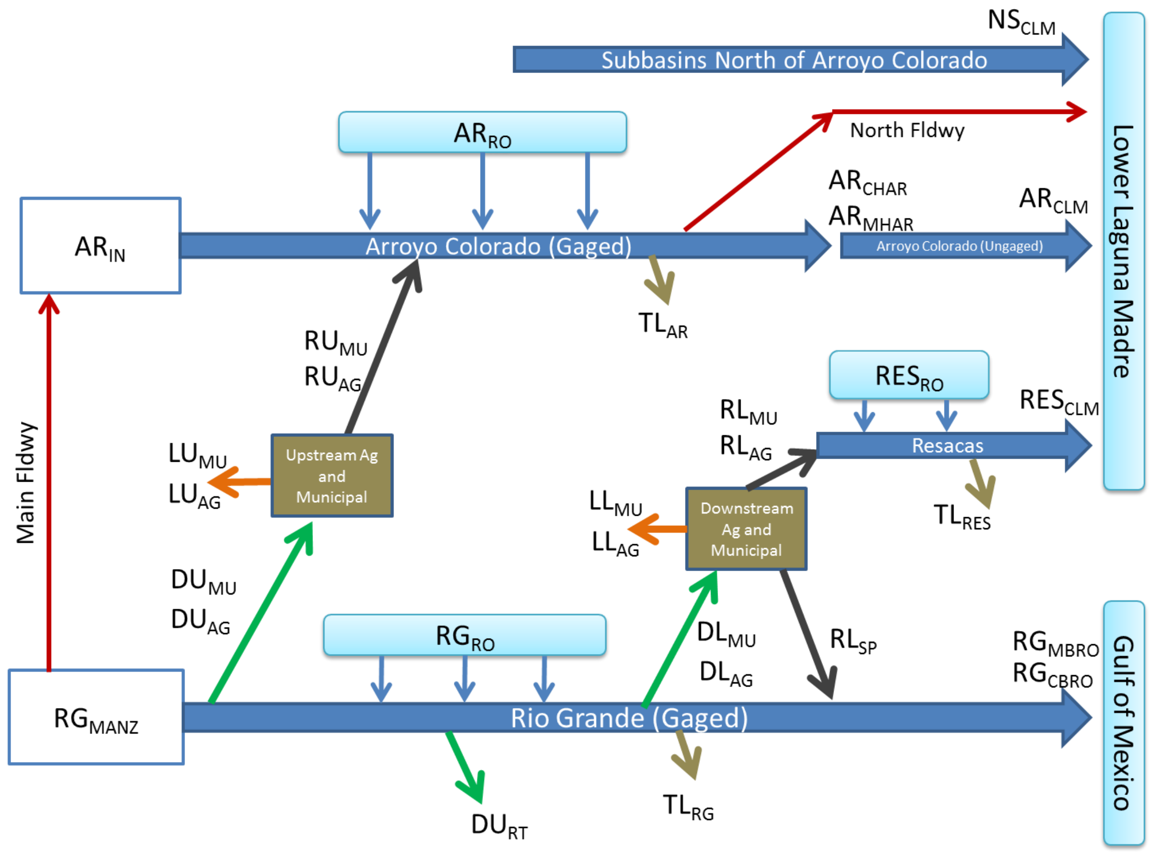


Figure 2.6.1. Flow schematic for the Arroyo Colorado, Rio Grande, and Resaca subbasins showing variables used in water balance calculations. (For a list of variables and descriptions see **Table 2.6.1**)

The schematic was constructed in such a way as to best illustrate flow patterns and generalized discharge locations for the three basins and in particular, the interbasin relationship between them. As can be seen from the schematic, the Rio Grande serves as the primary water source for both upstream and downstream agricultural and municipal uses. Return flows from these uses do not normally discharge back to the Rio Grande, and in fact, return to the Arroyo Colorado or Brownsville area resacas and drainage ditches (see **Section 2.3** for a detailed discussion of withdrawal data and locations). This results in a net decrease of inflows to the Rio Grande estuary and a net increase to inflows into the Lower Laguna Madre. One of the primary reasons for conducting the water balance / flow analysis was to determine the relative impact of this diversion / withdrawal and return flow pattern on “existing” flow conditions.

Table 2.6.1 lists and briefly describes the variables used in the water balance / flow analysis completed for this study. Upstream diversions are associated with those diversions / withdrawals that occur between Anzalduas dam and Los Indios, Texas. Upstream returns are those returns associated with upstream withdrawals and that discharge to the Arroyo Colorado as illustrated. Downstream diversions are associated with those diversions / withdrawals that occur between Los Indios, Texas and Brownsville, Texas. Downstream returns are those returns associated with downstream withdrawals and that primarily discharge to the Laguna Madre through Brownsville area resacas, drainage mechanisms, and the Brownsville Ship Channel.

Table 2.6.1. List and Description of Variables used in the Water Balance / Flow Analysis Rio Grande River

Variable	Description
Rio Grande River	
RG_{MANZ}	Measured flow downstream of Anzalduas near Reynosa (Gage # 08469200)
RG_{MBRO}	Measured flow near Brownsville (Gage # 08475000)
$RG_{CBRO, NAT}$	Calculated flow near Brownsville (Existing and Natural)
RG_{RO}	Rainfall runoff for Rio Grande between Anzalduas and Brownsville (assumed negligible)
TL_{RG}	Transmission losses for Rio Grande between Anzalduas and Brownsville
DU_{RT}	Diversion in upper region for Retamal Dam
DU_{MU}	Diversion / Withdrawal in upper region for municipal use
DU_{AG}	Diversion / Withdrawal in upper region for agricultural use
DL_{MU}	Diversion / Withdrawal in lower region for municipal use
DL_{AG}	Diversion / Withdrawal in lower region for agricultural use
RL_{SP}	Return in lower region to Rio Grande from South Wastewater Treatment Plant in Brownsville, Texas
Consumptive Losses Upper Region	
LU_{MU}	Losses (consumption and transmission) in upper region - municipal
LU_{AG}	Losses (consumption and transmission) in upper region - agricultural
Arroyo Colorado	
AR_{IN}	Arroyo Colorado Headwater Inflow (assumed zero under non-flood conditions)
AR_{MHAR}	Measured flow at Harlingen (Gage # 08470400)
AR_{CHAR}	Calculated flow at Harlingen
$AR_{CLM, NAT}$	Calculated inflow to Lower Laguna Madre from Arroyo Colorado (Existing and Natural)
AR_{RO}	Rainfall runoff for Arroyo Colorado (Gaged and ungaged basins)
TL_{AR}	Transmission losses for Arroyo Colorado (Gaged and ungaged basins)
RU_{MU}	Return flow in upper region from municipal uses
RU_{AG}	Return flow in upper region from agricultural uses
Consumptive Losses Lower Region	
LL_{MU}	Losses (consumption and transmission) in lower region - municipal
LL_{AG}	Losses (consumption and transmission) in lower region - agricultural
Brownsville Area Resacas / Drainage Network	
$RES_{CLM, NAT}$	Calculated inflow to Lower Laguna Madre from Brownsville Area Resacas / Drainage Network (Existing and Natural)
RES_{RO}	Rainfall runoff for Brownsville Area Resacas / Drainage Network
TL_{RES}	Transmission losses for Brownsville Area Resacas / Drainage Network
RL_{MU}	Return flow in lower region from municipal uses
RL_{AG}	Return flow in lower region from agricultural uses

Variable	Description
Subbasins North of the Arroyo Colorado that Contribute to the Lower Laguna Madre	
$NS_{CLM, NAT}$	Calculated inflow to Lower Laguna Madre from Subbasins North of the Arroyo Colorado (Existing and Natural)

2.6.4. Rio Grande River Study Area Flows for the Period of Record (1999-2008)

The results presented and discussed in this section are for the section of the Rio Grande in the study area defined for this water balance. Additionally, they are presented as monthly average values over the period of record from 1999-2008 unless noted otherwise. Units for flow values are in ac-ft (per month) unless noted otherwise.

Municipal and Agricultural withdrawals made in the upper and lower regions of the study area needed to be combined into total withdrawals (Municipal + Agricultural) per region as discussed in **Section 2.3**. **Table 2.6.2** compares the upper and lower region combined municipal and agricultural diversions on a monthly average basis. Combined upper municipal and agricultural withdrawals were significantly larger than lower region withdrawals. This is largely due to the larger agricultural irrigation demands for that region and the larger population in Hidalgo County. An annual pulse of higher withdrawals can be observed roughly from March – August that is associated with the irrigation season. This pulse is much more pronounced in the upper region owing to the larger agricultural demand in Hidalgo County. Tabulated monthly values for diversion data are graphed in **Figure 2.6.2**.

Table 2.6.2 Comparison of upper (DU) and lower (DL) diversions (withdrawals) for combined municipal and agricultural use.

Units: ac-ft / month	$DU_{MU} + DU_{AG}$	$DL_{MU} + DL_{AG}$
Average	49,955	7,422
Median	43,002	6,766
Standard Deviation	30,871	4,053

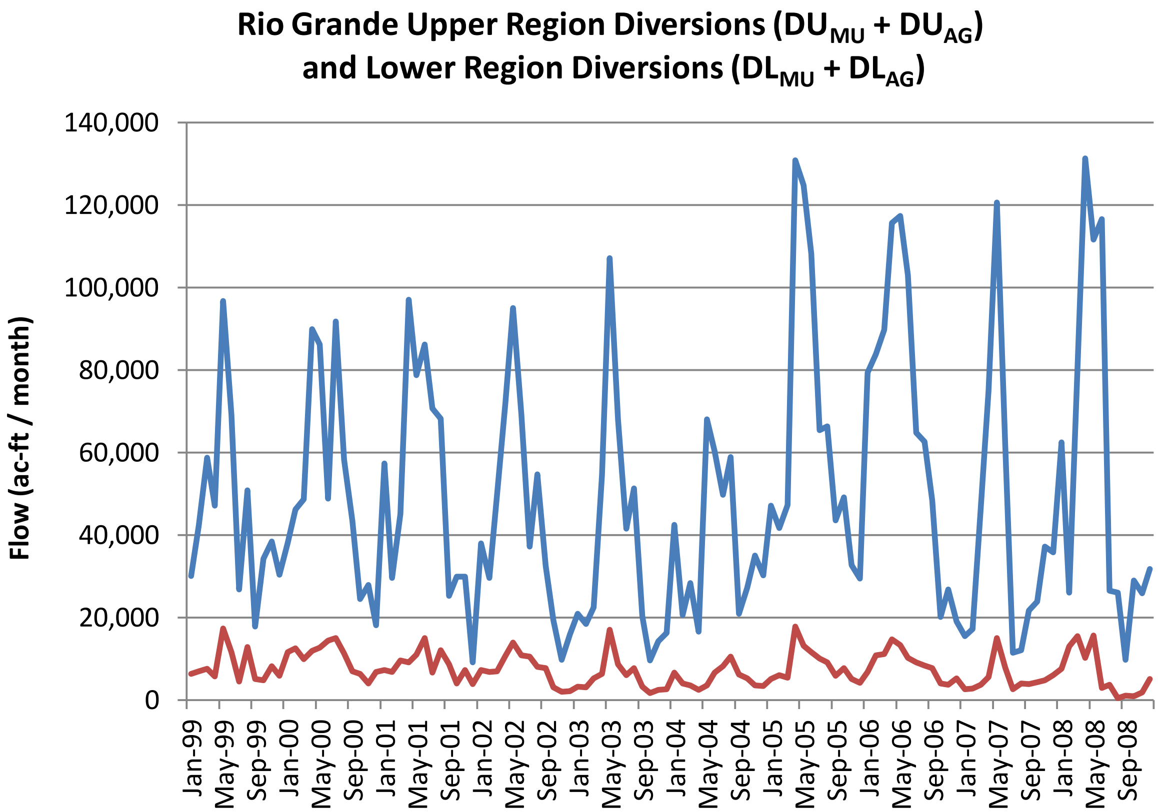


Figure 2.6.2. Monthly average flows for Upper Region and Lower Region Diversions / Withdrawals from the Rio Grande River for combined municipal and agricultural uses.

The above municipal and agricultural withdrawals represent the primary cause of the flow reductions observed between gaging stations in Anzalduas and Brownsville. **Table 2.6.3** compares the average, mean, and standard deviation for gaged flows in the Rio Grande just downstream of Anzalduas (RG_{MANZ}) as well as Brownsville (RG_{MBRO}). The table also includes average, mean, and standard deviation for calculated water balance output variables including "calculated existing flow" and the "estimated natural flow" at Brownsville – RG_{CBRO} and $RG_{CBRONAT}$ respectively.

Table 2.6.3. Rio Grande river flow statistics for measured data at Anzalduas and Brownsville, as well as calculated flow at Brownsville for existing and natural conditions.

Units: ac-ft / month	RG_{MANZ}	RG_{MBRO}	RG_{CBRO}	$RG_{CBRONAT}$
Average	92,621	26,993	30,474	81,618
Median	77,085	16,703	21,449	67,928
Standard Deviation	52,537	38,901	36,456	46,295
Coefficient of Variation	0.57	1.44	1.20	0.57

Figure 2.6.3a graphs the gaged flow data values over the period of record. The dry years from 1999-2002 are reflected in the exceptionally low flow values at Brownsville. Irrigation season induced higher flow values can once again be seen in the March – August period at Anzalduas, but is not reflected in the Brownsville gage due to agricultural diversions between the two locations. Shorter duration, high flow periods associated with heavy rainfall in the more upstream regions of the Rio Grande watershed are observed when both gages spike as in the Fall of 2003, Summer and Fall of 2004 and 2008.

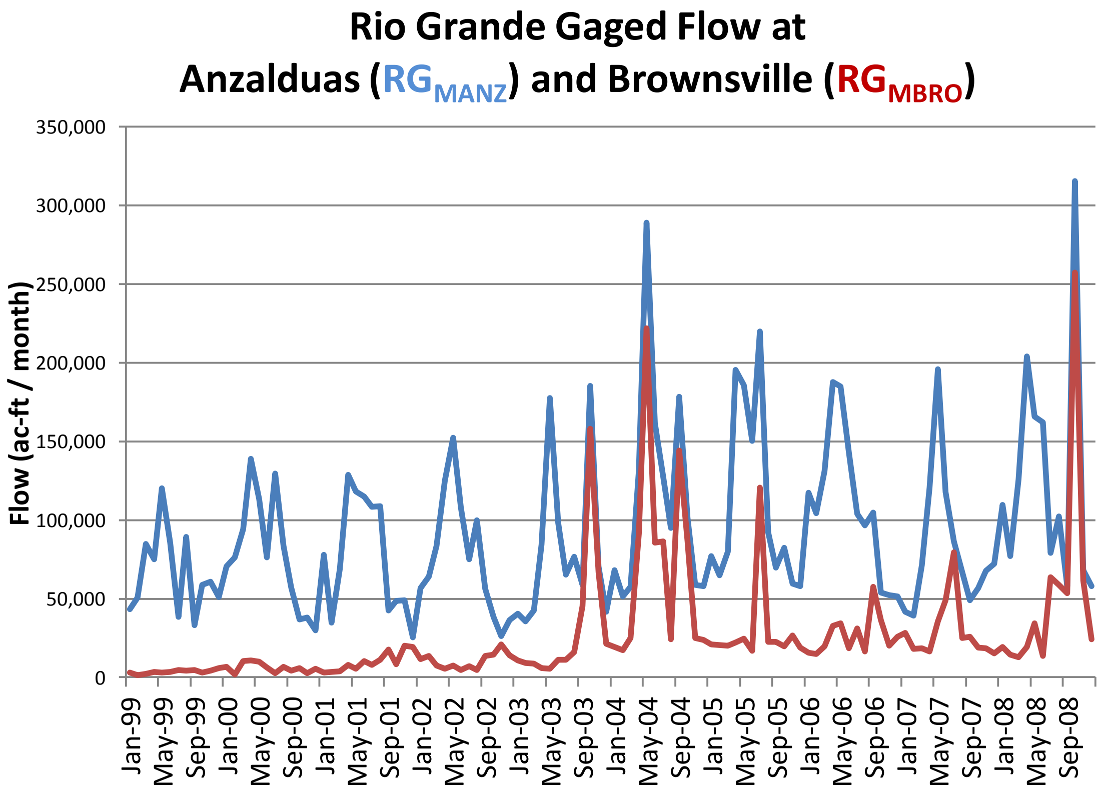


Figure 2.6.3a Monthly average flows for Rio Grande gages just downstream of Anzalduas (blue) and at Brownsville (red).

Figure 2.6.3b compares the gaged Brownsville flow and the estimated flow at the same location after removing the agricultural and municipal diversions discussed earlier and accounting for losses. The calculated flows compare favorably during peak events as would be expected due to the reduced impact of withdrawals during higher flow events. Additionally, during lower flow events, calculated flow values (RG_{CBRO}) are consistently a bit higher, with average value flows of 26,993 ac-ft / month measured and 30,474 ac-ft / month calculated. This might be attributed to the fact that no agricultural and municipal diversions for Mexico were included in the study area reach of the Rio Grande. The difference between calculated and measured values is more pronounced during the drier periods of the period of record, 1999-2003.

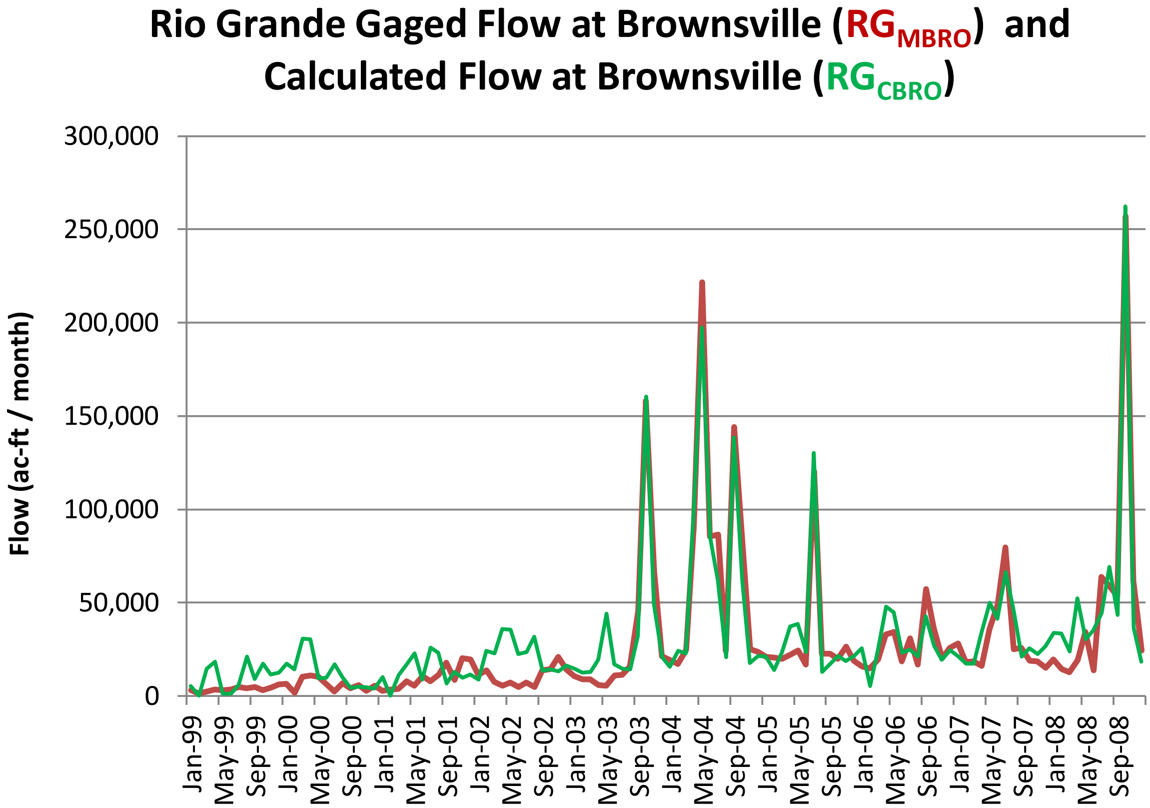


Figure 2.6.3b. Comparison of measured (gaged) flow and calculated flows in the Rio Grande at Brownsville.

Estimating natural flow conditions for any river or stream necessitates studying the entire watershed. As mentioned earlier in this chapter, various limitations prevented the entire Rio Grande watershed from being analyzed. As such, a true natural flow estimation attempt could not be made for this report. For the purposes of comparisons to the other watersheds in the study, an estimate using the flow past Anzalduas as the input flow and eliminating all withdrawals due to municipal and agricultural uses was adopted as a rough approximation of the natural flow condition. Only losses based at a rate of 0.08% of flow per river mile (Brandes 2003) were applied to this input flow. Again, no losses to Mexico were considered. This approximation of the natural flow, or $RG_{CBRONAT}$, therefore closely resembles the Anzalduas or RG_{MANZ} flow profile over the period of record. **Figure 2.6.4** illustrates the flow values estimated using this methodology.

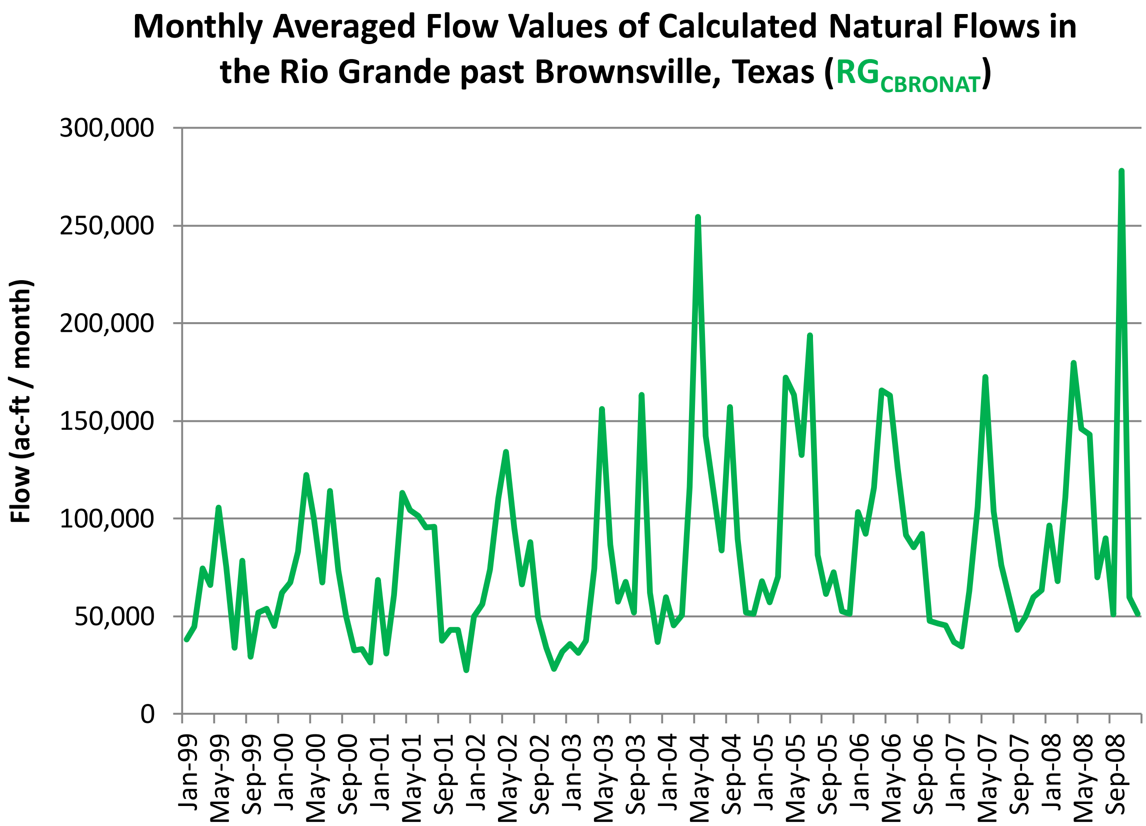


Figure 2.6.4. Monthly average flows for estimated natural flows in the Rio Grande past Brownsville, Texas. (Note: "Natural Flows" were estimated by assuming no agricultural or municipal withdrawals from the Rio Grande within the study area.)

Table 2.6.11 provides minimum, maximum, and percentile flow estimations calculated over the period of record of 1999-2008 for both RG_{MBRO} and $RG_{CBRONAT}$, the measured flow and approximated natural flow past Brownsville respectively. (Other critical inflow parameters to the Rio Grande estuary and Lower Laguna Madre are also provided in this table and will be discussed in the following sections as appropriate.)

The Rio Grande Water Availability Model, or Rio Grande WAM, provides a significantly more complete watershed based estimation of natural flows at various points along the Rio Grande River including the reach below Anzalduas Dam (Brandes 2003). A comprehensive comparison between the limited approximation used in this report and the WAM estimations for natural flows was not possible due to there being only two years of overlap between the periods of record – namely 1999 and 2000. For those two years, however, the WAM report listed 3,000,000 ac-ft and 2, 250,000 ac-ft of natural flow for 1999 and 2000 respectively. This report's estimation methodology yielded approximately 800,000 ac-ft for 1999 and 950,000 ac-ft for 2000.

Both estimations of natural flow conditions show flow rates that are higher than existing flows in the Rio Grande below Anzalduas Dam and in particular, at or downstream of

Brownsville. The WAM estimation of natural flows for the Rio Grande average greater than 4,000,000 ac-ft per year based on approximately 60 years of data. If evenly distributed, this value equates to 333,000 ac-ft / month, exceeding the currently observed monthly average of 27,000 ac-ft / month past Brownsville by over a factor of twelve. The average value of $RG_{CBRONAT}$ of 81,618 ac-ft also greatly exceeds the observed monthly average, but only by a factor of three. The WAM natural flow average of 333,000 ac-ft / month exceeds even the maximum calculated value of $RG_{CBRONAT}$ over the period of record 1999-2008, which was 278,042 ac-ft / month. This implies that complete elimination of agricultural and municipal flows downstream of Anzalduas would not be sufficient to meet the natural flow condition identified by the WAM study even under very high average flow conditions.

2.6.5. Arroyo Colorado

As discussed previously in this chapter, the Arroyo Colorado serves as the return flow path for municipal and agricultural uses, receiving a portion of its water flow from the Rio Grande through these uses. Without the steady and consistent addition of return flows, the Arroyo would be hydrologically similar to other coastal streams (arroyos) in South and Central coastal Texas, with strongly ephemeral flows. One of the several primary goals of the water balance study was to determine the monthly average volumes of these return flows to the Arroyo. Another was to determine the percentage make-up of the Arroyo flow owing to agricultural returns, municipal returns, and rainfall runoff. Lastly, the water balance was to estimate the existing and natural condition inflows the Arroyo Colorado provides to the Lower Laguna Madre. This section provides estimates for each of these.

Municipal and agricultural monthly averaged return flows to the Arroyo are shown in **Table 2.6.4** as RU_{MU} and RU_{AG}. These return flows correspond to the upper region diversions (withdrawals), DU_{MU} and DU_{AG}. This table also shows the rainfall runoff for the gaged portion of the Arroyo Colorado watershed. Monthly averaged values for each of these parameters are graphed over the period of record in **Figure 5.6.5**. Despite higher consumption rates for agricultural uses as compared to municipal uses, the higher diversion volumes for agriculture result in larger return volumes for agriculture on average (Rains, 2002). However, due to pulsing of flows during irrigation season, agricultural returns are not always higher than municipal. Municipal returns are more consistent and illustrate less variation from the mean than both agricultural returns and rainfall runoff.

Table 2.6.4. Flow statistics for municipal and agricultural return flows corresponding to upper region municipal and agricultural diversions (withdrawals) as well as rainfall runoff for the Arroyo Colorado.

Units: ac-ft / month	RU_{MU}	RU_{AG}	AR_{RO}
Average	2,350	8,464	6,946
Median	2,281	4,569	3,553
Standard Deviation	1,419	8,687	9,536

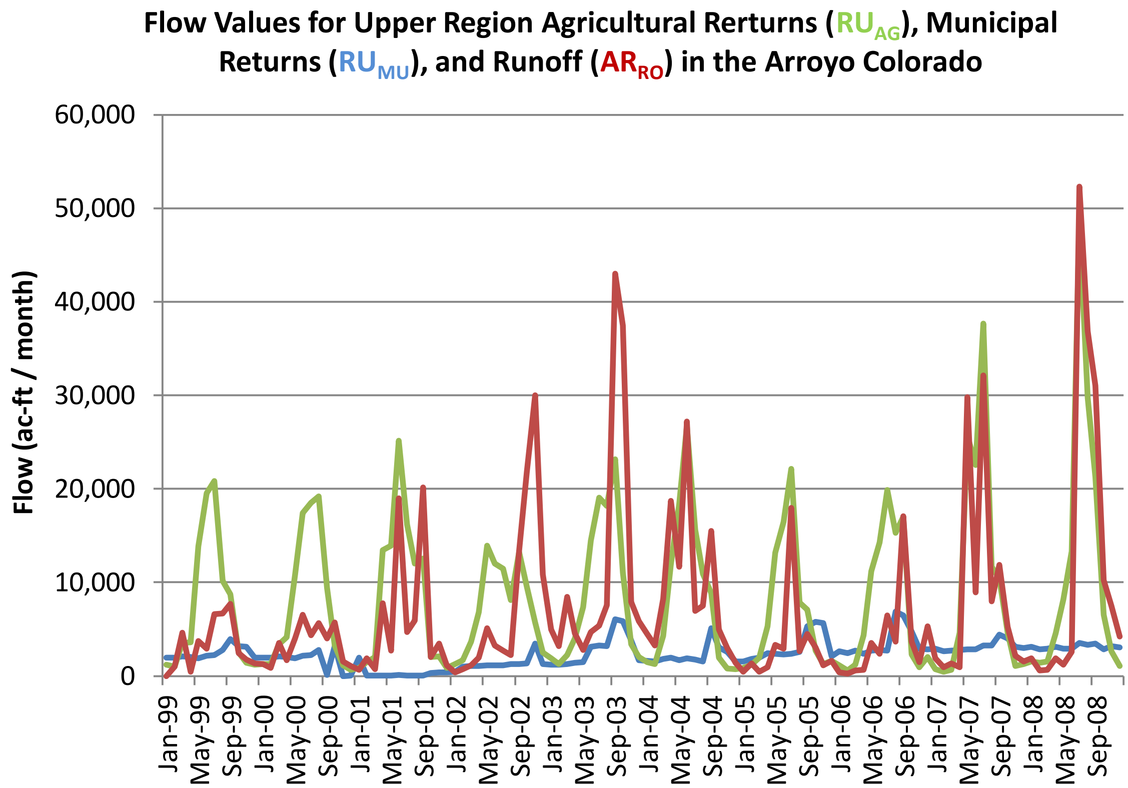


Figure 2.6.5. Monthly average flows for agricultural and municipal returns as well as rainfall runoff for the Arroyo Colorado.

While an attempt was made to determine the percentage makeup of flow at the Harlingen gage in the Arroyo Colorado corresponding to agricultural returns, municipal returns, and rainfall runoff on a monthly or seasonal basis, the lack of timing data for returns prevented anything less than an annual average estimate. **Table 2.6.5** provides an annual average estimate of the percentage of flow in the Arroyo due to each of the three sources. This is a rough estimate only and the reader is cautioned that important factors such as baseflow and groundwater / interflow were not considered in this study. However, despite these limitations in the methodology, the values should provide a rough estimate of the constituency of the flow past Harlingen.

Table 2.6.5. Percentage of flow past the Harlingen gage on the Arroyo Colorado corresponding to listed source based on annual average estimate.

Annual Average Estimate	% of Flow at Harlingen Gage due to source listed
Agricultural Returns	48%
Municipal Returns	13%
Rainfall Runoff	39%

Table 2.6.6 and Figure 2.6.6 compare the gaged or measured Arroyo Colorado flow at Harlingen with the calculated (estimated from water balance) flow and the estimated flow at the same location. The calculated flows compare very favorably with measured flows when compared at the annual average level; however, despite an excellent match for monthly averaged data, the calculated values ($AR_{CHAR)}$ exhibit far greater variation – with over-predictions during the irrigation season and under-predictions during the non-irrigation season. This difference is likely due to the fact that the water balance methodology only incorporated volumetric analysis and did not attempt to account for the delay in timing (often significant) between withdrawals and returns. The model may be improved if necessary by accounting for these timing issues by estimating average travel times via groundwater and surface flow for agricultural returns as well as average residence times for municipal reservoirs.

Table 2.6.6. Percentage of flow past the Harlingen gage on the Arroyo Colorado corresponding to listed source based on annual average estimate.

Units: ac-ft / month	AR_{CHAR}	AR_{MHAR}
Average	17,759	17,112
Median	12,102	13,531
Standard Deviation	17,238	10,763

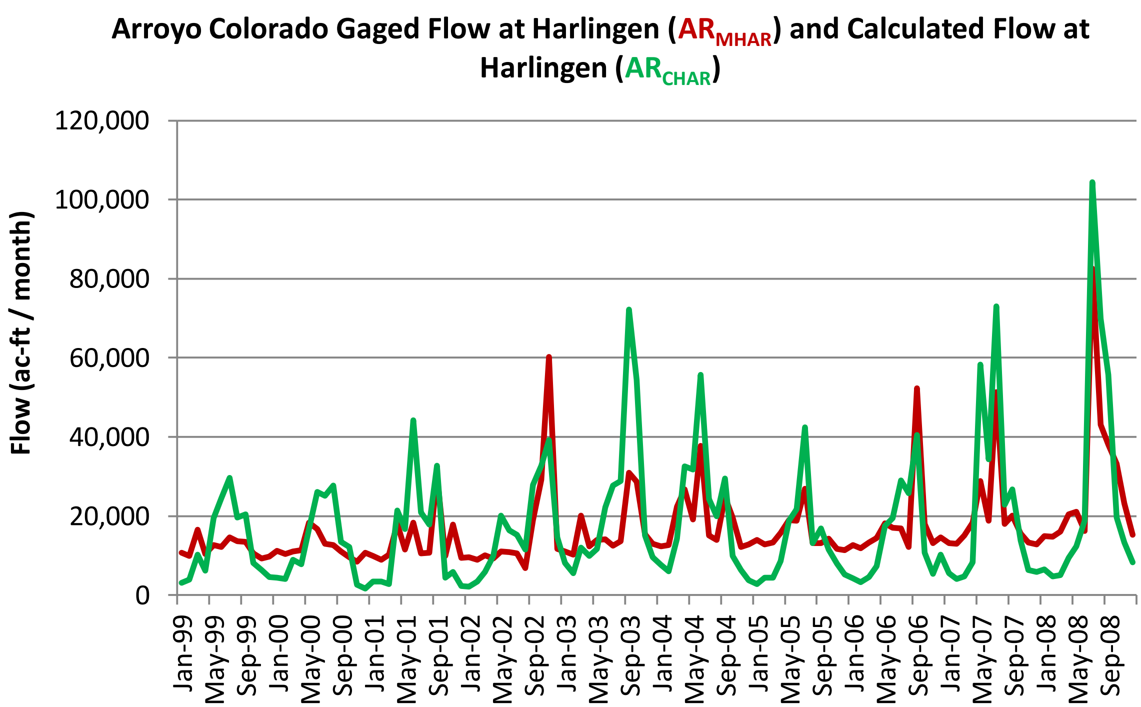


Figure 2.6.6. Comparison of measured (gaged) flow and calculated flows in the Arroyo Colorado at Harlingen.

Table 2.6.7 shows the average monthly flow values for existing and natural condition inflows to the Lower Laguna Madre from the entire Arroyo Colorado basin (both gaged and ungaged sections). Natural conditions again is meant to portray the flow regime for the Arroyo Colorado given no agricultural or municipal return flows – leaving only rainfall runoff and estimated losses. As the most downstream gage for the Arroyo Colorado leaves a significant portion of the watershed ungaged, estimates of runoff, returns, and withdrawals had to be taken from multiples sources – namely the SWAT model and TWDB model discussed in **Section 2.4** and **Section 2.5**.

Figure 2.6.7 shows both inflow conditions graphed over the period of record. As is clearly seen, without return flows, the natural inflow often approaches zero flow during the normally drier months of the year (January – March) and the natural, ephemeral nature of the Arroyo Colorado becomes more apparent.

Table 2.6.11 provides minimum, maximum, and percentile flow estimations calculated over the period of record of 1999-2008 for both AR_{CLM} and $AR_{CLMNAT.}$ As can be seen in this table, the difference between existing and natural flow conditions is more significant at lower percentile flows. This should be expected as return flows would play a less significant role during high flow periods normally induced by heavy rainfall events.

Table 2.6.7. Flow statistics for existing (AR_{CLM}) and natural inflows (AR_{CLMNAT}) to the Lower Laguna Madre from the Arroyo Colorado. (Both gaged and ungaged basins)

Units: ac-ft / month	**AR_{CLM}**	**AR_{CLMNAT}**
Average	21,102	9,928
Median	15,680	4,273
Standard Deviation	17,412	16,213

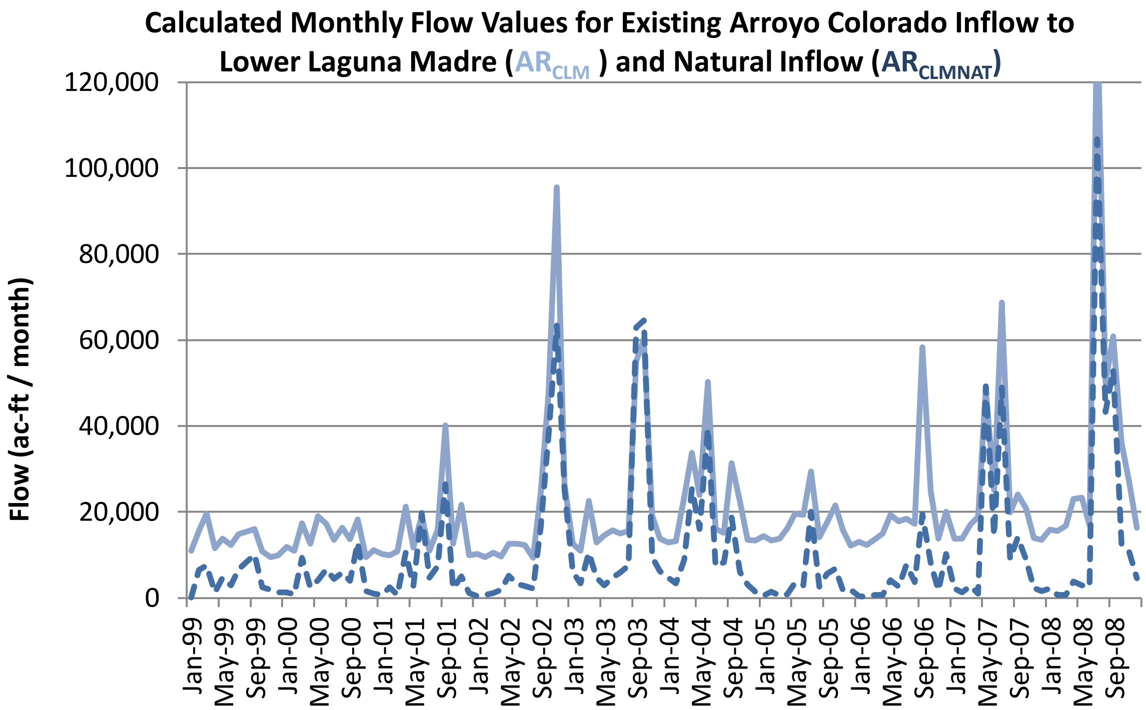


Figure 2.6.7. Graph of existing (AR_{CLM}) and natural inflows (AR_{CLMNAT}) to the Lower Laguna Madre from the Arroyo Colorado. (Both gaged and ungaged basins)

2.6.6. Brownsville / Resaca Watersheds

As discussed in **Section 2.1**, the Brownsville / Resaca watershed represents the hydrologic area between the southern watershed divide of the Arroyo Colorado and the northern watershed divide of the Rio Grande River. This area extends to include the majority of the City of Brownsville, Texas, and all areas east of the city including the Brownsville Ship Channel area – which serves as one of the primary flow paths for drainage and returns for this watershed. Northward, this collection of smaller subwatersheds extends to the Resaca de los Cuates – which largely forms the south-eastern boundary of the Arroyo Colorado watershed. This area is comprised of a number of ungaged subbasins ranging from largely urban basins in Brownsville, to a mix of suburban and agricultural (see **Figure 2.1.3** for a map of study area subbasins). The flow data provided in this section relies heavily on data in Schoenbaechler et al. (2011) for runoff estimates and return data.

There are multiple outfall locations for these subwatersheds as well with some of the northern resacas (Resaca de los Cuates) draining directly to the Lower Laguna Madre, while the majority of the southern, more urbanized subwatersheds drain to common ditches and coastal lakes which in turn drain to the Brownsville Ship Channel. The eastern end (or navigation entry) of the Brownsville Ship Channel is connected to the southern reach of the Lower Laguna Madre – forming a four-way connection with the Ship Channel to the west, the Lower Laguna Madre to the north, South Bay to the south, and the Brazos Santiago Pass to the east.

As discussed earlier, the lower region agricultural and municipal withdrawals from the Rio Grande were assumed to return within this subwatershed area. This assumption was necessary due to the limitations of scope of this report as well as the complexity of the irrigation and drainage networks in the area.

Table 2.6.8 shows the average, median and standard deviation for agricultural and municipal return flows associated with the lower region withdrawals from the Rio Grande. The table also shows the average monthly discharge of Brownsville's South Wastewater Treatment Plant which discharges to the Rio Grande River. The right column shows the flow statistics for the estimated runoff resulting from rainfall over all subwatesheds in this region.

Table 2.6.8. Flow statistics for municipal (RL_{MU}) and agricultural (RL_{AG}) return flows corresponding to lower region municipal and agricultural diversions (DL_{MU} + DL_{AG}) as well as the discharge flow for Brownsville's South Wastewater Treatment Plant (RL_{SP}), which discharges to the Rio Grande River.

Units: ac-ft / month	**RL_{AG}**	**RL_{MU}**	**RL_{SP}**	**RES_{RO}**
Average	773	854	523	4,110
Median	633	857	520	750
Standard Deviation	547	167	51	10,302

Figure 2.6.8a graphs the return flows in this watershed and provides monthly fluctuations of flow over each month throughout the period of record. Irrigation return flows again can be seen to vary with the irrigation season and municipal return flows are particularly consistent as expected. Another important fact is that the return flows in this subwatershed are significantly smaller than the upper region return flows (those that drain to the Arroyo Colorado). In fact, the average RL_{MU} value of 773 ac-ft / month is roughly one-third (32.9%) of the average RU_{MU} value of 2,350 ac-ft / month. The difference in agricultural returns is even more significant with the RL_{AG} average value of 773 ac-ft / month representing only 9.1% of the upper region agricultural return, RU_{AG}, average value of 8,464 ac-ft / month.

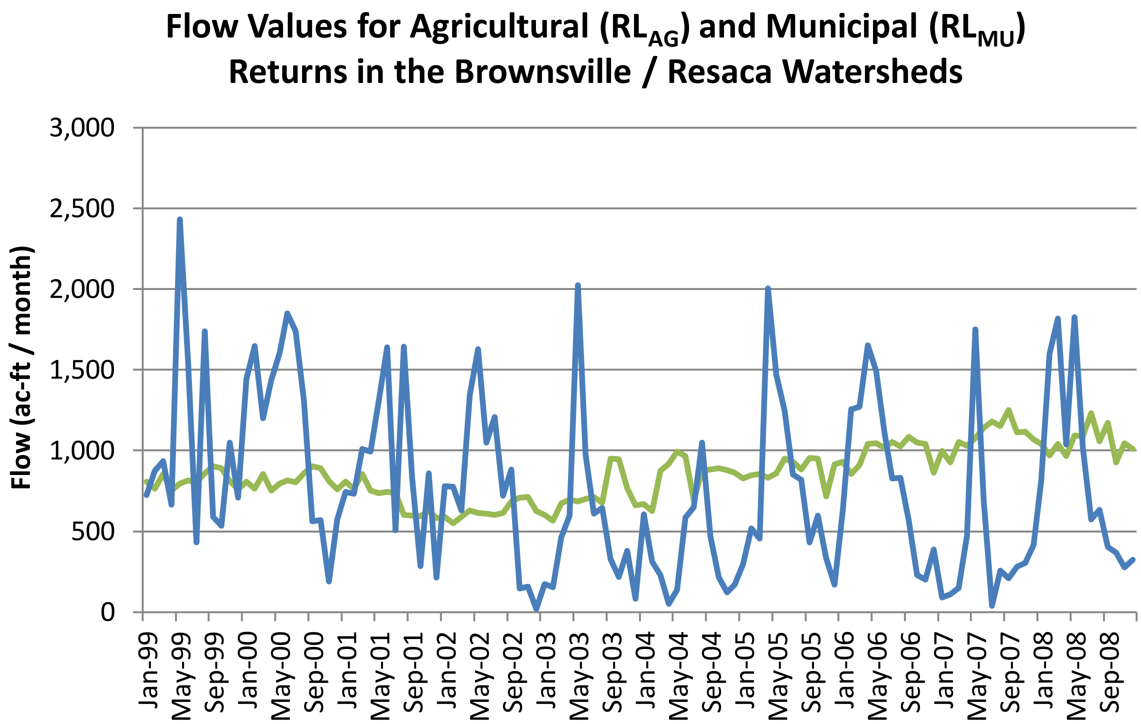


Figure 2.6.8a. Monthly average flows for agricultural and municipal returns in the Brownsville / Resaca watersheds.

Figure 2.6.8b graphs the monthly average flows for estimated rainfall runoff in the Brownsville / Resaca watersheds. As can be seen from both graphs and **Tables 2.6.8 and 2.6.9**, runoff forms a significantly larger component of the outflows from this group of watersheds as compared to the Arroyo Colorado. It is important to point out that no-cost water during high flow periods may or may not be completely accounted for in the municipal and agricultural water withdrawal data collected for this report.

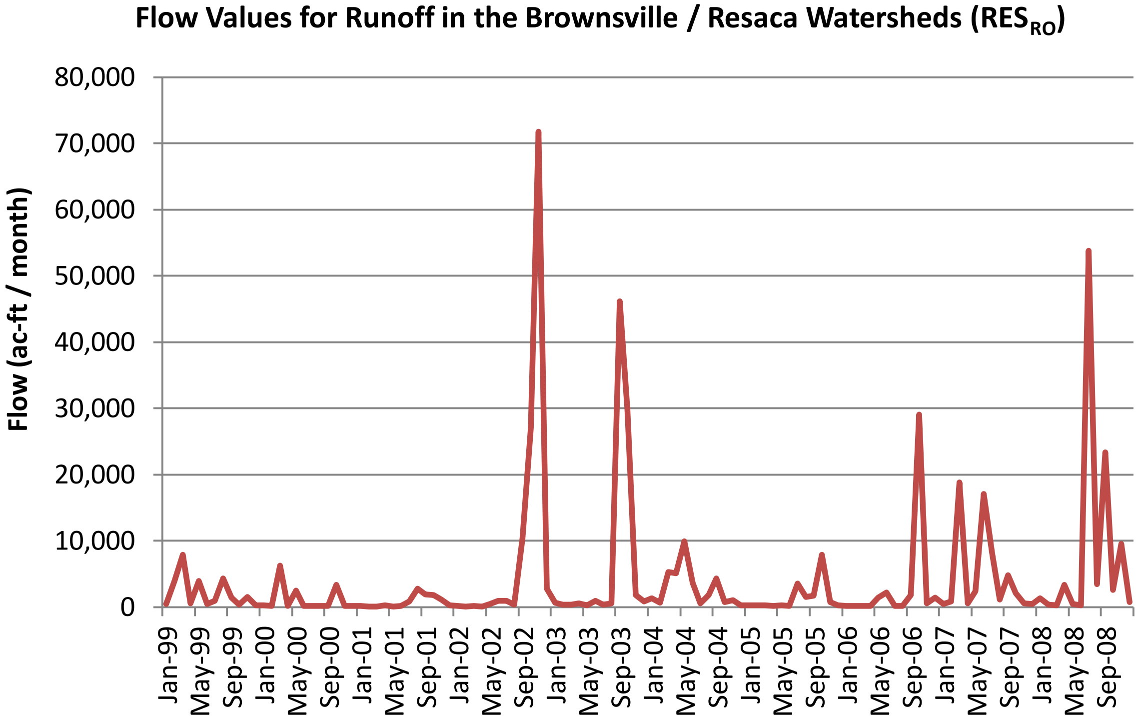


Figure 2.6.8b. Monthly average flows estimated rainfall runoff in the Brownsville / Resaca watersheds.

Table 2.6.9. Percentage of flow in the Brownsville / Resaca watersheds corresponding to listed source based on annual average estimate.

Annual Average Estimate	% of Flow in Brownsville / Resaca watersheds due to source listed
Agricultural Returns	13%
Municipal Returns	15%
Rainfall Runoff	72%

Table 2.6.10 shows the average monthly flow values for existing and natural condition inflows to the Lower Laguna Madre from the Brownsville / Resaca watersheds. Natural conditions again is meant to portray the flow regime for the Brownsville / Resaca watersheds given no agricultural or municipal return flows – leaving only rainfall runoff and estimated losses. As these basins are all ungaged, a water balance check was not possible in here as it was for the Rio Grande and Arroyo Colorado basins (see **Figures 2.6.3b** and **2.6.6**).

Table 2.6.10. Flow statistics for existing (RES_{CLM}) and natural inflows (RES_{CLMNAT}) to the Lower Laguna Madre from the Brownsville / Resaca subwatersheds. (All basins ungaged).

Units: ac-ft / month	RES_{CLM}	RES_{CLMNAT}
Average	5,486	3,979
Median	2,496	726
Standard Deviation	9,879	9,972

Figure 2.6.9 shows both inflow conditions graphed over the period of record. As is clearly seen, the natural and existing flow conditions are closer for this set of watersheds as compared to the Arroyo Colorado and Rio Grande; however, the natural conditions flow is still lower due to the removal of return flows from agricultural and municipal uses.

Table 2.6.11 provides minimum, maximum, and percentile flow estimations calculated over the period of record of 1999-2008 for both RES_{CLM} and RES_{CLMNAT}.

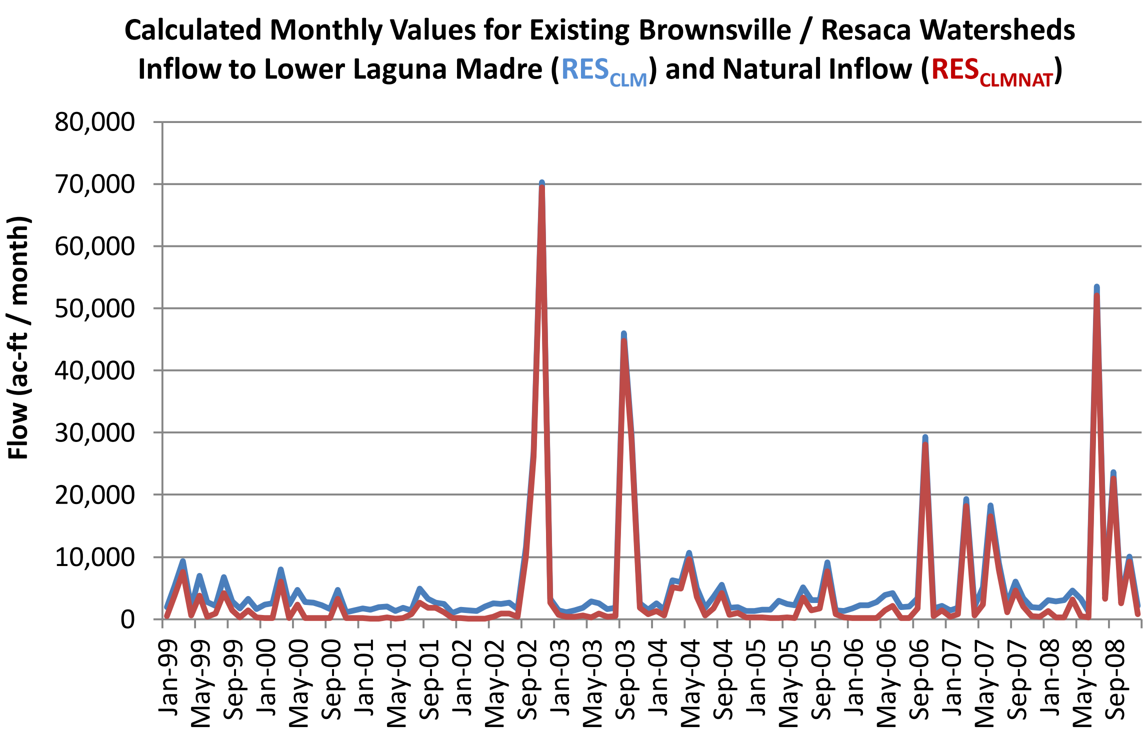


Figure 2.6.9. Graph of existing (RES_{CLM}) and natural inflows (RES_{CLMNAT}) to the Lower Laguna Madre from the Brownsville / Resaca subwatersheds. (All basins ungaged).

2.6.7. North Subbasins

While not part of the original study area for the water balance and flow analysis conducted for this work, flow data for the subbasins north of the Arroyo Colorado watershed were requested from the TWDB (Schoebaechler et al. 2011) in order to provide a comprehensive set of inflow numbers to the Laguna. An estimate of natural inflows for the subbasins was attempted; however, the limited return and diversion data available in this area indicates that the results for this subbasin should be considered a rough approximation. **Figure 2.6.10** shows the calculated monthly values for existing and natural inflows to the Lower Laguna Madre. The flow values are very similar due to the limited return and diversion data available.

Table 2.6.11 provides minimum, maximum, and percentile flow estimations calculated over the period of record of 1999-2008 for existing (NS_{CLM}) and natural inflow (NS_{CLMNAT}) conditions for the North Subbasins.

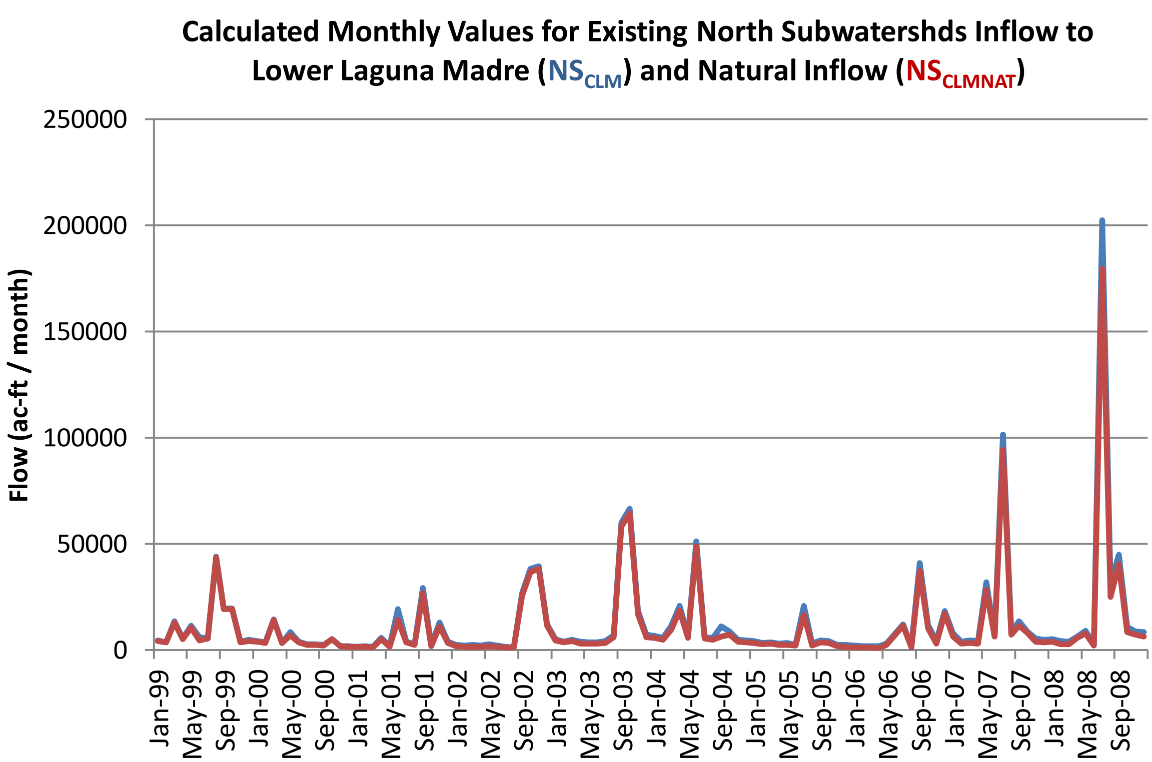


Figure 2.6.10. Graph of existing (NS_{CLM}) and natural inflows (NS_{CLMNAT}) to the Lower Laguna Madre from the basins north of the Arroyo Colorado. (Both gaged and ungaged basins)

2.6.8. Individual and Combined Basin Flow Statistics for Existing and Natural Flow Conditions

Table 2.6.11 provides data requested by the Lower Rio Grande BBEST, including percentile flow estimations for the existing and estimated natural flow conditions for the individual basins analyzed in this study. From left to right it provides this data for the North subbasins, the Brownsville / Resaca subbasins, Rio Grande River, and the Arroyo Colorado.

Table 2.6.12 provides the same data as the above table but provides flow statistic data for the summed inflows to the Lower Laguna Madre from all contributing subbasins including the North, Brownsville / Resaca, and Arroyo Colorado subbasins. The last column provides the percentage of existing flows that is comprised of natural inflows. In essence, this column provides the percentage of the existing flow that is due to precipitation derived runoff. For example, the median combined existing inflows to the Lower Laguna Madre for all months in the period of record from 1999-2008 is 23,654 ac-ft / month. The median value for the natural inflow over the same period of record is 9,428 ac-ft / month, or 39.9% of the existing flow. Conversely, this percentage may be used to estimate the percentage of existing flow that is comprised of agricultural and municipal returns. Continuing the previous example, for the same median flow value 60.1% (100% - 39.9%) of the existing flow is due to agricultural and municipal returns.

It can also be seen that while the percentage due to runoff increases and the percentage due to municipal and agricultural returns decreases as the percentile value increases, the difference in flow values remains relatively uniform. The average difference between the existing flows and natural flows at all percentiles (from .05 to .95) is approximately 13,000 ac-ft / month. This difference ranges from 11,614 ac-ft/ month at the low end (0.05 percentile) and 16,231 ac-ft / month at the higher end (0.75 percentile). This relatively constant value is likely due to two factors – first, municipal return flows are fairly consistent across months and second, while agricultural return values spike during the irrigation season, it largely coincides with the wetter months of the year. Thus, when runoff values are high, irrigation return values are also high. This result may play an important part in the formation of inflow regimes that incorporate water quality concerns as well total accumulated flow volumes.

Table 2.6.11. Summary table for key parameters in the water balance showing minimum, maximum, average, median, standard deviation, and percentile flows for existing and natural flow conditions for each of the four subbasins studied in this report: North Subbasins, Brownsville / Resaca Watersheds, Rio Grande, and Arroyo Colorado.

		Flows (ac-ft/month)							
		NSclm	**NSclmnat**	**RES$_{clm}$**	**RESclmnat**	**RGmbro**	**RGcbronat**	**AR$_{clm}$**	**ARclmnat**
	Min	1,316	928	998	60	1,353	22,507	9,356	153
Percentile	0.05	1,761	1,288	1,332	127	3,092	31,908	9,932	609
	0.10	1,978	1,508	1,414	153	3,661	35,641	10,771	748
	0.25	3,065	2,513	1,767	232	7,098	50,094	12,828	1,850
	0.50	4,837	3,888	2,496	726	16,703	67,928	15,680	4,273
	0.75	11,272	8,693	4,291	2,571	24,857	103,297	21,340	9,092
	0.90	29,376	25,802	9,420	8,035	61,810	146,897	36,585	25,323
	0.95	43,917	40,525	23,839	22,792	86,608	165,838	55,240	48,905
	Max	202,516	179,531	70,273	69,429	257,054	278,043	137,218	106,682
	Average	12,077	10,786	5,486	3,979	26,993	81,618	21,102	9,928
	Median	4,837	3,888	2,496	726	16,703	67,928	15,680	4,273
	St. Dev.	22,989	20,993	9,879	9,972	38,901	46,295	17,412	16,213

Table 2.6.12. Statistical values for combined inflows to the Lower Laguna Madre from all contributing subbasins for both existing and natural conditions for all months in the period of record 1999-2008. Contributions from the North Subbasins, Brownsville / Resaca Watersheds, and Arroyo Colorado are included. (Note: This excludes contributions from the Rio Grande River as that body drains directly to the Gulf of Mexico.)

		Existing Inflows to Lower Laguna Madre	Natural Inflows to Lower Laguna Madre	% of Nat Flows / Existing flows
	Units	(ac-ft/month)	(ac-ft/month)	%
Percentile	Min	12,313	1,426	11.6%
	0.05	13,997	2,383	17.0%
	0.10	15,649	3,428	21.9%
	0.20	17,736	4,515	25.5%
	0.25	18,441	5,097	27.6%
	0.50	23,654	9,428	39.9%
	0.75	39,962	23,732	59.4%
	0.80	41,291	29,342	71.1%
	0.90	66,732	55,286	82.8%
	0.95	113,411	101,365	89.4%
	Max	393,204	338,325	86.0%
	Average	38,665	24,692	N/A
	Median	23,654	9,428	N/A
	St. Dev.	46,948	43,906	N/A

Tables 2.6.13 and **Tables 2.6.14** show percentile flow values for the dry and wet seasons of the Lower Rio Grande Valley respectively. On average, the LRGV receives approximately 70% of its annual rainfall over the six month period between May and October. Average annual rainfall over the study area varies from 22.5 inches / year in the McAllen, Texas area to 27.5 inches / year in the Brownsville, Texas area. Due to this marked variation in seasonal rainfall, the same analysis completed for the entire 120 months in the period of record was conducted for the 60 dry months and 60 wet months in the period of record.

Dry season median flows are reduced as expected when compared to results in the previous table (all months), with existing median inflows of 19,610 ac-ft / month. There is an even more marked reduction in the median flow value for the dry season natural flows compared to the full 120 month data. The natural dry season median flow value of 5,695 ac-ft / month represents only 29% of the existing dry season median flow value. This shows that a significant percentage, at least 71%, of flow in the Arroyo Colorado is comprised of municipal and agricultural return flows 50% of the time during dry season months. The same pattern of consistent differences in flow volumes between existing and natural flows across various percentile flows that was observed for the entire 120 month data set also holds for dry month data.

Wet season data calculated from only the May-October months from 1999-2008 show increased flow volumes compared to dry months and all 120 month datasets. The natural wet season median inflow of 14,445 ac-ft / month is only 46.3% of the existing wet month median inflow value of 31,213 ac-ft /month. This shows that during wet months, at least 53.7% of flow in the Arroyo Colorado is comprised of return flows 50% of the time during wet season months. Thus, even during wet season months, median flow values support the claim that the majority of flow in the Arroyo Colorado is comprised of return flows over monthly time periods. Differences in flow volumes between existing and natural flows over different percentiles vary a bit more when compared to dry season and all month data, but maintain a similar average difference. The average difference in existing and natural dry season flows across various percentiles was 12,673 ac-ft; however, the range increased from a low value difference of 5,455 ac-ft / month at the 0.95 percentile to a high value difference of 16,767 ac-ft / month at the 0.50 percentile flow.

As discussed earlier in this section, the results of the water balance and flow calculation estimations discussed here have limitations resulting from data availability and other factors. In particular, the period of record of 1999-2008 is much smaller than the period of record used in Schoenbachler et al., 2011. As part of the additional work needed to validate the data sets used in the water balance calculations and associated flow recommendations, further statistical tests should be performed to test whether the "period of record" flow data from 1999-2008 comes from the same population as the flow data from 1977-2010 used in Schoenbachler et al. (2011). Additionally, while precise flow values are shown in **Tables 2.6.11** through **2.6.14**, this is a result of the deterministic approach used in the water balance. Additional work is required to more accurately ascertain and illustrate the uncertainty and range of variability inherent in streamflow values, particularly in areas like South Texas that are prone to large deviations in total annual average precipitation.

Table 2.6.13. Dry Season (November – April) statistical values for combined inflows to the Lower Laguna Madre from all contributing subbasins for both existing and natural conditions.

		Existing Dry Season Inflows to Lower Laguna Madre	Natural Dry Season Inflows to Lower Laguna Madre	% of Nat Flows / Existing flows
	Units	(ac-ft/month)	(ac-ft/month)	%
Percentile	Min	12,446	1,426	11.5%
	0.05	13,537	1,895	14.0%
	0.10	14,109	2,381	16.9%
	0.20	16,270	3,428	21.1%
	0.25	16,872	3,613	21.4%
	0.50	19,610	5,695	29.0%
	0.75	25,504	12,901	50.6%
	0.80	29,900	15,215	50.9%
	0.90	40,833	28,023	68.6%
	0.95	42,559	30,077	70.7%
	Max	205,357	170,970	83.3%
	Average	26,342	12,669	N/A
	Median	19,610	5,695	N/A
	St. Dev.	25,596	23,087	N/A

Table 2.6.14. Wet Season (May – October) statistical values for combined inflows to the Lower Laguna Madre from all contributing subbasins for both existing and natural conditions.

		Existing Wet Season Inflows to Lower Laguna Madre	Natural Wet Season Inflows to Lower Laguna Madre	% of Nat Flows / Existing flows
	Units	(ac-ft/month)	(ac-ft/month)	%
Percentile	Min	12,313	3,613	29.3%
	0.05	16,386	5,007	30.6%
	0.10	17,743	5,531	31.2%
	0.20	20,909	6,908	33.0%
	0.25	21,214	7,888	37.2%
	0.50	31,213	14,445	46.3%
	0.75	51,620	38,152	73.9%
	0.80	66,072	52,894	80.1%
	0.90	107,042	92,771	86.7%
	0.95	156,861	151,407	96.5%
	Max	393,204	338,325	86.0%
	Average	50,988	36,715	N/A
	Median	31,213	14,445	N/A
	St. Dev.	59,004	55,327	N/A

Section 3 Lower Laguna Madre

3.1 Geographic Scope

The Lower Laguna Madre comprises the south Texas estuary bounded by the barrier island, South Padre Island, and extending from near Brownsville north to the Land Cut, and intersected by Mansfield Pass at Port Mansfield. The Lower Laguna Madre Estuary (LLM) comprises a shallow (avg. depth < 1.5 m), subtropical lagoonal system draining into the Gulf of Mexico (GOM) at the south through Brazos Santiago Pass and to the north through Mansfield Pass (**Figure 3.1.1**). Famous as one of only 5 such lagoons in the world, the LLM historically was a hypersaline lagoon system, whose early history is well-described by Hedgpeth (1947), Breuer (1962), and Tunnell and Judd (2001).

Several anthropogenic factors have contributed to irreversible changes in LLM hydrology since the 1950s. The chief alteration was the dredging of the Gulf Intracoastal Waterway (GIWW) completed in 1950. It is the barge and shipping channel running north through the Land Cut to the Upper Laguna Madre and south from the Land Cut to Brazos Santiago Pass and Brownsville. The other main human change occurred from opening of Mansfield Pass in 1958 to the GOM at the northern end. To a lesser extent, the deepening of the Arroyo Colorado and opening of the North Floodway have produced additional changes. These geomorphological alterations have allowed for dynamic mixing and circulation of LLM waters with the GOM, and have greatly reduced its hypersaline lagoon characteristics. However, the system still functions as a large lagoonal estuary very restricted by the world's largest barrier island, South Padre Island, and the south Texas mainland region known as the Lower Rio Grande Valley (LRGV).

The area of LLM is 1,308 km^2, comparable to other large Texas bays such as Trinity-Galveston Bays at 1,456 km^2 and Lavaca-Matagorda Bays at 1,115 km^2 (Diener 1975, NOAA NEA 2007). However, LLM has a rather small watershed area of 13,165 km^2 making its watershed to estuary area ratio of 10.1 one of Texas' smallest. Additionally, due to its shallow depth, LLM has a much smaller estimated volume of 994 x 10^6 m^3 (35,124 x 10^6 ft^3) at low tide or 2,317 x 10^6 m^3 (81, 872 x 10^6 ft^3) at high tide, leading to a potentially long water residence time and very low turnover rate. In fact, with average annual combined freshwater inflow of *ca* 524,000 ac-ft (22,869 x 10^6 ft^3) per year from 1977 – 2010 (TWDB data), this would cause the residence time to be very long, when coupled with the large negative water balance of the LLM due to much higher evaporation than precipitation ratio. A preliminary calculation by George Ward (Univ. of Texas at Austin, pers. comm.) indicates that the residence time or freshwater flushing time is in fact on the order of 284 days, or a turnover time of less than 1.28 times per year.

The classified Land Use/Land Cover features for the LLM watershed are comprised of: Agriculture (4,672 km^2 - 35.8%), Rangelands/Pasture (6,742 km^2 – 51.7%), Urban (800 km^2 – 6.1%), Woodlands (655 km^2 – 5 %), and Wetlands (179 km^2 – 1.4%), giving a watershed total of 13,048 km^2 (NOAA NEA 2007).

3.2. Ecology and Biology

The restricted, shallow-water nature of this lagoonal system, and its arid, subtropical physiography, has contributed to its unique ecological habitat (Hedgpeth 1947). A variety of extremely salt-tolerant flora and fauna have adapted to the environment (Gunter 1967, Carpelan 1967). While intertidal salt marsh wetlands are rather scarce (Tunnell and Judd, 2001), the system is dominated by wind-tidal flats with cyanobacterial mats on the backside of South Padre Island, drifting macroalgae (mostly subtropical, but some tropical species do occur), and submerged rooted vegetation, known as seagrass meadows or beds. In fact, the Lower Laguna Madre of Texas contains about 60% of the seagrass beds in the State of Texas (46,180 ha in 2000) (Pulich and Onuf 2007). These submergent plant communities support highly productive marine fisheries, both within the estuary and in the Gulf of Mexico.

The seagrass acreage and composition in the LLM has changed significantly in the past 50+ years, as documented by Breuer (1962), McMahon (1968), Merkord (1978), and Quammen and Onuf (1993), and Onuf (2007). From the 1960s until 1988, total acreage decreased from approx. 59,150 ha to 46,624 ha, and then dropped slightly to 46,174 ha in 1998. However, species composition changed dramatically. In mid 1970s, *Syringodium* (manatee grass)and *Halodule* (shoal grass) were the most common species (25.9% and 70.0 % cover, respectively), and *Thalassia* (turtle grass) was only 3.0 % cover. By 1988, *Halodule* had decreased to 46.3 % cover, *Syringodium* had increased to 37.7 % cover, and *Thalassia* had increased to 8.5 % cover. By 1998, *Thalassia* (24.1%) had expanded and replaced some of the *Syringodium* (27.8 %), while *Halodule* remained stable at 45.7% cover. Beginning in 2000, anecdotal reports indicated that more reduction in seagrasses started to occur (Chris Onuf, pers. comm.). As documented in this report, an actual 24% decrease (*ca* 8,906 hectares), between 2000 and 2009, especially in *Syringodium* and *Thalassia*, in the area 5 – 7 miles south and 15 miles north of the Arroyo Colorado channel mouth, has occurred. Since salinities in LLM had stabilized by the late 1970s, seagrass dynamics since 1988 represent a dramatic example of unexplained ecological change.

The TPWD Coastal Fisheries Resource Monitoring program (Martinez-Andrade et al. 2009) has been collecting coastal water quality data since approximately 1977 associated with 20 random bag seine and 10 trawl samples per month throughout the LLM. A descriptive summary of this TPWD data is presented in the **Appendix 3.1**. Examination of these historical TPWD data provides a good picture of the hydrographic/ environmental conditions, as well as populations of fisheries organisms, characteristic of the LLM over the past 30+ years. Jim Tolan (TPWD, Coastal Program, Corpus Christi) kindly compiled results from this database and provided hydrographic data summaries on a seasonal basis to the BBEST study team. For purposes of this report, seasons were defined as follows: winter as Dec-Feb, spring as March-May, summer as Jun-Aug, and fall as Sep-Nov.

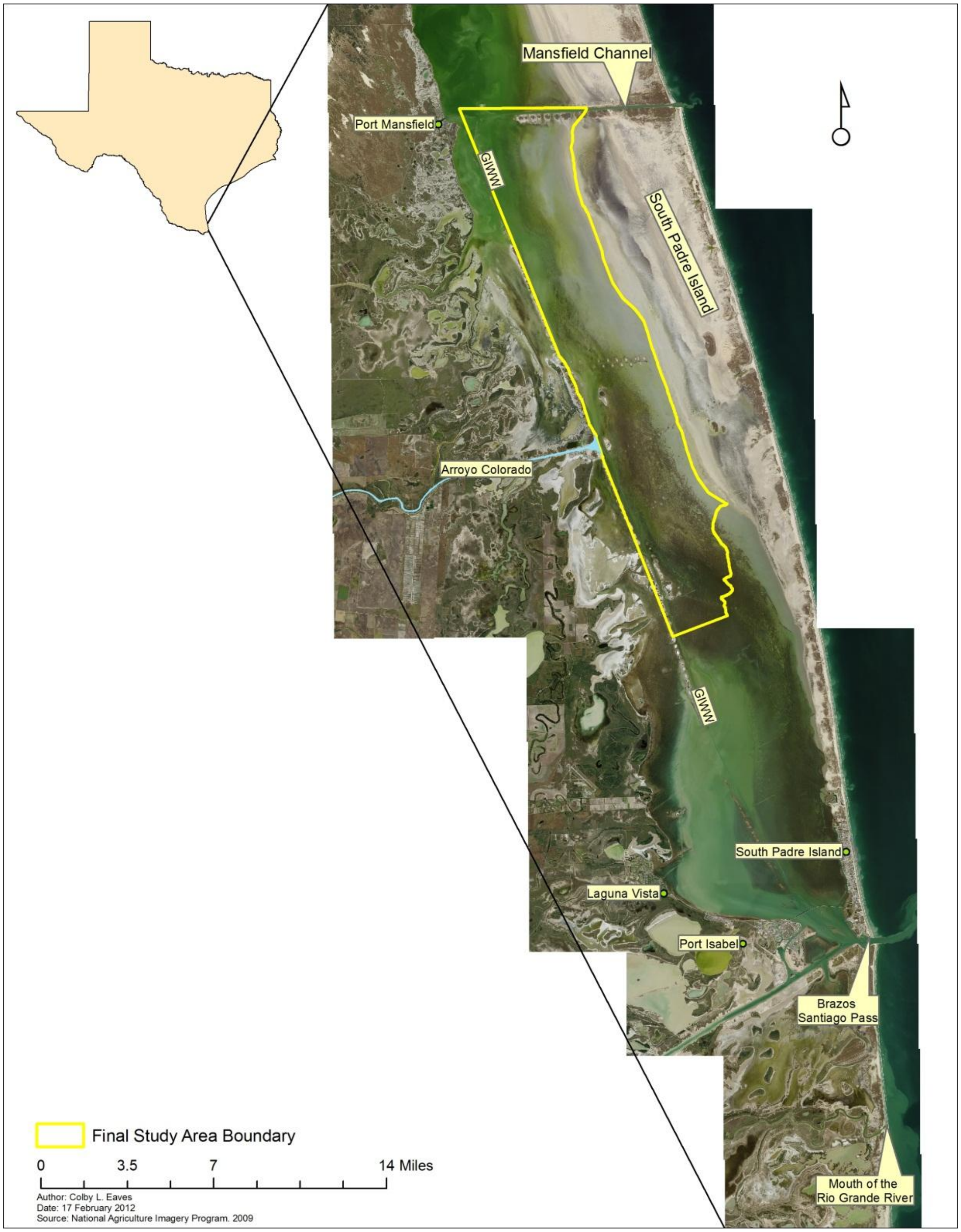


Figure 3.1.1. Color aerial photography mosaic of Lower Laguna Madre taken in January 2009 by National Agricultural Imagery Program (NAIP).

An example of summary data over the spring months (March – May) are presented in **Figures 3.2.1 and 3.2.3** for the 1977 to 2010 period. **Figure 3.2.1** presents the spring averaged data for salinity, temperature, dissolved oxygen, and turbidity collected with bag seine samples over the entire LLM study area depicted in **Fig. 3.2.2** below. Noteworthy results for the entire LLM show an increasing water temperature trend (approx. a one degree C rise over the period 1990 to 2005), and salinity which averages around 32 PSU. This has been reported on by Tolan (2006).

However, because of the large area comprised by the LLM, spatial variations in environmental parameters can be quite large between locations. In order to demonstrate the spatial differences in the north-south gradient of the LLM, the same previous water quality parameters were compared separately between the northern and southern portions of the LLM, with the entrance of the Arroyo Colorado lying in the northern part, and Stover Point forming the dividing line between the 2 regions. **Figure 3.2.1** shows corresponding differences between average summer salinity fluctuations, and temperature and turbidity regimes for these areas. As an example of the geographic variation, summer salinity averaged 34 PSU for the southern area, and 30 PSU for the northern area. The main hydrographic differences observed are that salinity and turbidity are higher and lower, respectively, in the lower part of the LLM than in the upper LLM. The salinity difference (34 PSU in upper, 38 PSU in lower) particularly reflects the influence of freshwater input on the upper LLM compared to higher salinity water entering from the GOM, in concert with high evaporation in the lower part of the LLM. **Figure 3.2.4** shows the corresponding average salinity fluctuations, temperature and turbidity regimes in fall months.

Similar summary analyses were performed for spring (Mar-May) and winter (Dec- Feb) months, and generally similar differences were observed (see **Appendix 3.2** for these other results).

The Arroyo Colorado (AC or Arroyo) is the main direct freshwater source for the LLM (data in Chap. II). Nutrient loading (nitrogen, N, and phosphorus, P) from the Arroyo which drains wastewater and agricultural return flows from the Lower Rio Grande Valley to the LLM has been suspected as a major cause of some of the observed seagrass changes. However, response of the seagrass habitat and other estuarine ecosystems within the lagoon to freshwater inflows is largely unknown, except for the obvious factor of salinity changes. It has been postulated that lower salinity waters enriched with dissolved nutrients (especially inorganic N) may play a role (Quammen and Onuf 1993); and recently Kowalski et al. (2009) presented results relating sediment nutrient conditions and water quality gradients to *Halodule* growth dynamics.

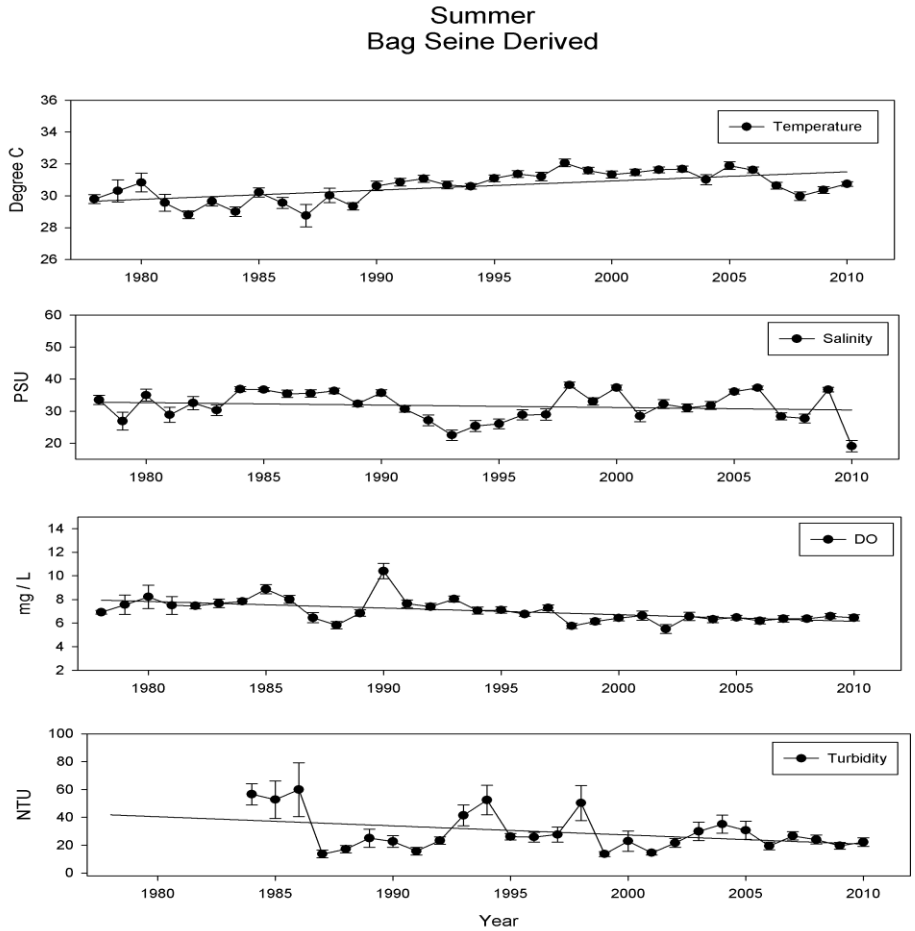


Figure 3.2.1. Mean values of four hydrographic parameters for summer months (Jun-Aug) over entire LLM. Data from TPWD Coastal Fisheries Resource Monitoring database, courtesy of Jim Tolan, TPWD.

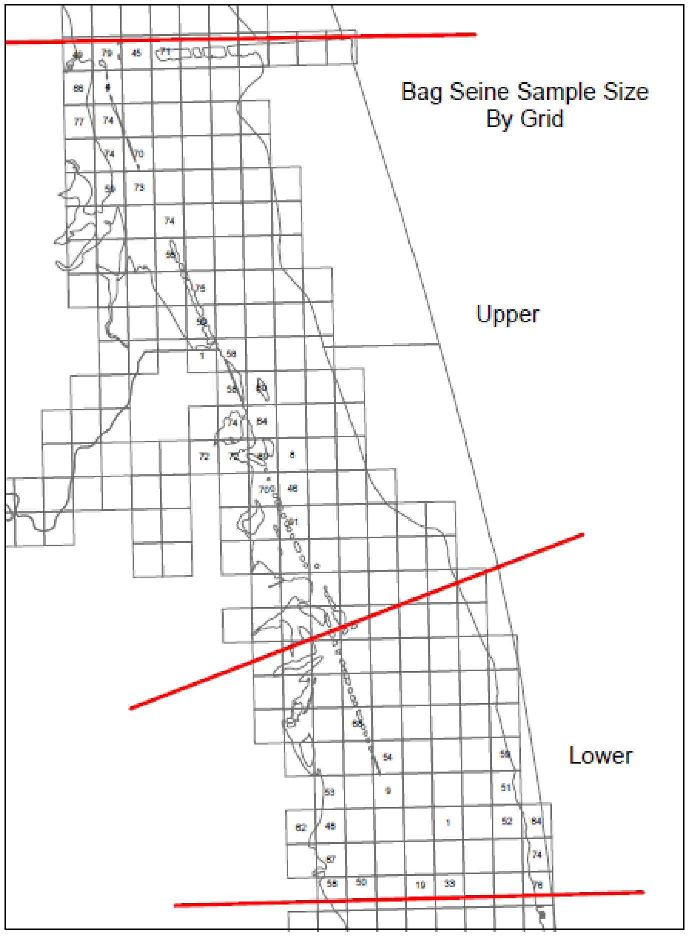


Figure 3.2.2. TPWD sampling stations grid for bag seine collections in LLM study area. Red lines divide study area into northern and southern parts. Data from TPWD Coastal Fisheries Resource Monitoring database, courtesy of Jim Tolan, TPWD.

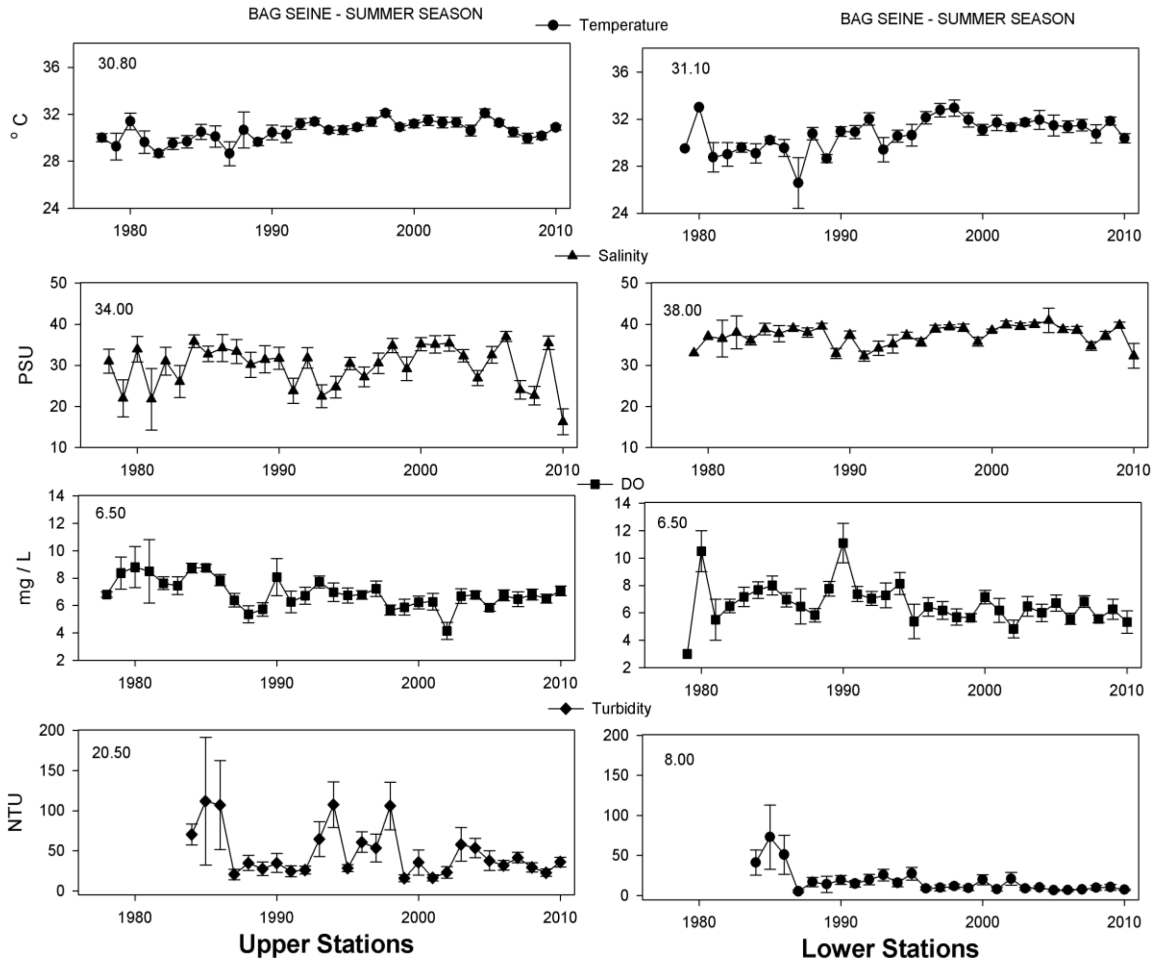


Figure 3.2.3. Mean values of four hydrographic parameters for summer months (Jun-Aug) calculated separately for northern (Upper) and southern (Lower) parts of LLM study area. Mean values listed in upper left corner of graphs. Data from TPWD Resource Monitoring database, courtesy of Jim Tolan, TPWD.

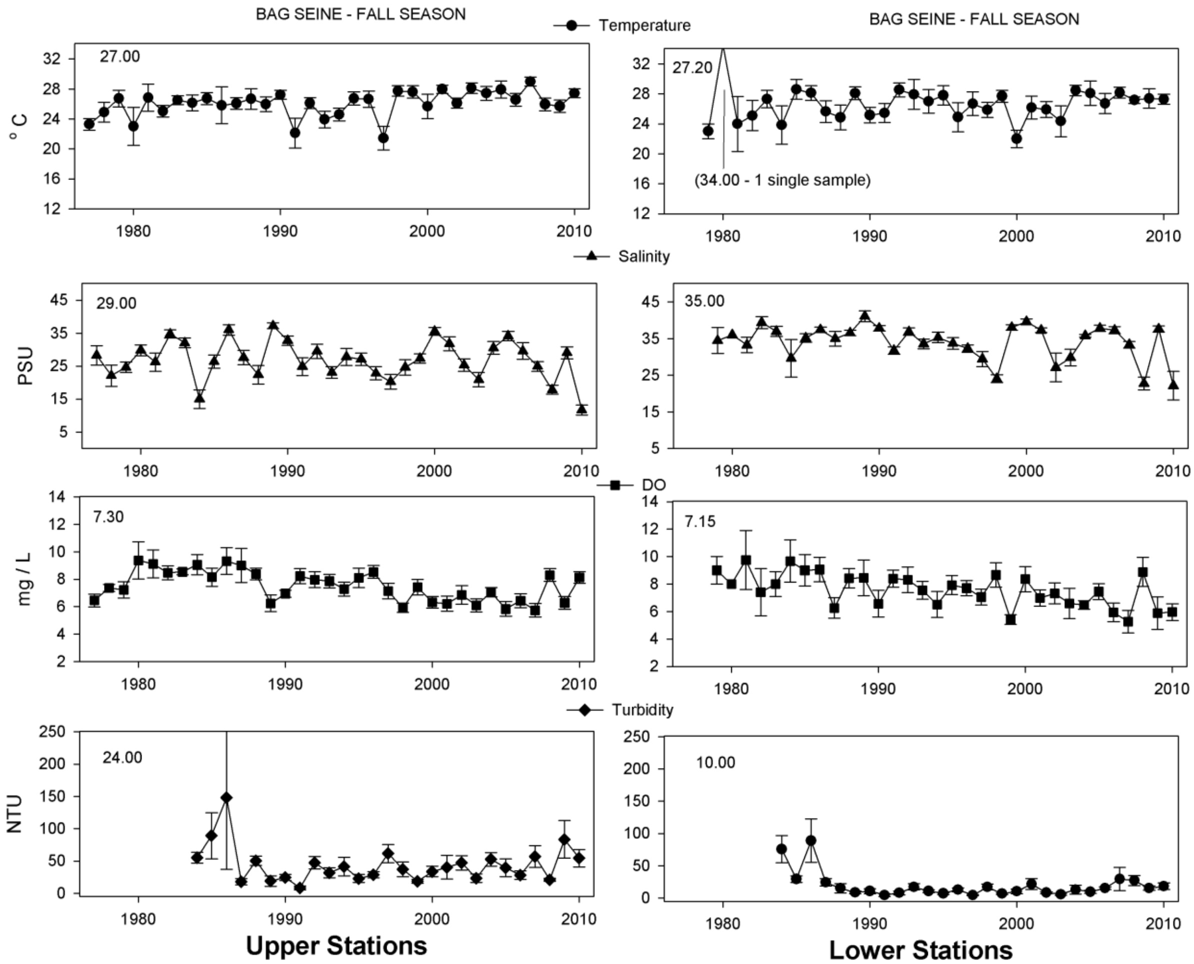


Figure 3.2.4. Mean values of four hydrographic parameters for fall months (Sep-Nov) calculated separately for northern and southern parts of LLM study area. Data from TPWD Resource Monitoring database, courtesy of Jim Tolan, TPWD.

The impact of extreme freshwater flooding due to Hurricane Alex in the summer of 2010 has raised the issue of freshwater discharge impacts due to concomitant lowering of salinity. This 2010 flooding produced the largest discharge into the LLM since 1967 (Hurricane Beulah), and largest since the North floodway was built in 1988. Following the hurricane, salinity in an area 13 km north and south of the Arroyo was less than 5 PSU for a month (Kowalski & DeYoe, unpubl. 2011). During this period, seagrasses, especially *Thalassia* and *Syringodium*, died off in large areas around that part of LLM (DeYoe, pers. comm.). Since salinity can also have a synergistic effect along with nutrients on seagrasses (van Katwijk et al. 1999, Fourqurean et al. 2005, Burkholder and Tomasko 1997), the quality of freshwater inflows to the LLM from the Arroyo Colorado may perhaps be more critical to seagrass health than inflow quantity.

3.3. Disturbances (Harmful Algal Blooms)

Occurrence of algal blooms represents a good proxy for water quality degradation. In the case of the LLM, harmful algal blooms (HABs) have been monitored regularly since the early 1990s when the well-known Texas Brown Tide was discovered in the Upper Laguna Madre. Several brown tide events were encountered intermittently in the LLM during the 1990s, especially from around the Arroyo Colorado northward into the Land Cut, and monitored by UT Marine Science Institute scientists (Whitledge & Stockwell 1994). A comprehensive database on HABs has also been maintained by Texas Parks and Wildlife since the 1990s. For this report, the BBEST contacted Meridith Byrd with Coastal Fisheries Division, Victoria office, and was kindly provided with a complete record of red tide (*Karenia brevis*) blooms for the LLM from the TPWD PRISM database. The TPWD PRISM database showed that major red tide blooms, within or just outside the Lower Laguna Madre near Mansfield or Brazos-Santiago Passes, have occurred 4 times since 1999, and three events were since 2006.

The following interpretation of red tide data was given by Ms. Byrd to the BBEST with permission for inclusion in our report. "Research suggests that blooms of the red tide algae *K. brevis* begin offshore in the Gulf of Mexico and are transported to nearshore waters via currents. Once the blooms enter the passes, they can persist in bays and estuaries even after dissipating from the Gulf beaches." Ms. Byrd also stated that since the first recorded *K. brevis* bloom in Texas at Port Aransas in 1935, "subsequent blooms occurred approximately once per decade until the 1990s, when they began happening more frequently. Research into the cause of these more frequent occurrences is ongoing."

DeYoe (pers. comm.) has also observed nuisance micro- and macro-algal blooms regularly in LLM since the late 1990s. Dense macroalgae or drift algae accumulations have been reported by Kopecky and Dunton (2006) to accumulate over areas of dense seagrass cover.

Section 4 Rio Grande Estuary

4.1 Background

The Rio Grande Estuary consists of the lowermost, 48-mile (80 km) tidal reach of the river below Brownsville in Cameron County, Texas (**Figure 4.1.1**). The estuary lies within the Tamaulipan biotic province, a semiarid, subtropical biogeographical zone (Blair 1950, Thornthwaite 1972). The vegetative communities of this biogeographic area are those characteristic of the South Texas Coastal Plain (clay-sand, alluvial soils covered with grasslands or evergreen thorn shrubs), the riverine riparian corridor, and estuarine wetlands comprising the present river delta. Human impacts on the native riparian woodlands and wetlands have been especially dramatic, primarily from agricultural clearing of native thorn brush and woody vegetation, introduction of exotic species, and hydrologic modifications in the Lower Rio Grande Basin (LRGB). Since the 1920s, more than 95% of these native woodlands and brushlands in the LRGB have been cleared and converted to agricultural or urban use (Raney et al. 2004). The occurrence and ecology of native LRGB plants are described in Jahrsdoerfer and Leslie (1988) and Lonard and Judd (2002). Maintenance of the aquatic habitats and vegetative communities requires hydrologic regimes that support unique wetland plant ecosystems and linkages between Rio Grande inflows and wetland functions.

Discussions of western Gulf of Mexico (GOM) estuaries often fail to include the Rio Grande estuary, which now exists as only a small, tidal river estuary. Some 4000 years ago, however, the high-flowing Rio Grande emptied into the current Texas Laguna Madre system to the north. When large amounts of sediment from the river began filling in the Laguna's estuary, this caused the River mouth to begin moving southward toward its present location. The smaller, present-day delta system that now separates the Texas and Mexican Laguna Madres was gradually formed (Britton and Morton 1989). The building of Falcon Reservoir in 1952, and early 1900s water control projects (i.e. levees, canals, drainage ditches) along the lower Rio Grande, have seriously disrupted natural flow regimes; and this has resulted in degradation of native wetlands and riparian communities (Raney et al. 2004). Hydrologic reduction and alterations, mostly due to municipal and agricultural water diversions in the upper Rio Grande watershed in New Mexico, around El Paso, and in northern Mexico, have so greatly reduced the River's total flow that it now very rarely discharges and overbanks into the limited US-Mexico Delta. The Rio Grande, similar to the Brazos River in Texas, now mostly flows directly into the Gulf of Mexico.

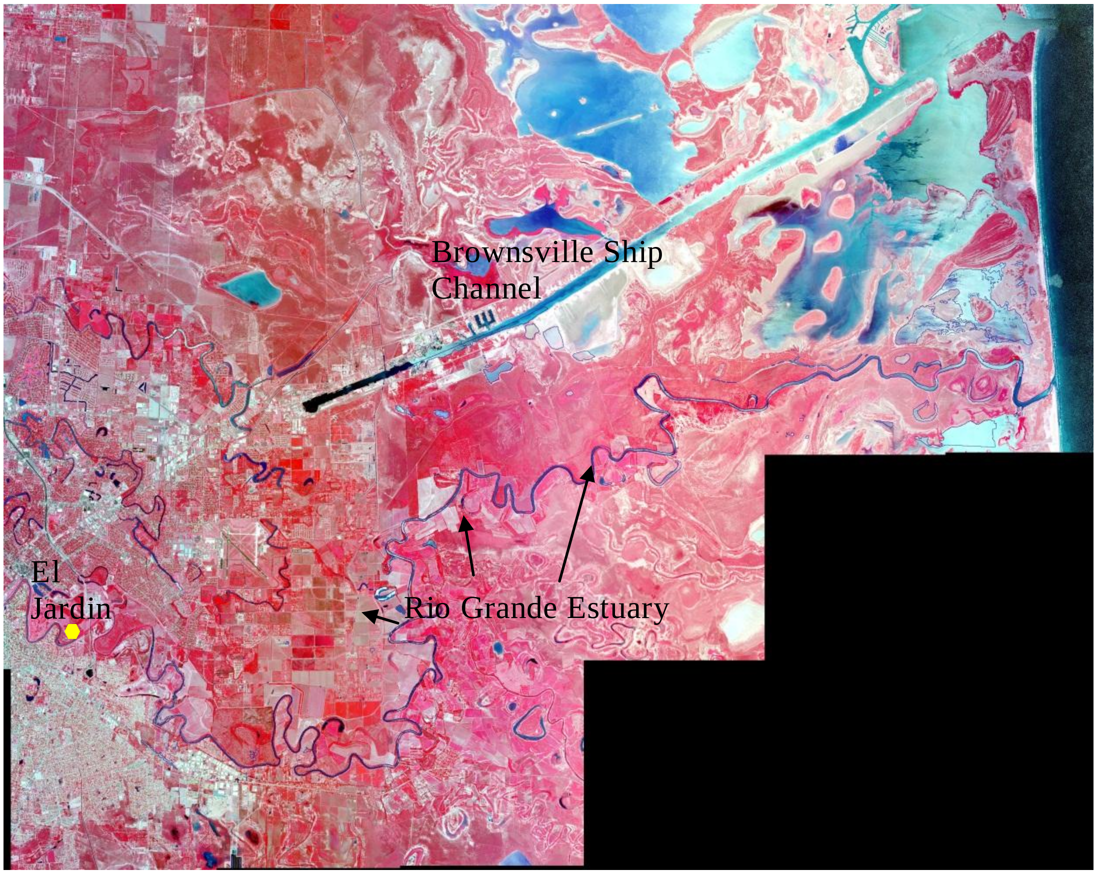


Figure 4.1.1. NAIP 2008 color infrared photography showing the Rio Grande estuary Brownsville (48 mile reach from El Jardin weir to Gulf of Mexico).

4.2. Characteristics of Freshwater Inflows to the Rio Grande Estuary

The ecological health and integrity of this fragile estuary, just as for all estuaries, is greatly dependent on specific regular freshwater inflow regimes. Such estuarine inflow requirements reflect: 1) regular, minimum seasonal amounts to maintain estuarine in-channel aquatic habitat, and 2) periodic flood events that flush the system and cause overbanking for the essentially tropical riparian vegetative community. The freshwater inflow needs of estuaries are an objective of ongoing environmental studies by the state of Texas Bays and Estuaries Research Program, as mandated under state of Texas Water Law. Before FWI needs can be determined for the Rio Grande estuary, studies, such as the subject of this report, are needed to provide basic ecological information and to characterize the dynamics of native Rio Grande biological communities in response to inflow regimes. Long range climate and drought patterns are also emerging, unpredictable factors that should be taken into account.

The hydrology of the tidal Rio Grande estuary is best described as pulsed or “flashy”. This terminology refers to the intermittent flow regime caused by the arid climatology and physiography of the region. As mentioned above, the ‘normal’ flow regimes of this system have been severely altered by the two upstream reservoirs (Amistad and Falcon Lakes) and major diversions of water downstream to supply municipal water supplies to LRGV cities and for agriculture irrigation projects. These reservoirs normally hold back flows even to above-average levels, and it is mainly when flood-level flows occur that episodic releases occur to the estuary. Under these pulsed inflows, the estuary comprises a more lagoonal system susceptible to large swings in salinity regimes.

As described above and in Chap. II, Rio Grande flows to the LRG Valley highly depend on water diversions made for irrigation, industrial, and municipal uses in the upper and middle watershed. A disjunct hydrology is created by Lower Rio Grande flows into the Gulf of Mexico being controlled by river flows diverted at the Anzalduas Dam at McAllen and subsequent tidal exchange from the adjacent Gulf of Mexico. This interaction generally dominates the flow, with a very low mixing regime except during locally heavy rainfall of the late summer to early fall monsoon period (White et al. 1986). Due to generally low rainfall and river flows, the river system is often stratified with freshwater flow on the surface down to river mile 12 and a saltwater wedge on the bottom which extends variably upriver. **Figure 4.1.2** presents data from Texas Parks & Wildlife (Coastal Fisheries Brownsville Office; Randy Blankinship, pers. comm.), demonstrating that saline, bottom waters extended some 23 miles upriver during the 1992 – 1997 period, a period of consistently low flows. Later work since 2005 by the Texas Water Development Board and the City of Brownsville has resulted in collection of basic data on river current velocity, conductivity and temperature at three estuarine monitoring sites.

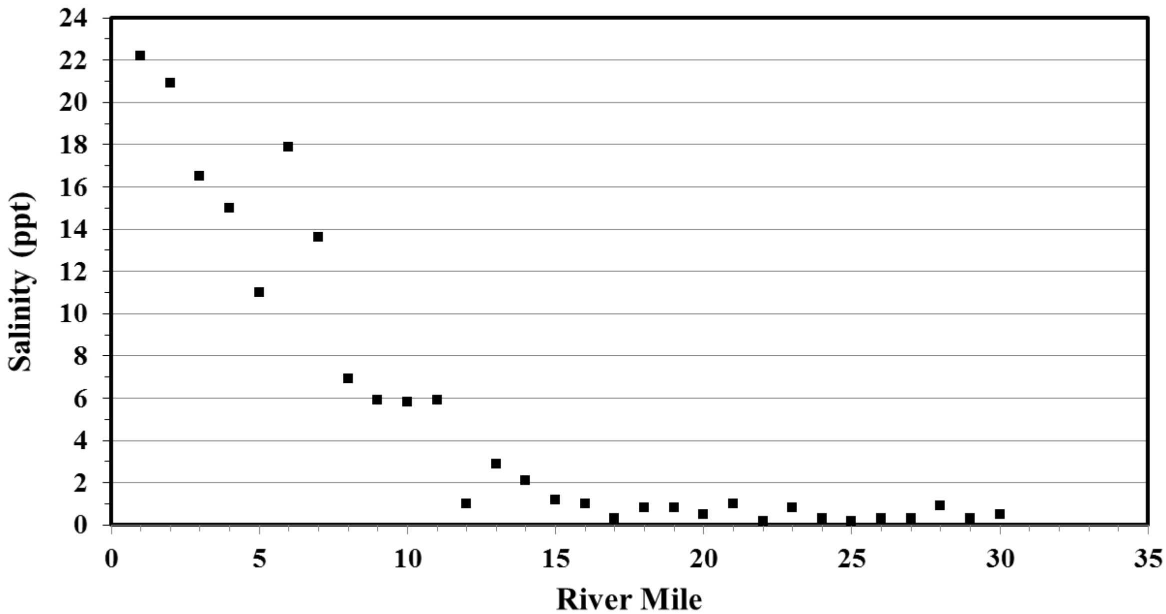


Fig. 4.1.2. Bottom salinity along Rio Grande tidal segment, 1992 to1997 (from TPWD, Brownsville, Coastal Fisheries Lab.).

Although pulsed river flows from upstream of the LRGV are now ‘typical’ for this estuary, future water development projects in the lower river basin itself (viz. Brownsville Channel Dam) have the potential to further threaten the estuary’s functionality. Increases in water diversion and wastewater treatment projects means that freshwater quantity problems are expected to be exacerbated if the estuary is further deprived of much needed fresh water, while untreated or undertreated municipal or industrial wastewaters continue to be discharged into or upstream of the tidal portion of the river. More frequent lower flows, coupled with nutrient- or contaminant loadings, would exacerbate eutrophic or noxious conditions deleterious to a high quality estuary. Nutrients, in particular, would increase harmful algal blooms or rooted noxious plant growths, eg. *Hydrilla* or water hyacinth. Studies of flow regimes in the tidal river section are needed to verify these suspected relationships with noxious phytoplankton or macrophyte accumulation.

Fig. 4.1.3. Aerial photograph of closed mouth of Rio Grande, Feb. 2001.

It was early in 2001 that the precarious nature of this estuary truly became demonstrated when the mouth of the river at Boca Chica was blocked off by a sand bar deposited during low flow conditions due to severe drought that the Lower Rio Grande basin had been experiencing since 1995 (**Fig. 4.1.3**). After the Rio Grande mouth closed in Feb. 2001, the IBWC planned and contracted for preliminary analysis addressing the issue of minimum flows required to maintain that the river mouth would remain open to the Gulf (Contract Study for IBWC; Sandia Laboratories, 2003). The question was considered from predominately a hydraulic engineering standpoint, but the answer also has significant biological ramifications. Without regular periodic flushing, the tidal portion of the river would become a closed lagoon system, preventing ingress and egress of estuarine species as predicted by TPWD. Water flows were monitored prior to and following the closing of mouth of the Rio Grande in 2001. Data from the IBWC gage below Brownsville is shown in **Figure 4.1.4** and **Table 4.1.1**.

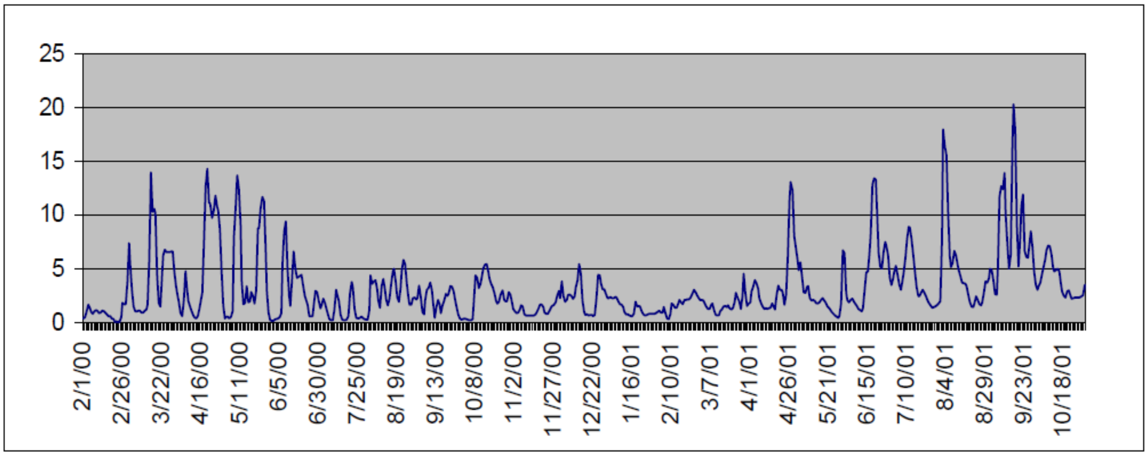


Figure 4.1.4. Summary of flow data in daily average cubic feet per second from IBWC monitored river gage south of Brownsville, Texas, February 2000 to October 2001.

Table 4.1.1. Average flow rates of the Rio Grande at Brownsville around period when the river mouth was closed (IBWC Station 08-475000).

Period of Analysis	Average Flow (cubic feet per second)
5-year average flow (2/3/1996-2/3/2001)	91
Four months prior to river mouth closure (10/3/2000-2/3/2001)	68
During river mouth closure (2/4/2001-7/20/2001)	112
After trench excavation through the sandbar blocking the river mouth (7/21/2001-10/31/2001)	190

4.3. Flora

Among Texas estuaries, the Rio Grande exhibits unique estuarine species and biological productivity because of the climate and lack of typical, extensive coastal saltmarshes found further north along the Texas coast. The estuarine delta comprises a succulent halophyte and mangrove–dominated wetland ecosystem in Texas. The macrophyte vegetation of this estuary is characterized by high-marsh halophytes (e.g., *Batis maritima*, *Salicornia* spp. and *Borrichia frutescens*), intertidal black mangrove thickets (*Avicennia germinans*), and intertidal fringe bands of salinity-resistant smooth cordgrass (*Spartina alterniflora*), saltmarsh bulrush (*Bulboschoenus maritimus*), and common reed (*Phragmites australis*). Since the 1960s, scattered red mangroves (*Rhizophora mangle*) have also been recorded here, until recently its northernmost limit in the western GOM. Relationships between hydrological/physiographical factors and growth dynamics of these halophyte/mangrove and riparian wetlands, however, are poorly characterized. TWDB-funded work by UT-Pan American (started in 2005) and USDA-funded studies by Texas State Univ.-San Marcos (started in 2007) have been defining relationships between nutrient loadings and flow regimes in the tidal river section and primary producer (esp. phytoplankton and macrophyte) dynamics, information that is essential to planning estuarine management and restoration programs (DeYoe, unpubl; Pulich 2008, Yr 3 SAWC report; Pulich and DeYoe 2010, Yr 4 SAWC report). Nutrients, salinity and surface water flows in other tidal river estuaries are known to affect competitive interactions between dominant estuarine marsh vegetation (e.g. mangroves, smooth cordgrass, bulrushes, *Phragmites*) and typical riparian freshwater communities [e.g. water hyacinth (*Eichhornia crassipes*), cattails, giant cane (*Arundo donax*).

Low river flows have exacerbated infestations of floating macrophytes in the river below McAllen, mostly water hyacinth, *Hydrilla verticillata*, and water lettuce (*Pistia stratioides*). These highly productive invasive plants, in addition to rooted salt cedar (*Tamarix* sp.), and giant cane, use tremendous amounts of water through evapotranspiration, and, without competition from native species, are choking many riverine and riparian areas in the lower and middle reaches of the Rio Grande (Everitt et al. 1999). The cause of such infestations may be linked to both decrease in inflow quantity and poor water quality. The latter stems from discharges of nutrient-laden flows from primarily wastewater treatment plants on the Mexican side of the border, and secondarily from agricultural runoff (Texas Clean Rivers Program, 2003). As a result of industrial plants (Mexican maquiladoras) and agricultural activities, discharges of additional nutrients and contaminants (arsenic, selenium, etc. and organic compounds), are also suspected (Davis et al 1995, TNRCC 1999). Because water hyacinth also tolerates low salinities up to 2.5 psu before showing reduced growth (Gopal 1989), hyacinth mats are capable of survival for prolonged periods under these lower salinities when washed down into the estuary.

4.4. Fauna

Some fish species with tropical affinities reach their regular, northern occurrence here in the western GOM, such as common snook (*Centropomus undecimalis*) and tarpon (*Megalops atlanticus*). Abundance of other species (e.g., blue crab, white shrimp) compares favorably with other well-known Texas estuaries.

The aquatic fauna in the Rio Grande estuary are inadequately documented, however limited studies suggest the Rio Grande provides important habitat for a number of species, including sport fish and uncommon species found only in the lower Texas coast (TPWD 2001c; Landry and Harper 1990; Clark 1997; Edwards and Contreras-Balderas 1991). Changes to the native fish communities from historical accounts appear to be correlated with modification of river hydrology and water quality. Analyses of historical occurrences of fish species suggest that freshwater species originally present have been replaced by estuarine and marine forms, possibly in response to decreasing stream flows over time (Edwards and Contreras-Balderas 1991). Despite alterations of the fish community, the Rio Grande is widely viewed as a significant and productive estuary. TPWD data show use of the Rio Grande by white and brown shrimp (*Litopenaeus setiferus* and *Farfantepenaeus aztecus*), blue crab (*Callinectes sapidus*), common snook, largescale fat snook

(*Centropomus mexicanus*), fat snook (*Centropomus parallelus*), threadfin shad (*Dorosoma petenense*), striped mullet (*Mugil cephalus*), Atlantic croaker (*Micropogonias undulates*), Gulf menhaden (*Brevoortia patronus*) and other species (TPWD 2001c). These data suggest that, although the estuary may be degraded in comparison to historic conditions, it still serves as a nursery for numerous important fish and shellfish species.

A study by the University of Texas-Pan American in the 1980s and 1990s, shown in **Table 4.4.1** revealed large numbers of juveniles in the tidal reach of the Lower Rio Grande, indicating use as a nursery or spawning ground for many species (Edwards and Contreras-Balderas 1991, Contreras-Balderas et al. 2002).

Table 4.4.1. Juvenile fish species taken in the tidal portion of the Lower Rio Grande in October-November 1981-1993 (Edwards and Contreras-Balderas 1991, Contreras-Balderas et al. 2002).

Fish Species	N	% of Total
Sciaenops ocellata	32295	65.55
Mugil curema	4126	8.37
Micropogonias undulatus	2195	4.46
Eucinostomus argenteus	1521	3.09
Anchoa mitchilli	1492	3.03
Eucinostomus melanopterus	969	1.97
Cyprinodon variegatus	690	1.40
Harengula jaguana	624	1.27
Gobionellus boleosoma	590	1.20
Leiostomus xanthurus	537	1.09
Anchoa hepsetus	504	1.02
Menidia peninsulae	482	0.98
Dorosoma petenense	400	0.81
Pogonias cromis	297	0.60
Brevoortia patronus	277	0.56
Sardinella anchovia	178	0.36
Eucinostomus gula	160	0.32
Lagodon rhomboides	153	0.31
Citharichthys spilopterus	138	0.28
Synodus foetens	118	0.24
Eutremeus teres	111	0.23
Strongylura marina	106	0.22
Fundulus grandis	77	0.16
Centropomis undecimalis	75	0.15
Menidia beryllina	69	0.14

Fish Species	N	% of Total
Polydactylus octonemus	66	0.13
Bathygobius soporator	63	0.13
Symphurus plagiusa	62	0.13
Diapterus olisthostomus	56	0.11
Agonostomus monticola	53	0.11
Chloroscombrus chrysurus	48	0.10
Syngnathus louisianae	47	0.10
Evorthodus lyricus	40	0.08
Membras martinica	38	0.08
Erotelis smaragdus	36	0.07
Lutjanus synagris	35	0.07
Trachinotus carolinus	35	0.07
Oligoplites saurus	34	0.07
Caranx hippos	31	0.06
Achirus lineatus	30	0.06
Bairdiella chrysoura	29	0.06
Lutjanus griseus	26	0.05
Mugil cephalus	19	0.04
Astyanax mexicanus	15	0.03
Scorpaena plumieri	15	0.03
Gobionellus hastatus	14	0.03
Poecilia latipinna	13	0.03
Brevoortia gunteri	11	0.02
Gobiosoma robustum	11	0.02
Abudefduf saxatilis	10	0.02
Dormitator maculatus	10	0.02
Gambusia affinis	9	0.02
Platybelone argalus	9	0.02
Dorosoma cepedianum	8	0.02
Gobiomorus dormitor	8	0.02
Fundulus similis	7	0.01
Myrophis punctatus	7	0.01
Paralichthys lethostigma	7	0.01
Arius felis	6	0.01
Cynoscion arenarius	5	0.01
Lutjanus campechanus	5	0.01
Prionotus tribulus	5	0.01
Sphoeroides parvus	5	0.01

Fish Species	N	% of Total
Trachinotus falcatus	5	0.01
Lobotes suranamensis	4	0.01
Selene vomer	4	0.01
Gerres cinereus	3	0.01
Hemicaranx amblyrhynchus	3	0.01
Poecilia formosa	3	0.01
Pomatomus saltatrix	3	0.01
Sphyraena barracuda	3	0.01
Syngnathus scovelli	3	0.01
Urophycis floridanus	3	0.01
Citharichthys macrops	2	0.00
Cynoscion nebulosus	2	0.00
Elops saurus	2	0.00
Etropus crossotus	2	0.00
Gobiesox strumosus	2	0.00
Histrio histrio	2	0.00
Lutjanus analis	2	0.00
Oostethus brachyurus	2	0.00
Alosa chrysochloris	1	0.00
Centropomis parallelus	1	0.00
Cyprinus carpio	1	0.00
Epinephelus cruentatus	1	0.00
Etheostoma gracile	1	0.00
Lutjanus apodus	1	0.00
Monocanthus hispidus	1	0.00
Orthopristis chrysoptera	1	0.00
Rachycentron canadum	1	0.00
Sphyraena borealis	1	0.00

Randy Blankinship, formerly of TPWD Coastal Fisheries Division, noted that juveniles of two species of fish that are generally tropical fish, the common snook and fat snook, have been caught in large numbers in the Rio Grande estuary. These two examples of fish, which evidently use the estuary as a nursery, are not found in abundance north of the Rio Grande (Blankinship 2001; TPWD 2001f).

The habitat preferences of juvenile common snook and their role in the fish assemblage in the lower portion of the Rio Grande, Texas from January through March 2006 using a bottom trawl and boat-mounted electrofishing gear was recently studied by C. Huber, T Grabowski, K. Pope and R. Patiño (unpubl. data). Common snook distribution was not random, rather they were captured above kilometer 12.9 in freshwater habitats often associated with faster currents, higher conductivity and steeper banks. This was considered by the authors as quite different as the habitats used elsewhere in their range. Overall catch rates of common snook were highest in January and gradually decreased through March. Commonly encountered species with the common snook are shown in **Table 4.4.2**.

Table 4.4.2. Species captured during trawl and electrofishing from January-March 2006 in the tidal portion of the Lower Rio Grande.

Channel habitat (trawl)	**N**	**% of Total**
Yellowfin mojarra *Gerres cinereus*	1420	0.49
Pinfish *Lagodon rhomboides*	373	0.129
Striped mullet *Mugil cephalus*	197	0.068
Gafftopsail catfish *Bagre marinus*	179	0.062
Atlantic croaker *Micropogonias undulatus*	164	0.057
White mullet *Mugil curema*	102	0.035
Spot *Leiostomus xanthurus*	92	0.032
Common snook *Centropomus undecimalis*	82	0.028
Age 1	80	
Age 2	2	
Age 3+	0	
Channel catfish *Ictalurus punctatus*	68	0.022
Gulf menhaden *Brevoortia patronus*	36	0.012
Bank habitat (electrofishing)		
White mullet *Mugil curema*	1870	0.578
Striped mullet *Mugil cephalus*	1119	0.346
Common snook *Centropomus undecimalis*	142	0.041
Age 1	104	
Age 2	28	
Age 3+	10	
Fat snook *Centropomus parallelus*	21	0.007
Gulf menhaden *Brevoortia patronus*	20	0.007
Bigmouth sleeper *Gobiomorus dormitor*	17	0.005
Yellowfin mojarra *Gerres cinereus*	11	0.003
Common carp *Cyprinus carpio*	11	0.003
Violet goby *Gobioides broussonetii*	9	0.003
Gizzard shad *Dorosoma cepedianum*	3	0.001

Based on a 1990 study, the distribution of fish and macroinvertebrates within the estuary appeared to be largely a function of tidal influence or salt wedge penetration. Euryhaline species as well as many fresh water species characterized the upper portions of the tidal Rio Grande (Landry and Harper 1990). Estuarine species decreased in abundance upstream and were replaced by freshwater species approximately 25 miles upstream of the mouth of the Rio Grande.

Prior to the US IBWC action reopening the river connection with the Gulf (IBWC 2002), the temporary barrier at the mouth of the river/estuary prevented migration of estuarine dependent species and potentially impacted species recruitment (Blankinship 2001; Landry 2001). The severing of this connection eliminated migration of aquatic organisms during a period when data suggest peak use by many species.

Results of analyzing TPWD Rio Grande survey data collected from 1992-1997 were consistent with statements by TPWD biologists concerning peak use of the estuary for certain species. Species analyzed included common snook, largescale fat snook, fat snook, threadfin shad, striped mullet, Atlantic croaker, Gulf menhaden, black drum, white and brown shrimp, and blue crabs. The percent distribution was calculated and graphed to show general trends in species use of the river (**Figures 4.4.2** and **4.4.3**). In general, the spring and fall represent periods of highest use by species analyzed. Concentrations were highest for the shrimp in April, May and June; from October through January for the blue crab; and from January to April for the mullet and croaker. For the species analyzed, the closure of the Rio Grande occurred at the period of highest use and subsequent re-establishment of estuarine conditions occurred at a less then optimal time.

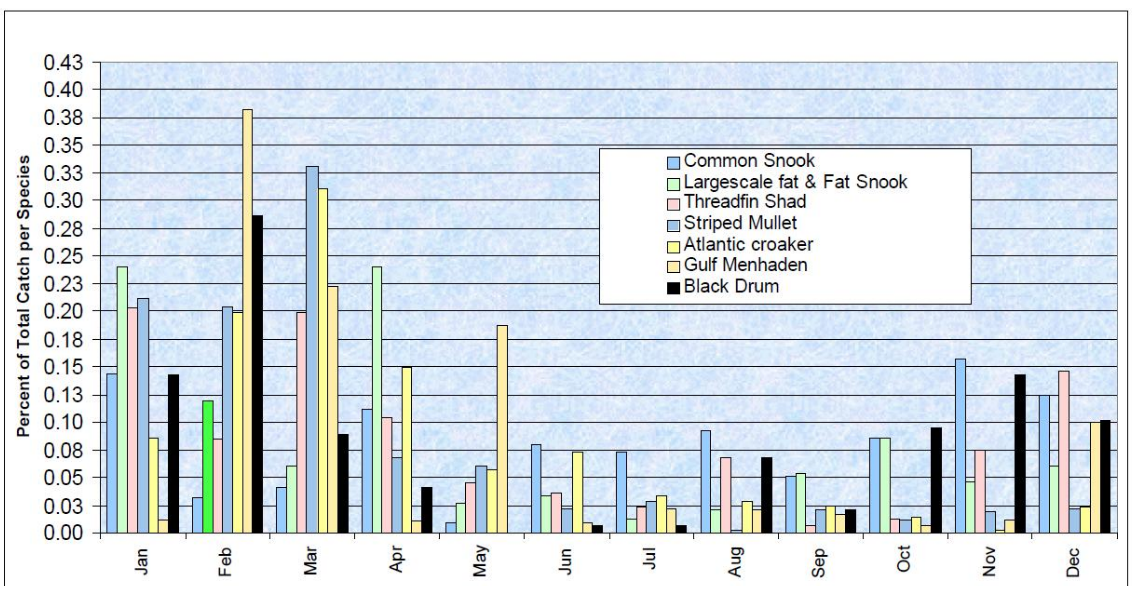


Figure 4.4.2. Percent distribution of selected fish species from the mouth of the Rio Grande to approximately 25 miles upriver. Original data were collected by TPWD from the fall of 1992 to the fall of 1997.

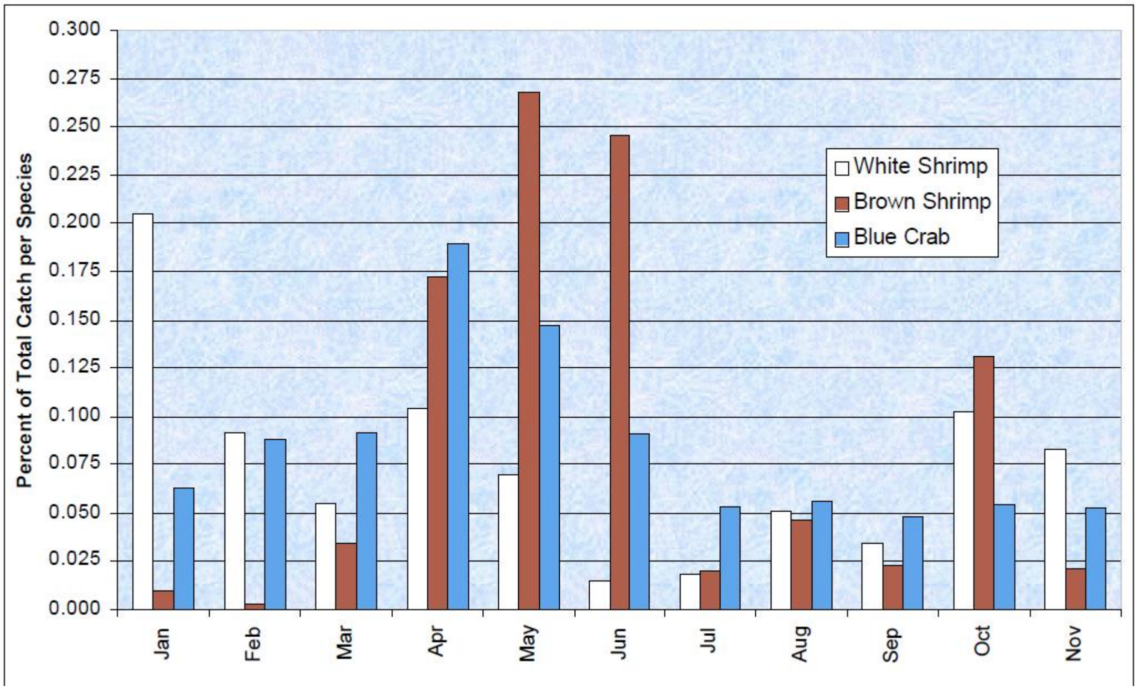


Figure 4.4.3. Percent distribution of white and brown shrimp and blue crab from the mouth of the Rio Grande to approximately 8 miles upriver. Original data were collected by TPWD from the fall of 1992 to the fall of 1997.

Benthic surveys of this estuary occurred between 2001 and 2005 by Montagna (2006). The Rio Grande has oligomesohaline (salinity from 0.5-18 ppt) community characteristics and was similar to benthic communities of secondary bays (Lavaca Bay and Cedar Lakes) and rivers (San Bernard River and Brazos River) in Texas (Palmer et al. 2011). The Brazos River and Rio Grande estuaries compared to other Texas estuaries had similarly low macrofaunal biomass (2.79 vs. 0.81 g m^{-2}) and abundance (17,600 vs. 5, 600 individuals m^{-2}) but abundance was four times higher in the Rio Grande compared to the Brazos River. Diversity was low in both systems with 80% of the individuals comprised of only 3 species in the Rio Grande. Despite the fact that these estuaries are located in different climatic regions along the Texas coast, they had considerable similarity (Montagna 2006; Palmer et al. 2011).

TPWD conducted fishery trawl surveys in the estuary from 1992 until 2000 as part of its Coastal Resource Monitoring Program (Coastal Fisheries Brownsville Office; Randy Blankinship, pers. comm.). This monitoring documented the biological production of the estuarine system and revealed how the system functions as an estuary. The most important function of the lower river is to provide lower salinity habitat for post-larval and juvenile marine species to complete their life cycles. Without a means of ingress and egress to this habitat, such fisheries production would be impacted (TPWD, Randy Blankinship; pers. comm.).

4.5. Habitat Description of Tidal Rio Grande

4.5.1. Biogeography

Figure 4.1.1 showed the Lower Rio Grande Valley below Brownsville viewed from 2004 NAIP (USDA-National Agricultural Imagery Program) color infrared aerial photography obtained from TNRIS (1:24,000 scale, 2m per pixel resolution). The tidal-portion of the lower Rio Grande consists of all or parts of four USGS 1:24,000 quadrangles (i.e. mouth of Rio Grande, Palmito Hill, Southmost, and East Brownsville).

A more detailed map of the tidal Rio Grande river corridor (**Figure 4.5.1)** gives an overview of key riparian zone and estuary study sites along the lower Rio Grande, extending from Brownsville, 48 river miles downstream to the river mouth opening into the GOM. The weir located on the river at El Jardin (Station 2, 48 mi upstream) marks the extent of the estuary, since this low-water dam prevents saltwater from intruding any further upstream. This entire region, 18,614 ha of study area, includes a 1-2 mile riparian corridor along either side of the river. A number of major river survey sites referred to in this report are shown along the 1-2 mile river corridor and briefly described in **Table 4.5.1**. These sites are locations where water quality or vegetation/land use analysis was performed for various studies from 2005 to present.

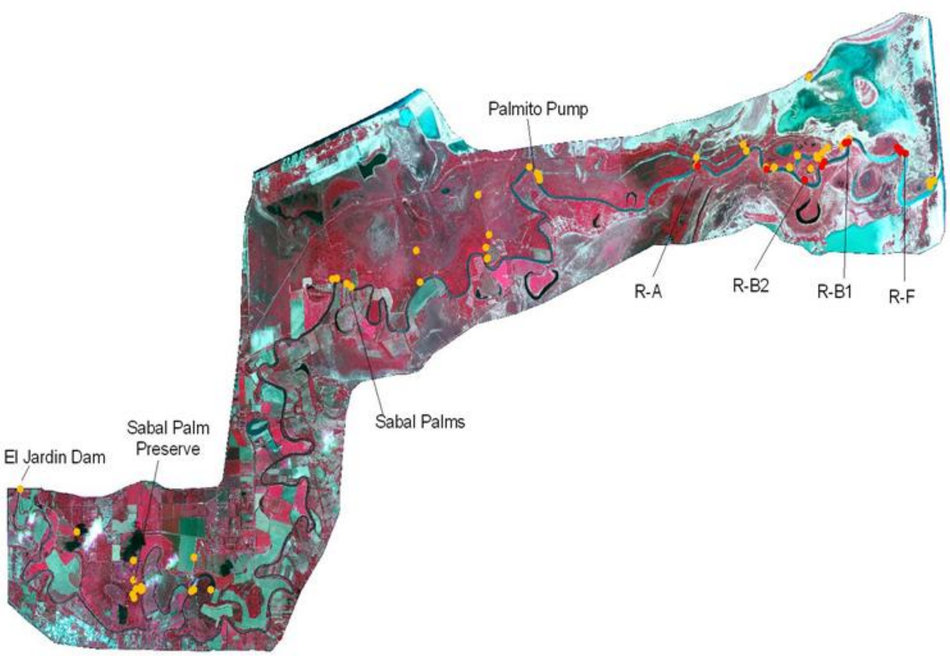


Figure 4.5.1. NAIP 2004 color infrared photography of 1-2 mile corridor along RG estuary, with locations of field study sites. Yellow and red points indicate sampling stations for field surveys since 2007 (yellow) and from 2008-2011 (red).

Table 4.5.1. Rio Grande Survey Stations and Habitat Descriptions.

Station/miles from Gulf of Mexico	Description
Mouth (mile 0)	Mouth of Rio Grande at Gulf of Mexico
Rio-F (mile 2.5)	First large black mangrove cove, 2.5 mi upstream from mouth
Rio-B1 (mile 3.8)	Second black mangrove cove, 3.8 mi upstream
Rio-B2 (mile 8)	Last upstream black mangrove observed; S. alterniflora still present
Boat Launch (mile 9)	Boat launch with adjacent Phragmites and Typha; some bulrushes; no S. alterniflora
Rio-A (mile 12.5)	Rio-A, with Typha, Arundo, Phragmites, and willow along shore
Palmito (mile 17)	Palmito Pump: upland thornscrub, huisache, and grasses
#8	Riparian woodland (ebony, thornscrub, huisache, ash, cedar elm)
#7	Riparian woodlands (Sabal palms, tepeguaje, ash, cedar elm)
TNC (mile 37)	Texas Nature Conservancy site (Riparian plants; Phragmites, Arundo)
#9 (mile 39)	Sabal Palm Grove Preserve
El Jardin weir (mile 48)	Saltwater dam and IBWC Stream gage #08475000

4.5.2 Land Cover/Land Use and Riparian and Wetlands Communities

A GIS inventory of recent land use, wetlands vegetation and riparian land cover of this LRGV region was performed during a previous study (Pulich 2008) from image classification of 2004 NAIP (USDA Farm Service program) color infrared digital aerial photography. Spatial extent and dynamics of Land Use/Land Cover over recent years for the 17 mile, lowermost estuary corridor, were determined, with special emphasis on US accessible wetlands and riparian areas (**Figure 4.5.2**). This lower portion of the Estuarine zone from river mile 17 down to the river mouth is comprised of arid, upland shrub/scrub vegetation, coastal salt prairie, salt flats, and estuarine wetlands dominated by common reed, salt marsh grasses, and mangroves (latter only up to mile 8). Vegetation distribution was also correlated with major geomorphological and hydrological data. Datasets on hydrographic and environmental parameters of the LRGV estuarine, riverine and riparian regions were compiled from an analysis of historical GIS data and aerial photography

Field surveys (by car and boat) from 2007 (50 and 27 GPS points, respectively), Sept. & Nov., 2008, Feb, May, Aug. and Nov. 2009 (28 GPS points), and March & Nov. 2010 have established the exact locations and extent of the dominant, estuarine aquatic plant species (black mangrove, common reed, smooth cordgrass, and saltmarsh bulrush) and brackish/freshwater species (water hyacinth, cattails, common reed, giant cane).

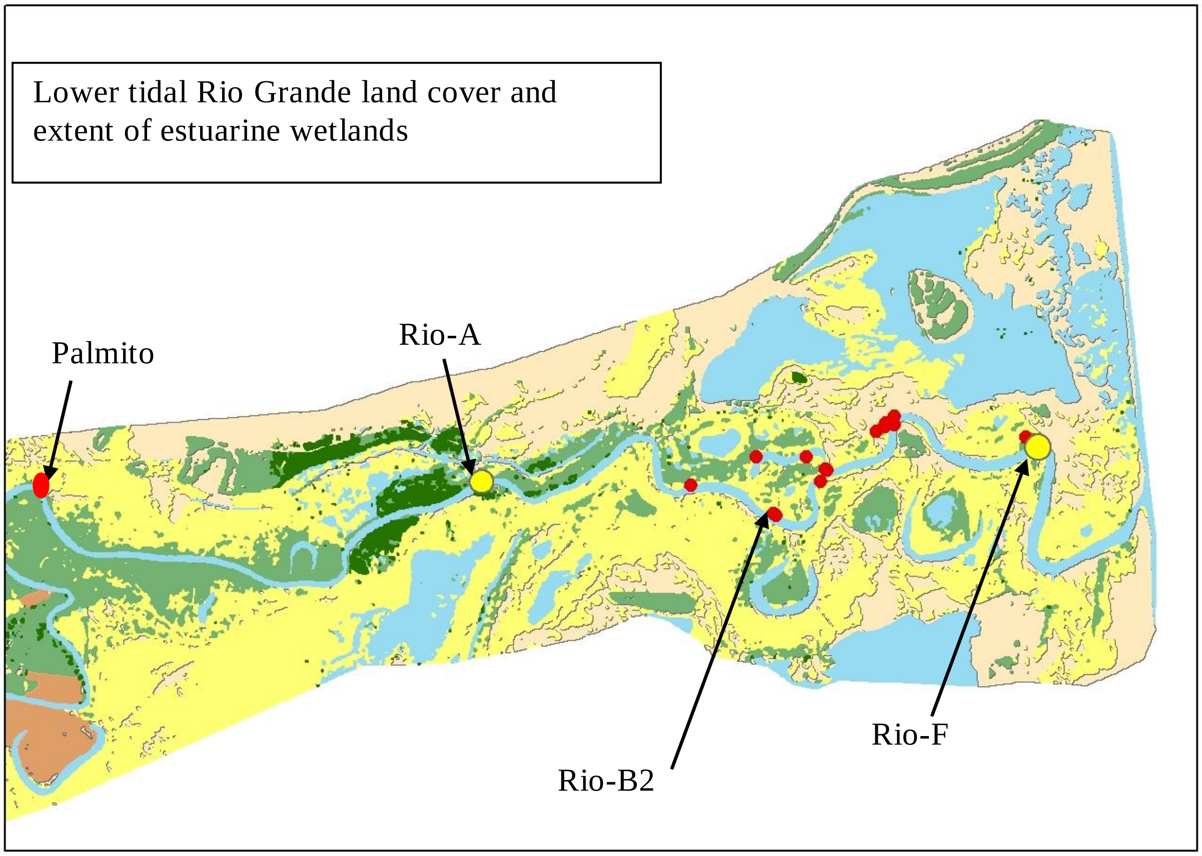


Figure 4.5.2. Enlargement of lower part of Rio Grande estuary below Brownsville (17 mile region from Palmito to Gulf of Mexico), showing classified land cover/land use. Classified areas are: grasslands (yellow), sand/salt flats (beige), shrublands (light green), woodlands (dark green), agriculture (brown), and water (blue).

GPS surveys (Pulich 2008, Pulich & DeYoe 2010) confirmed the identity and spatial distribution of vascular plant species at river stations (**Figures 4.5.1 and 4.5.2**). Results showed the habitat dynamics of the estuarine zone as evidenced by salinity-tolerant estuarine plants species, including black mangroves, smooth cordgrass, common reed, and saltmarsh bulrush. Riverine vegetation indicative of very low-brackish to freshwater conditions (viz. cattails, and giant cane) showed an inverse relationship with these higher salt-tolerant species. Although well out of the estuarine zone, the sabal palm forest shown in

Photo 4.5.1 is also noteworthy as a unique LRGV riparian, freshwater wetland type. As mentioned previously, these palm forests probably represent a remnant historical community covering much of the original LRGV riparian corridor. Their production has now decreased greatly because of vegetation clearing and decreased river overbanking.

Based on distribution of fixed habitat communities and macrophyte species, spatial extent of the estuary was delineated for the stations shown in **Figure 4.5.2**. Salt-tolerant estuarine vegetation such as smooth cordgrass, saltmarsh bulrush, and both black and red mangroves, reached their upstream extent near site Rio-B2, to where the surface water salinity gradient also normally extends (**Photo 4.5.2**). Riverbank species such as the common reed are much more widely distributed, essentially occurring along the entire riverbank from Rio-F up to El Jardin in places where bank geomorphology allows. Because of their tolerance to transition conditions from low salinity water to fresh water, cattails and giant cane became common in the region from just above Rio-B2 up to Rio-A, and beyond. Interestingly, barnacles attached to submerged objects, and blue crabs, regularly occur up to Rio-A (approx. 12.5 mi, 21 km upstream); and only during prolonged periods (several weeks) of freshwater inflow were barnacles killed. This overlap between sessile estuarine faunal species and rooted estuarine plant habitats provides further verification for the long-term integrated conditions that constitute the Rio Grande “oligohaline zone”.

Sampling station Rio-A, some 12.5 miles upstream, is characterized by completely freshwater vegetation (**Photo 4.5.3**). Occasionally water hyacinths totally covered the entire river channel (**Photo 4.5.4**). The river reach between stations Rio-A and Rio-B2 appears to be a transitional zone between truly freshwater and estuarine plant species, as shown by the mixed assemblage of species in **Table 4.5.1**. At site Rio-B2, the most upstream extent of smooth cordgrass and black mangroves was observed, indicating a regularly saline environment. Because these rooted species are integrators of the water and nutrient conditions over periods of months, their presence indicates that oligohaline to brackish conditions routinely exist in this area over much of the year. Thus, the river region around Station Rio-B2 has been identified as a key site for future monitoring and assessment.

4.5.3 Water Quality

Since 2001, the tidal segment of the Rio Grande has been monitored quarterly or bimonthly for nutrients, chlorophyll, and field parameters including temperature, salinity, dissolved oxygen, and pH. Three sites (El Jardin, Rio-A and Rio-F) have been monitored the longest time, with other sites such as Rio-B2 and South Bay added in 2008 (**Figure 4.5.2**). Chlorophyll and nutrient analyses were performed using standard techniques in the lab of Dr. DeYoe (UTPA). Much of this work was funded by TWDB and the USDA. A portion of the data from these projects is presented below.

Water column temperatures range from 32ºC in summer to about 15 ºC in winter (**Figures 4.5.3 and 4.5.4**). Salinities range from about 0 to 35 psu with clear evidence of a salt wedge at Rio-A and Rio-F (**Figures 4.5.5 and 4.5.6**). Surface dissolved oxygen levels range from 6-12 mg O_2/L while bottom oxygen levels occasionally dip below 2 mg O_2/L in summer months (**Figures 4.5.7 and 4.5.8**). Nitrate and phosphate but not ammonia concentrations generally peak in the colder months (**Figures 4.5.9-4.5.11**). Chlorophyll levels which represent phytoplankton abundance are moderately high and show little seasonality (**Figure 4.5.12**).

The tidal segment of the Rio Grande can be considered eutrophic to mesotrophic in regards to nutrient levels and phytoplankton abundance. There are differences in the water quality as one moves downstream from El Jardin (just below the rock weir at Brownsville) to Rio-F which is 4.2 km (2.6 mi) upstream of the confluence with the Gulf of Mexico (**Table 4.5.2**). Average salinity increases and nutrient levels generally decrease going seaward except for one interesting site, Rio-A (**Table 4.5.2** and **Figures 4.5.5, 4.5.6, 4.5.9, 4.5.10, 4.5.11**). At Rio-A, levels of nitrate and phosphate peak for the tidal segment possibly due to additional return flows between El Jardin and Rio-A. Although nutrient levels are quite high at El Jardin, phytoplankton abundance as measured by water column chlorophyll (WC Chl) are low (**Figure 4.5.12**). A reason might be that the nutrient additions occur a short distance upstream from El Jardin not giving the phytoplankton enough time to respond to the nutrient increase. At all sites the DIN/DIP ratios are near the Redfield ratio of 16N:1P suggesting that the phytoplankton is equally limited by nitrogen and phosphorus.

Table 4.5.2. Water quality data summary for tidal segment of Rio Grande and South Bay for the period November 2008 to March 2010. Salinity is reported in psu, chlorophyll is µg/L, and nutrients as mg/L. Site locations can be found in **Figure 4.5.2**.

mg/L	n	Salinity	Salinity	WC Chl	WC Chl	NO_3-NO_2	NO_3-NO^2	NH_4	NH_4	PO_4	PO_4	DIN/ DIP
		Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg
El Jardin	7	0.7	0.2	1.5	0.9	1.03	0.05	0.20	0.05	0.18	0.01	15.36
Rio A	7	2.8	5.3	25.2	25.6	1.35	1.27	0.14	0.13	0.21	0.12	15.74
Rio B2	7	8.8	11.6	19.1	13.7	0.99	0.76	0.20	0.19	0.15	0.08	17.24
Rio B1	7	11.6	13.1	20.1	15.0	0.92	0.75	0.12	0.12	0.14	0.08	16.08
Rio F	7	13.7	13.8	12.2	10.6	0.78	0.65	0.12	0.12	0.14	0.09	14.79
South Bay	7	36.3	5.5	2.3	2.5	0.02	0.01	0.09	0.08	0.02	0.03	14.45

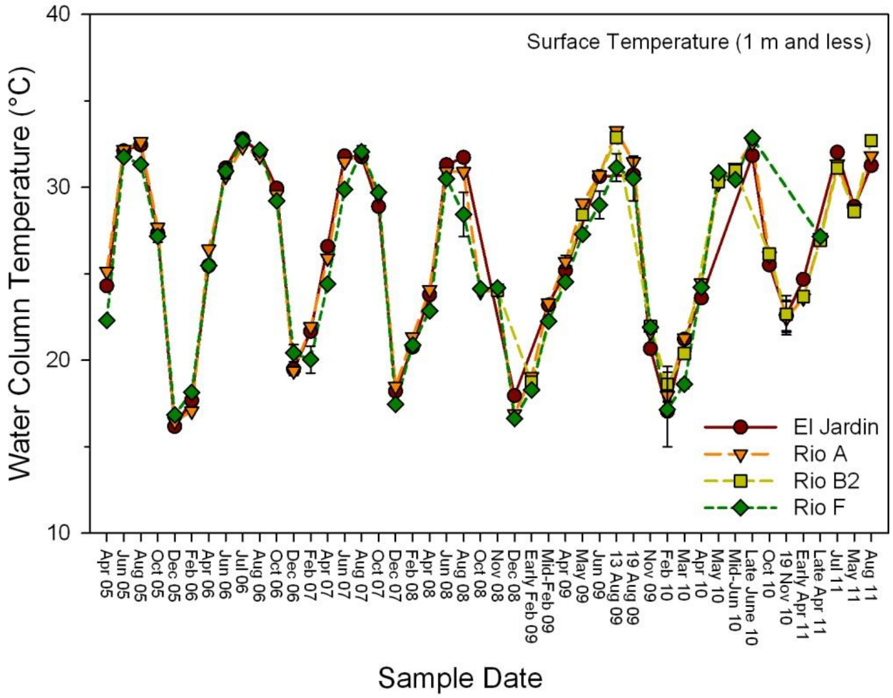


Figure 4.5.3. Tidal segment of Rio Grande surface temperature from April 2005 to August 2011.

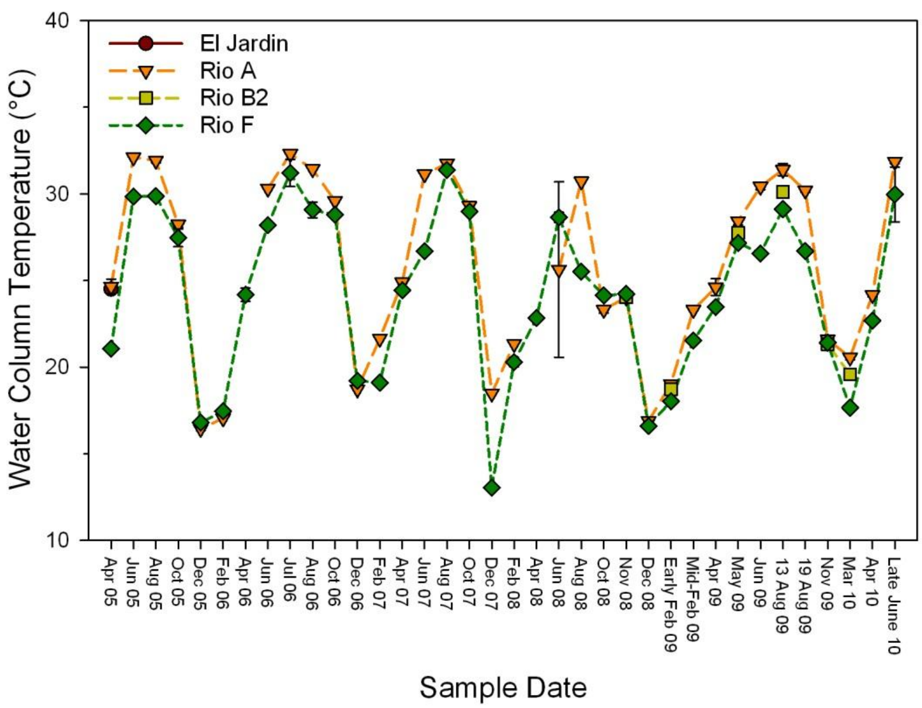


Figure 4.5.4. Tidal segment of Rio Grande bottom temperature (>1m) from April 2005 to June 2010.

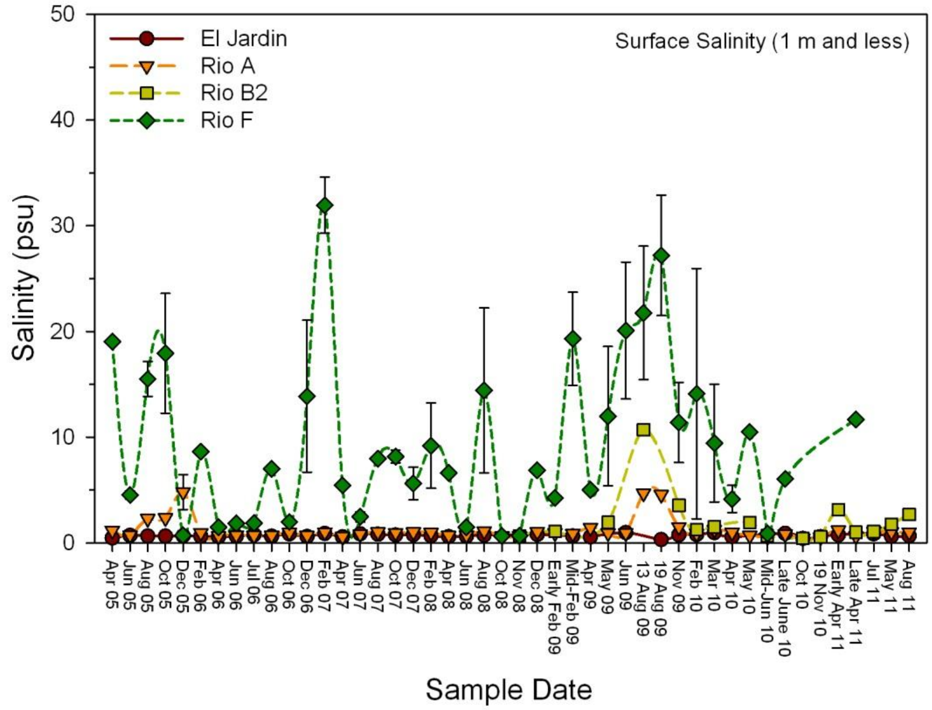


Figure 4.5.5. Tidal segment of Rio Grande surface salinity from April 2005 to August 2011.

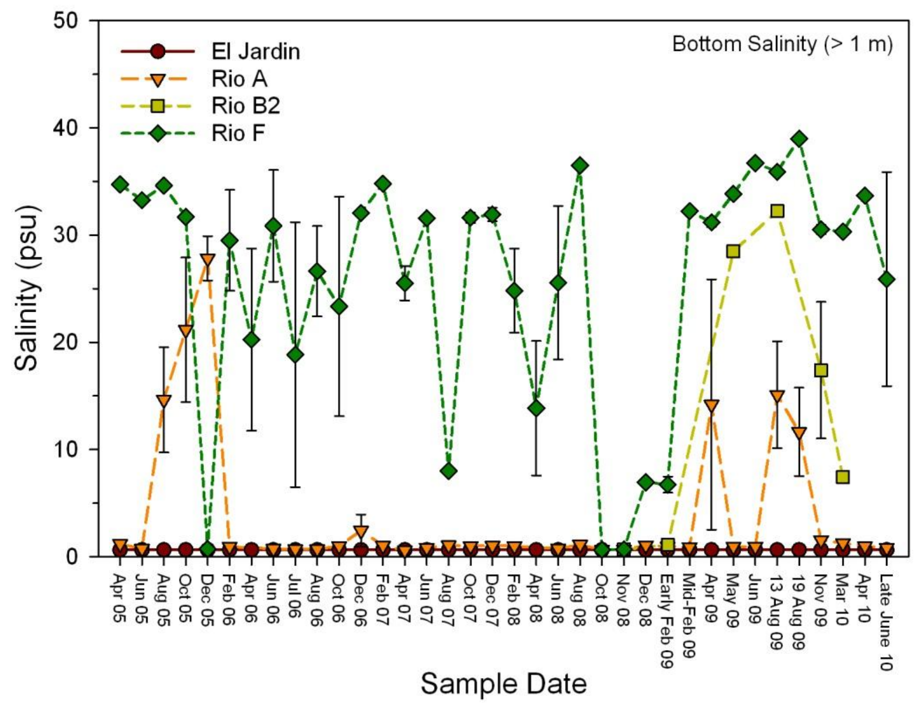


Figure 4.5.6. Tidal segment of Rio Grande bottom salinity from April 2005 to June 2010.

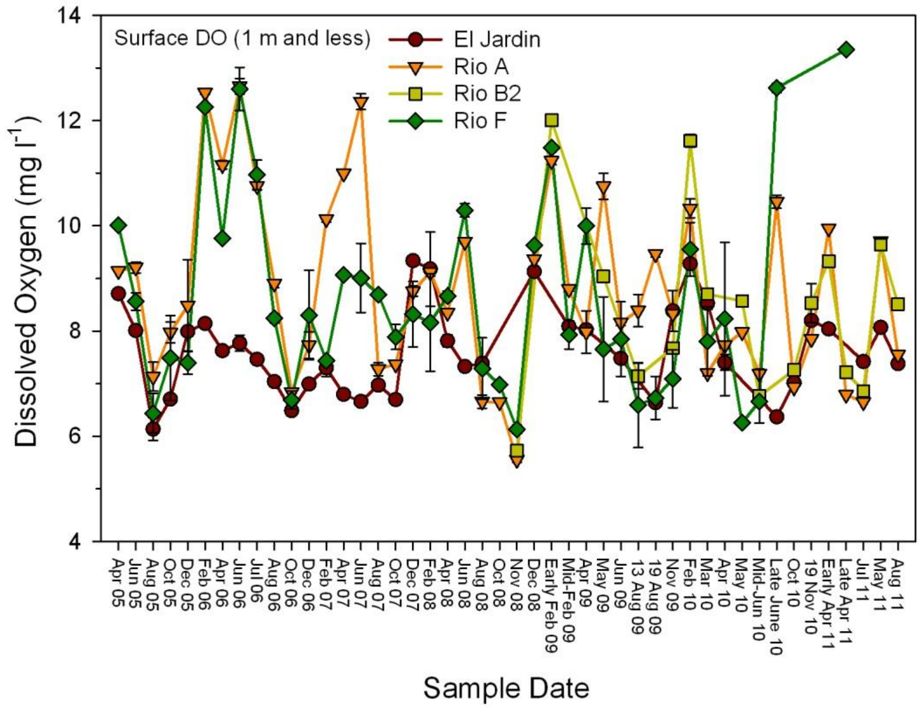


Figure 4.5.7. Tidal segment of Rio Grande, surface dissolved oxygen from April 2005 to August 2011.

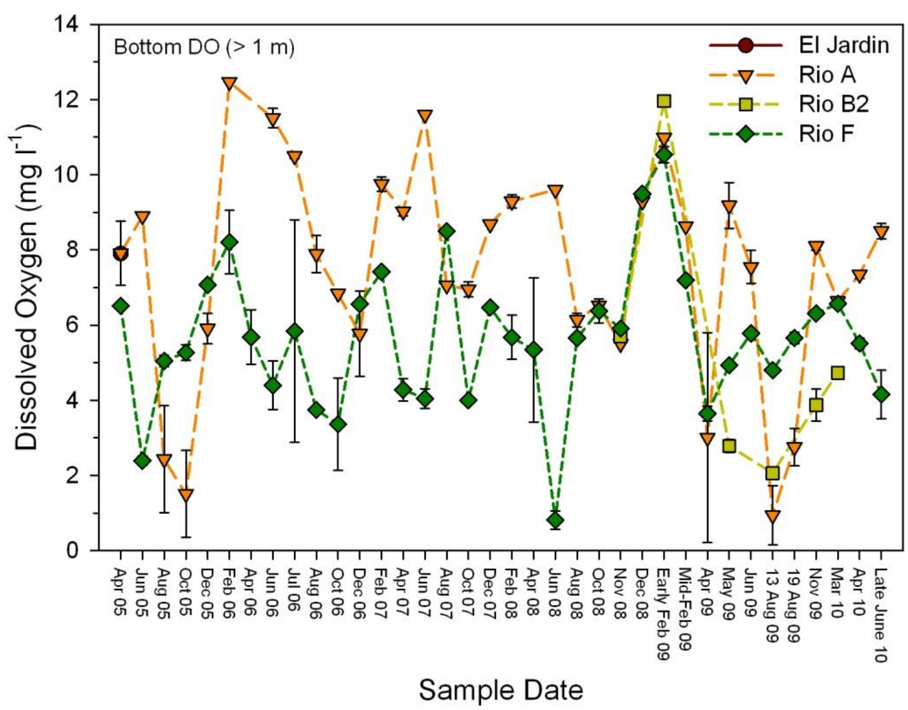


Figure 4.5.8. Tidal segment of Rio Grande, bottom dissolved oxygen from April 2005 to June 2010.

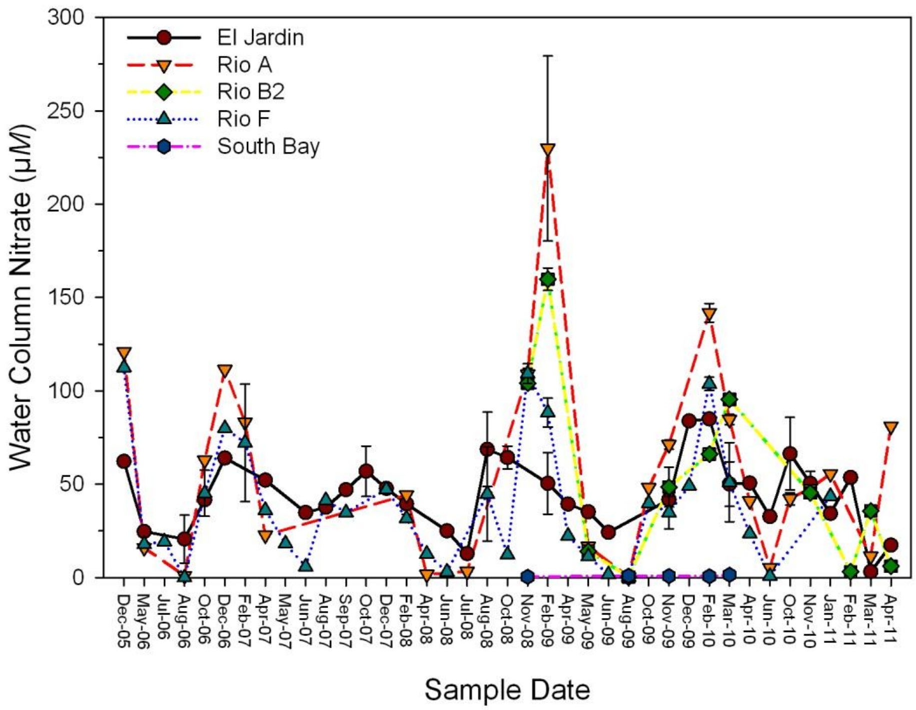


Figure 4.5.9. Tidal segment of Rio Grande surface nitrate-nitrite from December 2005 to April 2011.

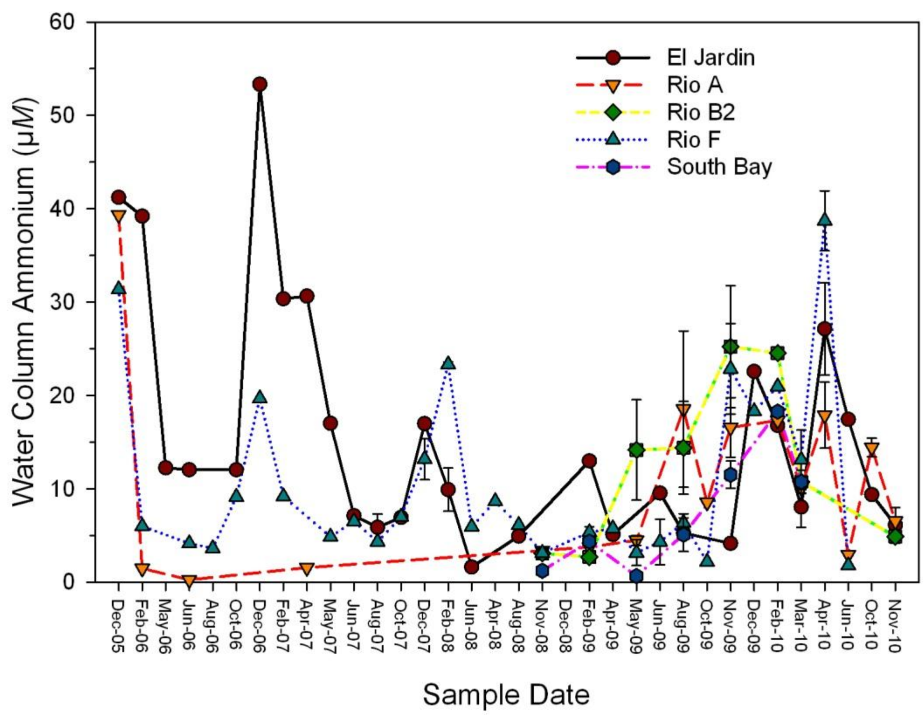


Figure 4.5.10. Tidal segment of Rio Grande surface ammonia from December 2005 to November 2010.

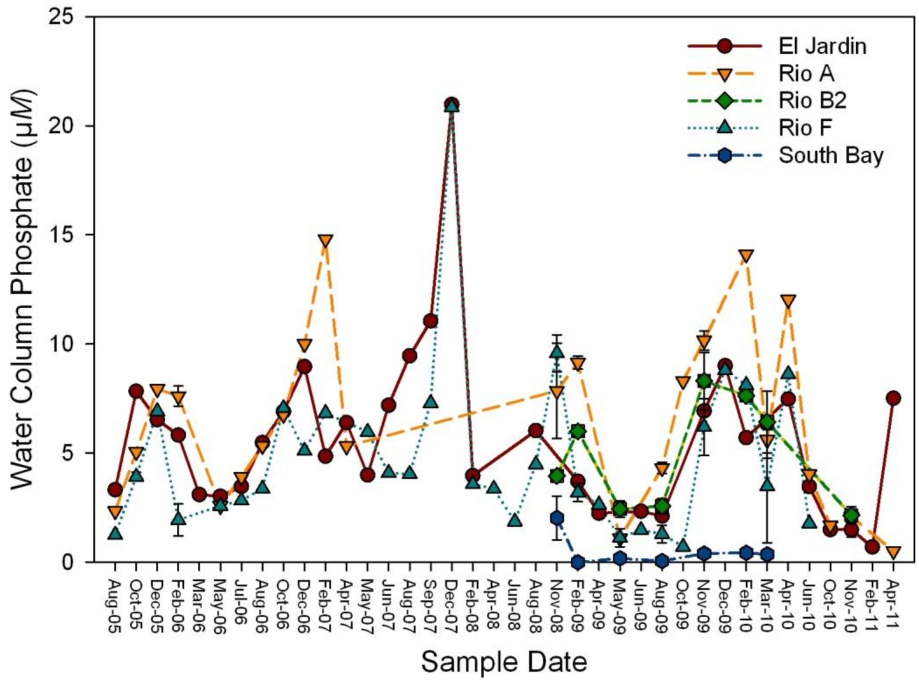


Figure 4.5.11. Tidal segment of Rio Grande, surface dissolved phosphate from August 2005 to April 2011.

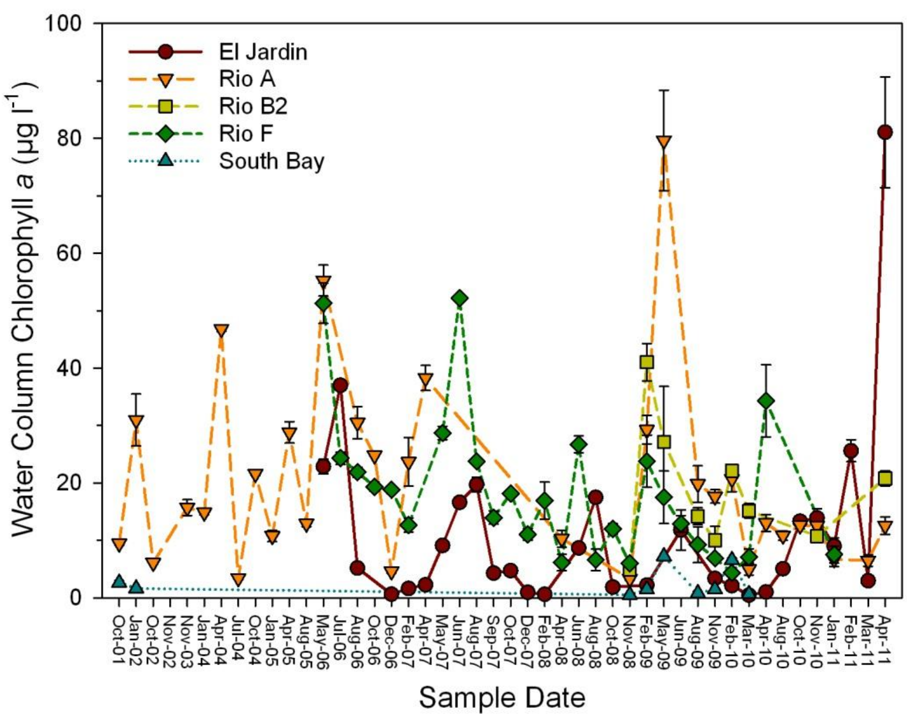


Figure 4.5.12. Tidal segment of Rio Grande surface water column chlorophyll from October 2001 to April 2011.

4.6. Hydrology of Rio Grande Estuary

Hydrologic data analysis is fundamental to describing the physicochemical dynamics of the Rio Grande estuary. The hydrograph of daily flows from the Brownsville El Jardin stream gage (#08475000) for 2000-2009 (**Figure.4.6.1**) shows that often Rio Grande flow is extremely pulsed and flashy. Indeed, the early period from 2000 – 2003 was a very low flow period, which correlates with the river mouth becoming blocked in early 2001. Later years in the mid 2000s indicate higher, moderate flows, while the 2008 – 2010 period has seen flood level flows not seen in decades.

Early on in the Rio Grande estuary inflow analysis process, the BBEST's plan was to perform hydrodynamic modeling of the riverine salinity conditions as a function of flow regimes measured at the El Jardin stream gage. The TWDB TxBLEND model was to be applied to the Rio Grande estuary as a basic two-dimensional linear transport model. For this purpose, continuously recording datasondes had been deployed by TWDB starting in 2005, at stations Rio-F, Rio-A, and El Jardin, in order to monitor water conductivity and salinity. This salinity data was then to be used in calibrating the TxBLEND model and developing the model regressions. Unfortunately, it was not possible to complete the quality assurance of these datasonde data in time for the BBEST study, and daily TxBLEND model output was found to be somewhat erratic at the lower estuary station Rio-F which is far removed downstream (Schoenbaechler et al. *in prep*.).

An example of this problem is reflected in the daily salinity record in this portion of the river. Although tide gage records were not examined, there was clear evidence of daily tidal changes reflected in the datasonde salinity record in the Rio-F portion of the river (**Figure 4.6.2**). Salinity on some days seemed to vary between 4 to 28 psu over the course of one day at Station Rio-F. In addition, water lines were evident on mangrove roots and marsh grass over the course of a day indicating fluctuating water levels in the lower river. Some of the problem may reflect movement of the salt wedge on the bottom, and mixing of top with bottom water layers. However, because TxBLEND is a two-dimensional, vertically-averaged model, it was unable to simulate salinity stratification. TWDB will continue to seek improvements to the Rio Grande TxBLEND model in the hopes of capturing the observed tidally-induced salinity variations.

4.6.1 Salinity vs. Flow Analyses.

As noted above, salinity data from the continuous datasonde records was available from TWDB (Bays and Estuaries Studies Program, Austin) and additional, unpublished data from Hudson DeYoe (University of Texas–Pan American), who has performed river surveys since 2005. Some of these data were previously used in the Water Quality section to demonstrate the salinity gradient dynamics of this variable system (see **Section 4.5.3, Figures 4.5.5 and 4.5.6**). A typical estuarine salinity wedge was frequently detected in the river channel between Stations Rio-F (river mile 2.5) and Rio-A (river mile 12.5) as shown in Fig IV.2 – 7. At Rio-F, bottom salinity (approx. 2.5 m depth) between 2006 and 2008 was routinely around open Gulf levels (30 – 35 psu), while surface salinities at the same time were around 5 psu. Moving upstream, the wedge becomes less defined until at Rio-A, salinities on the bottom (2.5 m depth) decreased to low oligohaline values (< 5 psu), and were almost fresh at the surface (0 – 0.5 psu).

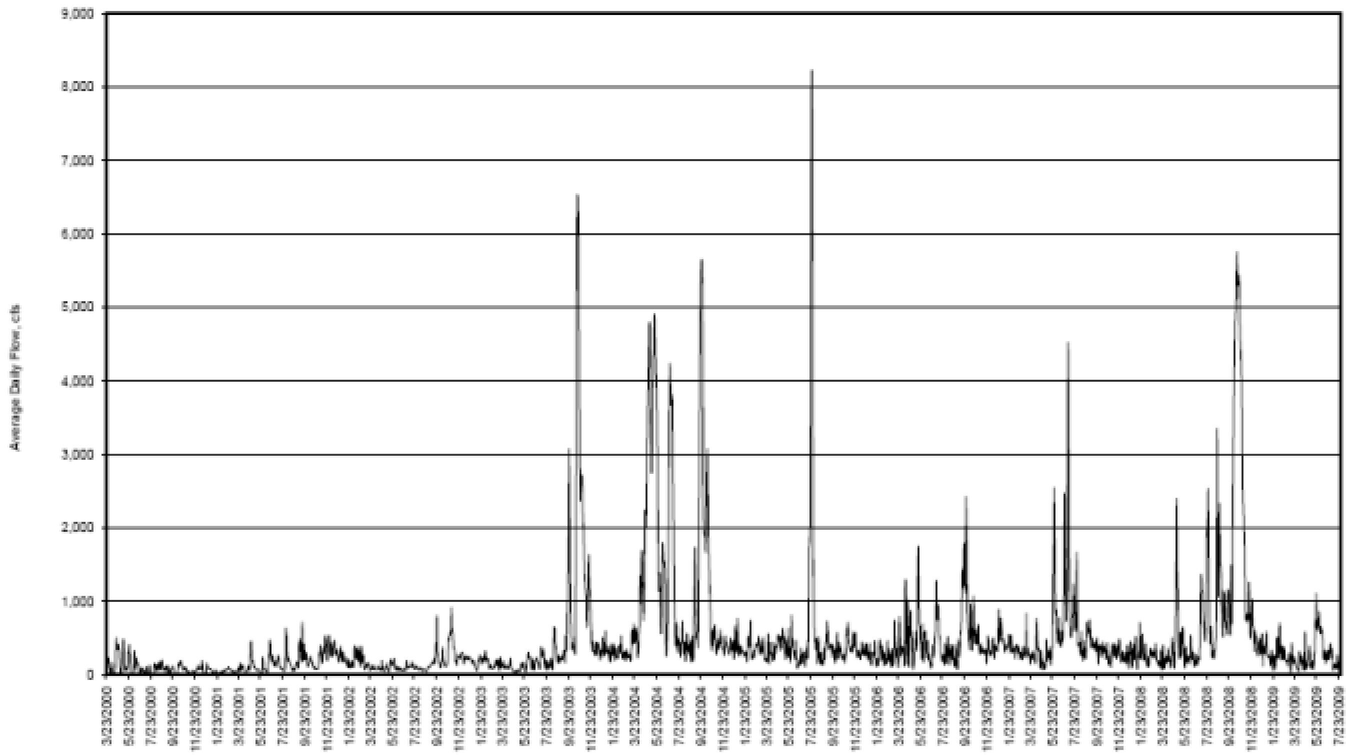


Figure 4.6.1. Rio Grande daily river flow at Brownsville gage at El Jardin dam (IBWC #08475000) from 2000 to mid-2009 (from IBWC database).

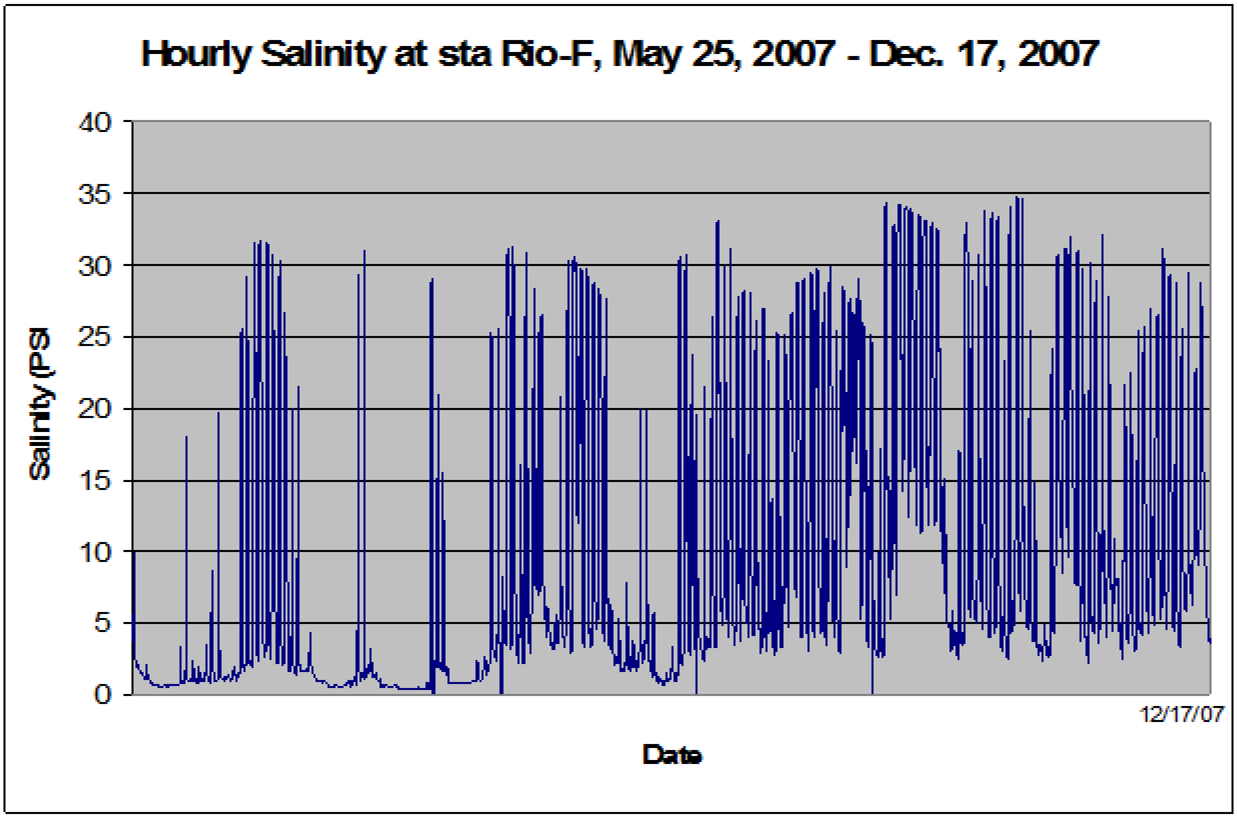


Figure 4.6.2. Hourly salinity datasonde record at Station Rio-F from May to December 2007

Although a rigorous TxBLEND analysis could not be conducted, some of the datasonde data were examined, and an empirical regression model was developed to illustrate how salinity vs. flow relationships would be analyzed. Regression analysis between simultaneous river salinity and flow regimes during the 2007-2008 study period are presented in **Figure 4.6.3**. Daily average salinity at the lowermost river station Rio-F was regressed against daily average flow levels at the El Jardin stream gage for 2 time periods. **Figure 4.6.3** presents the more significant correlation for a one-day lag between flow rates and salinity regimes ($R^2 = 0.62$), while the same-day correlation only had an $R^2 = 0.54$. This result suggests that freshwater inflows ca 46.3 mile upstream at the El Jardin weir took one or more days to travel downstream and affect salinities 2.5 mi from the river mouth under flow regimes during that year.

Another example would be to apply regression analysis to streamflows at El Jardin vs. salinity dynamics in the region between stations Rio-B2 and Rio-A (river mile 8 to river mile 12.5), the distinct "transitional zone" from regularly salty to regularly freshwater. Such an analysis would define the range of flows which maintain salinities between approx. 0.5 psu at station Rio-A to 5.0 psu at station Rio-B2. This psu range defines the classical "oligohaline" zone of estuaries. Unfortunately, complete datasonde records from Rio-A are currently not available.

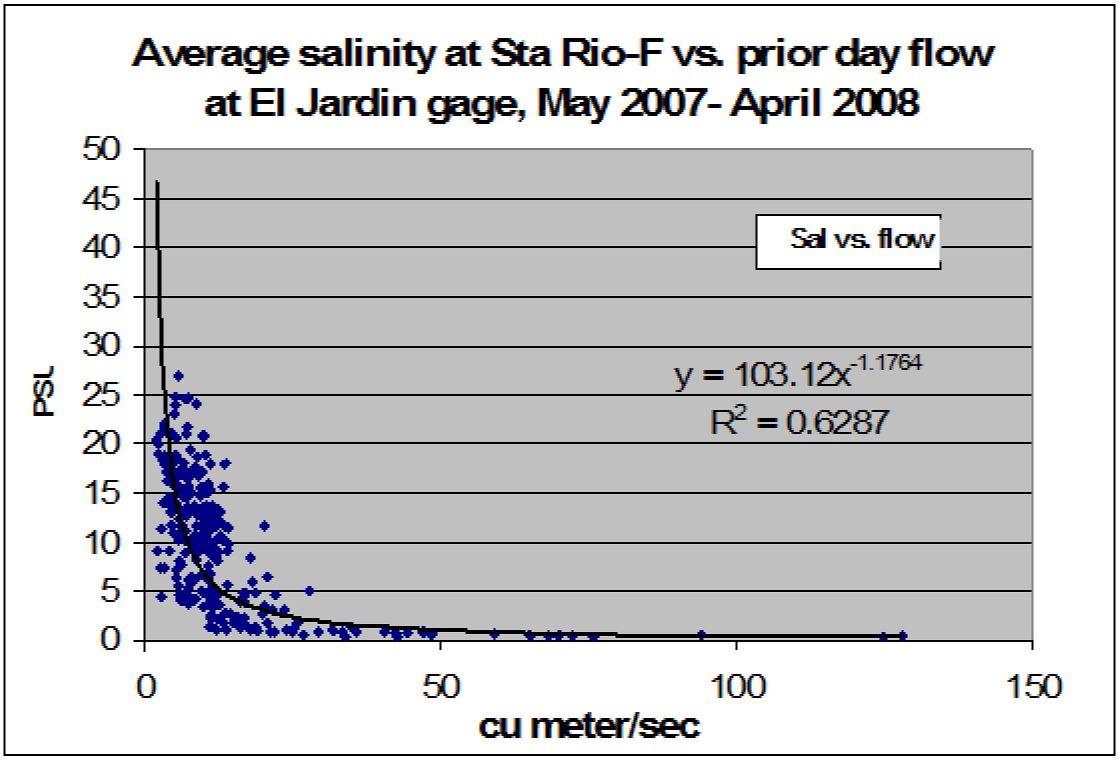


Figure 4.6.3. Daily Average Rio Grande flow at Brownsville gage near El Jardin dam, 2007 – 2008 correlated with next day average daily salinity as psu at Station Rio-F, 2.5 miles from the river mouth.

4.6.2. Brownsville Channel Dam Water Right Permit Requirement.

When Brownsville Water Utility was granted a water rights permit (TCEQ #5259) in the late 1990s to impound residual flows using a channel dam at the El Jardin site, the permit stipulated a lower flow limit whereby impoundment would not cause conductivity levels to rise above 2,250 µS at the location designated as river mile 23.6, east of Brownsville. The flow limit in the permit was 25 cfs at the El Jardin streamgage. River mile 23.6 was chosen partly as a result of environmental monitoring surveys by TPWD (R. Blankenship, Olmito Office) during the 1992 – 1997 period, which showed that a salinity wedge occasionally extended up to that river location during low flows. Additional background on this water permit can be found in TPWD's recommendation material submitted to TCEQ (TNRCC at that time) (see Appendix. "Chap. IV.3.2 – TPWD Brownsville PUB.pdf"). In order to verify that the permit condition was being met, the City of Brownsville contracted to perform test monitoring of water salinity conditions at mile 23.6 and mile 34 during the years of 2000-2009 when flows occasionally did reach the lower level specified in the permit, A Technical Memo on the study was prepared by James Machin PE, from TRC in Austin (an engineering firm) and this Memo is included in its entirety in the Appendix as "Chap. IV.3.2. Brownsville Weir Permit Memorandum". The BBEST reviewed the results and the consultant's summary is presented verbatim as follows.

“Two monitoring stations were installed on the Rio Grande in support of the proposed Brownsville-Matamoros Weir and Reservoir Project. The primary purpose of the stations was to monitor instream conductivity on a continuous basis. The water right issued for the Project by TCEQ (Water Use Permit No. 5259) includes a provision that water may only be impounded when the specific conductance at River Mile (RM) 23.6 is less than 2,250 µS/cm and that a minimum flow of 25 cfs be maintained at the IBWC Brownsville gaging station. The two monitoring stations were installed at RM 23.6 and approximately 10 miles upstream at RM 34. The Weir site is at approximately RM 48. See Figure 1. The stations contained water quality sondes (Hydrolab®) that recorded conductivity and other parameters on an hourly basis. There were periods when data are missing because of battery problems, sonde removal for maintenance, and sonde removal in anticipation of flood flows. Average daily flow at the gaging station for the period of interest was obtained from IBWC records. The daily flows at the IBWC gaging station for the period monitored are presented in Figure 2.

Monitoring was performed over all or parts of 10 years. The RM 23.6 station was installed March 23, 2000. The RM 34 station was installed October 16, 2000. Both stations were removed July 30, 2009. The intent of the conductivity limitation in the water right was to limit upstream migration of the salt wedge from the Gulf of Mexico during times of low flow. Early monitoring indicated occasional rises in conductivity at RM 23.6 that would rise and fall smoothly. The RM 34 station was installed to determine whether similar rises and falls were occurring prior to those at RM 23.6, which would indicate that the high conductivity water was originating upstream and flowing downstream, and not migrating up from the Gulf. I personally had previously conducted an instream survey from a boat and identified a high conductivity discharge into the river upstream that appeared to be originating from a tank truck parked next to the bank on the Mexican side.

The monitoring did indeed indicate that many rises and falls in conductivity at RM 23.6 were preceded by similar rises and falls at RM 34, indicating that high conductivity water was originating upstream and not migrating up from the Gulf. The occasions when high values greater than 2250 µS were observed at RM 23.6 but were not preceded by high values at RM 34, were:

- November 23 – December 2, 2000. Max value = 4626 µS.
- August 7 – 13, 2005. Max value = 2556 µS.
- July 16 – September 22, November 22 – 24, and December 1 – 31, 2008. Max value = 6435 µS.
- January 1 – 27, March 17, April 8 – 9, June 27 – 28, July 14 – 15, 2009. Max value = 7810 µS.

Many of the high values did not occur during times of low flow, contrary to the premise of the conductivity limitation in the permit. It is likely that some of the high conductivity periods occurred in response to tropical systems in the Gulf and associated high tides, pushing saline water up the Rio Grande. A summary of the monitoring data is presented in Table 1. <u>*During five of the ten years monitored, there were occasions when the specific conductance values at RM 23.6 exceeded the criterion of 2,250 µS. During the first two years (2000-2001), there were days when the flow at the IBWC gaging station was less than*</u>

or equal to 25 cfs. During these times, if the Weir was in place, water would likely not have been allowed to be impounded in the reservoir under the terms of the permit, and inflows would have had to be passed through. Exceedances resulting from high conductivity water originating upstream could potentially reduce the number of days of limitations. Charts showing the continuous monitoring data for each year are presented in Figures 3-12." (Underlining and italics added by BBEST for emphasis)

4.7. Analysis of Hydrodynamic Processes

4.7.1. River Flow Impacts on Focal Species

This inflow study specifically focused on analyzing relationships between river inflows and salinity conditions that affect estuarine vegetative communities or aquatic habitats of the tidal Rio Grande segment. However, sessile fauna (e.g., oysters, barnacles, etc.), which also occur in the lower part of the estuary, offer potential for similar determination of flow vs. salinity relationships. In the adaptive management work phase of this project, rates of barnacle colonization along the estuary gradient from Rio-A to Rio-F would constitute an appropriate faunal estuarine indicator.

Previous studies have dealt with invasive and noxious plants (Everitt et al. 1999) or fish species and assemblages (TPWD, UT-Pan American) in this river reach. In fact few studies prior to this report have described the occurrence or distribution of native estuarine plants, which are briefly addressed in Jahrsdoerfer and Leslie (1988) and Lonard and Judd (2002). The report of Raney et al (2004) listed only the general occurrence of black mangrove and smooth cordgrass near Boca Chica, but no information on extent of these species upstream. The current report establishes the precise distance upstream for several of these indicator estuarine plants, and describes the general location of floating hyacinth, and brackish water species, relative to hydrologic dynamics. These distribution data for estuarine indicator plants provides definite locations of the fixed boundaries of the "oligohaline estuarine zone". Based on locations of smooth cordgrass, *Phragmites*, black mangroves, saltmarsh bulrush, cattails, and water hyacinth, there appears to be a distinct, transitional zone between river miles 8 and 12.5, where the aquatic habitat (characterized by surface and bottom salinity and possibly nutrients) is critical for maintaining oligohaline vascular vegetation.

Analysis of the streamflow hydrograph for 2000-2008 (Fig. 13) shows that often Rio Grande flows are extremely pulsed and flashy. Indeed, the early period from 2000 – 2003 was a very low flow period, and it is easy to understand how the mouth of the river silted in and became closed during 2001. Since 2003, however, such very low flow periods have not reoccurred, and this later period reflects a return of flow regimes to more typical, moderate levels. The period from 2004 to 2008 even appeared much wetter. Very high flows during 2008 corresponded with summer/fall tropical weather events (e.g. hurricane Dolly and Mexican monsoons), which almost completely flushed salinity from the entire estuary. Since late 2008, reduced flows have been accompanied by return of the salinity wedge extending approx. 8 to 10 miles upstream. With the onset of the extreme flooding in July 2010, the river again became totally fresh all the way down to station Rio-F for over 6 months.

During the study period of 2006-2008, rooted plants such as black mangrove, cordgrass, bulrush, cattails, and *Phragmites* showed no noticeable decreases, while the floating species, water hyacinth, increased greatly downstream from station Rio A, almost to 2.5 mi from the mouth. Thus, hyacinth abundance displays a highly positive correlation with high river flows and a reduced salinity gradient produced by river flooding. Over the time period 2005 to 2008, there is preliminary evidence that residence time of nutrients (especially N) also increased in the estuary, and this may contribute to enhanced growth of the nuisance plants like hyacinth.

4.7.2. Flow Impacts on Geomorphology at the Rio Grande Mouth

When the mouth of the river silted over in 2001, the impact of extreme reduction in total flow became dramatically apparent. This situation raised questions concerning the amount of river flow needed to counteract the sediment depositional effects of long-shore currents in the GOM. As a result, the IBWC contracted for a special hydraulic engineering study by Sandia National Laboratories to analyze the effects of GOM currents on sediment transport through the river mouth . The results of this report by Sandia Labs (which is included in the Appendix as ‘Chap. IV- Report IV.2. Sandia Labs’) are presented and summarized verbatim as follows.

<u>Conclusion</u>

The study demonstrated that the sediment observed within the surf zone, extending onshore through the Rio Grande Delta and at least 75 m into the Rio Grande Channel have very similar erosional properties and mean particle sizes. These sediments are predominately homogeneous mixtures of sand, having critical, erosional shear stresses between 0.25 and 0.35 Pa. Inchannel flow rates large enough to produce bottom shear stresses greater than this critical shear are required to transport sediments obstructing the Rio Grande Channel. All analyzed sediments transported completely as bedload at shear stresses of 0.5 Pa or lower. The finest grained sediments (sand, silt, clay and organic material) observed in core procured approximately 500 m upstream in the Rio Grande Channel (RGC2) were significantly more difficult to erode than the coarser grained sediments (sand) found proximal to the shore. This was to be expected, as the near-shore current is too strong to accumulate cohesive clay and organic deposits.

Longshore current velocity measurements taken in the surf zone correlate with erosional shear stresses of approximately 0.20 Pa or lower, with peaks approaching 0.40 Pa. When we compare these shear stress values to those measured in the erosion rate tests, all of the sediments analyzed would be eroded and transported northward by the Gulf’s long shore current. Because the transport is 100% bedload at these velocities, none of the material would be carried offshore in the overlying water. <u>*If the velocities of the Rio Grande discharge are not higher than the Gulf’s longshore current (> 0.3 m·s-1 [average], > 0.43 m·s-1 [peak]), the effects of longshore transport can and will introduce enough coarse material into the Rio Grande Delta Region capable of plugging the Rio Grande Channel*,</u> causing the river to breach its banks and inundate the adjacent flood plain.” (underline and italics added above for emphasis by BBEST).

The BBEST can only reiterate this study's conclusion that a discharge of > 0.3 m per sec (or 1 ft per sec) from the Rio Grande is required to maintain sediment transport and prevent blockage of the river mouth**.** In order to translate this flow velocity to flow volume (i.e., cfs), we would need to use a standardized cross-sectional channel area for the Rio Grande mouth. Based on dynamics of the channel mouth, and assuming a channel area of 5 ft. avg depth X 50 ft. width, this would equate to an average flow volume of 250 cfs needed to maintain an open river mouth of this size. A later study (Ernest et al. 2007) performed geomorphologic analysis using satellite remote sensing imagery and historic flow rate assessment, followed by a two-dimensional, depth averaged, finite element numerical modeling analysis to simulate the hydrodynamics of the tidal river portion. This study concluded that the peak shear stress increased with increasing discharge towards the mouth of the river and a 1.27 m^3 per s (45 cfs) discharge was necessary to maintain the opening of the river mouth. However, this flow would translate to a very small channel mouth.

4.8. Flow Regime Summary

This study reviewed and investigated various hydrologic, water quality and dissolved nutrient dynamics and their relationships to estuarine environmental processes and/or wetland ecology in the lower 48 mile reach of the Rio Grande below Brownsville. Hydrologic impacts to estuarine indicator wetland flora and fauna in this river reach were recognized as critical, but data supporting specific flow regimes for ecological functions were sparse and qualitative. A key measure of ecological health in the Rio Grande tidal is faunal ingress and egress to the estuarine habitat within the Rio Grande channel. If the mouth were to remain closed for an inordinate period or during the wrong season, the estuary habitat would be inaccessible to larval or juvenile fauna needing to migrate into the estuary according to their life cycle requirements. Conversely, adult fauna would be trapped and prevented from leaving the closed river in order to spawn. The Rio Grande tidal is ecologically important since it provides brackish water habitat that is not commonly encountered on this relatively arid portion of the Gulf coast.

The blockage of the river mouth in 2001 due to drought and low-flow sediment deposition raised awareness of the need to maintain sufficient flow to keep the river mouth open to the Gulf. Two subsequent studies evaluated relationships between flow, velocity, and maintenance of flow to the Gulf of Mexico. The special Sandia Laboratories study (Sandia Laboratories 2003) supported by the IBWC concluded that a velocity of > 0.3 m per sec (or 1 ft per sec) from the Rio Grande is required to overcome long-shore current sediment transport. When this velocity is translated into an actual flow volume, it equates to ca 250 cfs when a channel mouth cross section 5 feet deep and 50 feet wide is considered. Discharge of 45 cfs at the river's mouth was estimated to provide the peak shear stress necessary to prevent sediments from blocking the mouth of the river (Ernest et al. 2007).

Blockage of the river mouth in 2001 was associated with an extended period of relatively low flows and presence of large surface mats of water hyacinths that covered long reaches of the tidal river from bank to bank. Literature suggests that transpiration rates of water hyacinths may be from 50% to 400% greater than evaporation rates of open water (Van Der

Weet and Kamerling 1974; Timmer and Weldon 1966). These accumulations of water hyacinths may have considerably reduced flow in the Rio Grande tidal downstream of the Brownsville gage. The gaged flow into the Rio Grande tidal averaged 39 cfs for the 28 days prior to the river mouth closing on February 4, 2001 with a maximum daily average flow during that time of 83 cfs.

Complex interactions between many different factors like evaporation rates, transpiration rates of water hyacinths, population size of water hyacinths, Gulf longshore current patterns, antecedent low flows, magnitude and frequency of pulse flows, etc., affect the relationship between the connection of the river with the Gulf . Once the river mouth was closed, substantial flows were required to open it again. For example from February 4 to July 20, 2001, the period when the mouth was closed until it was mechanically opened, the maximum daily average flow was 473 cfs and the average daily average flow was 112 cfs. Conversely when conditions are different such as during 1999 when the river mouth was open, the maximum daily average flow was 322 cfs and the daily average flow was 60 cfs.

Streamflow data document the highly pulsed, episodic nature of inflows to the estuary (IBWC 2010). Under very reduced flows, salinity may rise to harmful concentrations in the upper reaches of the estuary. The City of Brownsville Water Permit for the Brownsville-Matamoros Weir contains flow and salinity restrictions for impoundment of water in the proposed reservoir upstream of the El Jardin site. Impoundment of river flows can only be made when the specific conductance in the river is less than a value of 2,250 uS at river mile 23.6 and when the flow at the Brownsville gage is 25 cfs or higher. This salinity level is the highest value recorded in recent years during extremely low flow periods, which were reached when the river mouth became plugged. In a recently completed monitoring study over the period 2000 – 2009 (Machin 2009), it was shown that low river flows will in fact produce these elevated bottom salinities at mile 23.6.

Environmental Flow Recommendation for the Rio Grande tidal (as measured at the Brownsville gage)

> <u>Minimum Flows</u>: Minimum flow of 60 cfs at all times to maintain a salinity transition zone that supports the vegetative communities that transition along the length of the estuary and helps keep the mouth of the river open. It is 25% greater than the 45 cfs identified (Ernest et al. 2007) as necessary to keep the mouth open and it is higher than the average flow of 39 cfs into the tidal reach for the 28 days prior to the mouth closing in February 2001.
>
> <u>Pulse Flows to Keep the Mouth Open</u>: Daily average flow of 175 cfs at least once every 2 months (based on flows during 1999, which had lower total inflow than all but one other year during the period of record from 1934 to 2010), when there were 7 pulse periods with at least one day of daily average flow exceeding 175 cfs.
>
> <u>Daily Average Flows</u>: Daily average flow of 880 cfs at least once each year (based on the November 3, 2002 flow of 915 cfs which was part of a wet period that helped

naturally reopen the river mouth by November 7, 2002). No pulse flows of this magnitude occurred from February 4, 2001 through November 3, 2002, during which period the river mouth was closed (except when artificially opened in late July 2001).

Work should continue evaluating the relationship between water hyacinths and their effects on evapotranspiration, variability in sediment transport by Gulf longshore currents, changes in relative sea level rise, overbanking flows into flats along the Texas and Mexico shores near the mouth, variability in river mouth morphology, and other factors that determine whether or not the river mouth remains open. Additionally the configuration of the open mouth of the river is important in allowing movement of marine and estuarine organisms back and forth at water depths that minimize predation from herons, egrets, and terns.

There are very little data on these factors (with the exception of flow data) and even less analysis of the ways in which they interact to affect the opening of the river mouth. The BBEST makes these environmental flow recommendations with the knowledge that flows in the Rio Grande basin are over-appropriated. The BBEST also acknowledges that the complex interactions of physical and biological factors may cause the river mouth to close at flows greater than these recommendations or may allow the mouth to remain open at flows less than these recommendations. However these environmental flow recommendations are intended to emphasize the importance of maintaining a connection between the river and the Gulf to the ecological health of the Rio Grande tidal. These values will serve as a starting point for future analysis and consideration of strategies to protect and restore ecological health in the Rio Grande tidal

4.8.1. Flow Regimes supported by Studies of Estuarine Indicator Species

Analysis of the stream flow, nutrient, and salinity data for the 2004-2010 time period suggest that pulsed flow regimes produce riverine salinity gradients and oligohaline habitat conditions which promote nutrient cycling and primary production. During 2007-2010, field surveys documented a clear transition between oligohaline and freshwater riverbank vegetation in the lowermost 8 to 12.5-mile (13.3 - 21 km) reach of the estuary which also correlated with hydrographic salinity gradients. While response to the salinity gradient is involved, we also hypothesize that wetland plant production and possibly species succession are dependent on river nutrient loadings. Further monitoring studies on the nutrient gradient and habitat transition from the regular freshwater zone (at river mile 12.5) down to about 2.5 mi from the mouth of the River are recommended during the adaptive management work phase. Over the past 5 years, a picture has emerged showing how the transition occurs, both in wetland plant species dominance and response to dissolved nutrients, particularly NO_3–nitrogen. Floating freshwater nuisance macrophytes (ie. water hyacinth and water lettuce; see Photos 3 and 6) are excellent indicators for monitoring because of their rapid growth response to river flow and their direct contact with dissolved nutrients.

4.8.2. Rio Grande Estuary Management under Drought and Warming Climate Cycles.

With the onset of global climate change, long range drought and weather patterns are now extremely unpredictable. However, the Rio Grande may be subject to these factors even more so than other GOM areas because of its geographic location. Flowing through the arid southwest U.S., the Rio Grande is influenced heavily by climatic regimes, similar to many Mexican, South African and Australian rivers. Such estuarine systems offer examples for water planning and management operations in arid-semiarid areas. From a comparative perspective, more studies should be reviewed of how water management in river systems in other parts of the world may be similar to the Rio Grande. *Enhancement of the Rio Grande estuary may not be feasible by increasing the amount of freshwater inflow, but partial restoration could be feasible by decreasing nutrient loadings to the river below Brownsville*. First though, the source of these nutrients must be determined, and this should be part of the focus of future adaptive management studies on the Rio Grande estuary.

Maintaining the normal historical timing and frequency of lower Rio Grande hydrology is critical to any management plans involving restoration of river flows. Return flows of most water diverted from the Rio Grande currently pass down the Arroyo Colorado and empty into the Texas Laguna Madre, the estuary to the north of the Rio Grande. A particularly intriguing idea is maintaining (perhaps even increasing) freshwater return flows to the Rio Grande estuary, despite the current pressures on water usage in the LRGV. If some of this diverted flow were re-routed from the Arroyo Colorado and returned to the tidal portion of the Rio Grande, then this could help to restore the minimal freshwater inflow requirements of the Rio Grande estuary. Rerouting flows from the Arroyo Colorado could also protect the LLM where excess nutrients may cause serious eutrophication problems. Similar water diversions (mostly for crop irrigation) occur on the Mexican side of the border. Much of the water diverted from the Rio Grande into Mexican irrigation canals below Reynosa and Matamoros is ultimately discharged into the Mexican Laguna Madre. If some of this water were returned to the tidal portion of the Rio Grande, it would also help maintain the functionality of the Rio Grande estuary.

Photo 4.5.1. Riparian Sabal Palms near Sabal Palm Grove Sanctuary, SE Brownsville.

Photo4.5.2. Open Rio Grande at Station Rio-A in Feb. 2009 (Mexico on left)

Photo.4.5.3. Floating mats of water hyacinth and water lettuce observed at station Rio A during March 2008. Photo courtesy of Tom Eubanks, UTPA.

Photo 4.5.4. Rio Grande shoreline on US side, approx. 8.5 miles upstream from river mouth. Vegetation shown: cattails in far background; bulrush middle foreground; *Phragmites* right foreground. June 2007.

Photo 4.5.5. Black mangrove cove at station Rio F on US side of lower Rio Grande estuary during Feb. 2009.

Photo 4.5.6. Water hyacinth and water lettuce mats observed in mangrove cove at station Rio B1 during Sept 2008. Cove is surrounded by black mangrove thicket.

Section 5 Ecological and Hydrological Characterization Above Tidal Segment of the Rio Grande from above Anzalduas Dam to El Jardin Weir

5.1. Background

The Rio Grande in its above tidal reach should not be considered sound ecological environment when compared to its historical condition prior to the early 1900s. The hydrology has been substantially altered since dams and flood control structures have eliminated flooding from the Rio Grande. Flows in the river have also been reduced since the initiation of gravity irrigation which has removed a substantial portion of the original water flow. In this segment, water flow influences the quality of the environment. Persistent low flows can lead to degradation of water quality, accumulation of aquatic vegetation and sediment. Water quality issues (high nutrient levels, low dissolved oxygen) are likely to become more common with population growth and use of various irrigation practices.

The LRG/LLM BBEST agreed to consider a definition of sound environment that focused on the current condition and whether it supported sustainable populations of native species.

Application of this definition to the above tidal portion of the Rio Grande from above the Anzalduas flood control structure downstream to the El Jardin weir indicates that an ecologically sound environment would:

Sustain a riparian plant community dominated by a diverse group of native riparian plants; Absence of invasive, exotic aquatic plants like water hyacinth, water lettuce, and *Hydrilla*; and Sufficient freshwater inputs to support an aquatic community including one or more threatened amphibians like the Rio Grande siren, black-spotted newt, or white-lipped frog, 2 or more species of native turtles, and a mixed community of native fishes including approximately two-thirds to three-quarters of the species being primary freshwater species including native species with a range of feeding habits including top predators, and which is not dominated by exotic fish species and approximately one-quarter to a third of the species being secondary freshwater or estuarine species.

A qualitative recommendation was made for this ecosystem due to lack of available data.

5.2 Geographic scope

The above tidal portion of the Rio Grande is situated from above the Anzalduas Dam downstream to an area east of Brownsville at the El Jardin weir. This area is part of the Tamaulipan Biotic province of Blair (1950) and is represented as a small part of the South Texas Plains vegetational area of Gould (1975). Griffith et al. (2004) characterized the area as the Lower Rio Grande Valley and Lower Rio Grande Alluvial Floodplain ecoregions. Within this area, the Rio Grande proper is surrounded by the Mid-Valley Riparian Woodland along most of its stretch and the Sabal Palm Forest at its easternmost terminus

(Jahrsdoerfer and Leslie Jr., 1988). The Mid-Valley Riparian Woodland is a bottomland hardwood forest consisting of cedar elm, Berlandier ash and sugar hackberry with some granjeno and mesquite. Old stream meanders of the Rio Grande (resacas) provide some water habitat for a variety of wildlife species (Jahrsdoerfer and Leslie Jr. 1988). The Sabal Palm Forest is a remnant stand of Mexican palmettos (*Sabal mexicanus*) and is only found in the United States in a very limited area in the Texas Southmost area of Brownsville (Jahrsdoerfer and Leslie, Jr. 1988).

The 172-acre Sabal Palm Grove Sanctuary in Cameron County just downstream from Brownsville, a unique ecosystem dependent on Rio Grande flooding, is a prime example of riparian habitat change. This sanctuary contains a remnant stand of native sabal palms (*Sabal mexicana*) remaining from a 4,000 acre palm forest community that existed back in the 17th century, when the early Spanish settlers arrived in that region. Since then, agricultural clearing and drainage modifications in the LRGV have eliminated all other remaining large areas of this riparian palm jungle.

The U.S. Fish and Wildlife Service (USFWS) and National Park Service, the Texas Parks and Wildlife Department (TPWD), and land conservation organizations (e.g., Texas Nature Conservancy [TNC]) have recognized the significance of scarce riparian and aquatic ecosystems of the LRGV. Two major USFWS properties in the LRGV with riparian woodlands are critical habitat for federal-listed, endangered species: the Santa Ana National Wildlife Refuge (NWR) (2,088 acres) and the Lower Rio Grande Corridor NWR (presently 65,000 acres), the latter envisioned as a corridor network, linking protected tracts of brushland, woodlands and wetlands along the Rio Grande from Falcon Reservoir to the mouth of the Rio Grande. TPWD also operates approximately 15 state parks, wildlife management areas (WMA), recreation areas, or historical sites in the LRG basin. The major state park properties potentially influenced by Rio Grande flows are Las Palomas WMA (3,990 acres), and Bentsen-Rio Grande Valley SP (588 acres. TNC maintains a 462-acre property along the river just east of the Sabal Palm Grove Sanctuary where the goal is to restore native riparian habitat.

5.3 Hydrology

The daily flow of the Rio Grande has been measured at Brownsville from January, 1934 to present and these data are reported by the International Boundary and Water Commission (IBWC). In **Figure 5.3.1** are the daily flows measured in cubic meters per second and a linear regression line (flow (y) = -0.0038 * date(x) + 143.23).

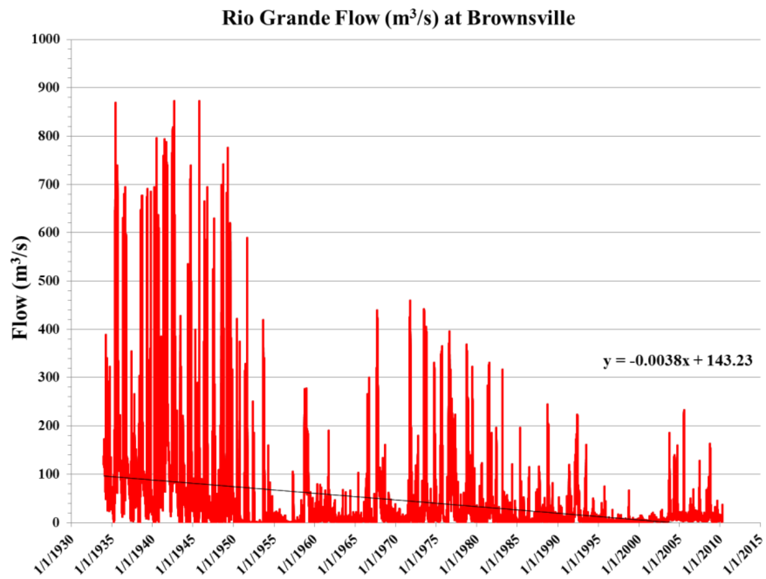


Figure. 5.3.1. Flow in Rio Grande at Brownsville gage measured by IBWC, 1935 to 2010.

5.3.1. Physical Processes

The quantity of sediments in the Rio Grande below Falcon Dam has dramatically decreased since the dam was closed in 1953 (USGS). This is not unexpected from reservoir construction as these sediments settle in the reservoir themselves (Juracek 2011) (**Figure 5.3.2**).

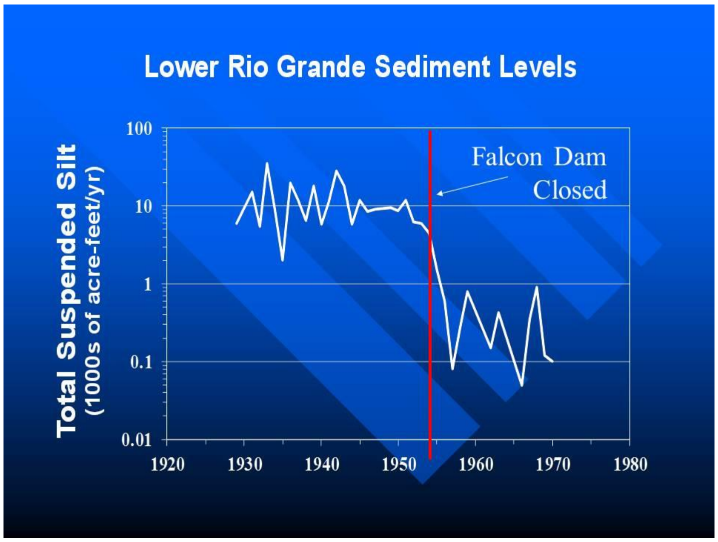


Figure 5.3.2. Suspended sediment loads in the Rio Grande below Falcon Reservoir from 1930 to 1972 showing the effect of the closure of Falcon Dam in 1954 on the passing of suspended sediments in the Lower Rio Grande. Data are from USGS.

5.4. Water quality

TCEQ has monitored 7 sites in the above-tidal portion of the Rio Grande between Falcon Dam and Brownsville (segment 2302) for about three decades. Ten years of data (December 1998 to April 2009) for two sites- one just below Falcon Dam and the other above the El Jardin weir were used to characterize the water quality in this segment. These two sites show distinct differences (**Table 5.4.1**). All parameters were significantly higher at the Brownsville site except for water column chlorophyll. Between these two sites are numerous small towns and cities but most notably the McAllen-Reynosa urban zone. Generally, municipalities on both sides of the river remove water but besides local sheet runoff there are few return flows to the river from the U.S. side. There is one Brownsville wastewater treatment plant that discharges into this segment and an undetermined number of return flows from the Mexico side along with sheet runoff which may be contributing to the higher parameter values noted above.

The water quality in the segment decreases going downstream and can be characterized as mesotrophic at the upstream site and tending towards eutrophic at the downstream site. As this water is processed and used for drinking water in the LRGV, taste and odor issues are of concern. One source of taste and odor chemicals is algae in the water. Control of nutrient levels is an effective control of algae abundance. The nutrient content of the water of this segment also contributes to the nutrient load of the estuarine segment (see **Section 4**).

Table 5.4.1. Water quality data for the above tidal Rio Grande near Brownsville, Texas and Falcon Dam (downstream) for the period Dec 1998 to April 2009.

Rio Grande		Temp	Cond	TDS	Chloride	NO_3	NH_4	Ortho P	Total P	Chloro
Segment		**°C**	**µS/cm**	**mg/L**		**mg N/L**	**mg N/L**	**mg P/L**	**mg P/L**	**µg/L**
2302-07	Avg	23.0	928.6	616.9	113.2	0.31	0.30	0.09	0.23	8.2
Falcon	SD	5.1	145.4	179.9	28.2	0.79	0.42	0.22	0.61	7.5
	n	221	224	235	221	137	192	112	193	153
2302-01	Avg	25.5	1318.8	871.5	183.8	0.97	0.16	0.20	0.40	11.2
Brownsville	SD	4.8	292.0	352.5	59.4	1.97	0.21	0.14	0.82	14.6
	n	156	162	167	158	130	152	112	152	100

Wastewater treatment is improving in the Lower Rio Grande watershed. In 2008, a $76 million wastewater treatment plant began operation in Matamoros, Mexico (The Monitor June 25, 2011). Although population and development has continued to increase in the region, NADBank is providing loans and grants to address water quality issues of the border region. It is unclear if these efforts to improve water quality will offset the effects of population growth and continued development.

5.5. Biology

Before the 1980s, there were three general surveys of fishes in the lower Rio Grande. During the 1850s, John H. Clark and others took a series of fish samples near the mouth of the river and close to Brownsville, Texas, as part of the United States and Mexican Boundary Survey. These collections were reported by Baird and Girard (1853, 1854a, 1854b), Girard (1856, 1859a, 1859b) and reviewed by Evermann and Kendall (1894). Approximately 100 years later, in 1953, Treviño-Robinson (1955) completed a survey of the fishes of the Rio Grande which coincided with the closure of Falcon Dam. In 1975, Olmos (1976) undertook a similar set of collections in the Rio Grande below Falcon Reservoir. Beginning in 1981 and continuing through the present, Edwards and Contreras-Balderas sampled throughout the Lower Rio Grande as a part of their studies on historical changes that have occurred in the fish communities of the region (Edwards and Contreras-Balderas 1991; Contreras-Balderas et al. 2002; Edwards unpubl. data) (**Table 5.5.1**).

Table 5.5.1. Fishes found in the above tidal portion of the Lower Rio Grande (1853-2011) from Anzalduas pool to the El Jardin weir in Brownsville.

		Historical (Prior to 1980)	**Modern Era 1981-2011**
Species	**Common name**		
Scaphirhynchus platorynchus	shovelnose sturgeon		Extirpated
Atractosteus spatula	alligator gar	X	
Lepisosteus oculatus	spotted gar		X
Lepisosteus osseus	longnose gar	X	X
Anguilla rostrata	American eel		X
Dorosoma cepedianum	gizzard shad	X	X
Dorosoma petenense	threadfin shad	X	X
Astyanax mexicanus	Mexican tetra	X	X
Colossoma nigripinnis	pacu		Introduced
Carassius auratus	goldfish		Introduced
Ctenopharyngodon idella	grass carp		Introduced
Cyprinella lutrensis	red shiner	X	X
Cyprinus carpio	common carp		Introduced
Hybognathus amarus	Rio Grande silvery minnow	X	Extirpated
Macrhybopsis aestivalis	speckled chub	X	X
Notropis amabilis	Texas shiner	X	
Notropis braytoni	Tamaulipas shiner	X	X
Notropis buchanani	ghost shiner	X	X
Notropis jemezanus	Rio Grande shiner	X	
Notropis orca	phantom shiner	X	Extinct
Pimephales vigilax	bullhead minnow	X	X
Carpiodes carpio	river carpsucker	X	X
Moxostoma congestum	gray redhorse	X	

		Historical (Prior to 1980)	Modern Era 1981-2011
Species	**Common name**		
Ictalurus furcatus	blue catfish	X	X
Ictalurus punctatus	channel catfish	X	X
Pterygoplichthys disjunctivus	vermiculated sailfin catfish		Introduced
Strongylura marina	Atlantic needlefish		X
Cyprinodon variegatus	sheepshead minnow	X	X
Fundulus grandis	Gulf killifish		X
Lucania parva	rainwater killifish	X	
Poecilia formosa	Amazon molly	X	X
Poecilia latipinna	sailfin molly	X	X
Gambusia affinis	western mosquitofish	X	X
Membras martinica	rough silverside	X	X
Menidia beryllina	inland silverside	X	X
Menidia peninsulae	tidewater silverside		X
Morone chrysops	white bass	Introduced	Introduced
Morone saxatilis	striped bass		Introduced
Lepomis auritus	redbreast sunfish		X
Lepomis cyanellus	green sunfish	X	X
Lepomis gulosus	warmouth		Introduced
Lepomis macrochirus	bluegill	X	X
Lepomis megalotis	longear sunfish		X
Lepomis microlophus	redear sunfish		Introduced
Micropterus salmoides	largemouth bass	X	X
Pomoxis annularis	white crappie	Introduced	Introduced
Etheostoma gracile	slough darter		X
Percina macrolepida	bigscale logperch		X
Selene vomer	lookdown	X	
Aplodinotus grunniens	freshwater drum	X	X
Oreochromis aureus	blue tilapia		Introduced
Cichlasoma cyanoguttatum	Rio Grande cichlid	X	X
Agonostomus monticola	mountain mullet		X
Mugil cephalus	striped mullet	X	X
Gobiomorus dormitor	bigmouth sleeper	X	X
Awaous banana	river goby		X
Gobiosoma bosc	naked goby		X

Section 6 Bahia Grande and San Martin Lake Complex

6.1. Background

The Bahia Grande wetland complex which includes the San Martin Lake complex is east of Brownsville, Texas and borders the Lower Laguna Madre on the north and the Rio Grande Delta area on the south (**Figure 6.1.1**). The 21,762 acre Bahia Grande Unit (BGU) is part of the U.S. Fish and Wildlife Laguna Atascosa National Wildlife Refuge. The BGU contains a wide diversity of habitat types including open bays, basins, lomas (small hills), low-lying flats, resacas, and native brush. The Unit's major wetland complex includes a series of three interconnected shallow basins. Bahia Grande, the major wetland feature, is a large 6,500-acre basin. The other two basins, Laguna Larga and Little Laguna Madre, are smaller at 1,669 and 1,411 acres, respectively. Adjacent to BGU is the San Martin Lake complex (San Martin Lake), a series of three shallow basins in which the last is connected to the Brownsville Ship Channel and receives freshwater inflow near its north end from the Brownsville area. Tidal exchange of the Bahia Grande with adjacent coastal waters was severely reduced in the 1930s following the excavation of the Brownsville Ship Channel, deposition of the dredged material, and the construction of Texas State Highway 48 (**Figure 6.1.2**). Contrarily, San Martin Lake has had a connection with the Brownsville Ship Channel at least since the construction of Highway 48 in 1953.

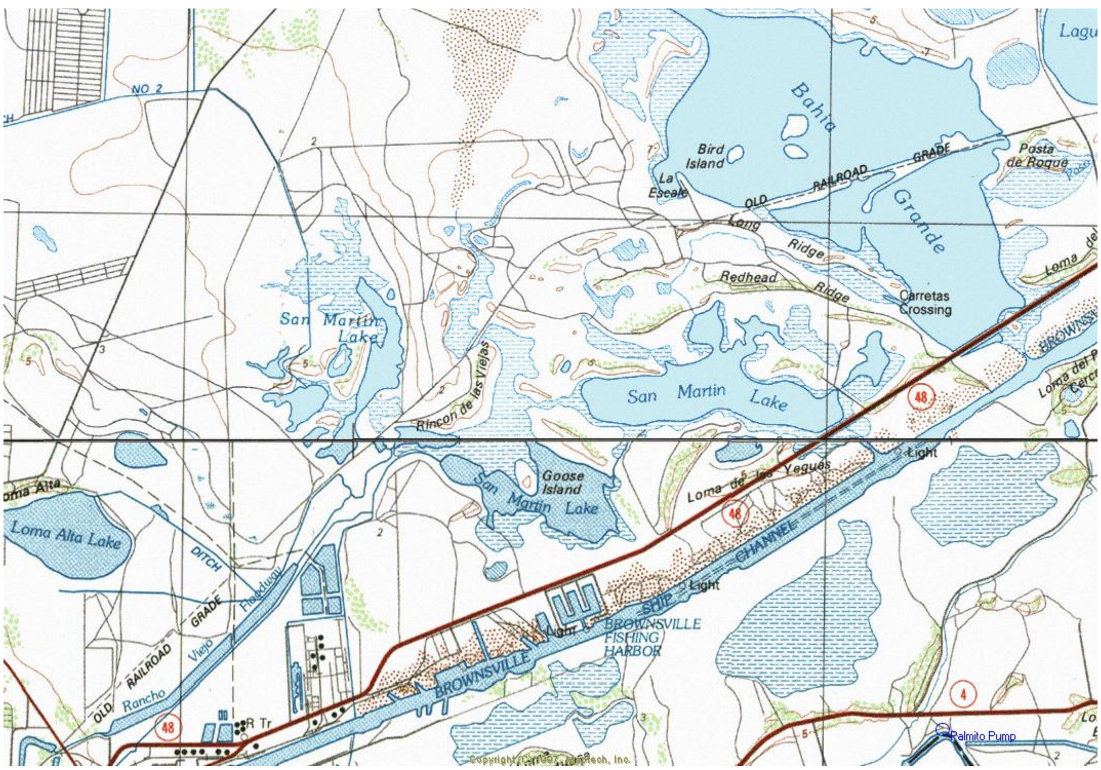


Figure 6.1.1. Map of the current Bahia Grande and San Martin Lake systems.

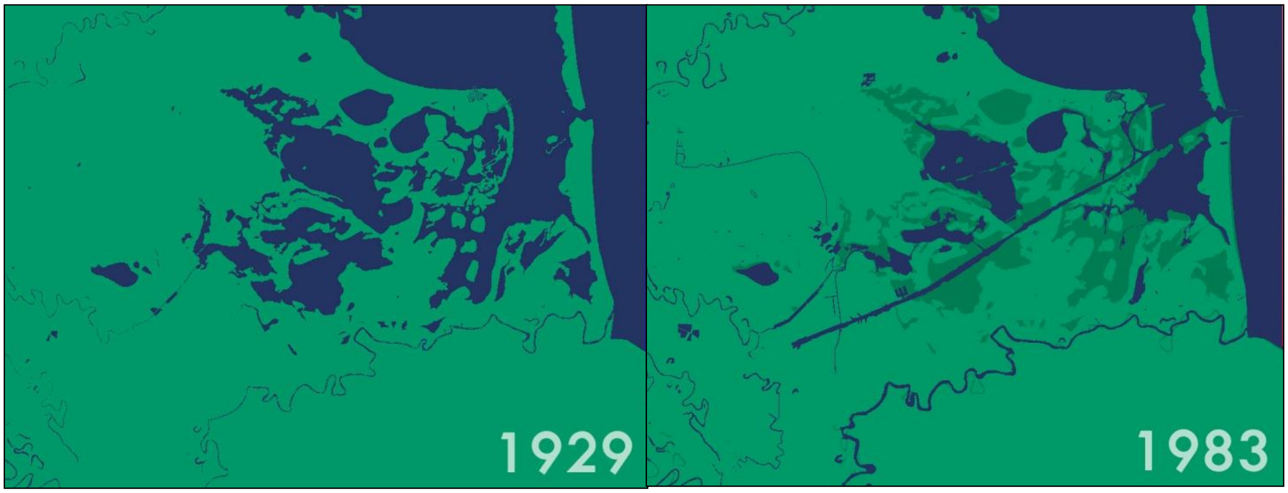


Figure 6.1.2. Changes in water surface area in the Bahia Grande/San Martin Lake area from 1929 to 1983. Maps courtesy of Jude Benavides and Anthony Reisinger, III.

For over 70 years, the Bahia Grande maintained surface water only temporarily following extreme rainfall events or tropical storm surges. A majority of the time, the basin was barren and dry, and large amounts of sand and clay were blown out of the basin impacting adjacent upland vegetation. Thus, the bay had not contributed to fish and wildlife populations in the area since the 1930s.

In July 2005, the United States Fish and Wildlife Service (FWS) flooded the main basin of Bahia Grande by construction of a 15-foot wide, 2,250-foot long pilot channel that connects Bahia Grande with the Brownsville Ship Channel (**Figure 6.1.3**). FWS constructed additional channels to connect the upper basins, Laguna Larga, and Little Laguna Madre. There are plans to widen the pilot channel in 2012. The permanent channel will be 150 feet wide and 9 feet below MSL and will eventually replace the pilot channel. The Texas Department of Transportation widened State Highway 48 in 2007 to 4-lanes and constructed a 256-foot long bridge which will span the width of the permanent channel once constructed allowing better tidal exchange for the system.

A large portion of the Bahia Grande is now permanently inundated forming a shallow bay habitat for fish, shrimp, crabs, shorebirds, wading birds, and waterfowl. The development of fringe vegetation including mangroves, particularly along tidal channels and adjacent shorelines has been stunted by poor water quality and insufficient water circulation. The significant reduction of wind-blown soil onto adjacent upland habitats has improved conditions for native shrubs, forbs, and grasses.

The long-term goal of the Bahia Grande Restoration Project is to restore the wetland complex to its historical function. Accordingly, a biological monitoring program was implemented to provide the USFWS with data for evaluating the ecological success of restoration efforts thereby allowing for adaptive management of the ecosystem. Physical, chemical, and biological features are being used to evaluate the function and restoration effects of the reintroduction of water to the Bahia Grande system including:

- Water level & hydrodynamics
- Water quality
- Geochemical sediment parameters
- Establishment of the marine algal community including the phytoplankton,
- Benthic microalgae, seagrass epiphytes, drifting macroalgae and wind-tidal algal mats;
- Establishment of a seagrass and mangrove habitats; and
- Development of benthic, epibenthic, and nektonic faunal communities

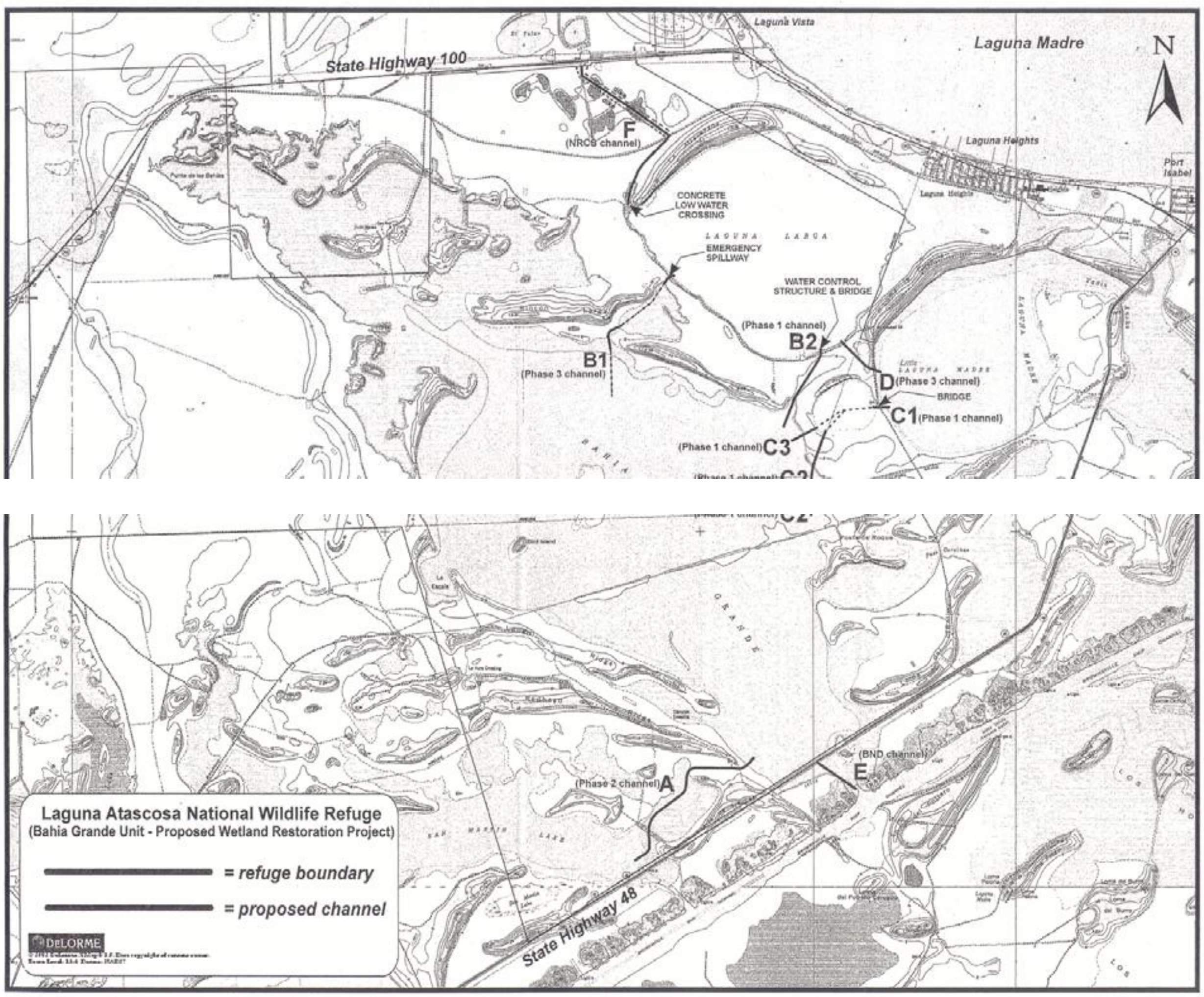


Figure 6.1.3. 2005 Map of Bahia Grande showing the location of the pilot (marked as channel "E") and internal channels, B, C and D. Channel A has not been constructed. To the west is one basin of the San Martin Lake system.

For the Bahia Grande critical base maps were generated for collection, analysis, and display of spatial information associated with the restoration site. Historical aerial photographs and maps were collected, digitized and geo-referenced to a common projection. Supporting GIS data included new bathymetric data, LIDAR data, and radar rainfall data.

6.2. Hydrography/Hydrology (from Hicks et al. 2010)

6.2.1. Bahia Grande

The Bahia Grande and surrounding area regularly experiences negative effective precipitation (i.e. evapotranspiration losses typically exceed precipitation inputs (Brown et al., 1980)). As a result, basins with restricted circulation like the Bahia Grande can develop high salinities but also may have large sudden drops in salinity due to their large surface area to volume ratios from moderate to severe tropical storm events.

Astronomical tides are generally small in this region ranging from 0.6 to 1.2 m at the coast but in the Brazos-Santiago Pass a 0.6 m tide is reduced to 0.24 m near Marker 73 (BND 1982) indicating that tidal energy is relatively weak. This feature combined with the narrow inlet channel for the Bahia Grande results in poor circulation in this basin. San Martin Lake has a wider connection with the Brownsville Ship Channel and is a narrower basin so tidal flushing is more effective.

Pilot channel velocity measurements showed marked increases for both incoming (320%) and outgoing (235%) tidal flows following the removal of three culverts and subsequent construction of the new Highway 48 Bridge. The maximum inflow to Bahia Grande when the three culverts were in place was only 85 acre-feet for an incoming tide event increasing to 272 acre-feet with the newly constructed Highway 48 Bridge. Using an estimate of 10,000 acre-feet of water for the total volume of water within the Bahia Grande wetland complex and associated wetlands during a high tide event, the exchange of water has increased from less than 1% total volume to about 3% total volume with the new Highway 48 Bridge

The drainage patterns in the vicinity of the Bahia Grande and San Martin Lake are complex because of the low relief of the area and the various drainage ditches, irrigation ditches, and levees. The Bahia Grande and San Martin Lake receive runoff from adjacent agricultural (range land) and urban/industrial lands. Inundation of the area has been common for two reasons: floodwaters from the Rio Grande and tidal surge associated with tropical storms. Since construction of the Amistad and Falcon dams and the floodway diversion channels inundation from the Rio Grande no longer occurs (BND 1982). San Martin Lake receives treated effluent from the City of Brownsville. Presumably, nutrient levels are elevated in this basin but no data exists supporting this statement.

Bahia Grande watershed is limited to the area between Route 48 and Route 100 which is bordered on the west by San Martin Lake and various shallow basins and the Laguna Madre on the east. The main source of freshwater for the Bahia is surface runoff from the north end of the basin. SML receives treated effluent from Brownsville, surface runoff, drainage from Rancho Viejo floodway and a ditch draining an old industrial site to the west (BND 1982).

6.2.2. San Martin Lake

No data was found characterizing the freshwater input or the tidal exchange to San Martin Lake. It is assumed that the western basin has been connected to the Brownsville Ship Channel at least since the construction of Route 48 in 1953. It is not known when freshwater inputs started to the San Martin Lake complex.

6.3. Water and Sediment Quality (from Hicks et al. 2010)

6.3.1 Bahia Grande

Quarterly water quality data for the Bahia Grande was collected as part of a USFWS study for the period of 2005 to 2008. Water temperature within Bahia Grande followed seasonal trends, with higher temperatures from March to October (25-33 °C) and lows in the winter (18-25 °C) but continuous data from sondes shows greater fluctuations (**Figure 6.3.1 and - 6.3.2**). Dissolved oxygen, as percent saturation (80-90) or concentration (5 – 9 mg/L), was also within the typical range for a shallow-estuarine basin in southern Texas, however continuous data from sondes shows dissolved oxygen going below 2 mg/L regularly (**Figure 6.3.3**). Salinity averaged > 60 PSU in 16 of 49 months of record (2005-2009). Basin salinity appears to be influenced primarily by evaporation and precipitation. In additional to temporal fluctuations, a spatial gradient of increasing salinity with increasing distance from the pilot channel was observed with average salinity being generally lower in the southern sectors, S, (50.7 PSU), and increased towards the NE (58.3 PSU) and NW (54.9 PSU) sectors. The water level of sampling stations within the basin ranged from 0.29 to 0.72 m. The lowest mean water levels of record occurred in August 2006 and highest water levels in October 2007 and 2009. Nutrients in the Bahia Grande are generally low with NH^{+4} nitrogen levels less than 8 µM, NO_3-NO_2 nitrogen levels generally less than 4 µM, and dissolved PO_4 phosphorus levels less than 2 µM.

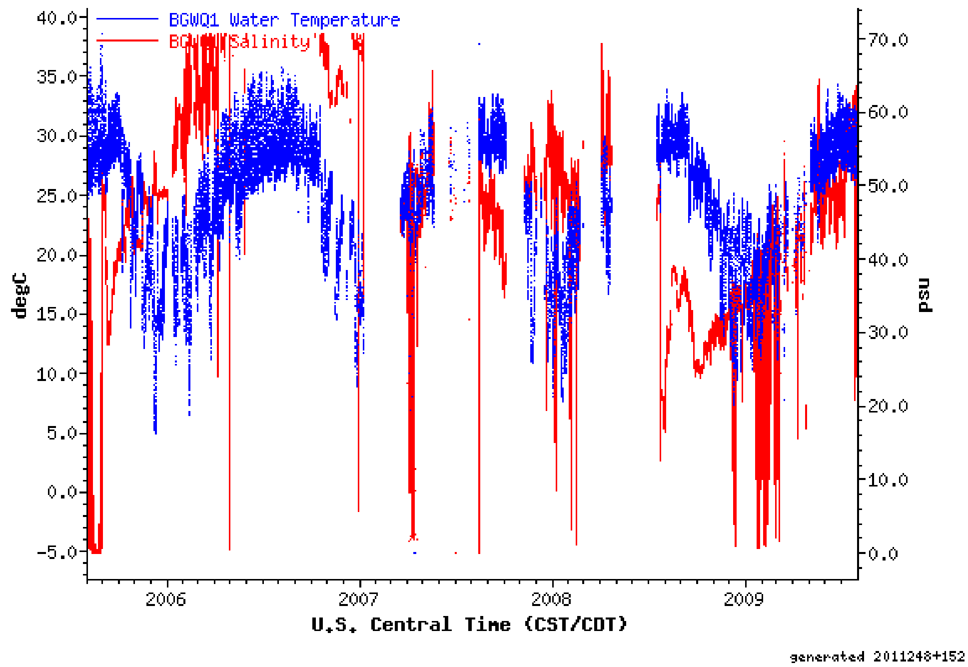


Figure 6.3.1. South sub-basin Bahia Grande water temperature and salinity, August 2005 to July 2009. Salinity date is truncated above 70 PSU. Data from TCOON (http://lighthouse.tamucc.edu/TCOON/ HomePage).

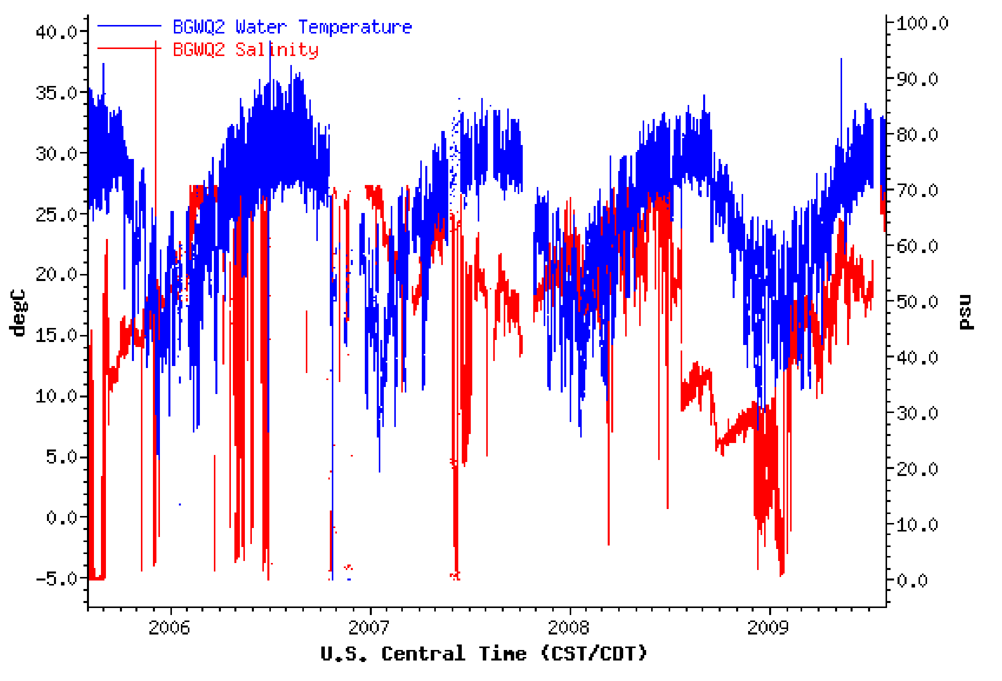


Figure 6.3.2. North sub-basin Bahia Grande water temperature and salinity, August 2005-July 2009. Salinity date is truncated above 70 PSU. Data from TCOON (http://lighthouse.tamucc.edu/TCOON/HomePage).

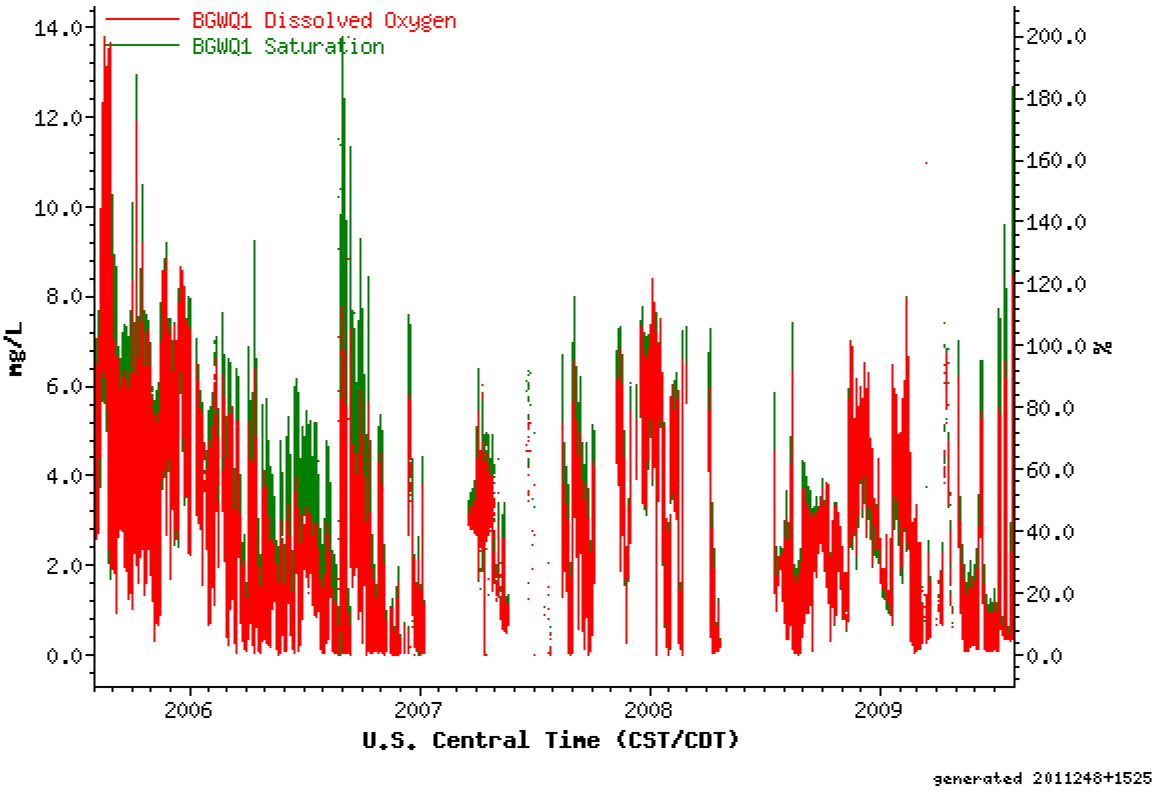


Figure 6.3.3. South sub-basin Bahia Grande dissolved oxygen and percent saturation, August 2005-July 2009. Data from TCOON http://lighthouse.tamucc.edu/TCOON/HomePage).

Sediment characteristics were monitored in order to evaluate environmental conditions conducive to seagrass, benthos and mangrove development. The northern sectors (NE/NW) of Bahia Grande contained greater proportions of sand indicating more water movement in these areas. A seasonal trend was also observed wherein coarser fractions of clastic sediments accumulated during summer months and returned to slightly increased silt and clay fraction during winter months. Sediments were additionally evaluated for organic carbon, carbonate and major sediment elements including essential metals (Cu, Fe, Mn, and Zn), non-essential metals (Pb, Cr, As), and major cations (Ca, Mg, Na and K). Average organic carbon content of basin sediments ranged 0.75 to 1.5 % (by dry weight). Carbonate (primarily of $CaCO_3$ and $MgCO_3$) comprised approximately 17% of sediments basin wide.

6.3.2 San Martin Lake

Water quality data has not been collected for San Martin Lake by the TCEQ. Based on a exploratory January 2012 survey a south to north decreasing salinity gradient was noted (DeYoe, unpubl. data). Preliminary grain size data indicates that San Martin Lake sediment is dominated by the finer grain size fractions but not as severely as the Bahia Grande (**Table 6.3.4**).

Table 6.3.4. Sediment characteristics for San Martin Lake (east basin), Bahia Grande and South Bay. (unpubl. data, DeYoe)

	% Carbonate	% Organic Matter	% Coarse Sand	% Sand	% Fine Sand	% Silt/Clay
San Martin	8.6	0.3	0.1	20.5	25.7	53.7
Bahia Grande	13.7	0.4	0.5	1.2	5.6	92.8
South Bay	9.0	0.6	0.1	5.5	15.0	79.4

6.4 Biology and Ecology (from Hicks et al. 2010)

6.4.1 Bahia Grande

Water column phytoplankton biomass was considerable at times with chlorophyll values exceeding 40 μg L^{-1} (winter and spring 2008). The phytoplankton community largely consisted of indeterminate coccoid microalgae ranging in diameter from 2-5 microns. Pennate diatoms and cyanobacteria were the next most common groups. Benthic primary productivity resulted from microalgae colonization of sediments. Sediment chlorophyll values exceeded 50 mg g^{-1} during winter and spring 2007. Northern sectors (NE and NW) sediment chlorophyll values exceeded 100 mg·g^{-1} during winter 2007. No seagrass or macroalgae were noted in the basin during the 4 year study.

The faunal benthic community was dominated by annelid worms (16 polychaete and 1 oligochaete species) with capitellids and spionids being the dominant taxa. Other taxa include small benthic crustaceans (corophids, cumaceans, and isopods), nemerteans (1 species), echinoderms (1 species), bryozoans (1 species), molluscs (3 species), and insect larvae and adults (3 species). Benthic community species richness reached its highest level during January 2008 and 2009 as salinity declined from maximum values. During periods of extreme hypersalinity diversity was generally low. Species richness was generally higher in the southern sector. Bag seine and gill net sampling methods were utilized to monitor nekton community composition and structure. Despite the high number of fish species captured in bag seine samples, the assemblage was dominated by a single species, *Cyprinodon variegatus*, accounting for 91% of the total abundance among 24 species. Of the 12 species captured utilizing gill nets, the most common species was *Mugil cephalus*, representing 39.5% of total abundance. Other frequently captured species were *Pogonias cromis* and *Elops saurus*. The southern sector typically exhibited higher nekton diversity, higher nekton species richness, and lower salinity whereas the two northern sectors (NE and NW) typically had higher salinities and lower diversity and species richness. The salinity spatial and temporal distribution proved important in explaining variation in community structure.

6.4.2 Bahia Grande Historical Data

Espey, Huston and Associates study (1981) only found possum shrimp (*Mysidopsis bigelowi*) in the Bahia Grande. This would have been prior to the opening of the pilot channel (2005) so the water in the basin was likely rainwater. *Rangia cuneata* shells were found in dry bed of the Bahia Grande. Also *Cyrtopleura costata* (Angel wings) and some oyster shell was found (Kumpe et al., 1998) suggesting periods of moderate salinity.

6.4.3 San Martin Lake

The Texas Parks and Wildlife Department has no data on the San Martin Lake system. The east basin is surrounded by black mangroves (maybe some red also?) and has extensive oyster beds in the southern half of the basin. The east basin is heavily fished but perhaps this is more due to easy access than to fishing success. The oysters may be benefiting from a phytoplankton community whose growth is stimulated by the nutrients coming from the freshwater input. On the other hand, the basin is suspected of being a red tide “incubator” due to the history of red tide occurrences in that area and its environmental features (DeYoe, pers. comm.). An attempt was made to establish shoal grass in San Martin Lake but the transplants were either eaten by crabs or covered by the fine sediment. In tanks, San Martin Lake sediment did allow modest growth of shoal grass transplants (DeYoe, unpubl. data).

A study of the eastern basin of San Martin Lake complex is about to commence to describe its water quality and phytoplankton community (DeYoe, pers. comm.). No data on the other SML complex basins were found.

6.5 Environmental Flows and Sound Ecological Environment

6.5.1 Bahia Grande

The Bahia Grande is a moderately productive ecosystem with an ephemeral faunal community having low to moderate diversity due to periodic changes in salinity. In regards to whether it is a sound ecological environment, it appears that the ecosystem was (pre-1930s) naturally variable due to basin characteristics and geography (shallowness, large surface area, poor circulation and sensitivity to hydrologic events) but since construction of the pilot channel in 2005 this aquatic ecosystem is probably less variable but still stressed by high salinities and/or salinity variability. Freshwater inflows to the basin are currently all from direct input of rain or local sheet runoff. Because the volume of the basin is small compared to its surface area rainfall events can substantially and quickly alter salinity. It would be prudent to maintain/protect the watershed of the Bahia Grande to retain some inflow of freshwater.

Construction of a larger channel has been proposed and funded but even once built it will only substantially affect the southern sub-basin. The northern sub-basin will likely still have poor circulation and resulting variable salinities. As it is, the Bahia Grande is not a sound ecological environment but may become more so with the construction of a new wider channel if that channel will allow greater water exchange and lower salinities. Restricted internal circulation will still likely prevent homogenization of its waters.

6.5.2. San Martin Lake

So little is known about the San Martin Lake system that it is difficult to assess whether it has a sound ecological environment and therefore, just as difficult to make an environmental flow recommendation.

Section 7 Resacas and the Brownsville/Resaca Watershed

7.1 Background

Over thousands of years, the Rio Grande meandered back and forth across its low, flat delta. As it changed course, abandoned river channel was left behind. Afterwards, when the Rio Grande overflowed its banks, flood waters refilled those former river channels left by the Rio Grande's meanderings. These former river channels became known as resacas (USACE, 2009) (**Figure 7.1**). The USACE (2009) described the historical hydrologic function of resacas as "…diversion and dissipation of floodwater from the river." Oxbows, or the short bends in the Rio Grande channel that have been cut-off from the river and continue to retain water for part of the year, are known in this area as "bancos" (**Figure 7.2**). The resacas described in this section lie in the Brownsville/Resaca watershed which is hydrologically described in the hydrology portion (**Section 2**) of this report.

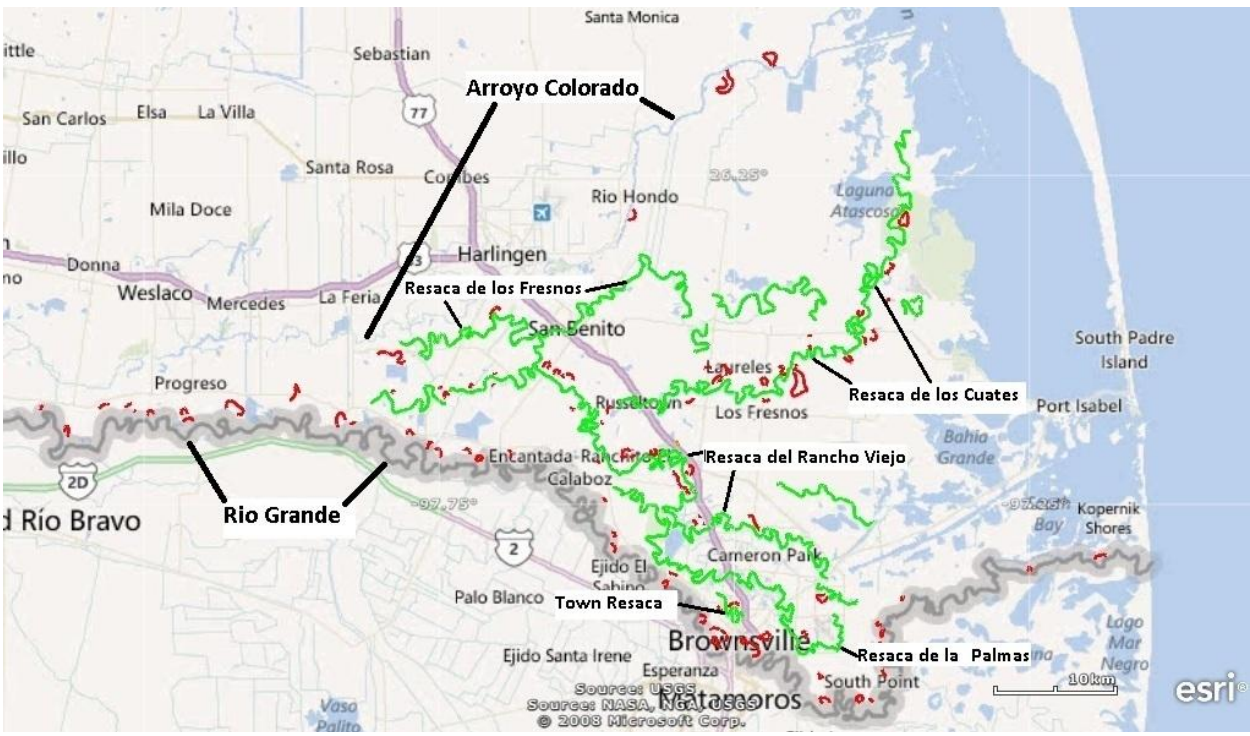


Figure 7.1.1. Resacas of Cameron and Hidalgo County, Texas.

Figure 7.1.2. Resacas and oxbows of the Lower Rio Grande Valley, Texas.

One hundred years ago, the U. S. Department of Agriculture soil survey for Cameron County (1908) described resacas as winding sloughs, 15-30 ft deep, and 75 to 150 yards wide which were filled during heavy rains or when the Rio Grande flooded. Resacas typically held water year-round. Sediments deposited by flooding along the margins of the resacas created natural levees of a light silty loam with considerable amounts of fine sand around them. Resacas provided irrigation water with lower levels of suspended sediment than water from the Rio Grande. High sediment levels in Rio Grande water tended to fill up irrigation ditches.

Over several decades, portions of some resacas have silted in and became bottomland (USACE 2009). Construction of dams and levees on the Rio Grande has virtually eliminated flooding of resacas with water from the Rio Grande. Today, resacas are typically filled with water pumped from the Rio Grande, rainfall runoff, or irrigation return flows. Resacas are now used to transport drinking water and irrigation water from the Rio Grande in some cases. Development of resacas as reservoirs and channels for irrigation water started in 1906 when a canal was excavated to connect Resaca de los Fresnos with a pumping station on the Rio Grande at Los Indios. The volume of water contained by resacas has been reduced by this process which has carried large quantities of suspended solids from the river that quickly settle out in the resacas.

The combined length of resacas is about 232 river miles. Resaca del Rancho Viejo, covering almost 6,000 acres (Brown et. 1980) and extending 64 river miles, has the most remaining acres of native resaca habitat, about 60 percent of the available habitat in the area. The next largest resaca, Resaca de los Cuates is about 54 river miles long. Town Resaca, only 4 miles long, has 200 acres (2 percent) of the study area's surviving resaca habitat (USACE 2009). Resacas cover about 130 square miles in Cameron County (Brown et al. 1980). The number of oxbows downstream of Falcon Lake totals 113, extending a combined distance of about 97 river miles. Sixty-eight oxbows are along the Rio Grande, 48 along resacas, and 3 along the Arroyo Colorado.

7.2. Ecology

Resacas are widely used by wildlife in the region (Jahrsdoefer & Leslie 1988). According to the National Biological Service, resacas "may be the key to the high biodiversity" found in the region, providing habitat for such aquatic creatures as the Amazon molly (P 1998). Undeveloped resacas retain the riparian vegetation characteristic of the main river channel (Clover 1937; Perez 1986). Shrub and tree species include anaqua (*Ehretia anacua*), cedar elm (*Ulmus crassifolia*), Berlandier ash (*Fraxinus berlandieriana*), brazil (*Condalia hookeri*), sugar hackberry (*Celtis laevigata*), tepeguaje (*Leucaena pulverulenta*) and Texas ebony (*Pithecellobium flexicaule*). Wildlife using riparian habitats of resacas is similar to those found in the riparian community of the Rio Grande. Perez (1986) suggests that threatened and endangered species found in resaca riparian communities include the southern yellow bat (*Lasiurus ega*), jaguarundi (*Felis yagouaroundi*), ocelot (*Felis pardalis*), Rio Grande siren (*Siren intermedia texana*), black-spotted newt (*Notopthalmus meridionalis*), speckled racer (*Drymobius margaritiferus*), and northern cat-eyed snake (*Leptodeira septentrionalis*). TPWD (1999) states that Coues' rice rat (*Oryzomys couesi*), black-striped snake (*Coniophanes imperialis imperialis*), Texas indigo snake (*Drymarchon corais erebennus*), white-lipped frog (*Leptodactylus fragilis*), and Mexican treefrog (*Smilisca baudini*) should be added to the list of threatened and endangered species present. A number of freshwater fish species may be present depending on water quality and permanency (Perez, 1986), and the freshwater turtles spiny softshell (*Apalone spinifera*), yellow mud turtle (*Kinosternon flavescens*), and red-ear slider (*Trachemys elegans*) are expected to occur in resacas.

Texas Parks and Wildlife Department has conducted several fisheries studies of resacas over the years. Results of those studies are summarized here:

- <u>Resaca de las Palmas</u>: The resaca was turbid with a silty bottom, steep banks, and a maximum depth of 7 feet. Cattails and water hyacinths were abundant in places. 13 species of fish were collected. The resaca was filled with water from the Rio Grande which was used for cooling, domestic water supply, and by adjacent land owners (TPWD 1959).
- <u>Resaca del la Guerra</u>: 31 species of fish were collected including red drum, naked goby, and 2 species of killifish in 1962. At that time the resaca was 31 miles long, 60 ft wide and less than 4 ft deep on average. Water levels fluctuated 2-3 ft per day as homeowners used water on lawns. Bottom feeding fish contributed to high turbidity. Summer dissolved oxygen was 2.2 to 8.4 mg/l. Aerial application of pesticides to near-by farms had caused fish kills in resacas (TPWD 1963).
- <u>Resaca de las Palmas in Resaca de las Palmas State Park</u>: The main riparian plants included Texas ebony, hackberry, retama, ash, and cattails. Fourteen

species of fish were collected with smallmouth buffalo the dominant species. The resaca had a very silty bottom (TPWD 1980).

- Resaca de los Cuates: The resaca at the time sampled was 41 miles long and used to store irrigation water. Longnose and spotted gar and channel and blue catfish were collected. The resaca had steep banks and lots of overhanging vegetation (TPWD 1973).
- Resaca de la Palma: Channel catfish, white crappie smallmouth buffalo, and freshwater drum were common. The resaca was 32 miles long. Irrigation return flow and runoff were the primary sources of water (TPWD 1973).

Dredging has been suggested as one technique for improving ecological health of resacas. Deepening resacas may increase fish habitat and improve water quality by removing oxygen-demanding sediments (Rust et al. 1996).

7.3. Water Quality

Many resacas receive high levels of nutrients which in turn cause excessive aquatic plant growths. These excessive nutrients probably come from development around the resacas. Additionally, siltation has partially filled resacas so that depths of 2 ft now common compared to earlier periods when resacas were at least 6 feet deep (EPA 2009) (Figure VII-3).

Figure 7.2.1. Resaca with high sediment load creating turbidity (photo by Seth Patterson).

As farming increased next to resacas followed in recent decades by the rapid growth of neighboring towns, resacas have experienced contamination with potentially toxic chemicals. Rainfall runoff from agricultural fields and residential areas washes some of these chemicals into resacas. In some cases, aerial application of pesticides onto fields adjacent to resacas has allowed pesticides to be carried by wind into resacas. Some resacas have received discharges of raw municipal sewage during heavy flooding. Gamble et al. (1988) reported that softshell turtle (*Apalone spinifera*) and fish (species not given) from Resaca de los Cuates had elevated residues of DDE and toxaphene, and a tilapia (Tilapia sp.) composite sample from the upper end of the resaca had a high chromium concentration (14.0 ppm, whole body, dry weight). Sediment from Resaca Lozano Banco, near downtown Brownsville, had detectable concentrations of 13 polycyclic aromatic hydrocarbons (Gamble et al. 1988); automobile emissions were thought to be the source.

7.4. Hydrology

Changes in river hydrology separated the Brownsville/Resaca watershed from the Rio Grande many years ago. Resacas now receive water almost exclusively from local runoff and rainfall (Mora et al. 2001). Hurricanes and tropical storms may create enough flooding at times to create flow through some resacas for several weeks. In some cases, this flow eventually enters the Lower Laguna Madre. Historically resacas have not contributed to flooding. Because of the natural levees built up around resacas, flooding historically occurred in lower areas between resacas. At present, many resacas are separated by weirs which control water movement and level in the resacas. Increased urbanization has been associated with increased frequency of flooding of some resacas. Some resacas have been modified by ditching and creation of stock ponds within the resacas. This ditching may lower groundwater and reduce variability in groundwater levels. As a result, plants more tolerant of drier environments have replaced species characteristic of resaca riparian zones (Whisenant and Wu 2007).

7.5. Sound Ecological Environment

Resacas should not be considered sound ecological environments when compared to their historical condition before the early 1800's. Their hydrology has been substantially altered since dams and flood control structures have eliminated flooding from the Rio Grande which historically was one of their primary sources of water. This pattern of flooding connected the hydrology, chemistry, and biology of the Rio Grande, the Brownsville/Resaca watershed, and coastal waters.

Despite changes over the past 200 years, resacas and oxbows provide over 329 linear miles of aquatic and associated riparian habitat. These water bodies provide valuable ecological services such as habitat for a variety of amphibians like the state-threatened Rio Grande siren, fish, and birds (**Figure 7.4.1**). Dense riparian plant communities surrounding some resacas provide habitat for migratory songbirds and semitropical birds found primarily in this subtropical region of Texas.

Figure 7.4.1. Wading and shore birds using a resaca (photo by Seth Patterson).

Current management of the Lower Rio Grande suggests the river will cease migrating back and forth over its lower flood plain between McAllen, Texas, and the Gulf of Mexico. With the loss of river migration, resacas will no longer be formed. Without human intervention to protect existing resacas they can be expected to gradually fill with sediment and stop functioning ecologically as perennial or semi-perennial water bodies. If provided with adequate water quantity and quality to support riparian communities and semi-permanent water bodies, resacas and oxbows of the Brownsville/Resaca watershed will serve many valuable ecological functions that are representative of sound environmental ecosystems.

Section 8 Arroyo Colorado

8.1. Background

"The river wont go down or up, the Arroyo Colorado wont overflow, and nothing exciting will happen, so if the paper is not newsy, it is because there is no news."
(Brownsville Daily Herald, Vol. 13, No. 286, Ed. 1, Friday, June 2, 1905)

The Arroyo Colorado is a former channel of the Rio Grande that has been extensively hydrologically modified over the past 120 years. It is a sub-watershed of the Nueces-Rio Grande Coastal Basin, also known as the South (Lower) Laguna Madre Watershed (Hydrologic Unit Code 12110208). Nearly three-fourths of the watershed is devoted to agricultural use, however the area is one of the fastest developing urban areas in Texas. Principal agricultural crops include cotton, citrus, sorghum, and sugar cane. The Arroyo watershed covers 706 square miles or 451,840 acres. The Arroyo channel width ranges from 40-200 feet and its depth averages 2 feet in some places and 13 feet in dredged portions.

An article in the October 7, 1904 edition of the Brownsville Daily Herald described the Arroyo Colorado as, *"The water in the Arroyo is scarcely more than back water from Laguna Madre, and is extremely salty under normal conditions"* (Brownsville Daily Herald 1904). The 1941 Soil Survey of Cameron County described it and the Rio Grande as the only two perennial streams in the county (USDA 1941). The same report included information about water chemistry reporting that samples collected in 1920 from the Arroyo at 1 mile southeast of Harlingen had a total dissolved solids concentration of 4,176 mg/l and at Rio Hondo had a total dissolved solids concentration of 5,695 mg/l. The Arroyo was described as a

"…deeply cut flood channel heading near Mercedes, in Hidalgo County, and extending through Cameron County to the Laguna Madre. The bottom of this channel has been cut below sea level, and salt water stands in it as far upstream as Harlingen. As its banks are 10 to 40 feet high, many short deep gulches have been cut by erosion along its course, forming a narrow belt of dissected land, a mile across in some places" (U.S. Department of Agriculture, 1941).

Today the Arroyo Colorado consists of a freshwater reach (TCEQ water quality segment 2202) extending from near the city of Mission in Hidalgo County about 63 miles to a point just past Cemetery Road downstream of the Port of Harlingen (NRA, 2010). This portion of the Arroyo averages 40 feet wide and 2-3 feet deep with a relatively soft, silty-clay bottom (ACWP, 2007). The watershed is in a relatively flat coastal plain with a slope of 1.5 feet per mile (ACWP, 2007).

Wastewater discharges from communities along the banks of the Arroyo combined with irrigation return flows maintain perennial flow in this part of the Arroyo. This reach has been channelized and leveed in order to maximize its capacity to transport flood waters from the Rio Grande. Transporting flood waters was one of its earliest functions. The Brownsville Herald describes the Arroyo Colorado as carrying much of the Rio Grande's flood waters during the flood of 1904. This flood was described as the largest flood on the

Rio Grande that residents of that time could remember. Some reports suggested at the time that the Rio Grande had diverted to the Arroyo Colorado permanently during the flood (Brownsville Herald, 1904). Its current physical modifications which include the North Floodway constructed in 1988 are intended to facilitate transport of floodwaters from the Rio Grande and the Lower Rio Grande Valley to the Laguna Madre to avoid flooding the communities along the Rio Grande downstream of Mission.

The Arroyo also has a tidally influenced reach (TCEQ water quality segment 2201) that is about 26 miles long from below the Port of Harlingen to the Arroyo's mouth at the Lower Laguna Madre. This reach was dredged and channelized in the 1940s to allow barges to move to and from the Intracoastal Waterway to the Port of Harlingen. The first barge navigated the Arroyo Colorado to the Port of Harlingen in 1952. The tidal portion of the Arroyo averages more than 200 feet in width and about 13 feet deep (ACWP, 2007). It provides recreational fishing opportunities and recreational fishing access to the Lower Laguna Madre.

8.2 Ecology

Typical riparian vegetation consists of reeds, huisache, mesquite, and Texas ebony (MacWhorter 2011). Giant reed (*Arundo donax*) is now widespread along its banks (DeYoe, pers comm.). Bryan (1971) sampled fish and invertebrates in the tidal reach of the Arroyo Colorado below Harlingen. Random samples of plankton were taken from km 3.2 to 32. Four genera of macroalgae (species not given) and one species of seagrass (i.e., widgeon grass (*Ruppia maritima*)) were documented. Invertebrate species observed included one copepod, one barnacle, two shrimp, two crabs, and three mollusks. Fifty-six fish species are listed in Bryan (1971). Juvenile menhaden (*Brevoortia sp*.), redfish (*Sciaenops ocellata*), and white shrimp (*Penaeus setiferus*) were the most numerous economically important species found in the survey (Bryan 1971). Brown shrimp (*Farfantopenaeus aztecus*) and blue crab (*Callinectes sapidus*) were present but less abundant. Spotted seatrout (*Cynoscion nebulosus*) was the most abundant adult species taken. Redfish (*Sciaenops ocellata*), black drum (*Pogonias cromis*), sheepshead (*Archosargus probatocephalus*), and southern flounder (*Paralichthys lethostigma*) were less abundant. Adults of these species were concentrated in the lower 12 river miles of the Arroyo and were not found more than 20 miles upstream from the Laguna Madre.

Bryan (1971) reported eight documented fish kills occurring during his study in 1966-69 of the lower reach of the Arroyo Colorado. Most of these occurred between June and September. No direct sources of pollution were found in any of the cases, but in two kills that were investigated while in progress found no oxygen at any level of the water column. The majority of fish found dead were menhaden, but other species were also found.

Bottom-dwelling invertebrates in the Arroyo are limited because of changing salinity and organic pollution (TPWD 1973). In the tidal segment of the Arroyo Colorado, the "high" aquatic life use level currently designated is not being met (Davis 1989) and macrobenthic community characteristics are considered worthy of an "intermediate" aquatic life use rating. Davis (1989) concludes that toxic chemicals do not appear to be an important causative factor. Rather, he suggests that likely stress-inducing factors include salinity stratification and high primary productivity which occasionally result in depressed dissolved oxygen in bottom waters, and periodic maintenance dredging which disturbs the benthic environment. Davis (1989) pointed out that the bottom consists of very fine particles and is very homogeneous, a condition not conducive to colonization by a diverse macrobenthic assemblage.

Texas A&M University at Galveston intensively monitored fish and benthic macroinvertebrates at three locations in the Arroyo Colorado tidal (Landry and Harper 1990). One site was at the mouth of the Arroyo Colorado, the second site was about 7 river miles upstream from the Laguna Madre near Arroyo City, and the third site was about 13 river miles upstream of the Laguna Madre and about half the distance between the Laguna Madre and the Port of Harlingen. Samples were collected in May, August, and November of 1989 and in February 1990. Relatively high numbers of young-of-year species like Gulf menhaden (*Brevoortia patronus*), striped mullet (*Mugil cephalus*), and Atlantic croaker (*Micropogonias undulatus*) were seined in shallow waters of the reach of the Arroyo from 7 to 13 miles upstream from the Laguna Madre. The number of species and numbers of individuals collected with bottom trawls was highest at the mouth of the Arroyo and declined at the upstream sites. These declines in diversity and abundance in mid-channel bottom waters were caused by low oxygen levels in the bottom waters of the Arroyo. Oxygen levels in Arroyo bottom waters decreased with increasing distance upstream. The Arroyo Colorado tidal is typically strongly stratified and bottom waters upstream in the tidal reach were commonly hypoxic. Samples collected for benthic macroinvertebrate analysis had anoxic sediments with a strong hydrogen sulfide odor during every sampling trip and at all stations in the Arroyo tidal. During the August sample event, only one specimen was collected from the three benthos samples.

Lingo and Blankinship (2012, in press) described sampling the Arroyo Colorado tidal by otter trawl during 2001-2003. Samples were collected at 6 locations along the Arroyo every two weeks. Over 13,000 fish representing 66 species were collected with 79% of the fish collected from locations in the downstream 9 river miles of the Arroyo. Species diversity, species richness, and abundance were much higher in this reach of the Arroyo than in samples from locations extending upstream more than 9 river miles from the Laguna Madre.

8.3. Water Quality

The Arroyo Colorado (including the North Floodway) has been known for over 30 years to have generally poor water quality (**Table 8.3.1**) due to a combination of high nutrient loading and morphometric features of the channel (TNRCC 2002). Most of the nitrate and ammonia are considered to come from agricultural non-point sources (TNRCC 2002). The levels of nitrogen and phosphorus as well as chlorophyll are high even compared to the Rio Grande (**Table 8.3.2 and 8.3.3**). These nutrients allow for high levels of phytoplankton to develop in the water which can become problematic for the ecosystem.

Table 8.3.1. Potential water quality problems in the Arroyo Colorado by segment number. From Fipps (1997).

SEGMENT 2200 (North floodway)	SEGMENT 2201 (Arroyo tidal)	SEGMENT 2202 (Arroyo non-tidal)
Nitrate	Nitrate	Nitrate
Dissolved Phosphorus	Dissolved Phosphorus	Dissolved Phosphorus
Total Phosphorus	Total Phosphorus	Total Phosphorus
Sulfate	Sulfate	Sulfate
Chloride	Chloride	------
------	Dissolved Oxygen	Dissolved Oxygen
Fecal Coliform	------	Fecal Coliform

Table 8.3.2. Water quality averages for select parameters for the Arroyo Colorado at the Port of Harlingen for the period March 1977 to August 2010.

	Sp Cond	**Total NH4**	**Total NO3**	**Total Kjeldahl**	**Total PO4**	**Ortho PO4**	**Chl a**
	uS/cm	mg N/L	mg N/L	mg N/L	mg PO4/L	mg PO4/L	ug/L
Avg	4436	0.56	2.64	1.53	2.33	1.40	33.71
SD	1465	1.39	1.33	0.44	1.34	0.56	21.74
N	185	161	76	98	36	34	136

Considering the high nutrient levels of the Arroyo, it is of interest to calculate their loading rates as loading rates in addition to concentration are important in producing effects in receiving waters i.e. the Lower Laguna Madre. We focused on nitrogen (nitrate and ammonia) as it is used by primary producers as it is typically limiting in marine systems and it is the nutrient that is usually in the highest concentration in the Arroyo. Nitrate concentrations were graphed against flow for wet, dry, and normal years, and seasonally. There appears to be no consistent trend of concentration with flow (**Figure 8.3.1**). It was determined that nutrient loadings (dissolved inorganic nitrogen and total phosphate) were highest in winter and spring (**Table 8.3.3**) and nitrogen loading rates also increased with increasing flow (**Table 8.3.4** and **8.3.5**).

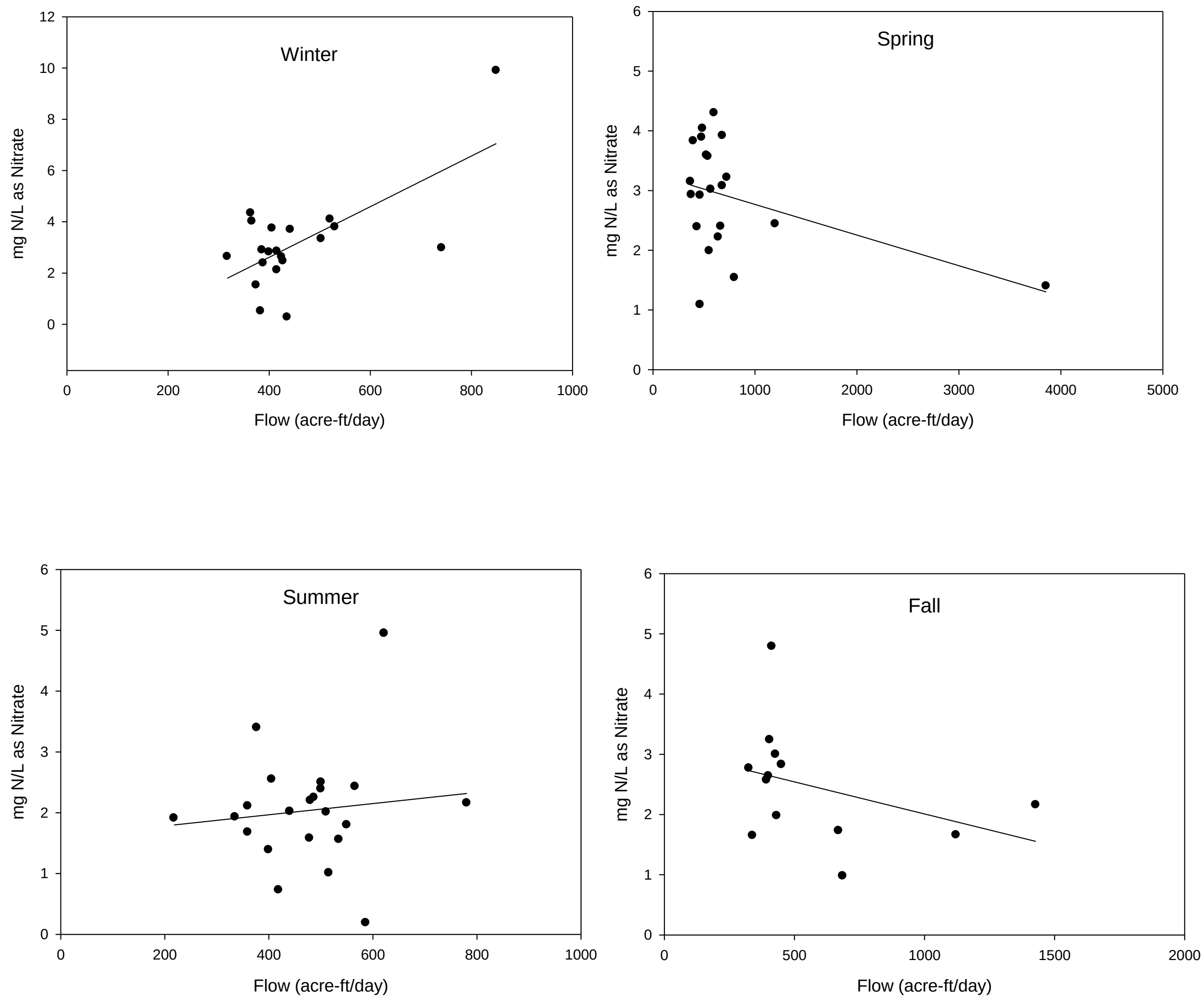


Figure 8.3.1. Seasonal relationships between nitrate-nitrogen concentration and flow in the Arroyo Colorado based on TCEQ water quality data from the Port of Harlingen and flow values from the Harlingen IBWC gage for the period 1978-2009. Note changes in scales of both X and Y axes.

Table 8.3.3. Seasonal dissolved inorganic nitrogen (DIN) and total phosphate loading rates for the Arroyo Colorado. Loading rate estimates are based on TCEQ water quality data from the Port of Harlingen and flow values from the Harlingen IBWC gage for the period 1978-2009.

				Avg	SD	Avg	SD	Avg
	Avg 5-day flow	**DIN**	**TPO4**	**DIN Load**	**DIN Load**	**PO4 Load**	**PO4 Load**	**Load N/P ratio**
	acre-ft/day	n	n	kg/day	kg/day	kg/day	kg/day	molar
Winter	427.5	38	11	1379.8	1961.7	496.0	347.2	6.4
Spring	569.4	46	7	1319.0	1578.9	923.9	1093.9	3.3
Summer	446.8	46	10	990.0	1935.3	344.5	77.6	6.6
Fall	548.3	31	8	957.0	1045.0	715.5	736.5	3.1

Table 8.3.4. Dissolved inorganic nitrogen (DIN) loading rates for high, average and low flow conditions in the Arroyo Colorado. Loading rate estimates are based on TCEQ water quality data from the Port of Harlingen and flow values (acre-ft/day) from the Harlingen IBWC gage for the period 1984-2002.

	Flow criterion		**Avg Daily Flow**	**Avg DIN**	**DIN**
	acre-ft/day	**n**	**acre-ft/day**	**kg N/day**	**SD**
High flow	>1000	9	2315	3689	3913
Avg flow	515-555	12	532	1364	1173
Low flow	<267	11	234	192	115

Table 8.3.5. Dates of high, average and low flow events in Arroyo Colorado used in calculation of loading rate values in Table 8.3.2.

High	Average	Low
9/25/1978	7/28/1981	7/17/1996
5/26/1982	2/3/1982	11/26/1996
1/26/1984	8/23/1982	2/25/1997
10/1/1985	7/20/1987	8/5/1998
10/31/1991	6/6/1989	8/19/1999
5/12/1993	5/29/1990	5/31/2000
11/19/2001	1/21/1992	12/11/2000
9/11/2002	3/9/1994	5/23/2002
8/14/2008	6/19/1995	7/22/2002
	4/2/1997	8/12/2002
	5/10/2005	4/22/2002
	2/21/2008	

The relationships between flow and dissolved oxygen, fecal coliform bacteria, nitrate, sulfate, dissolved phosphorus, and total phosphorus were examined by Fipps (1997). Only sulfate was significantly and inversely related to flow (Fipps 1997). About one-third to one-half of the BOD and nutrient loads are from urban point and nonpoint sources, although only 13 percent of the total land use in the basin is urban (Raines and Miranda 2002).

Lingo and Blankinship (2012, in press) found the saltwater wedge extended from the Laguna Madre up the entire length of the Arroyo Colorado tidal with the difference in salinity between the upper layer of water and the saltwater wedge averaging 11‰. Salinity stratification is one factor contributing to the low dissolved oxygen measured in the saltwater wedge. Lingo and Blankinship (2012, in press) found no oxygen in the Arroyo Colorado bottom waters at all locations further upstream than 6 river miles from the Laguna Madre from March through September during their sampling from 2001 through 2003.

Modeled estimates of pollutant loading to the Arroyo Colorado over the period from 1989 through 1999 indicate that about half of all biochemical oxygen demand, nitrogen, and phosphorus entering the Arroyo are from urban land uses and the other half are from agricultural land uses (ACWP 2007). Eighty-seven percent of sediment entering the Arroyo is from agricultural land uses. Most of the biochemical oxygen demand, nitrogen, and phosphorus from municipal wastewater treatment plants enter the Arroyo Colorado above the segment under tidal influence. Wagner (2012) reviewed past water-related studies on the Arroyo Colorado.

Fish kills in the Arroyo Colorado, particularly in Arroyo Colorado tidal near the Port of Harlingen have been documented since 1971 (TPWD 2011). These fish kills have been usually caused by low dissolved oxygen events, with some fish kills attributed to spills of unknown contaminants, and disease.

A number of fish kills have also been identified in irrigation canals and return ditches. The causes of many of these die-offs were not identified although some were attributed to low oxygen, others, particularly cold-intolerant introduced blue tilapia (*Oreochromis aureus*) to cold weather, and a few to pesticide applications, whether intentionally to control aquatic plants in irrigation canals, or unintentionally as a result of drift of aerially-applied pesticides.

During a 1995 water quality study on the Arroyo Colorado tidal, a crew sampled dissolved oxygen from the surface to the bottom every 2 river miles from the Laguna Madre upstream to the Port of Harlingen (Buzan, pers. comm.). The saltwater wedge was hypoxic beyond 10 river miles upstream of the Laguna Madre. As the sampling team finished sampling the uppermost location near the Port of Harlingen, they were passed by a loaded barge moving downstream. As the crew followed the barge downstream, they detected a strong odor of hydrogen sulfide, observed menhaden dying, and measured oxygen levels up to the surface near zero mg/l.

Table 8.3.6. Current Texas water quality standards for the Arroyo Colorado.

Water Quality Segment	Designated Recreational Use	Designated Aquatic Life Use	Chlorides (mg/l annual average)	Sulfates (mg/l annual average)	Total dissolved solids (mg/l annual average)	Dissolved Oxygen (mg/l as a 24-hr average)	pH (standard units)	Bacteria (#/100 milliliters)	Temperature (maximum °F)
Arroyo Colorado tidal, Segment 2201	Primary contact recreation	High				4.0	6.5-9.0	35 Enterococci	95
Arroyo Colorado above tidal, Segment 2202	Primary contact recreation	Intermediate	1,200	1,000	4,000	4.0(24-hr minimum of 2.0 mg/l)	6.5-9.0	126 *Escherischia coli*	95
Perennial freshwater drainage ditches flowing to Segment 2201 in Cameron, Hidalgo, and Willacy counties		Limited				3.0			
Perennial freshwater drainage ditches flowing to Segment 2202 in Cameron and Hidalgo counties		Limited				3.0			

8.4. Hydrology

The Arroyo is part of the U. S. International Boundary and Water Commission's (IBWC) Lower Rio Grande Valley Flood Control Project consisting of the Banker, Main, North, and Arroyo Colorado floodways. In its upper reach, the Arroyo is the pilot channel for the Main Floodway. It is channelized to facilitate movement of floods and receives flood waters from the Banker Floodway in Hidalgo County. At the Llano Grande, a small reservoir on the channel of the Arroyo Colorado, about 80% of the Arroyo flow is diverted into the North Floodway when flows exceed 1,400 cfs.

There is believed to be some groundwater contribution to base flow in the Cameron County reach (Arroyo Colorado Watershed Partnership, 2007). However, the main sources of flow to the Arroyo Colorado during dry weather are permitted discharges of wastewater and irrigation return flow. An example of these flows is seen during the dry period from November 14-27, 2011 when Arroyo Colorado flow at Harlingen ranged from 149 to 163 cfs. There was no recorded rainfall during October 2011 and the only rainfall during November 2011 was 0.15 inches (Weather Underground, 2012). These regular discharges to the Arroyo Colorado maintain a flow averaging 570 acre-ft/day. Arroyo flows can be substantial during flooding, particularly those caused by tropical storms in the Rio Grande watershed. During Hurricane Alex in 2010, flows in the Arroyo averaged 3900 acre-ft/day from July 1 to Oct 22.

8.5. Environmental Flows and Sound Ecological Environment

8.5.1. Arroyo Colorado Above Tidal

Some historical records indicate the Arroyo Colorado above its tidal reach was intermittent while others suggest it was perennial. It is likely that during wet periods or years it maintained some flow for extended periods, however; it is also likely that during the frequent dry periods occurring in this region, it ceased flowing. Undoubtedly, perennial flow was substantially lower than the present perennial flow maintained by wastewater discharges and agricultural return flows.

Perennial flow in the Arroyo Colorado above-tidal creates aquatic habitats that allow some fish and aquatic invertebrates to exist that would not exist in intermittent streams. However, the health of the current aquatic habitat is limited in terms of physical habitat and water quality. TCEQ (2010a) has identified the following water quality impairments of the Arroyo Colorado above-tidal: elevated bacteria, and DDE and PCBs in edible fish tissue. It has also identified the following water quality concerns for most of the Arroyo's freshwater reaches: elevated chlorophyll, ammonia, nitrate, and total and orthophosphorus. The same water quality concerns are identified for some of the tributaries to the Arroyo Colorado above-tidal. The elevated nutrients may result from wastewater discharges, urban nonpoint source pollution, and agricultural return flows (TCEQ 2010) which typically carry elevated levels of these nutrients. These elevated nutrients contribute to elevated chlorophyll levels. TCEQ (2010c) has designated this reach of the Arroyo Colorado with an intermediate aquatic life use.

The Arroyo Colorado above-tidal and the upstream half of the Arroyo Colorado tidal are not ecologically sound environments because of the degraded water quality they experience as a result of the combined effects of being wastewater-dominated most of the time and having highly modified physical habitats, channelized for movement of flood flows and barge navigation. Increased flow in the Arroyo Colorado above-tidal is not likely to improve the ecological health of the stream because the likely source of flow would be wastewater discharges. The relatively uniform shape of the channel prohibits many of the ecological benefits that natural stream channels receive with variable flow regimes.

Increased freshwater inflow to the upper reach of the Arroyo Colorado tidal may increase resistance to vertical mixing, possibly resulting in more extended periods of stratification. These periods of stratification in the upper two-thirds of the tidal reach might increase causing low oxygen conditions to become worse than at present and to persist longer.

The lower third (lower 7 rm) of the Arroyo Colorado may be considered a sound environment because its freshwater inflow creates estuarine habitat utilized by a diverse community of organisms that have limited access to estuarine environments along this relatively arid part of the Texas coast. Increased quantities of freshwater of adequate quality may enhance ecological health in this portion of the Arroyo Colorado tidal by creating more estuarine habitat. However, this enhancement would not reflect the historical ecological condition of the Arroyo which probably had little or no freshwater inflow for extended periods.

Section 9 Analysis of Freshwater Inflow Requirements of the Lower Laguna Madre

9.1. Background

The background information on LLM in the Introduction and Chap. III has emphasized the unique subtropical to tropical ecology of this highly productive, hypersaline lagoon that is characterized by historically low freshwater inflow (FWI) regimes. This paradoxical situation of low FWI regimes contrasts with other Texas estuaries where moderate to large amounts of FWI are considered essential to maintaining their estuarine productivity (e.g., GSAMAC BBEST 2011). For these upper Texas coast estuaries, FWI requirements have been determined to maintain critical, low-to-moderate salinity gradients, dissolved nutrients and particulate organic matter to support primary producers/food webs, and sediments to build estuarine marsh wetlands. However, none of the biological indicator species used to assess FWI requirements in these other estuaries (viz. eastern oyster, *Rangia* clam, brackish water plants like *Vallisneria* or *Spartina alterniflora*) either occur, or are dominant species, in the LLM. This is a true reflection of how different the LLM is from other Texas estuaries. Although a previous FWI study of LLM by TPWD and TWDB (Tolan et al. 2004) has concluded that the LLM "shows no apparent FWI requirements...", that study was based on an analysis of motile fish and shellfish species. The analyses focused on response to inflow levels by motile fisheries organisms, and significant effects of salinity regimes were not detected based on TPWD fisheries monitoring data (catch per unit effort data). Such motile species can simply swim away from an unfavorable salinity region, to areas where salinities are more favorable, even in the open Gulf.

We have alluded to signs of an "unsound or disturbed ecological environment" that are visible in recent years with the LLM. Several of these conditions (viz. submerged vegetation dynamics, nuisance/harmful algae, epiphyte accumulations, high ungaged inflow pulses) can be indicators of unsound FWI regimes. This chapter describes BBEST studies to identify and quantify distinct LLM inflow regimes over a 32 year POR that may have affected the "sound ecological environment" of the LLM, and specifically its dominant ecosystem indicators. The first step has been to select characteristic focal indicator species and/or habitat sensitive to the highly variable extremes of LLM inflows, and for which sufficient data are available for analysis. Subsequently, the main biological indicator, seagrasses, was subjected to spatial modeling (GIS) techniques and various quantitative analyses to detect relationships with inflow sources and LLM hydrodynamic patterns. Using available LLM hydrologic and water quality data, we tested the hypothesis that nutrient content of LLM inflows was more important to seagrasses than the mere quanitity of freshwater inflow. Synergistic interactions between inflow and hydrographic factors (salinity and nutrient loading) were examined. Final results of the analyses lead to conclusions about inflow regimes that favor or impact LLM seagrasses as indicators of the "sound LLM ecological environment".

9.2. Study Design for Analysis of LLM Freshwater Inflow Regimes

1) Select seagrass (submerged rooted vegetation) as a focal species, document trends in seagrass distribution in Lower Laguna Madre (LLM) based on aerial photography, and determine seagrass acreage changes over a ten-year period since 2000.

2) Apply the TWDB TxBLEND hydrodynamic and salinity transport model to demonstrate salinity plumes in the estuary and then correlate these plumes with gaged and ungaged inflow regimes over a 32 yr period of record (1978 – 2010).

3) Correlate salinity plumes with spatial changes in seagrass coverage and distribution over the last 10 years using GIS techniques to provide presumptive evidence that dissolved nutrients, as well as salinity, in inflows have a zone of impact on seagrass.

4) Examine nutrient composition of seagrass and algal primary producers and correlate with distance from the Arroyo Colorado (AC) mouth, as a putative source of nutrient input accompanying freshwater inflows.

5) Present evidence of FWI-mediated nutrient loading, which in combination, with salinity dynamics, is affecting LLM primary producers, particularly seagrass.

9.2.1. Focal Species Selection

The NAIP (National Agricultural Imagery Program, USDA) natural color photo image from Jan. 2009 (see Fig.III.1-1) shows the entire Lower Laguna Madre study area with its distinctive submerged seagrass beds, from South Bay and South Padre Island at the south end, north to the Arroyo Colorado, and then on to Port Mansfield and Mansfield Pass. As illustrated here, LLM is 75% vegetated by seagrass habitat (more so than all other Texas estuaries except for the Upper LM), and seagrass represents the dominant, critical fisheries/wetland ecosystem and base of the LLM food chain. In addition, seagrass comprises a stationary benthic habitat that integrates long-term inflow regime factors (including salinity, nutrients, and sediments), as inflow waters circulate over the habitat. The four species of seagrasses in the LLM have generally also been well-studied, providing information on tolerance limits for salinity and nutrient responses. Thus, seagrass was selected as the primary focal species for determination of LLM FWI regime requirements. Because the Arroyo Colorado (AC) is the dominant source of gaged FWIs to LLM (See **Section 2**), we originally focused this BBEST study on impacts of inflows from the AC and surrounding ungaged subwatersheds on adjacent seagrasses in the LLM. As shown in **Figure 9.2.1**, the original LLM study area boundary (in green) extends from Mansfield Pass to the area just south of Stover Point, a distance of 34.5 km (21.4 mi).

9.2.2. LLM Seagrass Distribution and Species Changes

Onuf (2007) extensively studied and summarized the changes in seagrass abundance and distribution that have occurred since the 1950s in the Lower Laguna Madre. Based on early field studies by Breuer (1962), McMahon (mid1960s), Merkord (1978), Quammen and Onuf

(1993), and Onuf (2007), LLM total seagrass extent and coverage had expanded to 59,150 ha (146,100 ac) by 1960s, decreased to 46,560 ha (115,000 ac) in 1970s, and then remained fairly constant at *ca* 46,500 ha (114,855 ac) total for next 22+ years. However, over 30+ years, species composition of seagrass beds changed radically from *Halodule*-dominated in the 1960s (88.9 % *Halodule* cover or 52,530 ha), to a mixed community in the 1990s, when beds were dominated by *Syringodium* and *Thalassia* (52 % combined *Syringodium* and *Thalassia* cover [24,000 ha] compared to only 45.7 % *Halodule* cover [*ca* 21,120 ha]). Because *Halodule* is considered a pioneer species while *Syringodium* and *Thalassia* are considered climax species, these changes up to the early 1990s are generally viewed as the result of natural seagrass succession processes (Pulich 1980, Onuf 2007). However, since 2000, when Onuf completed his surveys, the system has seen further loss of all species, especially *Syringodium* and *Thalassia* in the northern part, mostly in the vicinity of the Arroyo Colorado confluence, and *Halodule* in some southern, deeper areas.

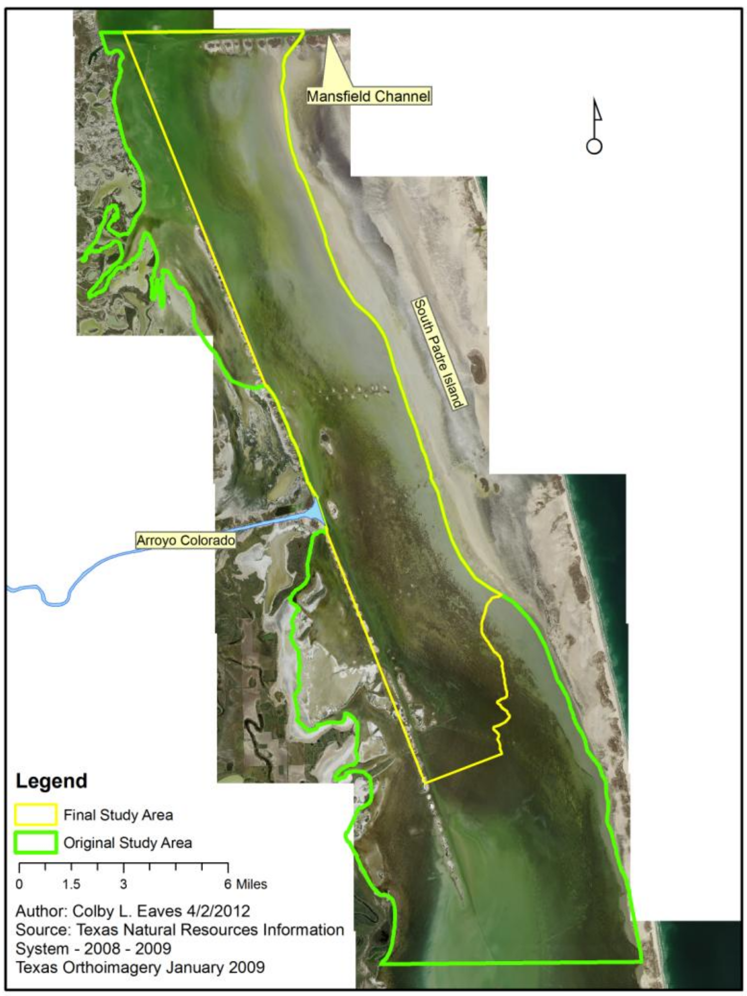


Figure 9.2.1. Lower Laguna Madre study areas outlined on 2009 NAIP color photography. Green area used initially, yellow area used later for change analysis.

The seagrass distribution map for 1999-2000 produced by Onuf (2007), was compared with the map produced from 2009 NAIP (see Fig IX.2-2). When the specific area from Stover Point to Port Mansfield was compared between 2000 and 2009, seagrass acreage had decreased *ca* 24% from 92,000 acres in 2000, to 70,143 acres in 2009 and most of this seagrass loss consisted of *Syringodium* and *Thalassia*.

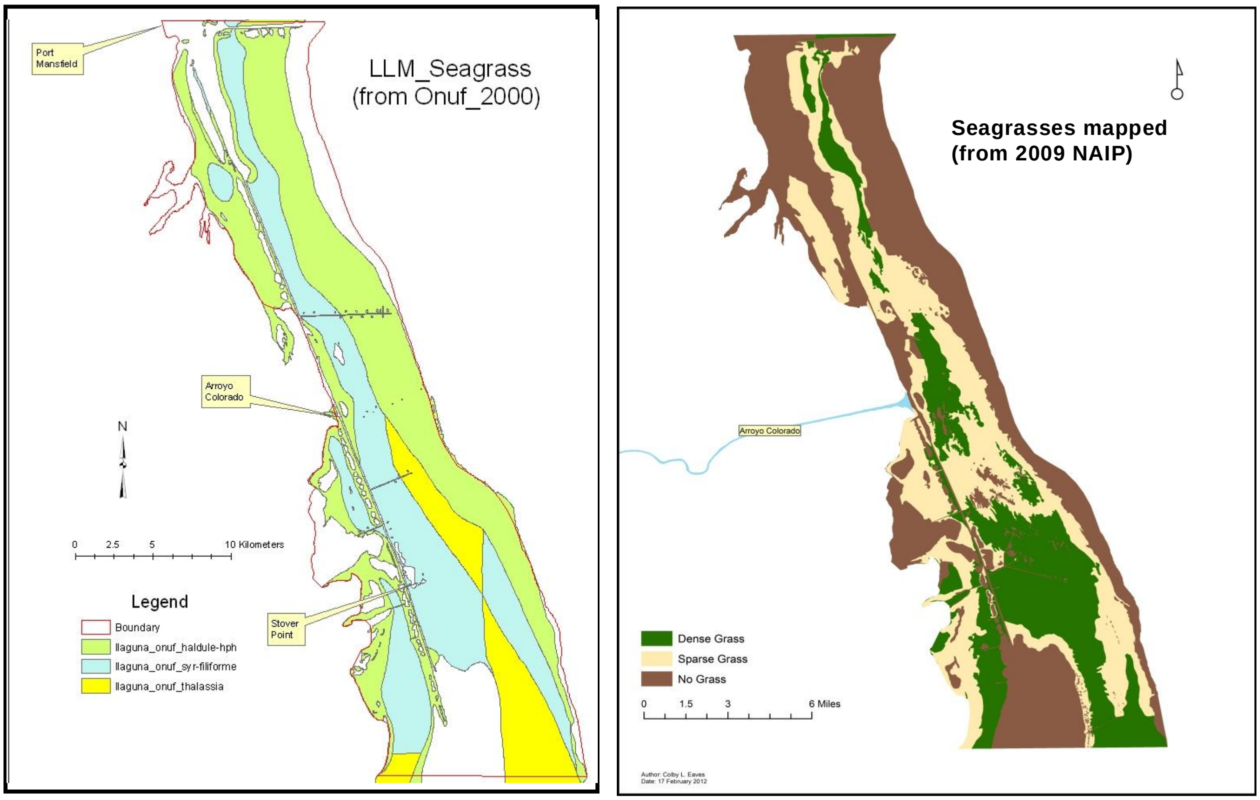


Figure 9.2.2. LLM maps of seagrass cover based on Onuf survey of 1999-2000 (left) and 2009 NAIP imagery (right).

Land use/land cover along the AC and North Floodway drainages is mostly agriculture (65%), and some residential/industrial, while further north towards Port Mansfield, it is dominated by native brushland (50%) and grassland (38%). A definite transition between developed lands and agriculture vs. native brushlands or pasture occurs along this south to north transition region between Port Isabel to Port Mansfield.

Figure 9.2.3. compares the seagrass mapped by this BBEST study between 2005 and 2009 aerial photography for a more limited area between Mansfield Pass and south to Stover Point proper, which focuses on the entrance of the Arroyo Colorado and the North Floodway. Color 2005 photography was obtained from the US Army Corps of Engineers, Galveston District Office (http://www.swg.usace.army.mil/pe-p/SeaGrass/), as part of

monitoring for impacts from dredging work on the GIWW in Laguna Madre. Seagrasses were photo-interpreted at high resolution, using ground-truthing data based on numerous field surveys by DeYoe over 2007-2011 (pers. comm.) and Dunton et al. (UTMSI, pers. comm. 2011). Hydrographic measurements (i.e. temperature, pH, salinity, dissolved oxygen) were also taken using water quality sondes by TPWD staff during their Fisheries Resource Monitoring surveys.

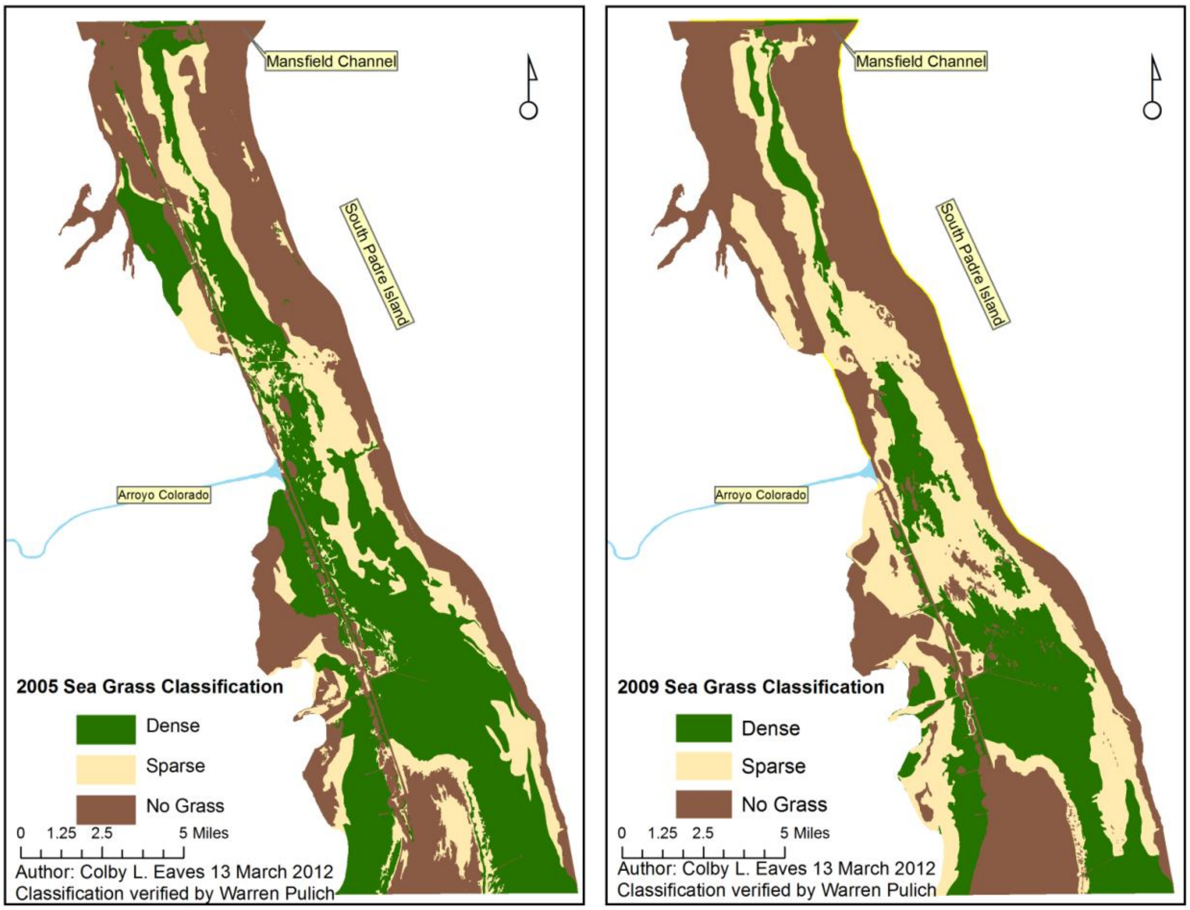


Figure 9.2.3. LLM seagrass distribution from 2005 USACE (left) and 2009 NAIP (right) imagery.

Table 9.2.1 compares seagrass acreage for the 2005 and 2009 time periods in the 39,048 ha (96,450 ac) original (green) study area shown in **Figure 9.2.1**. Comparison between 2005 and 2009 indicates that seagrass declined by 11.9 %, while unvegetated (no grass) areas increased by 19 %. In addition, much seagrass area changed from dense to sparse seagrass.

Table 9.2.1. Classified seagrass acreage from 2005 USACE and 2009 NAIP imagery for original (green) LLM study area as shown in **Figure 9.2.1**.

	Nov. 2005 USACE		Jan. 2009 NAIP	
	Acres	% area	Acres	% area
Dense Grass	39,134	40.6	24,067	25.0
Sparse Grass	21,532	22.3	29,784	30.9
Bare Area	35,782	37.1	42,605	44.2
TOTAL	96,448	100	96,456	100

Fortuitously, in October 2011, the Texas General Land Office (TGLO) was able to acquire aerial photography for a portion of the LLM as part of a coastal survey for the TGLO Coastal Management Program. Although the photography was color infrared, it was high resolution and under fairly clear water and weather conditions, such that we were able to perform accurate photo-interpretation using the maps from 2005 and 2009 for guidance.

However, the seagrass map area for 2011 (**Figure 9.2.4**) is a smaller study area (48,689 acres) than the previous efforts in 2005 – 2009, due to limited extent of the 2011 photography. These data confirm that additional loss of seagrasses occurred between 2009 and 2011, and some of this loss was undoubtedly related to the historic flood inflow event in summer 2010 caused by Hurricane Alex, and very low salinities which occurred in a large portion of the LLM, north and south of the Arroyo (H. DeYoe, unpublished data). Large expanses of unvegetated areas were mapped where previously in 2005 and 2009 *Thalassia* and *Syringodium* had occurred. In some of these bare areas, dead *Thalassia* roots and rhizomes were still found in the sediments a year later (field survey Aug. 2011). Overall there was a 19 % increase in bare area, and a 9 % decrease in seagrass (combined sparse and dense) over the 6 years (**Table 9.2.2**).

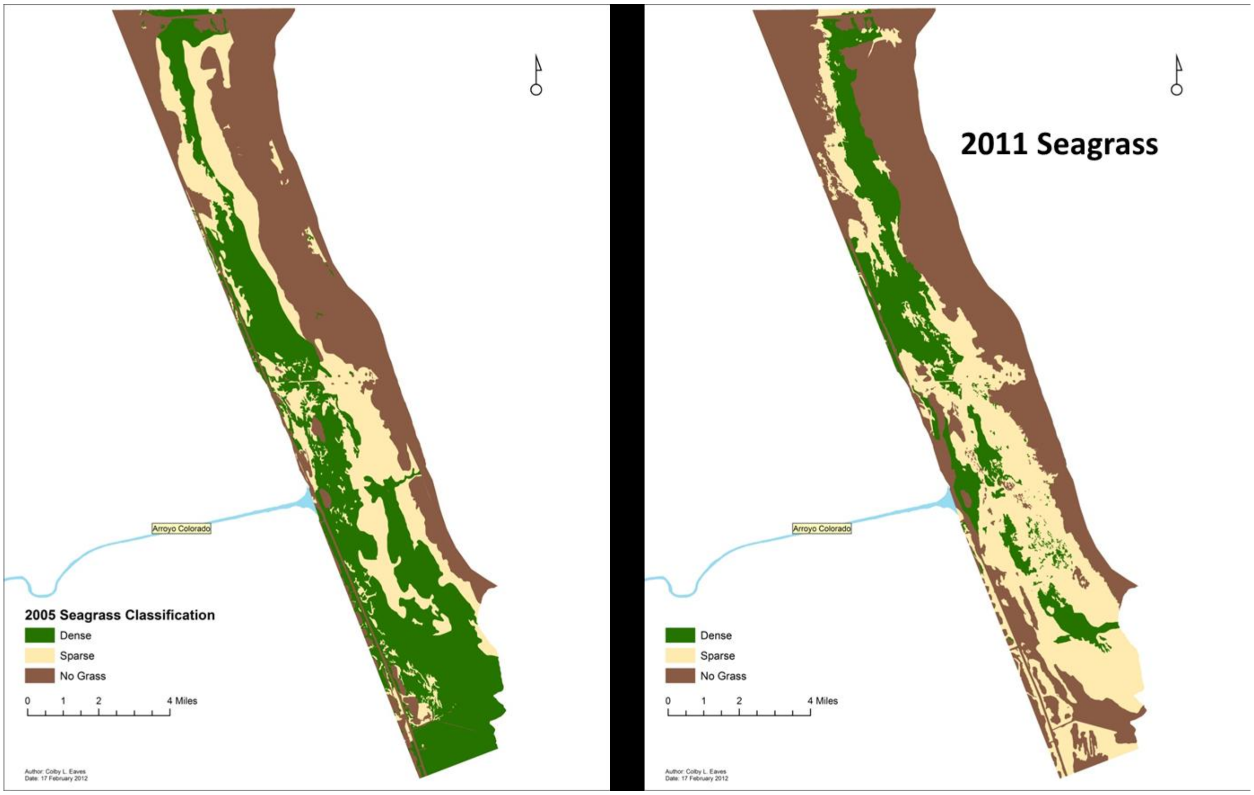


Figure 9.2.4. Comparison of seagrass areas in the northern portion of LLM mapped from 2005 USACE and 2011 TGLO photography. Modified study area used (yellow area in **Figure 9.2.1**).

Table 9.2.2. Comparison of seagrass acreage changes mapped from 2005 USACOE and 2011 TGLO photography for LLM study area.

	Nov. 2005		Oct. 2011	
	Acres	% area	Acres	% area
Dense Grass	18,453	37.9	9,324	18.3
Sparse Grass	11,946	24.5	16,748	35.1
Bare Area	18,289	37.6	22,614	46.6
TOTAL	48,689	100	48,689	100

The 2011 classified map was then used to perform an overlay change analysis with the 2005 classified seagrass map, and the resulting loss/gain change map is shown in **Figure 9.2.5**.

Table 9.2.3 presents the quantitative values of changes in acreage, but Fig. IX. 2 – 5 is more informative by providing the spatial location of seagrass changes, which are distinctly localized. The dynamics of this localized seagrass decline was the focus of recent field surveys and spatial modeling studies (DeYoe and Kowalski 2009, Pulich and DeYoe 2011, unpublished reports). When these changes in seagrass acreage and spatial distribution were considered, we postulated that freshwater inflow conditions in the LLM may have changed over the last 15+ years which have contributed to the seagrass steady decline. Because inflows from the AC watershed have the potential to lower salinities, increase nutrients, and possibly add other materials (e.g., contaminants, sediments) to which seagrass are sensitive, we attempted to document that the decreases in LLM were due to lowered salinities and elevated nutrient loading, as suggested by previous investigators (Onuf et al 2007).

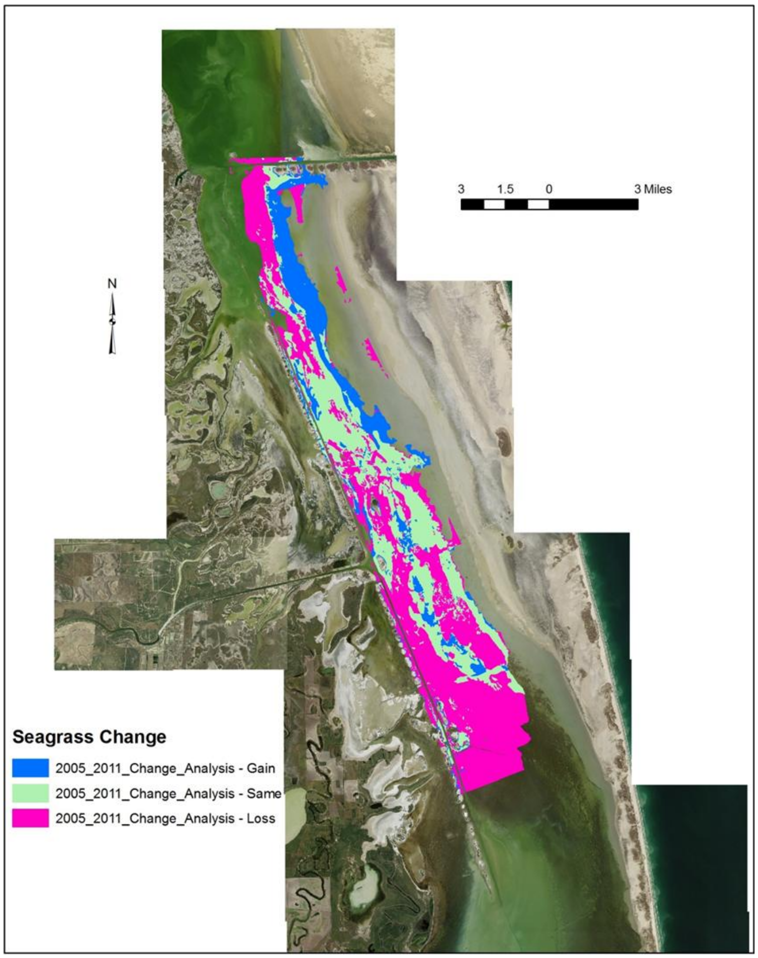


Figure 9.2.5. Change analysis map of LLM showing changes in seagrass areas between Nov. 2005 and Oct. 2011. Arroyo Colorado is on left in middle of map, and Mansfield Channel at top. Modified study area used from **Figure 9.2.1**.

Table 9.2.3. Change analysis acreage values.

2005 to 2011 Change Analysis Totals (Acres)	
NO CHANGE (55.3 %)	
Bare Area	16372
Sparse seagrass	5823
Dense seagrass	4763
LOSS (-33.4 %)	
Sparse seagrass to Bare	2597
Dense seagrass to Bare	3706
Dense to Sparse seagrass	9985
GAINS (+11.2 %)	
Bare to Sparse seagrass	1286
Bare to Dense seagrass	638
Sparse to Dense seagrass	3530
TOTAL AREA	48699

9.2.3. Salinity and Nutrient Responses for Lower Laguna Madre Seagrasses

The subtropical seagrass species found in LLM have strict salinity requirements as documented by numerous investigators (McMahan 1968; McMillan and Moseley 1967; Phillips 1960; Zieman 1974; Pulich 1980 and 1985). For these obligatory saltwater plants, salinity requirements are a function of exposure time, time of year (growing season), and temperature. Their growth tolerance limits also depend on root exposure to lower or higher salinity waters, but this relationship has rarely been investigated. The ranges of salinities tolerated by the four species of LLM seagrasses are listed in **Table 9.2.4**. While tolerance to maximum salinities varies among the four species, all species are tolerant of hypersaline conditions in the LLM up to at least 44 psu. *Halophila* and *Halodule* even grow well at continuous salinities above 45 or 55 psu, respectively. However, all four species can tolerate low salinity levels only very briefly down to the 6 to 13 psu range (*Halophila* survives 13 psu, while *Halodule* withstands 6 psu, and *Thalassia* or *Syringodium* survive 10 psu)

(McMillan and Moseley 1967). These low salinity levels will kill the seagrass leaves when exposed directly for over a few hours, and roots/rhizomes in the sediments are killed after a couple days exposure. Continuous reduced salinities between 13 and 20 psu for days or a few weeks will cause reduction of metabolic and physiological processes. At a minimum, the leaves are often shed, which temporarily stunts their growth (Zieman et al. 1999). Thus, all four species have minimum salinity tolerances for sustained growth only down to the low polyhaline range between 20 to 24 psu, with *ca* 24 psu seawater considered to be a lower threshold for sustained growth of *Thalassia* and *Syringodium (*Phillips 1960, Zieman *et al* 1999).

Table 9.2.4. Salinity tolerance ranges of LLM seagrasses. Data from McMahan 1968; McMillan and Moseley 1967; Phillips 1960; Zieman 1974; Pulich 1980 & 1985; Zieman et al. 1999.

Seagrass Species	Optimal Growth Salinity Range	Lethal Salinity Range
Shoal grass (*Halodule wrightii*)	20 – 44	6 or <; 70 or >
Clover or star grass (*Halophila engelmannii*)	23 – 40	13 or <; 50 or >
Turtle grass (*Thalassia testudinum*)	24 – 38	10 or <; 48 or >
Manatee grass (*Syringodium filiforme*)	24 – 38	10 or <; 44 or >

A previous FWI study by TPWD and TWDB (2005) concluded that the LLM “shows no minimal FWI requirements...” This study was based on an analysis of dominant fish and shellfish species data. The analyses focused on response to minimal inflow levels by the fisheries organisms, and no significant effects of inflows were detected on the species based on TPWD fisheries monitoring catch data. Such motile species simply swim away from an unfavorable salinity region, to areas where salinities are more favorable, such as the open Gulf. When sessile, rooted seagrasses are considered, the effects of unfavorable salinity conditions from FWI, particularly low salinity levels, will be much more stressful, even lethal. High inflows need to be addressed since the effects of low salinities produced by high inflows would be deleterious as shown above.

Nutrient additions (nitrogen and phosphorus) can have positive and negative, as well as direct and indirect impacts, on seagrass. Lee (1998) showed that *Thalassia* at one site in the LLM responded positively to ammonia additions with increased growth. In an example of a direct negative effect, Burkholder et al. (1994) found that nitrate in excessive amounts had a detrimental effect on the growth of *Z. marina*, a temperate zone species, due to its physiological characteristics; while the same nitrate treatment produced modest to substantial growth increase in *Halodule* and *Ruppia*, respectively. However, *H. wrightii* is inhibited at high nitrate levels (100 μM) while *Ruppia maritima* is inhibited by high ammonia levels (Burkholder et al., 1994). Long-term experimental fertilization of a *Thalassia testudinum* bed eventually led to its replacement by *Halodule wrightii* (Fourqurean et al., 1995). Direct responses by *Thalassia* and *Syringodium* to nitrogen loading have not been well-characterized. Indirect effects of nutrient enrichment include stimulation of the growth of phytoplankton, macroalgae and seagrass epiphytes that can lead to reduced seagrass productivity due to light reduction (McGlathery. 1995). Nutrient addition alone can lead to positive or negative effects on seagrasses, with negative effects typically occurring at higher loading rates. In the case of excessive macroalgae accumulations, shading occurs from macroalgae overgrowing and smothering the seagrasses (**Figure 9.2.6**).

The interactive effects of lowered salinity waters, enriched with nutrients or other dissolved materials, has not been intensively studied. As noted above, low salinities can have detrimental effects on seagrass. When large quantities of low salinity water also carry significant amounts of nutrients there is the potential for impacts due to low salinity, high nutrients and/or the combined effects of low salinity and high nutrients. Although Quammen and Onuf (1993) and others have discussed the impact of high nutrient loading, this was routinely in the context of nutrients only. Studies by Burkholder (2000) and Touchette (1999) on the temperate zone seagrass *Zostera marina* suggest that synergistic effects occur between temperature and nitrate enrichment, an example of how interactions between multiple factors can occur. A complex synergistic effect of nutrient concentration, salinity and seagrass ecotype

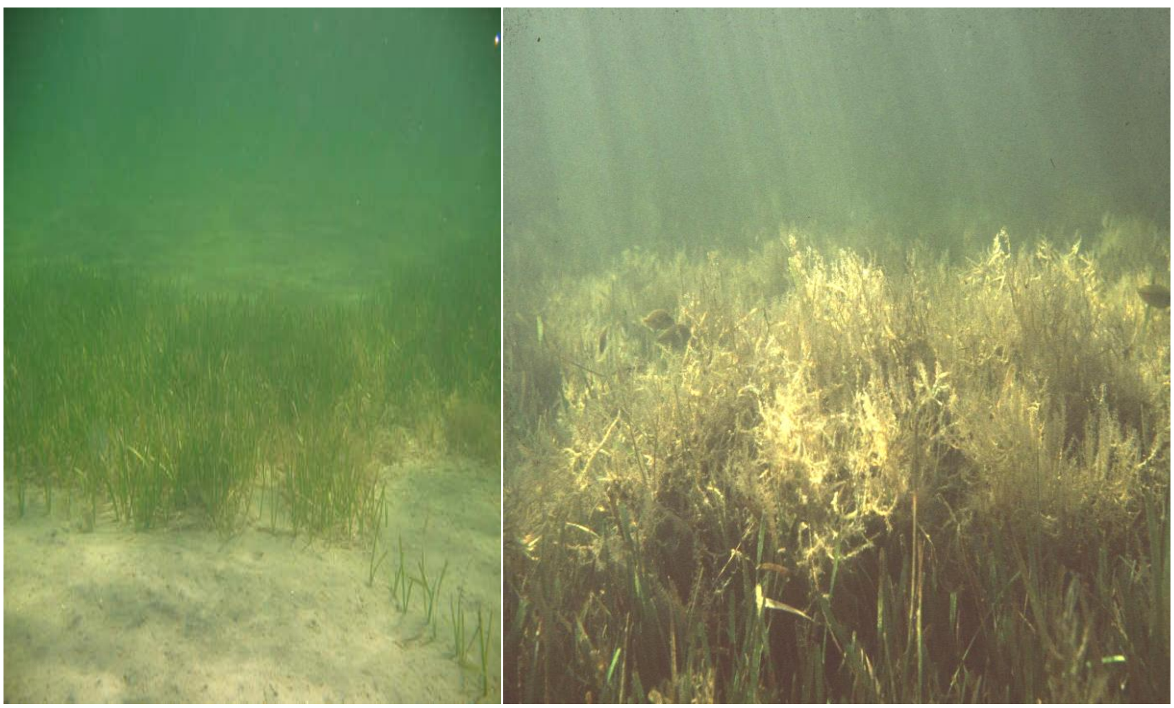


Figure 9.2.6. Examples of (left) healthy unimpacted *Thalassia* bed in LLM, and (right) *Thalassia* bed smothered by dense macroalgae and epiphytes. Photos by Hudson DeYoe.

has been shown for *Z. marina* (van Katwijk et al. 1999). There is little research on nutrient-salinity interactive effects for LLM seagrass species but the above references suggest interactive effects are possible.

Nutrient-temperature interactions

In addition, recent studies on *Zostera marina* have shown negative interactions between reduced light conditions in the water column and increased temperature (Jarvis and Moore 2011, pers. comm.). As described in **Section 3**, there has been a gradual one degree C rise in LLM water temperature over the last 20 years, especially in winter time (Tolan, 2006). High nutrient levels can reduce light conditions and, when combined with higher LLM water temperatures, could lead to similar interactive stress response for LLM seagrass such as *Thalassia*.

9.2.4. Seagrass Performance Study

Seasonal performance of the seagrass *Thalassia testudinum* (turtle grass) was measured four times (Apr 2006, Aug 2006, Oct 2006, Jan 2007) at four sites (Green Island, ABC, Bay West and South Bay)(**Figure 9.2.7**). These sites were selected, in part, due to their varying distances from the Arroyo Colorado. The Green Island (GI) site is 2.9 km (1.8 mi) northeast from the confluence of the Arroyo Colorado and the Lower Laguna Madre. Prevailing winds are from the southeast (April-Oct) so Arroyo water is usually directed towards this site resulting in generally elevated nutrient levels (see below) and biogenic (phytoplankton) turbidity (DeYoe, pers observation). Site Bay West (BW) is 18.9 km (11.8 mi) south of the Arroyo Colorado on the west side of the GIWW spoil islands. It was selected as an "average" LLM site with moderate nutrient levels and largely abiogenic turbidity. Site ABC (Andy Bowie Control) is 25.9 km (16.1 mi) south of the Arroyo Colorado and a clear water site with low nutrients. The South Bay (SB) site is probably the least human-impacted site and most influenced by Gulf water due its proximity to the Brazos-Santiago Pass.

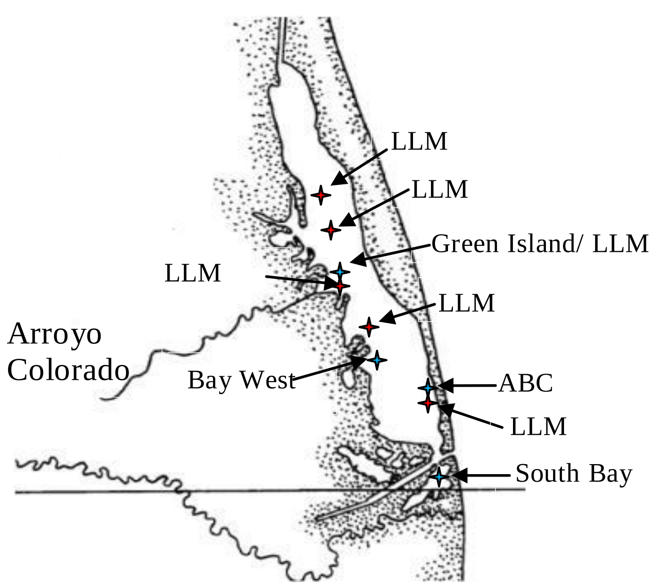


Figure 9.2.7. Study sites (Green Island, Bay West, ABC, South Bay) in the LLM for the *Thalassia* performance study (blue stars) and for the seagrass epiphyte study (LLM 050, 052, 053, 054, 055, 056)(red stars).

During each season, each site was visited to measure *Thalassia* shoot growth rates, biomass, shoot density and a variety of other measures. At each site, four 15-cm diameter cores (0.018 m^2) were collected to determine seagrass biomass and shoot density. Biomass cores were rinsed of sediment, sorted into above and below ground parts, dried and weighed. Shoot growth rates were determined by the leaf-marking method (Zieman 1974). Ten shoots at each site were marked and then about 2 to 4 weeks later the shoots were harvested for analysis.

Thalassia had lower average total biomass and shoot density at Green Island compared to sites more distant from the Arroyo Colorado (Figure 9.2.8). Seasonal areal production values were also generally as low or lower at Green Island than the other sites (**Figure 9.2.8**).

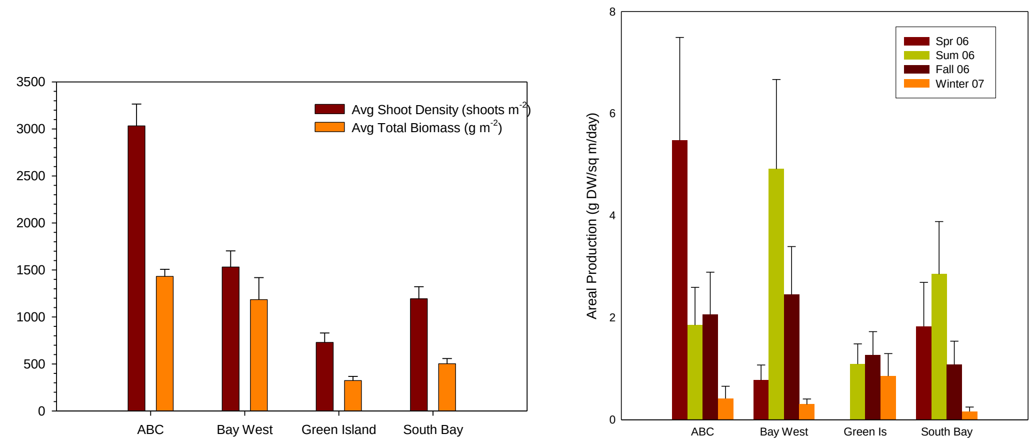


Figure 9.2.8. *Thalassia testudinum* shoot density, total biomass and areal production at four sites in the LLM from April 2006 to January 2007. No production data for spring 2006 at Green Island.

The average leaf length for October 2006 samples was greatest for Green Island (169 mm, SD=68, n= 29) compared to ABC (126 mm, SD=58, n= 39), South Bay (123 mm, SD=70, n= 39) and Bay West (107 mm, SD=84, n= 38)($p<0.05$).

<u>Seagrass Epiphyte Study</u>

On seagrass leaves grow a variety of small animals and plants including algae called epiphytes. Epiphyte accumulation on seagrass leaves is determined by the levels of light, nutrients, current regime and age of leaf as well as the grazers present like snails consuming the epiphytes. As a means to estimate epiphyte accumulation on seagrass leaves, artificial seagrass leaves were constructed of narrow black plastic strips to mimic *Halodule* leaves and anchored in the sediment at six locations (LLM 050, 052, 053, 054, 055, 056) along the GIWW that varied in distance north or south of the Arroyo Colorado (**Figure 9.2.7**). Five artificial seagrass leaves were deployed at each site each season during 2003 and then allowed to accumulate epiphytes for about 2-4 weeks depending on season. The strips were harvested and then the chlorophyll extracted and quantified using the solvent DMF and spectrophotometry (Porra et al. 1989).

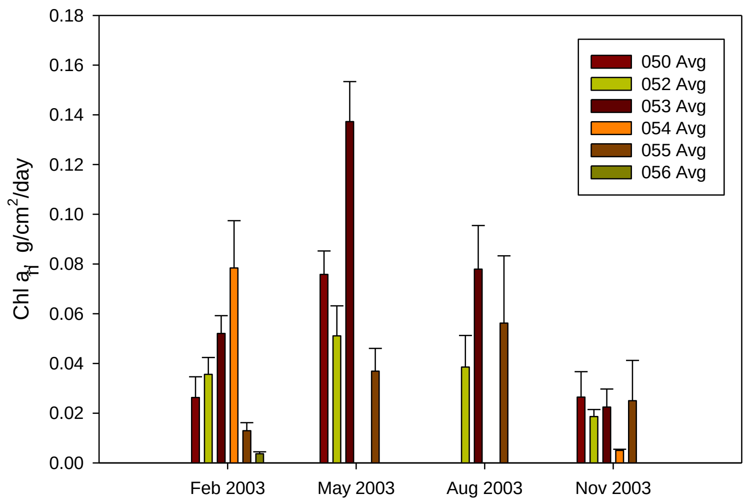


Figure 9.2.9. Epiphyte accumulation on artificial seagrass leaves at six locations in the LLM. Sites LLM 050 and 052 were south of the Arroyo Colorado. Sites 053 and 054 were nearest the Arroyo Colorado (near Green Island) while sites 055 and 056 were north of the Arroyo Colorado. There were no data at site 054 for May and Aug 2003.

Except for Nov 2003, epiphyte growth on artificial leaves was significantly higher ($p<0.05$) at the sites closer to the Arroyo Colorado (053, 054) than the other sites (Figure 9.2.9).
Water Column Data

In conjunction with a variety of LLM studies conducted between 2001 to 2010, water quality data were collected at Green Island, Bay West, ABC, South Bay (see descriptions above) and the tidal segment of the Arroyo Colorado (26.3380070ºN, 97.4364575ºW). Typically on field trips to these sites, a surface water sample was collected and stored on ice prior to processing. Water was filtered through glass-fiber filters (Whatman GF/C) and the water frozen until analysis. The filter was retained and frozen for chlorophyll a analysis to estimate phytoplankton abundance. Chlorophyll a was quantified by acetone extraction followed by fluorometric quantitation (APHA 1998). Filtered water samples were analyzed for ammonia-nitrogen, nitrate-nitrite nitrogen and soluble reactive phosphate using standard colorimetric methods (Strickland and Parsons 1972).

Table 9.2.5. Average water column chlorophyll and nutrient data for the Arroyo Colorado and four LLM sites. Green Island is nearest the Arroyo Colorado with South Bay being the furthest south. Bay West and ABC are also south of the Arroyo at intermediate distances. Period of record is from 2001 to 2010. SD = standard deviation, n = sample size.

	Chlorophyll µg/L			Ammonia, mg N/L			Nitrate, mg N/L			Diss.Phosphate, mg P/L		
	Avg	**SD**	**n**	**Avg**	**SD**	**n**	**Avg**	**SD**	**n**	**Avg**	**SD**	**n**
Arroyo Colorado	21.6	18.0	21	0.17	0.16	22	0.87	1.15	25	0.16	0.11	21
Green Island	5.88	6.58	7	0.12	0.15	29	0.11	0.29	27	0.02	0.03	28
Bay West	2.94	2.94	6	0.16	0.25	19	0.01	0.01	9	0.05	0.12	13
ABC	0.86	0.82	7	0.08	0.13	26	0.01	0.01	26	0.02	0.03	27
South Bay	1.16	0.36	6	0.12	0.16	15	0.03	0.06	21	0.03	0.04	18

<u>Summary</u>

Seagrass (*Thalassia*) growth, biomass and shoot density were generally lower at Green Island than the other LLM sites. Nutrient levels were at least as high or higher at Green Island (esp. nitrate) compared to the other study sites suggesting that *Thalassia* at Green Island was not likely to be nitrogen-deficient (**Table 9.2.5**). It is noteworthy that leaf lengths were longer while areal productivity was lower at Green Island compared to the other sites suggesting that light limitation adversely affected seagrass productivity at Green Island.

The two sites nearest the Arroyo Colorado (053 and 054) tended to have higher epiphyte accumulation on the plastic seagrass leaves suggesting that epiphyte growth on real seagrass near the Arroyo Colorado would also be higher compared to the other sites. Elevated epiphyte load and higher phytoplankton abundance nearer the Arroyo Colorado indicates higher nutrient levels at these sites. High epiphyte load and/or phytoplankton abundance could reduce the amount of light available to seagrass leading to slower seagrass growth and longer leaves as seen at Green Island. Unfortunately, supporting light data is not available. More noticeable differences in the above nutrient parameters may have been dampened by rapid uptake of nutrients by other bay primary producers (seagrass and other algae) and/or incorporation of nutrients into the sediment. In **Section 9.4.1**, we present evidence that Arroyo nitrogen is utilized by seagrass, drift algae and epiphytes.

In conclusion, it appears that nutrient loading from the Arroyo Colorado stimulates the growth of some primary producers (phytoplankton and epiphytes) likely causing reduction in available light leading to reduced productivity and loss of LLM seagrass near the Arroyo Colorado (**Figure 9.2.10**). Monitoring of light levels at Green Island and comparison sites is needed to substantiate this assertion. Besides light limitation, direct inhibitory physiological effects of nitrogen enrichment on seagrass are possible (see **Section 9.2.3**). As noted above (**Section 9.2.3**), salinity levels, except during high flow events of the Arroyo, are not likely to inhibit seagrass performance in the long-term for the area of the LLM influenced by the Arroyo.

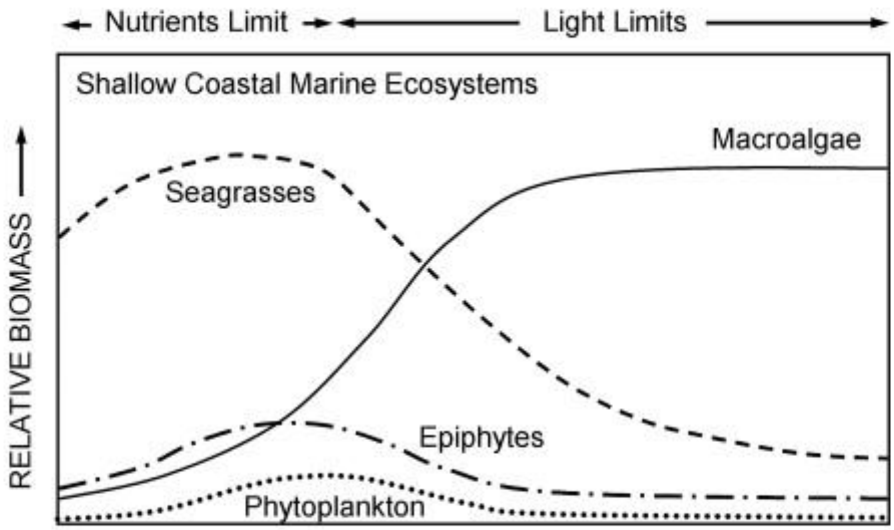


Figure 9.2.10. Generalized shift in the biomass of major groups of primary producers with increasing nutrient enrichment to shallow coastal marine waters. From Burkholder et al., (2007).

9.3. Hydrologic Data Analysis

9.3.1. TWDB Hydrodynamic Modeling

The Texas Water Development Board, Bays and Estuaries Program (TWDB), performs hydrodynamic simulation modeling of water circulation and salinity in the bays and estuaries such as Lower Laguna Madre, using the TxBLEND hydrodynamic and salinity transport model. TxBLEND is a two-dimensional, depth-averaged hydrodynamic and salinity transport model designed to simulate water circulation (currents) and salinity conditions within Texas bays (Matsumoto 1993, Powell et al. 2002). Model simulations allow for a quantitative depiction of the effects of volume and timing of freshwater inflows, such as from the Arroyo Colorado, and concomitant meteorological and tidal processes on the distribution and persistence of water circulation and salinity within the LLM estuary. TxBLEND produces high-resolution, dynamic simulations of estuarine conditions over daily to long-term periods, using a model grid mesh shown by the grid map for the LLM in **Figure 9.3.1**. The model has been used in a variety of coastal projects including freshwater inflow studies, oil spill response, forecasts of bay conditions, salinity mitigation studies, and environmental impact evaluations. For the LLM study, TWDB has incorporated finer resolution grid nodes and greater detail focusing on the area adjacent to the mouth of the Arroyo Colorado, Gulf passes, and deeper channels (e.g. GIWW).

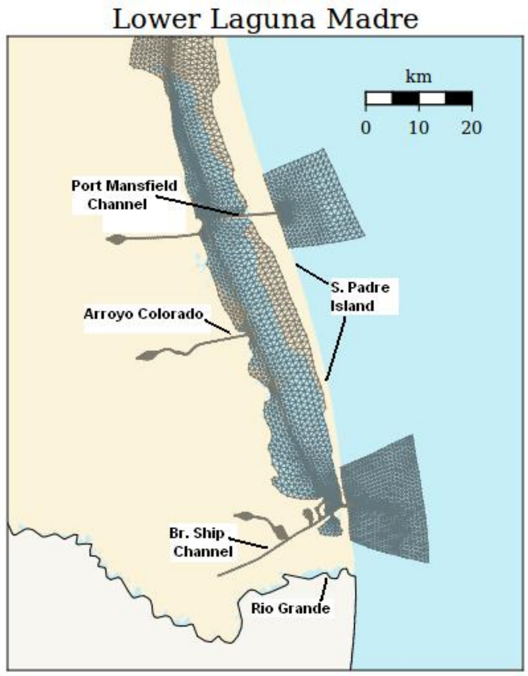


Figure 9.3.1 TxBLEND hydrodynamic model grid network applied to LLM.

Hydrodynamic modeling using TWDB's bay circulation model (TxBLEND) is potentially capable of demonstrating the spatial impacts of hydrographic factors (viz. currents, salinity regimes and dissolved nutrients) related to freshwater inflows on the LLM estuary. Therefore we chose a study design which would correlate TxBLEND output under known inflow conditions with spatial changes in seagrass distribution, a key biological indicator. We proposed to analyze the salinity grid output from TxBLEND modeling, and perform spatial overlay analyses with seagrass maps from the period 2000 – 2011.

9.3.2. Monthly Inflows to Lower Laguna Madre

Some background on the TxBLEND hydrology is critical to interpretation of effects of salinity and circulation dynamics on LLM seagrass distribution and plant responses. Fig. IX.3 – 2 shows the two gaged (hatched areas) and ten ungaged portions of the subwatersheds that contribute to inflows into the LLM below Port Mansfield. The TxBLEND model uses total combined inflow from these LRGV subwatersheds, comprising gaged flows, ungaged runoff, and diversions plus return flows. Gages #8470400 and #8470200 (i.e., red circles on the Arroyo Colorado and North Floodway in **Figure 9.3.2**) are the only 2 stream gages which measure gaged flows into LLM. Ungaged runoff into the LLM comes from all the other 10 subwatersheds shown, and this runoff is measured by the TXRR model (TWDB's rainfall runoff model).

Figure 9.3.2. Map of gaged and ungaged watershed areas contributing inflows to LLM. From TWDB, Bays and Estuaries Program.

The annual record for total combined monthly inflow to the LLM over the 1977 to 2010 period of record is shown in **(Figure 9.3.3**). Hydrologic data were provided by the Texas Water Development Board staff in the Surface Water Planning Division, Coastal Studies/Bays and Estuaries Program (see http://midgewater.twdb.texas.gov/bays_estuaries /hydrologypage.html), and the complete database is included in the Appendix. Based on these hydrologic records, various years stand out that showed large inflow events to LLM, while other years showed very low inflow. Since total inflow consists of gaged flows plus ungaged (modeled) flows, minus diversions plus return flows, we decided to examine the relative contribution of gaged and ungaged flows in greater detail. **Figures 9.3.4** and **9.3.5** show the relative amounts of monthly gaged and ungaged inflow for the same period of record in more detail.

This analysis allowed us to categorize several distinct types of flow years: 11 high flow (= Wet) years, and 10 moderate (Avg) flow years, and the rest defined as low flow (= Dry) years. The method/criteria for picking the dry-avg-wet thresholds included first visually identifying natural breaks (or 'pulses') in the monthly combined freshwater inflow pattern (**Figure 9.3.3**) over the 1977 to 2010 period of record. **Figures 9.3.4** and **9.3.5** were then scrutinized to identify the discrete months of the year and levels of flow per month comprising the pulse(s). Wet Years were categorized based on occurrence of several (2-3) monthly flows per yr above 100,000 ac-ft: 1984, 1988, 1991, 1993, 1998, 2002, 2003, 2004, 2007, 2008, and 2010. For the most part, these 'high flow months' occurred in succession. Dry years were 1986, 1987, 1989-1990, 1994, 2000, and 2005-2006, with all monthly flows always less than 40,000 ac-ft. These dry years were considered to have typical 'low-flow' months. Other years with some successive monthly flows between 50-75,000 ac-ft were considered as Average or intermediate inflow years (1982-83, 1985, 1992, 1995-96-97, 1999, 2001, and 2009), with ‘intermediate-flow’ months.

Figure 9.3.6 presents the flow record in greater detail for several years (1991-93, 2001-03, 2007-09) when large pulse flow events occurred. These examples show that the ratio of gaged (Ga) to ungaged (Ung) inflow differs significantly between High (pulse) and Low inflow months. The Ga/Ung ratio for regular Low flow months ranges from 3.9 to 4.1, while it changes to 0.37 to 0.4 during the High pulse flow months. This could indicate much more nonpoint source runoff affecting the Laguna Madre during high pulse inflow months, as opposed to the regular, low flow months.

The source of ungaged inflows could provide information on the composition of inflows. Since the TWDB ungaged inflow hydrology data is further compiled by discrete rainfall gage locations, we examined the ungaged data in more detail. **Figures 9.3.7** and **9.3.8** present the amounts of ungaged flow entering the LLM from 7 of the 10 ungaged subwatersheds in **Figure 9.3.2**. These ranged from the Port Mansfield and Raymondville areas in the north, down to Port Isabel and Brownsville areas in the southern region. Eight of the largest pulsed flow events were examined, occurring in 1984, 1991, 1993, 1998, 2002, 2003, 2007, and 2008. These results indicate that 4 of the seven subwatersheds (Raym, ArrCol, LagAt, Brwnville) most often contributed the majority of the total inflow. This is significant since these areas are expected to carry high nutrient loads, either from municipal storm drains (Brownsville), or agricultural field runoff (Arr Col, LagAt, Raym). A careful land use analysis is needed to help document these putative nutrient runoff sources. Two examples of so-called Ungaged inflows are photographs of culverts discharging to the lower Arroyo Colorado on May 11, 2012 after a 3-4 in. rainfall (**Figure 9.3.9** and **9.3.10**).

Although these ungaged hydrologic data are noteworthy, known nutrient composition of ungaged runoff is a deficiency in this analysis, and we recommend such water quality analysis for intensive study during the adaptive management phase. However, the inference for our BBEST analysis was that these High ungaged flows (> 40,000 ac-ft per month) were contributing higher than normal levels of nutrient loading than occurred at the Low monthly levels of 40,000 ac-ft or less.

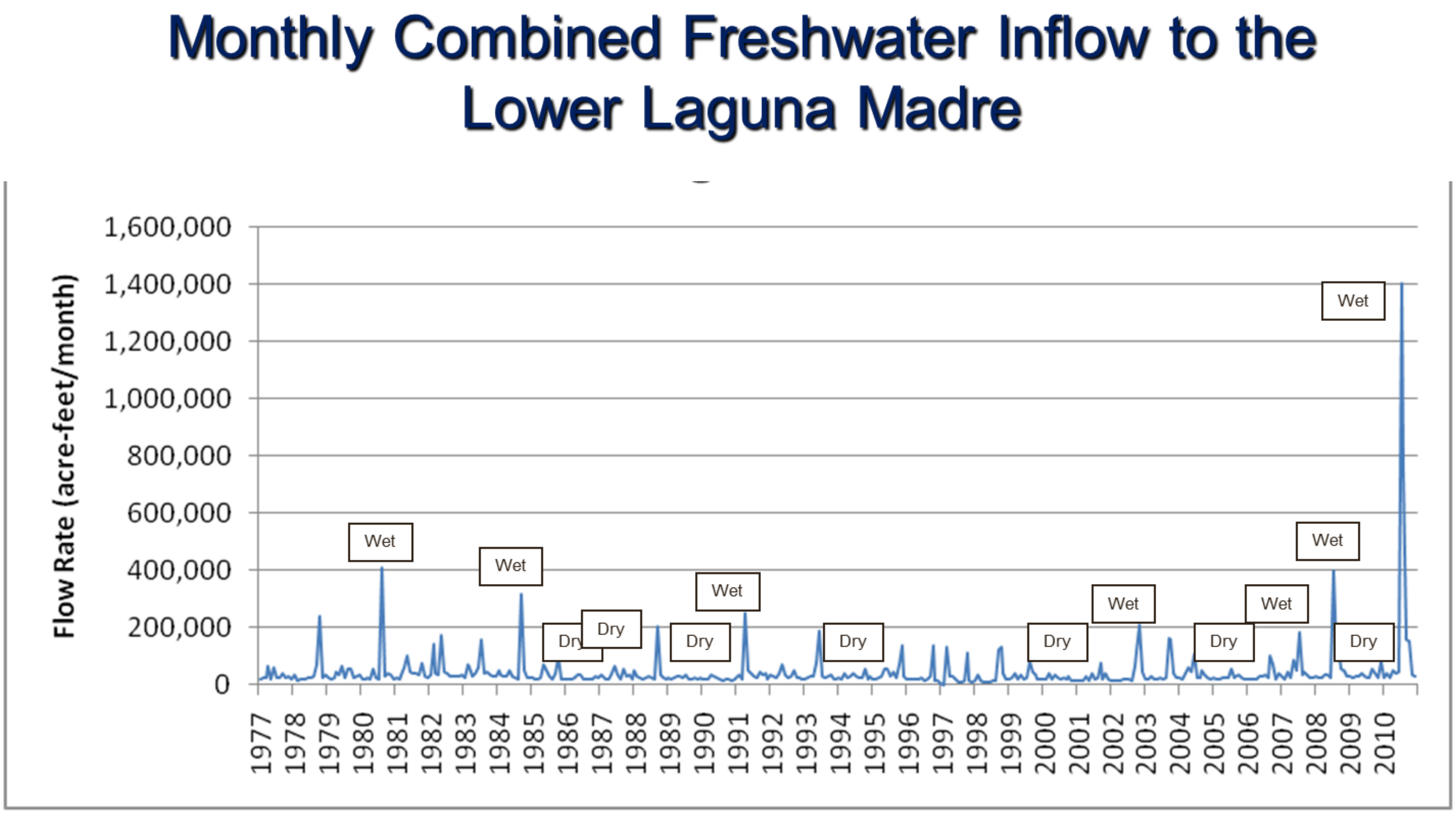


Figure 9.3.3. Monthly combined freshwater inflow to Lower Laguna Madre (graph from TWDB).

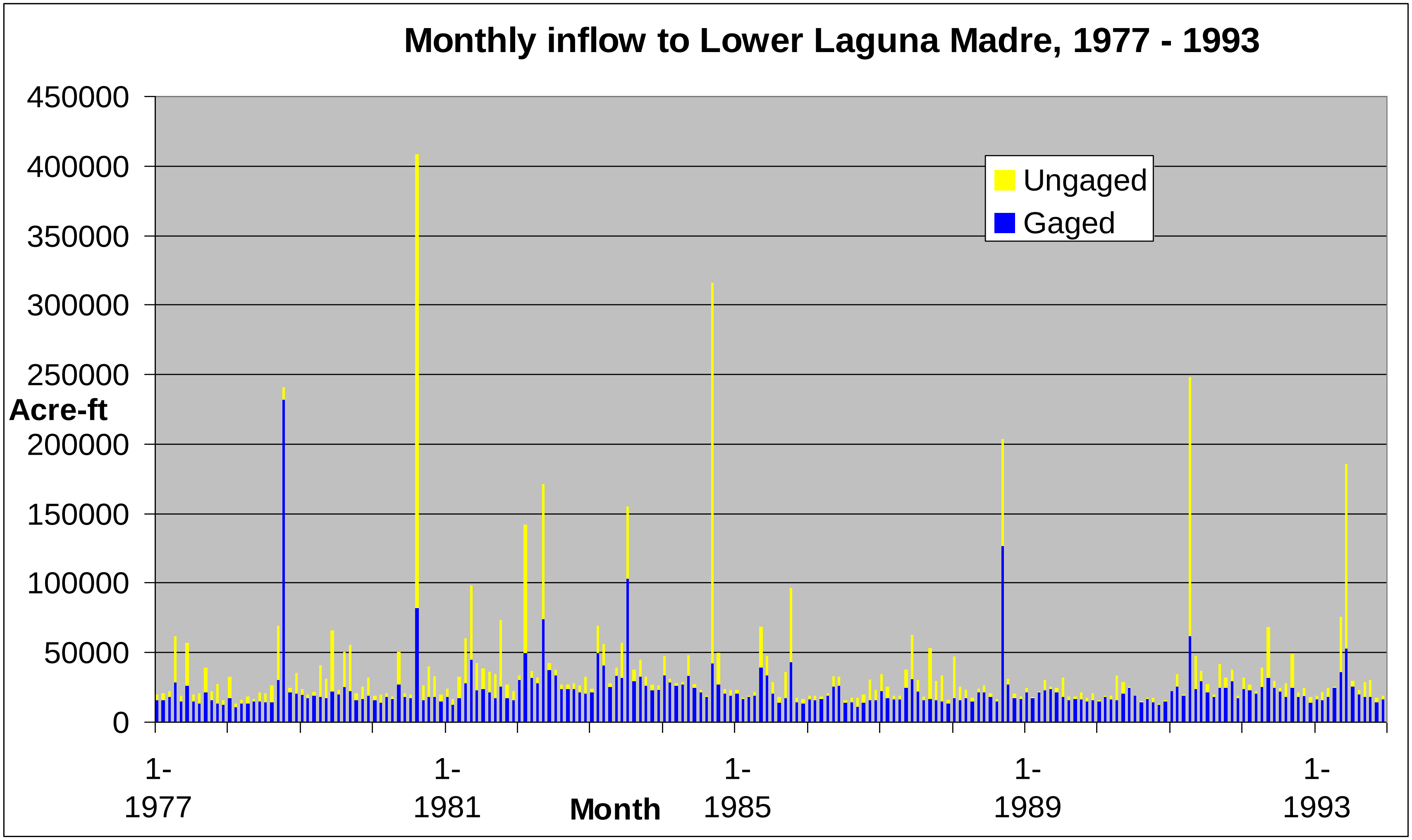


Figure 9.3.4. Monthly gaged and ungaged inflow to Lower Laguna Madre, 1977 – 1993 (data from TWDB).

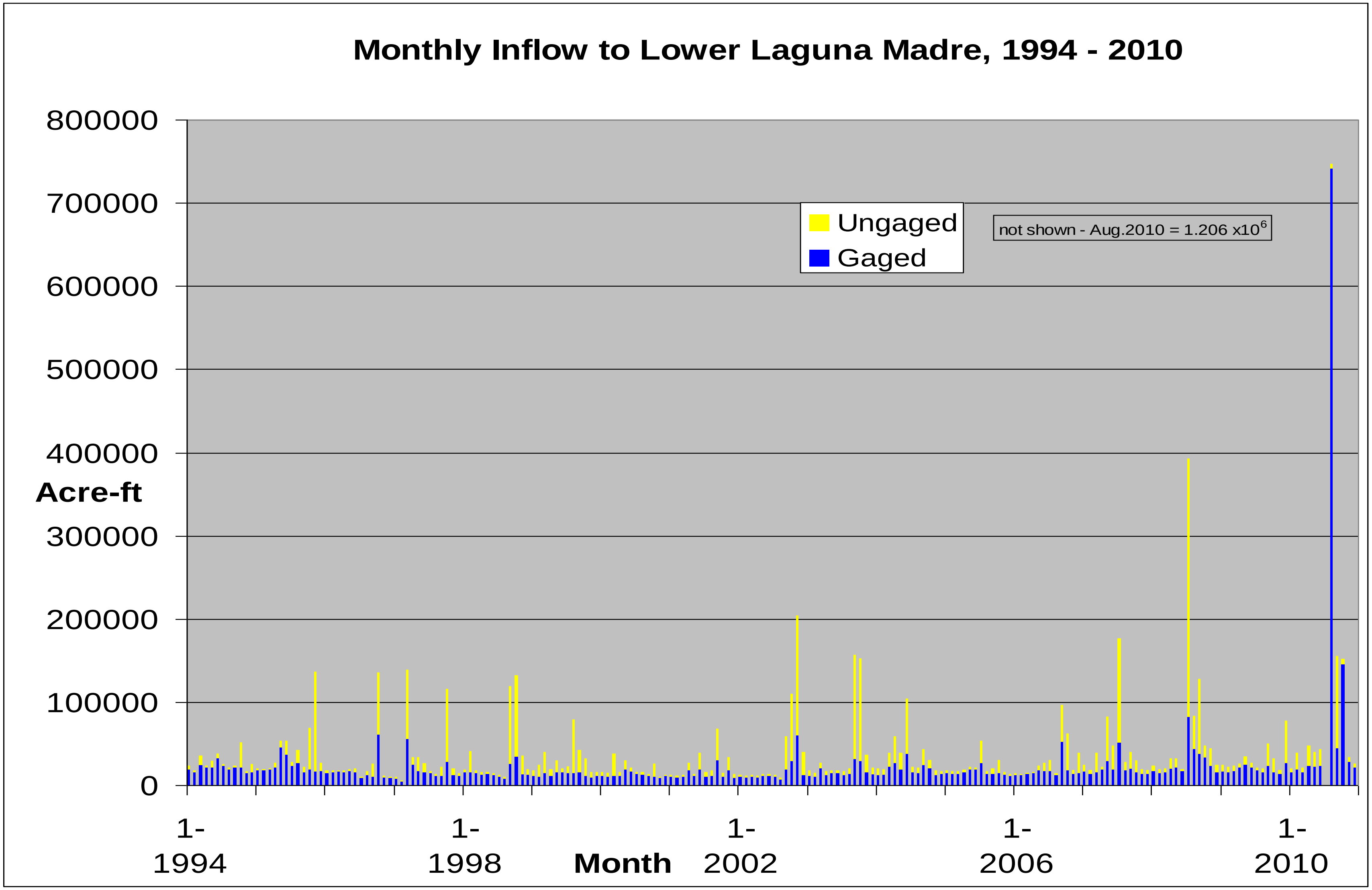
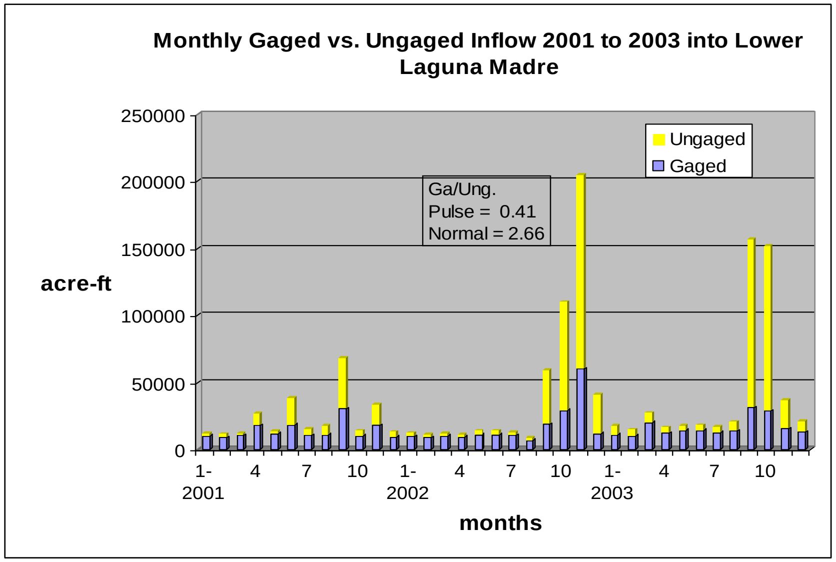


Figure 9.3.5. Monthly gaged and ungaged inflow to Lower Laguna Madre, 1994 – 2010 (data from TWDB).



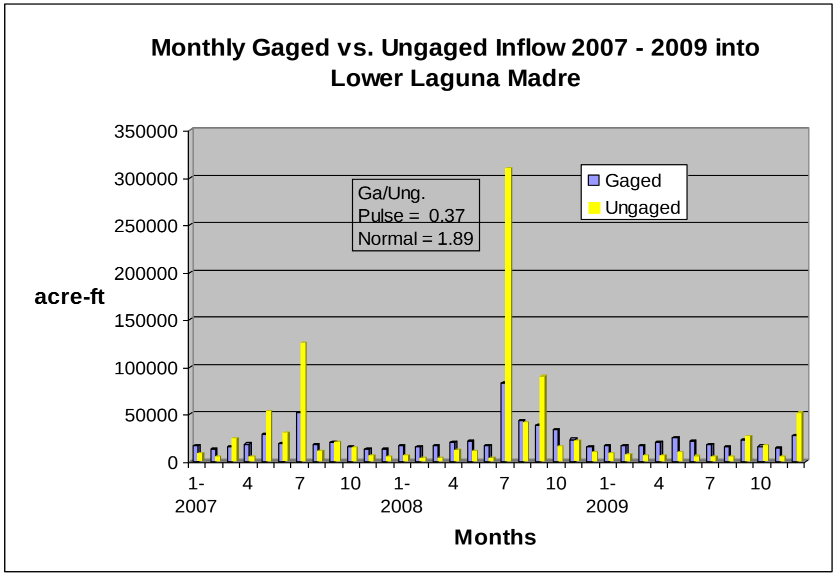


Figure 9.3.6. Separation of monthly inflows into gaged and ungaged flows for high flow years.

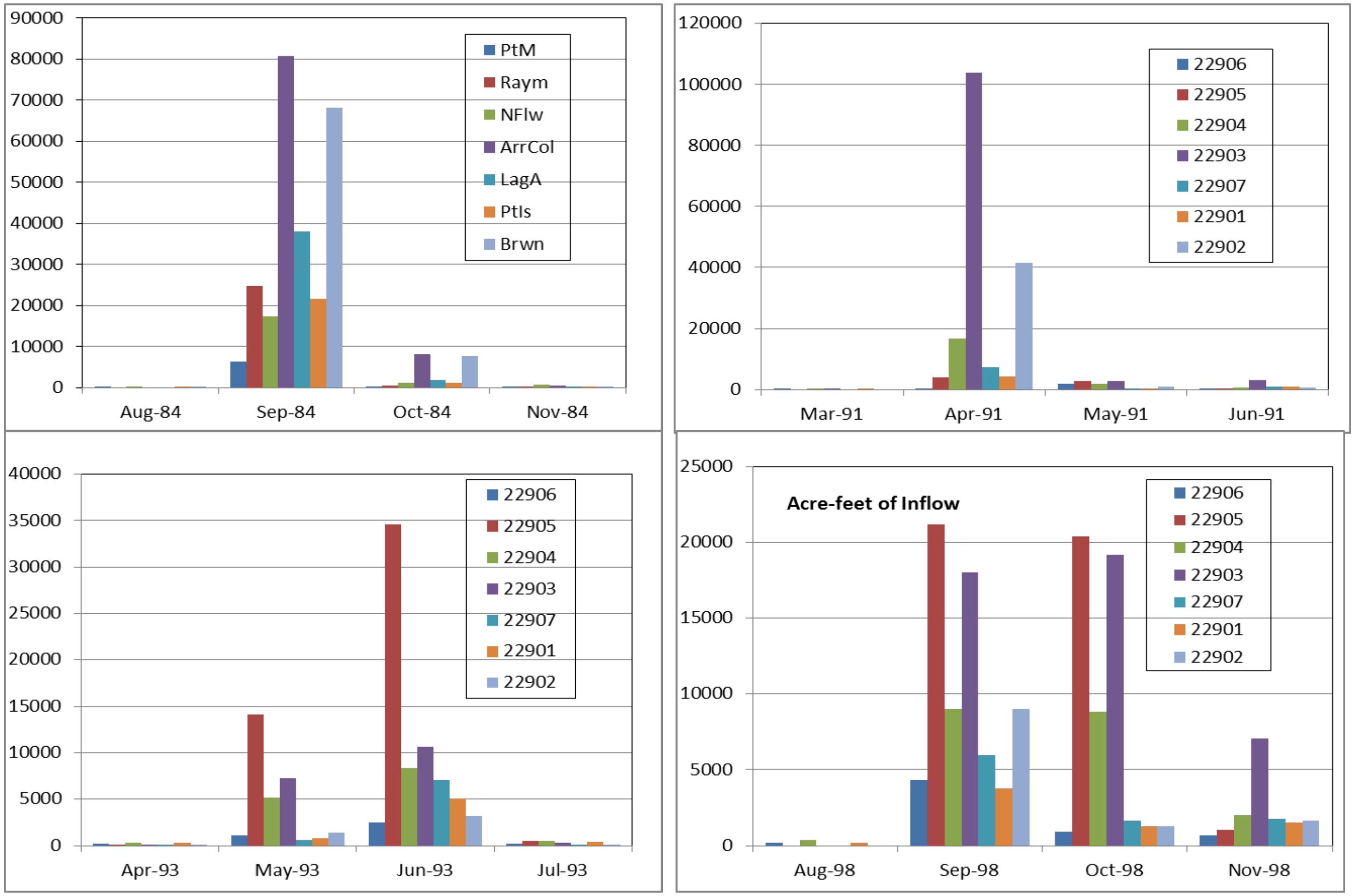


Figure 9.3.7. Volume of ungaged inflow pulses from seven LLM subwatersheds in 4 wet years. Legend numbers refer to ungaged subwatershed areas from Fig. IX.3 – 2. Top left figure uses local geographic names for subwatershed area numbers: PtM =Port Mansfield; Raym =Raymondville; NFlw =North Floodway; ArrCol =Arroyo Colorado; LagA =Laguna Atascosa; PtIs = Port Isabel; Brwn =Brownsville area

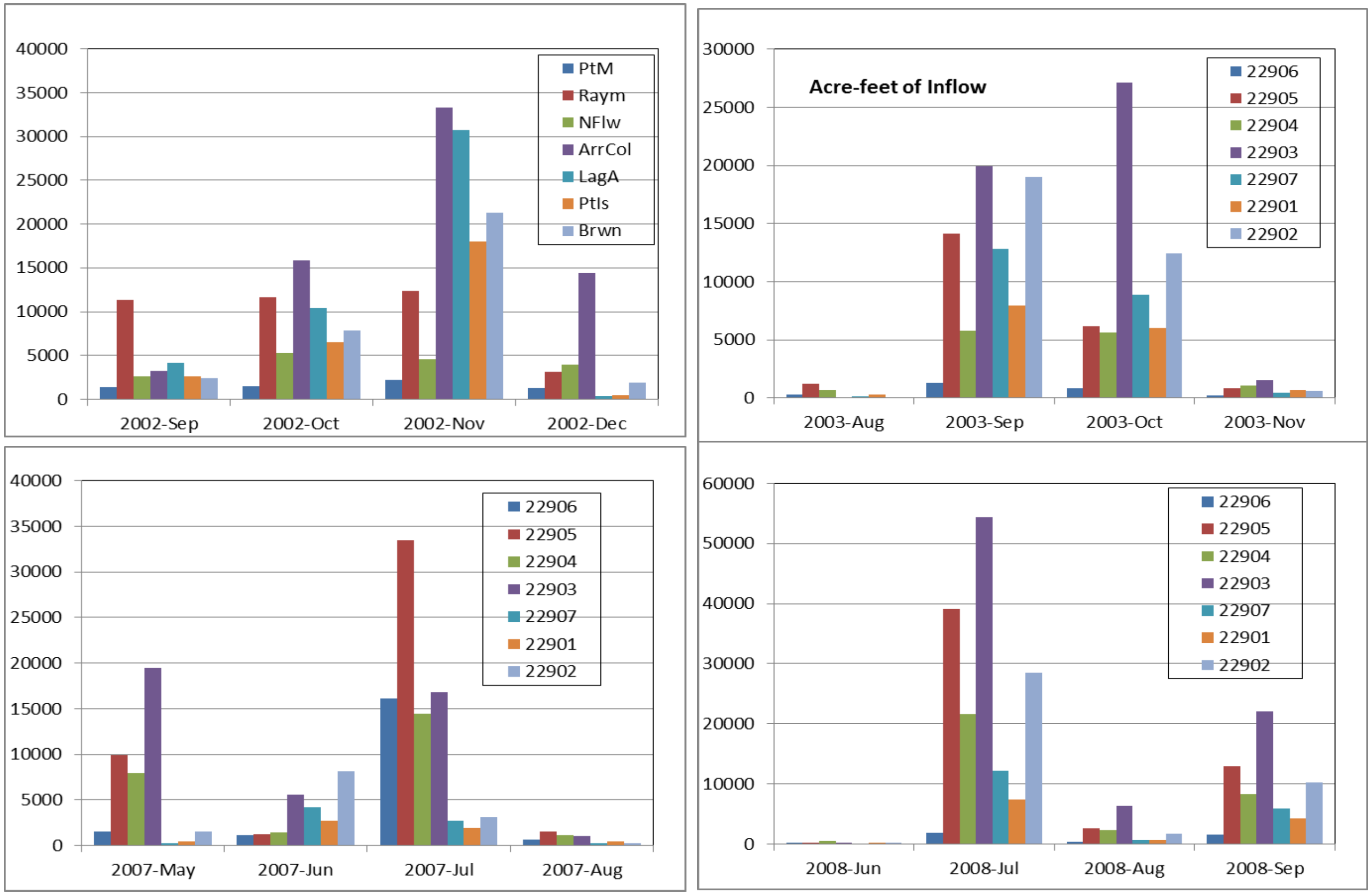


Figure 9.3.8. Volume of ungaged inflow pulses from seven LLM subwatersheds in 4 wet years. Legend numbers refer to ungaged subwatershed areas from Fig. IX.3 – 2. Top left figure uses local geographic names for subwatershed area numbers: PtM =Port Mansfield; Raym =Raymondville; NFlw =North Floodway; ArrCol =Arroyo Colorado; LagA =Laguna Atascosa; PtIs = Port Isabel; Brwn =Brownsville. area.

Figure 9.3.9. Ungaged discharge to Arroyo Colorado after local rainfall event May 2012.

Figure 9.3.10. Ungaged discharge to Arroyo Colorado after local rainfall event May 2012.

9.3.3. Salinity Plumes in LLM resulting from Freshwater Inflow Pulses

TxBLEND analyses were performed in order to demonstrate the effect of freshwater inflow pulses on the LLM salinity gradient. TWDB staff performed TxBLEND runs for the entire period of record (1978 – 2009) for which complete input data (i.e. all hydrology and weather data) were available. One notable year, 2010, was not included in the analysis due to lack of complete return and diversion data. After TxBLEND simulations were run for these 32 years, the salinity output from the model was taken and contoured in 2 psu increments to produce average monthly salinity maps of the LLM. The salinity contour maps were produced using a kriging technique by Lynne Hamlin of TPWD, similar to the analyses performed previously for the Guadalupe/San Antonio/Mission/Aransas Bays BBEST study (GSAMAC BBEST 2011). Based on the hydrographic record from **Figure 9.3.6**, a number of years were chosen which showed large inflow events to LLM. As described earlier, High Flow or Wet Years were categorized based on 2 to 3 monthly flows during that year above 100,000 ac-ft/mo : 1984, 1988, 1991, 1993, 1997-98, 2002, 2003, 2004, 2007, 2008, and 2010. Dry years were determined as 1986, 1987, 1989-1990, 1994, 2000, 2005, and 2009, with monthly flows less than 40,000 ac-ft. Other years with intermediate monthly flows (50-85,000 ac-ft/mo) were categorized as Avg inflow years (1982-83,1985, 1992, 1995-96, 1999, 2001, 2006, 2009).

After kriging was performed in 2 psu salinity increments, distinctly lower salinity plumes could be delineated in the LLM during mainly Wet years (**Figure 9.3.9** through **9.3.11**). Often, these plumes emanated from the Arroyo Colorado (1991, 2002, 2008) then moved northward towards the Port Mansfield area, and plumes persisted for at least 3 months. However, in one year (i.e., 2004, a wet yr), a large low-salinity plume was observed, which originated at the extreme southern end of the LLM and spread northward in Apr – June. No significant plumes were observed when salinity data for Dry years were examined (**Figure 9.3.10**, year 2000; data available but not shown for 1994 or 2009). When Avg (intermediate) years were examined (**Figures 9.3.10** and **9.3.11**), plumes were more variable; but more of them seemed to emanate from the lowermost part of the LLM. In addition, three Avg years (1997, 1998, 2006) showed multiple plume events during the year, one in spring and another in fall.

A series of sensitivity test scenarios were performed with 3 of the wettest years (1991, 2002, and 2008) to determine the dependence of plumes those years on total inflow. The total inflow for those years input to the TxBLEND model was reduced by 25% and 50% of the actual amount observed for those particular years, and additional TxBLEND scenarios were rerun (**Figures 9.3.12** to **9.3.14**). This resulted in 50 % reductions of peak monthly flow pulses as follows: (1) <u>Year 1991</u>: May peak reduced from 248,000 ac-ft to 124,000 ac-ft; (2) <u>Year 2002</u>: Oct. peak reduced from 208,400 ac-ft to 104,000 ac-ft; (3) <u>Year 2008</u>: July peak reduced from 396,000 ac-ft to 198,000 ac-ft. The decreases in flows changed the full inflow salinity gradient in the LLM over that year, and produced smaller and smaller plumes under the reduced scenarios. However, until flows were decreased below *ca* 100,000 ac-ft per month, the plumes were still distinct for 2 months, although their extents were greatly reduced (see Figures 3.2.12for 1991, Figure 9.3.14for 2008). In all 3 years, salinities still dropped to 28 psu or less for 1-2 months at the reduced flow. This helps corroborate the dependence for flows above 100,000 ac-ft per month needed to produce inflow plumes that would have major impact on salinities at 2 psu increments.

Significance of Salinity Plumes: Total Pulse Amount and Patterns

We interpreted these data to mean that inflows often enter the LLM in the middle part of the LLM (in the vicinity of the Arroyo Colorado e.g., 1991, 2002, 2008), then salinity plumes usually move further northward toward Port Mansfield and past Mansfield Channel. However, in one year (i.e., 2004 a wet yr), a large low-salinity plume was observed, which originated at the extreme southern end of the LLM and spread northward in Apr – June, until lowering the entire LLM salinity to the 26-28 psu range. In 2006, an intermediate flow year, another large plume began at the southern end and moved all the way northward. Generally, large inflows above 100,000 ac-ft per month produced significant salinity plumes of 2 psu increment differences in LLM water, and these plumes lasted for over 2 months. Although lower inflows per month produced shorter duration plumes, these flows were considered functional for hydrodynamic effects on the system. Average flow years (e.g., 1999, 2006) are good examples of this dynamic.

While we have examined salinity plumes to follow the dynamics of inflows, salinity is considered to be a proxy for other materials in the discharge plumes. The other two main components in inflows, namely nutrients and sediments, have been suspected for impacting seagrasses (Custer and Mitchell 1991; Quammen and Onuf 1993). The effects of these water quality constituents on seagrass tend to be indirect and require long-term, tedious monitoring to detect. As will be discussed shortly, more sophisticated techniques such as stable N isotope ratios ($\delta^{15}N$) and C:N:P ratios of seagrass tissue should be used.

Spatial Relationships between Salinity Plumes and Seagrass Changes

These TxBLEND salinity maps were used to correlate water quality zones under known inflow regimes with seagrass distribution and corresponding changes in seagrass. **Figures 9.3.15** through **9.3.17** (below) present overlays to demonstrate these spatial relationships. **Figure 9.3.15** shows the seagrass distribution in 2005 overlaid with the 2004 salinity map, while **Figure 9.3.16** shows seagrass distribution in 2009 with the 2008 salinity map. These overlays would be expected to show potential effects from large pulse inflows in the preceding 6 months (summer 2008) to 16 months (spring 2004) on seagrass distributions in Jan. 2009 and Oct. 2005, respectively. **Figure 9.3.17** shows the seagrass loss-gain change analysis over the 5 years between 2005 and 2011 and the 2008 salinity map. In this latter case, the 2008 salinity map is merely used for demonstration purposes, as a similar salinity map for 2010 would be more appropriate, but 2010 TxBLEND output data were not available.

These spatial overlays indicate that many areas where seagrass has declined, in fact, correspond to where lower-salinity inflow plumes remained stationary for 2 – 3 months in these higher flow years. This 2-3 month period would certainly be sufficient to expose seagrasses to higher nutrient conditions, and stimulate phytoplankton, macroalgal and epiphyte growth, which in turn would reduce water transparency and light conditions over the seagrass. If salinities were simultaneously reduced to around 20 psu or lower, then salinity would pose an extra stress on the seagrass. Most of these areas are where species composition also changed, and *Thalassia* and *Syringodium* in fact have disappeared (DeYoe et al, pers. comm.). Whether these latter two species return or are replaced by *Halodule* in time, remains to be seen (see **Section 9.2.3**).

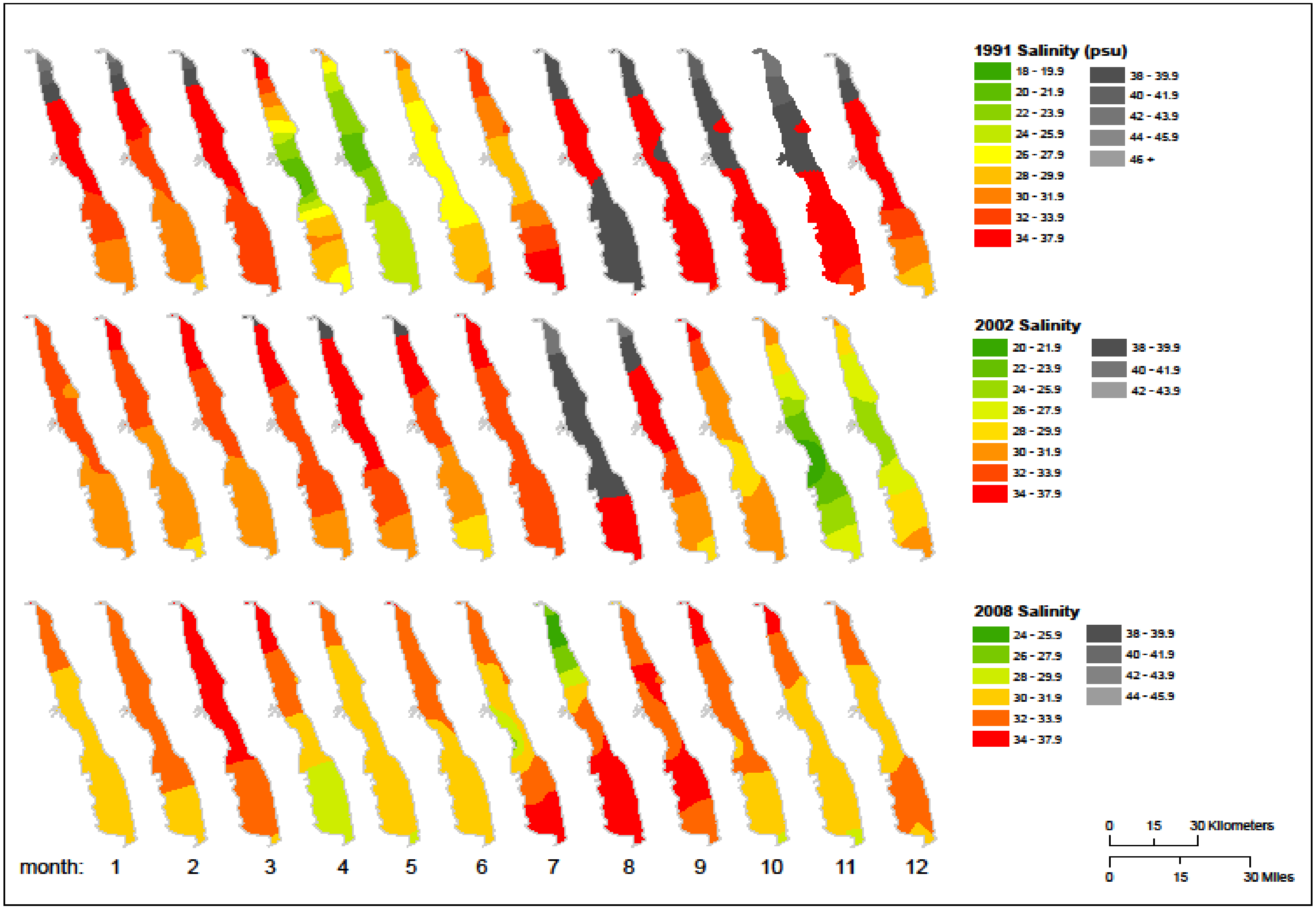


Figure 9.3.9. Salinity plumes during 3 Wet years (courtesy of L. Hamlin, TPWD).

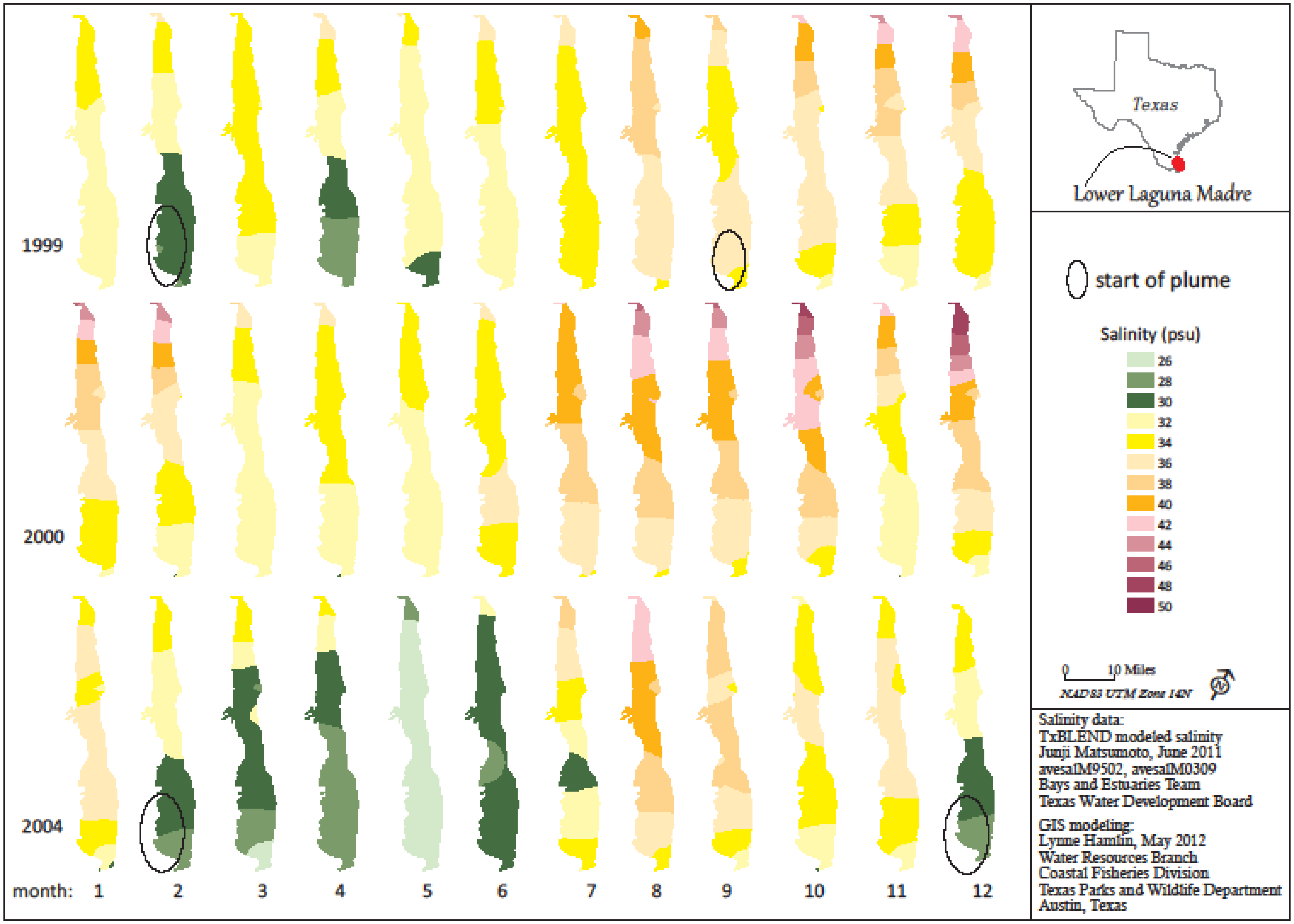


Figure 9.3.10. Salinity plume maps for LLM for 1999 Avg year, 2000 Dry year, and 2004 Wet year

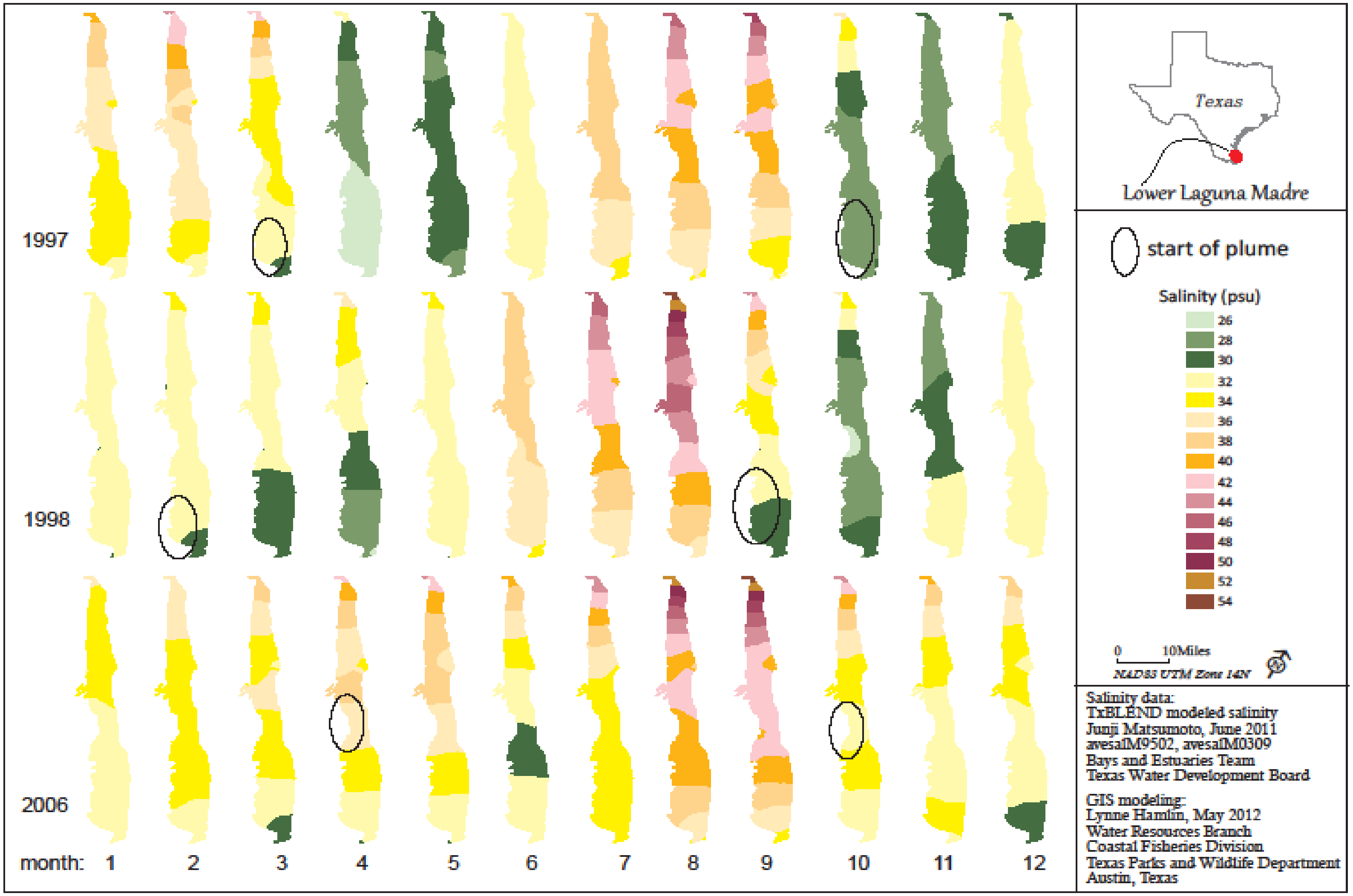


Figure 9.3.11. Salinity plume maps for LLM observed during three intermediate or Avg flow years

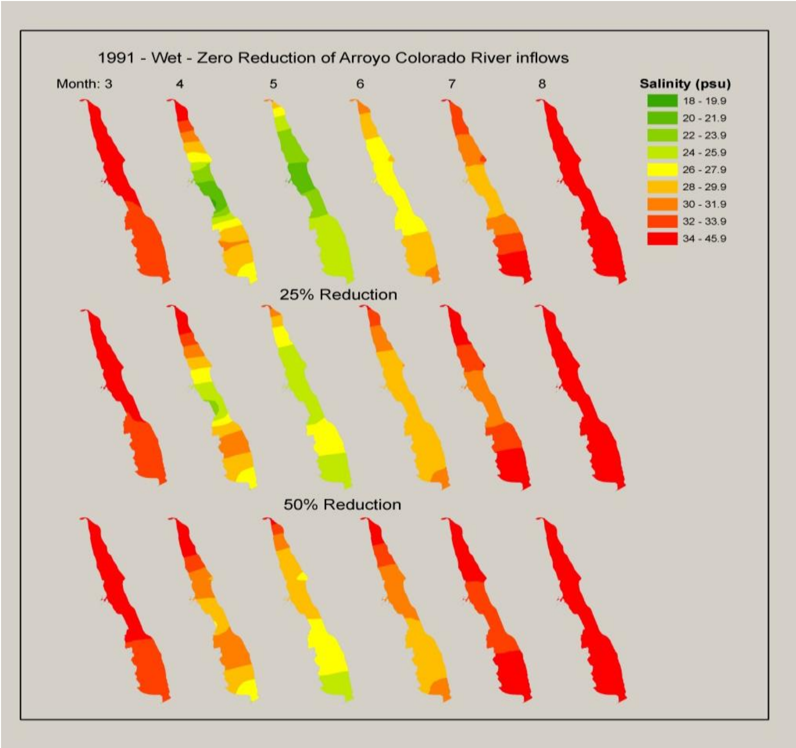


Figure 9.3.12. Salinity plume maps for LLM, 1991 (Wet year)

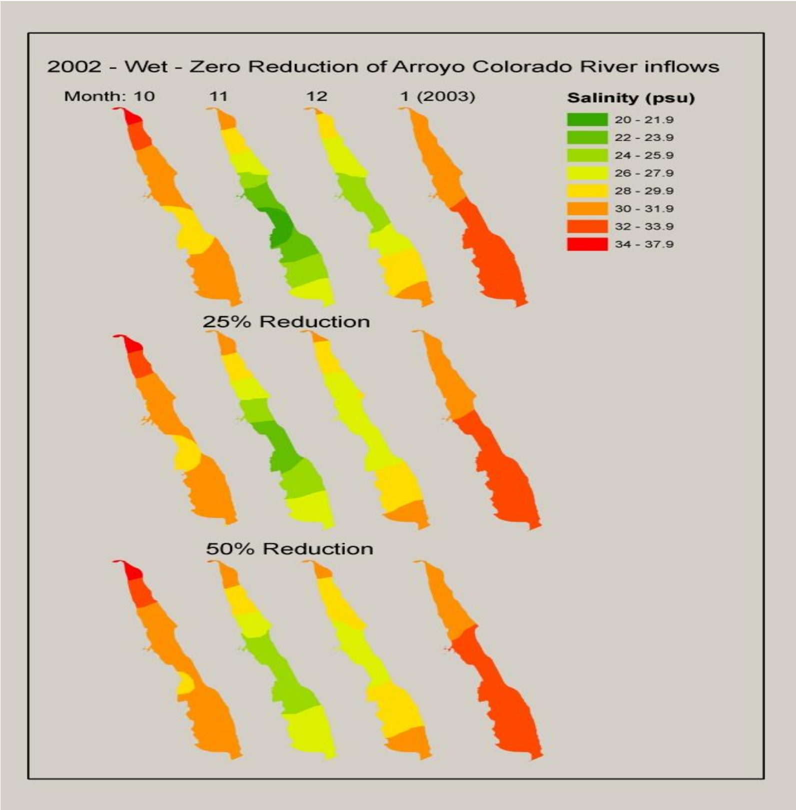


Figure 9.3.13. Salinity plume maps for LLM, 2002 (Wet year).

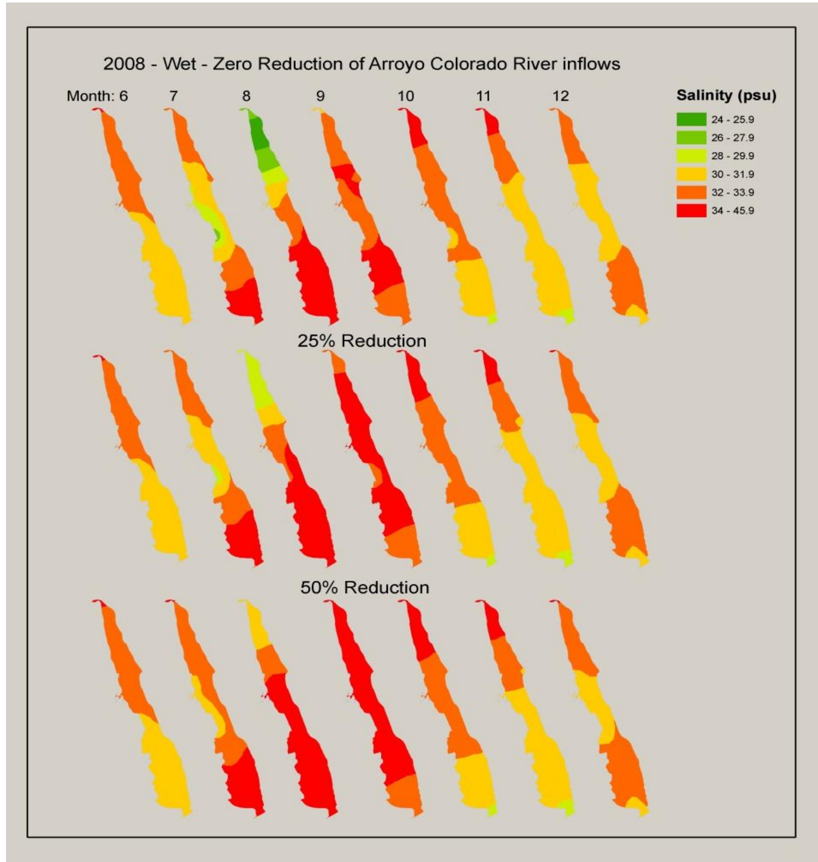


Figure 9.3.14. Salinity plume maps for LLM, 2008 (Wet year).

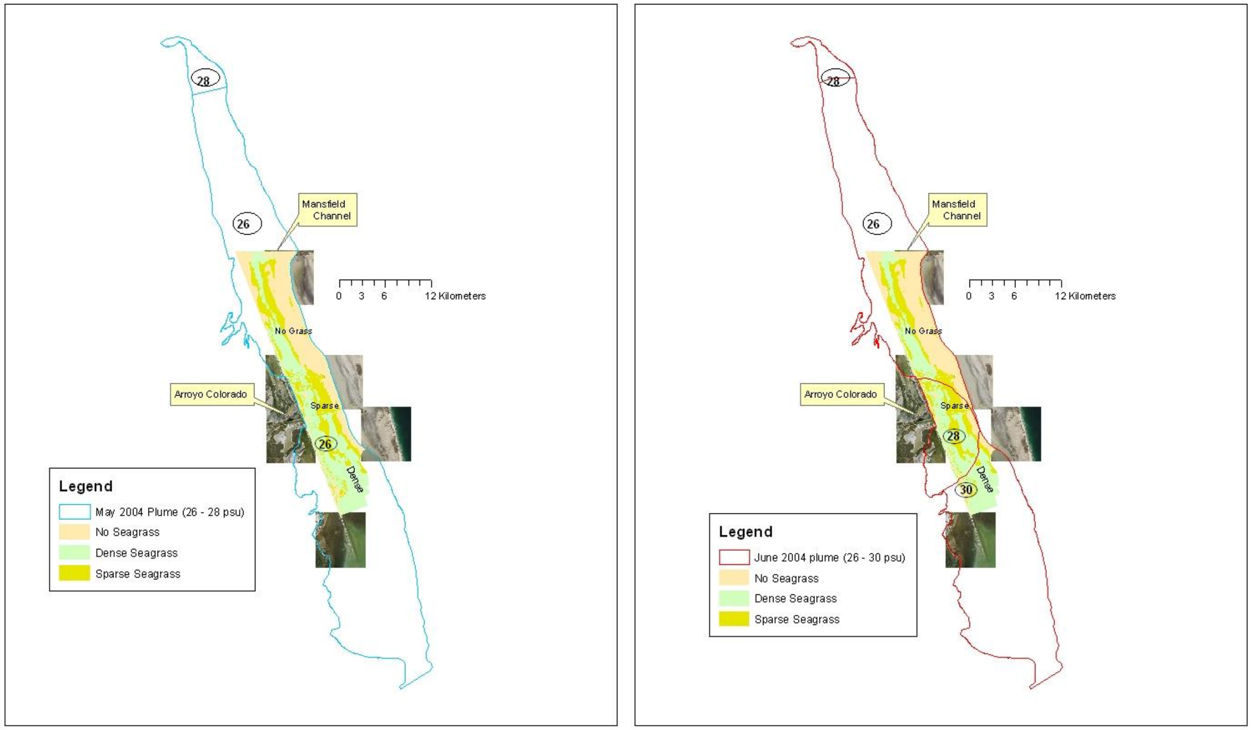


Figure 9.3.15. Salinity plumes in 2004 overlaid onto 2005 seagrass map.

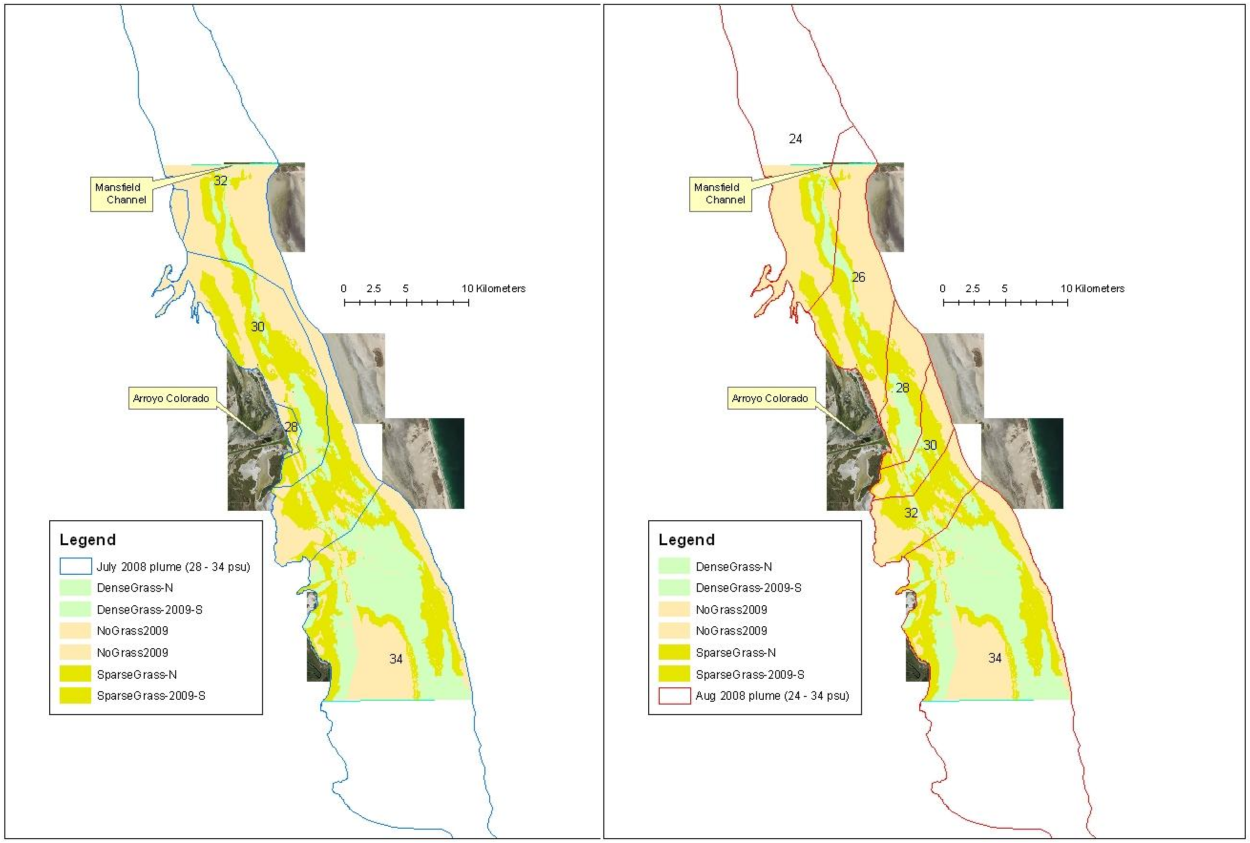


Figure 9.3.16. Salinity plumes in 2008 overlaid onto 2009 seagrass map.

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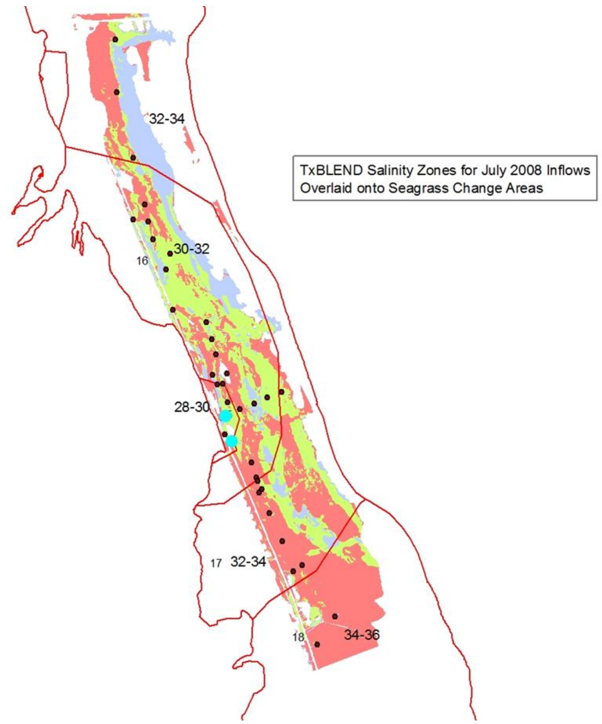


Figure 9.3.17. Salinity plumes in 2008 overlaid onto seagrass change map,between 2005 to 2011. Blue = Gain, Red = Loss, Green = no change in seagrass.

9.4 Tracking Arroyo Colorado Nitrogen into the LLM

9.4.1. Introduction

Impacts from the Arroyo Colorado, the major gaged source of LLM freshwater (**Section 2**), are a major concern as a factor causing some of the observed seagrass changes. For the most part, this concern is directed towards nutrient loading, due to the Arroyo's role in draining wastewater and agricultural return flows from the LRGV to the LLM (TCEQ, 2006). The Arroyo has been the target of TMDL assessment and regulatory action for the past decade (TCEQ, 2006) for oxygen depletion in part due to high algal densities fueled by high nutrient levels. Ambient nutrient levels in the Arroyo are higher than in the Laguna Madre (**Table 9.2.1**) and higher nutrient loading occurs with higher inflow conditions (See **Section 8**). Recent monitoring surveys of salinity and nutrient loading parameters have been undertaken, in combination with changes in seagrass biomass and macroalgae

Monitoring seagrasses as indicators of water quality degradation has the main objective of detecting sub-lethal seagrass impacts prior to bed-scale, physical loss of seagrass cover. In the case of LLM seagrass, effects of nutrient addition on seagrasses may be positive or negative depending on quantities (see **Section 9.2.3**). If nutrients (N or P) are limiting, there may be an increase in seagrass production with increases in nutrients or the relative abundance of seagrass species may change. Alternatively, added nutrients may decrease underwater light for seagrass due to reduction in water clarity from enhanced phytoplankton growth or by encouraging the growth of epiphytes on seagrass leaves. In addition, added nutrients may lead to growth of macroalgae (seaweed) resulting in drifting macroalgal mats that can smother seagrasses. Thus, it is considered important to determine the nutrient loading potential for the Arroyo Colorado inflow plumes under a range of flows, from low to high (<267 to >1000 acre-ft/day), and during different seasons (see **Section 8**).

We began an investigation to determine seagrass changes in the LLM over the last 10 years and whether the Arroyo Colorado is a main driver of change through its impact on LLM water quality. In order to estimate the zone of influence of Arroyo inflows on LLM water quality, we applied the Texas Water Development Board TxBLEND hydrodynamic model to visualize spatial and temporal changes in LLM salinity of the LLM-Arroyo confluence area as the Arroyo inflows change. The previous data correlate the salinity spatial patterns (plumes) determined from the TxBLEND model with changes in seagrass coverage and species' distributions. These salinity plume patterns could potentially reflect other water quality parameters such as concentrations of dissolved nutrients (N and P).

Based on water quality data from TCEQ and flow data from the USGS for the Harlingen gage, average seasonal daily nutrient loading rates were calculated (Table IX.4-1). Average annual nutrient loading rates from a 1995 TGLO Arroyo study were also obtained for a tidal site near the confluence of Arroyo with the LLM (TGLO 1995): DIN (dissolved inorganic nitrogen) was 1117 kg N/day and total phosphate was 450 kg P/day. Even though different data sets were used, the nutrient loading rates estimated by these two studies are similar. The Arroyo contributes significant amounts of nitrogen and phosphorus to the LLM and nutrient loading rates tend to be higher in winter (Dec-Feb) and spring (Mar-Jun) than summer (Jul-Sep) and fall (Oct-Nov). This occurs despite the fact that high flow events in the Arroyo are more likely to occur in the summer and fall. Besides flow, other factors could affect nutrient loading rates such as temperature (water and air) and agricultural fertilization and irrigation activity.

There are various possible fates of Arroyo nutrients (N and P) once they enter the LLM. Nutrients could be taken up by bacterioplankton, phytoplankton, benthic microalgae, macroalgae, seagrass epiphytes and/or seagrasses. In addition, LLM sediment can absorb and retain nutrients, nutrients can pass out of the system to the Gulf of Mexico or nitrogen can be lost to the atmosphere through denitrification. As mentioned earlier, stimulation of the growth of phytoplankton, seagrass epiphytes and/or drifting macroalgae can negatively impact seagrass by depriving them of light so it is important to know where nutrients go once they enter the LLM. Nitrogen is of special interest in marine ecosystems as nitrogen is typically found to be limiting. In the LLM, nitrogen was found to be limiting for turtle grass, *Thalassia testudinum* (Lee 1998; Lee and Dunton, 2000).

Nitrogen isotopes have been used as a tool over the past 30 years to track the fate of nitrogen in aquatic systems (Costanzo et al. 2001; Oczkowski et al. 2008). In this method, two stable isotopes of nitrogen, ^{14}N and ^{15}N with the former being more abundant, are used to identify sources of nitrogen because the ratio of ^{15}N to ^{14}N is distinctive for different sources (**Figure 9.4.1**). For example, sewage nitrogen is enriched in ^{15}N while fertilizer nitrogen is not. In practice, the ratio of $^{15}N/^{14}N$ in the material is compared to a world-wide standard and the relative amount of ^{15}N or $\delta^{15}N$ is calculated as follows:

$$\delta^{15}N(_{0/00}) = (Rsample/Rstandard-1) \times 10^{3}$$

Table 9.4.1. Average seasonal daily loading rates of dissolved inorganic nitrogen (DIN) and total phosphate (TP) at the Port of Harlingen based on TCEQ water quality data from 1978 to 2009 and IBWC gage data at Port of Harlingen.

	Flow 5-day			Avg	SD	Avg	SD	Avg
	avg	DIN	TP	DIN Load	DIN Load	P Load	P Load	Load N/P ratio
	acre-ft/day	n	n	kg/day	kg/day	kg/day	kg/day	(molar)
Winter	427.5	38	11	1380	1962	496	347	6.4
Spring	569.4	46	7	1319	1579	924	1094	3.3
Summer	446.8	46	10	990	1935	344	78	6.6
Fall	548.3	31	8	957	1045	716	736	3.1

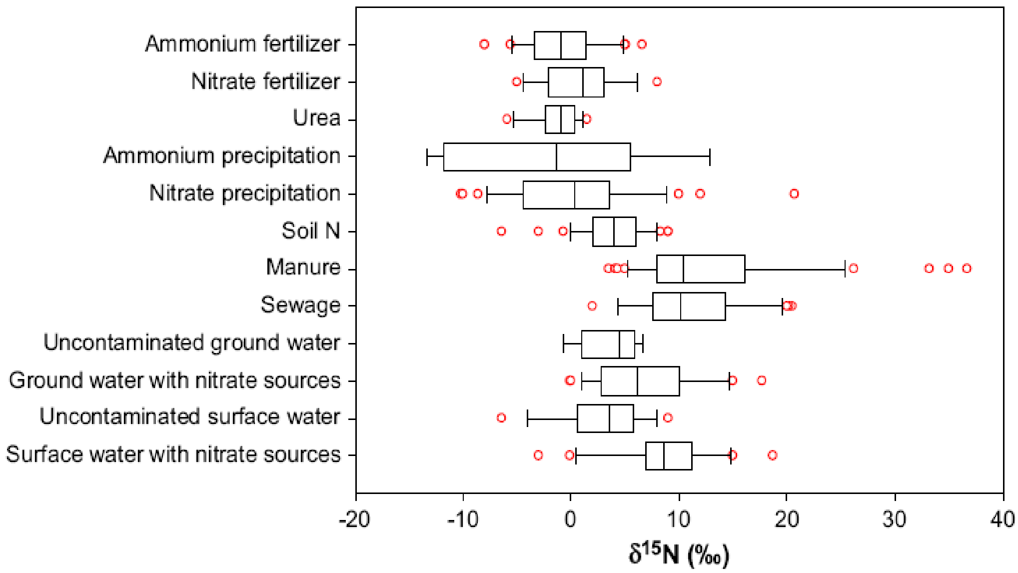


Figure 9.4.1. The range in $\delta^{15}N$ values for a variety of nitrate sources and sinks. Box plots illustrate the 25th, 50th and 75th percentiles; whiskers indicate the 10th and 90th percentiles; circles are outliers. From Xue et al. (2009).

To assess the fate of Arroyo nitrogen in the LLM, we collected different kinds of primary producers at varying distances from the Arroyo Colorado and analyzed them for their isotopic nitrogen content. It is expected that the high $\delta^{15}N$ values of the Arroyo due to sewage input would diminish as one moves away from the Arroyo and that the decreasing trend should be more abrupt going south from the Arroyo due to the general movement of Arroyo water northward caused by prevailing southeasterly winds.

9.4.2. Methods

On August 18, 2011, 27 sites arrayed along a N-S transect and an E-W transect (Fig. IX.4.2) were visited for collection of seagrass (*Halodule wrightii*), macroalgae (mostly *Palisada poiteaui*), and seagrass epiphytes. The tissue samples were rinsed, cleaned, dried, ground and then analyzed for C and N content and stable C and N isotope ratios by the University of Alaska Fairbanks Stable Isotope Laboratory. Total phosphorus (TP) content of tissue was measured by the method of Solorzano and Sharp (1980) at the UTPA DeYoe lab. In addition to the August 2011 samples, archived samples of seagrass and algae collected during other studies were also analyzed as above.

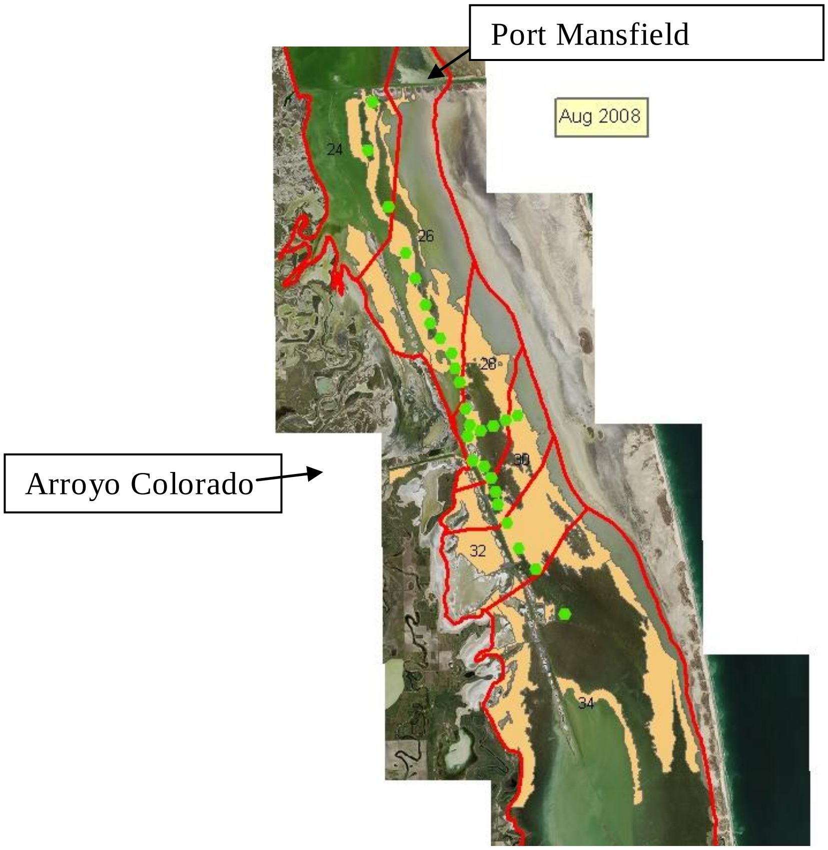


Figure 9.4.2. Green dots represent the sites in the Lower Laguna Madre visited on August 18, 2011 for collection of seagrass, drift algae and seagrass epiphytes analyzed for N isotopes. This isotope sampling design was laid out according to 2008 salinity plumes (red polygons in figure) observed as output from TxBLEND hydrodynamic modeling.

9.4.3. Results and Discussion

$\delta^{15}N$ values of primary producers were expected to be high in and near the Arroyo Colorado due to a significant amount of the Arroyo nitrogen being derived from wastewater treatment plants having a high $\delta^{15}N$ value. Periphyton (attached microalgae) collected from the Arroyo as expected had very high $\delta^{15}N$ values (**Table 9.4.2**).

Table 9.4.2 $\delta^{15}N$ values of periphyton collected from two sites in the tidal segment of the Arroyo Colorado. River Ranch is nearer Rio Hondo while Thomae Park is downstream and nearer the confluence of the Arroyo and LLM.

Collection Date	Site	Type	$d^{15}N$ (o/oo)
4/22/2011	River Ranch	periphyton	10.48
4/22/2011	Thomae Park	periphyton	12.47
8/02/2011	River Ranch	periphyton	16.90
8/02/2011	Thomae Park	periphyton	16.87

In the LLM, along the N-S transect $\delta^{15}N$ values were lower than Arroyo periphyton values and there was no discernible spatial trend in seagrass $\delta^{15}N$ values which ranged from 2 to 7 (**Figure 9.4.3**). Data for the seaweed, *Palisada. poiteauii* and the *Halodule* epiphytes (not shown) also did not show a trend along the N-S transect and did not match the N-S pattern seen for *Halodule*. All three data sets had low $\delta^{15}N$ values at the northernmost site near the Port Mansfield Pass suggesting little Arroyo influence in this area of the LLM. Part of the reason that the August 2011 N-S transect may lack a clear trend is that the North Floodway carries runoff and treated effluent to the LLM like the Arroyo but enters the LLM about 7.5 km (4.6 mi) north of the Arroyo so the influence of the inflow is spread over a wider area becoming more diffuse. In fact, there is a subtle increase in $\delta^{15}N$ values from 10 to 15 km north of the Arroyo before declining to the lowest value seen near the Mansfield Pass. In August 2011 as typical for the warmer months, water flows northward in the LLM which would spread inflow from the Arroyo and the North Floodway northward.

In contrast, the isotopic signatures along the E-W transect did show a distinct decreasing trend from west to east for the seagrass and a discernible but less pronounced trend for the seaweed and the seagrass epiphytes (**Figure 9.4.4**).

The archived seagrass samples collected along a N-S transect show a trend of increasing $\delta^{15}N$ values closer to the Arroyo (**Figure 9.4.5**). These transects had fewer sites but extended about 30 km further south than the August 2011 transect data which may explain why a more noticeable trend is seen. The 2007-08 *Halodule* data also indicates that the nitrogen isotopic signature of the Arroyo can be seen during most seasons of the year.

As expected, a dilution effect of the Arroyo nitrogen is seen as $\delta^{15}N$ values of the LLM primary producers are lower than those for the periphyton that was collected in the Arroyo Colorado. The east-west transect data (Fig. IX.4-4) and the archived sample data (**Figure 9.4.5**) indicates that nitrogen from the Arroyo is being utilized by primary producers (seagrass, seaweed and seagrass epiphytes) in the LLM. The 2011 N-S transect data lacks a clear trend most likely due to the diffuse distribution of nitrogen along the N-S transect.

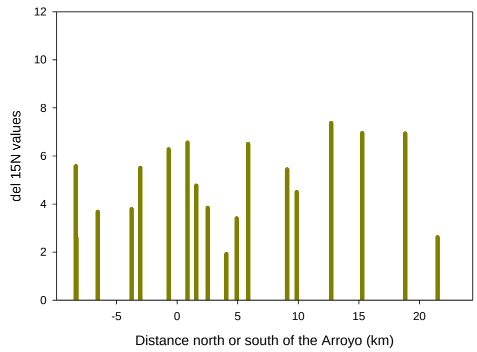


Figure 9.4.3. $\delta^{15}N$ values for the seagrass *Halodule wrightii* collected from the LLM along the north-south transect at varying distances from the Arroyo Colorado (at 0 km) on 18 August 2011. Negative values are south of the Arroyo while positive numbers are north of the Arroyo.

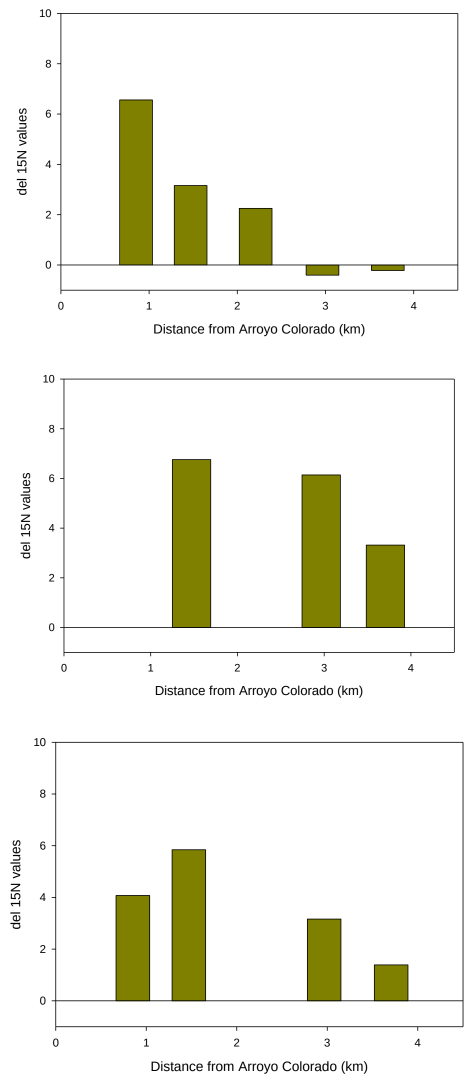
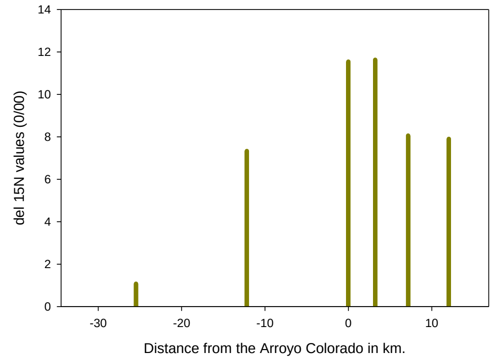


Figure 9.4.4. $\delta^{15}N$ values of the seagrass *Halodule wrightii* (top), the macroalgae *Palisada poiteauii* (middle) and epiphytes from *H. wrightii* (bottom) collected on August 18, 2011 in the LLM along the west to east transect starting near the Arroyo Colorado confluence.



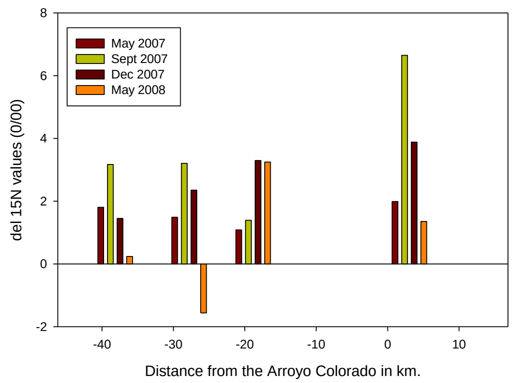


Figure 9.4.5. δ^{15}N values of the seaweed *Palisada poiteauii* (top) and the seagrass *Halodule wrightii* (bottom) collected from the LLM along a north-south transect in 2004 and 2007-08, respectively. Negative values along the X-axis indicate sites south of the Arroyo while positive numbers indicate sites north of the Arroyo Colorado.

From the above discussion, we have shown that significant amounts of Arroyo nutrients enter the LLM where they are utilized at least locally by several kinds of primary producers including seagrass epiphytes, drift algae and seagrass and likely by plankton (phytoplankton and bacterioplankton). Plankton and epiphyte growth stimulated by nutrient additions (**Table 3.2.1** and **Figure 3.2.2**) can reduce available light for seagrass thereby lowering seagrass production rates (**Figure 3.2.1**). Drift algae growth if excessive can produce thick mats overtopping seagrass. If a drift algae mat stays in one place too long it can lead to seagrass loss due to light deprivation (Peckol and Rivers 1996) and/or toxic sediment hydrogen sulfide effects (Holmer and Bondgaard 2001). Unfortunately with the data available, we cannot identify critical nutrient loading rates that produce levels of algae harmful (due to light limitation) to seagrass.

The timing of nutrient additions to the LLM is important as additions during cooler months will not likely have as much of an effect as additions during warmer months because algal and plant growth rates in winter are depressed as they are more a function of the cooler temperatures than nutrient levels. N loading rates are about 25% higher during winter and spring compared to summer and fall (**Table 9.4.1**). This regime would allow seagrass and drift algae to take up and store nitrogen (due to their large size) during cooler months with less competition from plankton and epiphytes. Plankton and epiphytes would likely compete more effectively for summer and early fall nutrient additions due to their small size and potential for rapid growth. The point is, nutrient additions would likely have a more detrimental effect on seagrass during summer and fall than winter or spring due to the greater potential for light reductions caused by rapid growth of plankton and epiphytes. As noted above, drift algae can also have detrimental effects on seagrass but their ability to respond to nutrient additions is slower than the plankton and epiphytes due to their slower growth rates.

Large precipitation events like tropical storms create a more complicated scenario as they can bring in large quantities of freshwater as well as extra nutrients during warmer months. Lowered salinity will, in general, depress metabolic activity of primary producers but the effect is a function of the duration, rapidity and magnitude of the salinity drop as well as the acclimation ability of the organism. Also the severity of the impact can vary with different seagrass species as each has its own salinity tolerance range (see **Section 9.2**). If the salinity drop is severe as with Hurricane Alex in 2010, seagrass will then die, which can alter the entire ecosystem. The impact of the 2010 hurricane on the LLM has not been well-studied.

9.5. Integration of Flow Regimes and Seagrass Impacts

9.5.1. Summary of Water Quality and Inflow Relationships

Direct Salinity Impacts

From examination of salinity records over 32 yrs (see TPWD data in **Section 3**, **Figures 3.2.4** and **3.2.5**), the salinity regime in the middle to northern reaches of LLM has dropped down into the 15 - 20 psu range a number of times. These were summer and fall during the years of 1984, 1993, 1997, 2002, 2003, 2004, 2008, and 2010. These lower readings are significant because they reflect lower average salinity conditions over 2-3 months of usually warm to hot seasons. *Thalassia* and *Syringodium* would be especially stressed during 2-3 months of low to mid-20s psu conditions. For the 2010 summer/fall period in particular, the especially low salinities of < 10 psu observed by DeYoe over that 6-month period were certainly able to kill *Thalassia* and *Syringodium* in the areas where seagrasses totally disappeared. During other periods, even decreases to the low-20s psu range accompanied by higher nutrient loads will be problematic such as during 2002-2004 or Hurricane Dolly of 2008.

Examination of the historical inflows record (**Table 9.5.1**) allows an identification of the actual values of monthly pulse flows during Wet years that produce stressful or deleterious lowered salinity conditions for seagrasses in the LLM for: 1984, 1988, 1991, 1993, 1995, 1997, 1998, 1999, 2002, 2003, 2004, 2006, 2007, 2008, and 2010.

Table 9.5.1 provides pulse flow volumes (in ac-ft) during High-flow years and 4 Intermediate-flow years (highlighted). Mean salinities occurring in northern (N) and southern (S) zones of LLM (see **Figure 3.2.2**) during the inflow pulses are derived from TPWD Fisheries Monitoring data.

Table 9.5.1. Pulse flow volumes (in ac-ft) during High-flow years and 4 Intermediate-flow years (highlighted). Mean salinities occurring in northern (N) and southern (S) zones of LLM (see Fig. III.2 – 2) during the inflow pulses are derived from TPWD Fisheries Monitoring data.

Year	Pulse Month(s)	Pulse Flows Range	Total Pulse Amt	Mean psu (N/S)
1984	Sept-Oct	49,600 – 316,000	365,570	16.6 / 23.6
1988	Sept-Oct	31,000 – 203,000	234,000	23.3 / 36.2
1991	Apr - May	48,380 - 248,800	297,183	16.4 / 26.7
1993	May- June	76,100 – 186,590	262,687	19.0 / 30.5
1995	May – Jun	53,725 – 53,721	107,450	30.7 / 35.3
1995	Oct – Nov	68,834 – 136,433	168,840	25.4 / 31.5
1996	Sept-Oct	25,800 – 136,024	161,820	21.9 / 33.0
1997	Mar		139,080	19.7 / 30.3
1997	Oct		115,537	17.9 / 24.5
1998	Sept – Nov	119,747 – 131,891	288,622	24.7 / 26.2
1999	Aug-Sept	79,423 – 42,444	121,867	23.4 / 36.9
2002	Sept – Nov	63,148 - 208,406	385,623	25.4 / 27.8
2003	Sept – Nov	162,951 – 40,825	362,518	20.5 / 27.8
2004	Apr – Jun	61,218 – 106,649	209,695	21.2 / 32.3
2006	Sept – Oct	67,468 - 102,500	169,963	28.7 / 37.8
2007	May – Jul	84,835 – 180,296	316,000	25.4 / 33.7
2008	June – Oct	396,000 – 51,157	665,200	19.5 / 29.4
2010	July – Oct	152,200 – 1,402,300	2,456,700	6.8 / 21.5

After reviewing these pulse flow amounts and corresponding salinity regimes produced in the mid-LLM, it appears that cumulative 2-3 month inflow pulses of >200,000 ac-ft, with a 1 month peak flow exceeding 115 – 150,000 ac-ft, regularly produce salinity zones of < 24 psu in the mid-LLM. These conditions are then predicted to cause moderate salinity stress on especially *Thalassia* and *Syringodium*. At higher flow levels (200 - 300, 000 ac-ft per month), salinities will decrease to << 20 psu, causing severe stress and eventually seagrass death. At moderate flow levels of < 100,000 ac-ft per mo, added stress from increased nutrient loading is predicted to become a synergistic factor along with salinity.

Nutrient loading Impacts

With seagrass loss beginning during the mid1990s, and accelerating into the 2000s, we hypothesized that nutrient (nitrogen) loading is implicated as a synergistic factor under moderate inflow pulses. This is because, as inflows increase from the low level of 40,000 ac-ft per mo, to 50,000 – 80,000 ac-ft per mo, salinity is still maintained within a favorable range for seagrasses. However, the Ga/unGa ratio of the total combined inflow changes from a value of 2-3 at 40,000 ac-ft/mo, to around 1-1.2 at these higher intermediate flow pulses. While data showing nitrogen (and likely phosphorus) loading from ungaged subwatersheds is sparse, increased nutrient loading is inferred (see **Section 8.3**). When coupled with warming temperature over the last 15 yrs (see **Section 3**), higher nutrient loadings from Non-Point Source runoff, coupled with reduced salinity pulses, would have the capacity to produce light-attenuating conditions indirectly for seagrass, from overabundance of phytoplankton, macroalgae and epiphytes as mentioned in **Section 9.2**.

At this time, we cannot quantitatively relate temperature to nutrient effects. We merely point out that the temperature increase in recent years (indicative of a warming environment after mid-1990s) is another factor that is superimposed on nutrient/inflow regimes. A warmer water temperature environment would exacerbate the salinity/nutrient effects through higher algae production, and cause light reduction for seagrasses.

9.5.2. Inflow Regimes and Seagrass Responses

Additional evidence for a critical inflow regime threshold for seagrass is obtained when we examine the monthly average inflows to LLM over the 32–year period of record (**Figure 9.5.1**). When the data are separated into two groups (pre-1994 and post-1994), it is apparent that there has been a shift in inflow from the winter-spring seasons to summer-fall seasons. In the pre-1994 period, seasonal monthly averages (ac-ft per month) were: Winter (Dec-Feb = 26,897); Spring (Mar-May = 40,286); Summer (June-Aug = 42,797); and Fall (Sept-Nov = 45,283). These values contrast with the post-1994 seasonal monthly averages of: Winter (Dec-Feb = 21,834); Spring (Mar-May = 30,595); Summer (June-Aug = 53,943); and Fall (Sept-Nov = 61,045). The latter period summer data omits the abnormally high inflow for July 2010 which would greatly skew the summer average. Basically, the post-1994 period showed slightly decreased inflows in the early part of the year compared to the pre-1994 period, but a highly significant increase (25 – 33%) in the summer – fall seasons. It is noteworthy that these long-term seasonal flow statistics verify a threshold value around 40,000 – 45,000 ac-ft per month, particularly in the warmer summer and fall seasons prior to 1994. This appears rather significant, since it parallels the seagrass decline observed after the late 1990s which was corroborated in this BBEST study. This provides support for our hypothesis that average higher inflows in warmer summer-fall months could transport higher nutrient loads, and produce more serious effects on the seagrass.

Thus, we conclude that three distinct LLM flow regimes affecting seagrass produce cumulative, synergistic conditions between salinity and nutrient loading. These regimes are characterized as follows:

1. **LOW-Flow Regimes produced during DRY years**: 1986, 1987, 1989, 1990, 1994, 2000, 2005, 2009. These years were characterized by average monthly flows of < 40,000 ac-ft total gaged and ungaged inflows, and with a ratio of Gaged to Ungaged flows of ca 3 to 1. We have inferred that this very low amount of ungaged runoff contributes a background level of nutrient loading. The gaged flow from the Arroyo Colorado is contributing the main percentage (25-30 %) of agricultural and wastewater flows to the LLM at this low monthly flow level, as determined by the water balance study (**Section 2.6**). However, because salinity changes occurring from the inflows are inconsequential, low stress or minimal effects on seagrass occur under this regime, and nutrients from the AC, particularly during summer and fall seasons, can be adequately assimilated by the LLM.

2. HIGH -Flow Regimes produced during WET years: 1984, 1988, 1991, 1993, 1997-98, 2002, 2003, 2004, 2007, 2008, and 2010. Years were characterized by 2 or 3 monthly flows during that year, usually in succession, all above 100,000 ac-ft. Total combined flows from these pulses ranged from 209,695 ac-ft/pulse (2004), to 2,456,700 ac-ft (2010). During these high inflow months, the ratio of Gaged to Ungaged flows was ca 0.4 to 1. Although these flow levels contain a high amount of ungaged runoff, and contribute high levels of nutrient loading, inflows greatly lower salinities during these years. As a result, seagrasses undergo exposure to lethal, low salinity and subsequent are killed under this regime, particularly during summer and fall seasons. These flows are considered flood conditions beyond the scope of water management.

3. INTERMEDIATE -Flow Regimes produced during AVG years: 1982-83, 1985, 1992, 1995-96, 1999, 2001, 2006. These years were characterized by monthly flow pulses of 50-85,000 ac-ft, up to 2 pulses per yr, and sometimes occurred only as a single month pulse. Total combined flows from these pulses ranged from 107,450 ac-ft/pulse (1995), to 170,000 ac-ft (2006). During the higher inflow pulses, the ratio of Gaged to Ungaged flows was ca 1.2 to 1, while lower flow months had Ga/Ung ratios of 2 to 1 or more. We infer that these intermediate inflow pulses, with moderate amounts of ungaged runoff, will contribute higher levels of nutrient loading, while causing moderate salinity reduction. Thus direct, or immediate, reduced salinity effects on seagrass may not occur under this regime, particularly during winter and spring seasons, but longer-term, synergistic negative effects between nutrient loading and salinity could result.

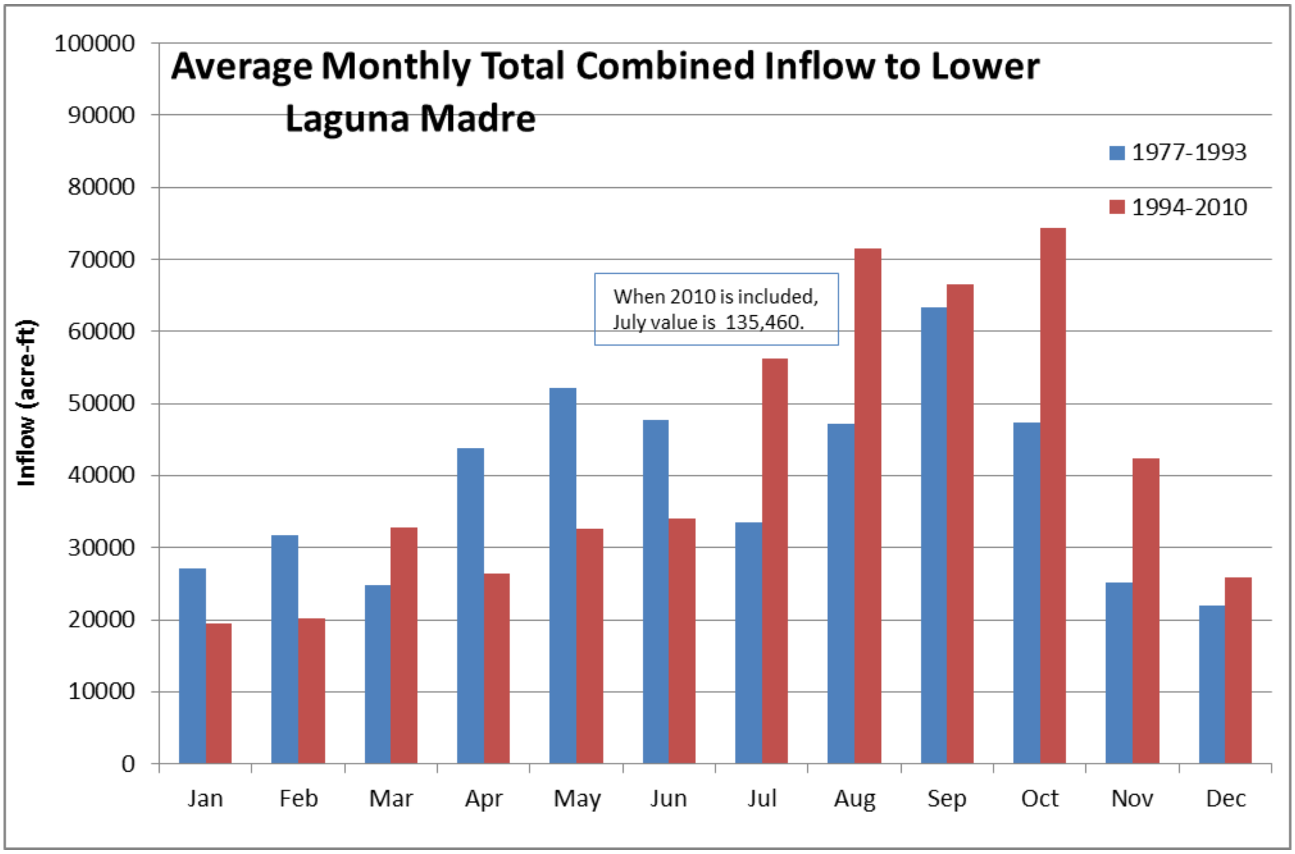


Figure 9.5.1. Average monthly total combined inflow to Lower Laguna Madre compared for two periods, 1977-1993 vs. 1994-2010. Value for July 2010 was excluded from the calculation because it greatly skews the average, being extraordinarily high at 1.4 x 10^6 ac-ft.

Section 10 Freshwater Inflow Recommendations

10.1. Lower Laguna Madre Inflow Recommendation

In contrast to other Texas estuaries, the LLM, as described in Chapter IX, is a lagoonal ecosystem that has not developed with a substantial reliance on freshwater inflow to maintain a sound environment. The Lower Rio Grande BBEST determined that freshwater flows negatively impact the LLM under two scenarios: a) under wet conditions, high freshwater pulses create low salinities that stress seagrass communities; and b) under dry conditions, freshwater inflows, which now exceed “natural” inflows are dominated by municipal and agricultural returns with resulting high nutrient loading that creates phytoplankton blooms, excessive growths of seagrass epiphytes and drifting macroalgae, , all of which can reduce light availability to sea grass.

Table 10.1.1 compares existing inflows into the LLM to estimated “natural” inflows over the period of 1999-2008. Natural inflows are based on the water balance analysis conducted by the Texas Water Resource Institute under contract to the Lower Rio Grande BBEST and were estimated by removing calculated municipal and agriculture return flows to the LLM (see Chapter 2.6 for a more detailed description of natural flows).

Table 10.1.1.Calculated freshwater inflows to the Lower Laguna Madre from 1999-2008. Units are acre-feet per month.

	Dry (October-March)			Wet (April-September)		
Percentile	**Existing**	**Natural**	**% of Natural Flows / Existing**	**Existing**	**Natural**	**% of Nat Flows / Existing flows**
Min	12,446	1,426	11.5%	12,313	3,613	29.3%
0.05	13,537	1,895	14.0%	16,386	5,007	30.6%
0.10	14,109	2,381	16.9%	17,743	5,531	31.2%
0.20	16,270	3,428	21.1%	20,909	6,908	33.0%
0.25	16,872	3,613	21.4%	21,214	7,888	37.2%
0.50	19,610	5,695	29.0%	31,213	14,445	46.3%
0.75	25,504	12,901	50.6%	51,620	38,152	73.9%
0.80	29,900	15,215	50.9%	66,072	52,894	80.1%
0.90	40,833	28,023	68.6%	107,042	92,771	86.7%
0.95	42,559	30,077	70.7%	156,861	151,407	96.5%
Max	205,357	170,970	83.3%	393,204	338,325	86.0%
Average	26,342	12,669	N/A	50,988	36,715	N/A
Median	19,610	5,695	N/A	31,213	14,445	N/A
St. Dev.	25,596	23,087	N/A	59,004	55,327	N/A

In order to ensure the LLM maintains a sound ecological environment in the future, the Lower Rio Grande BBEST recommends:

- Freshwater inflow during the dry season (November-April) is between 3,613 and 12,901 acre-feet per month (daily average flows of 61 to 217 cfs) during at least three months, does not exceed 217 cfs for more than 45 days during the season, and is not less than 61 cfs for more than 45 days during the season.
- Freshwater inflow during the wet season (May-October) is between 7,888 and 38,152 acre-feet per month (daily average flows of 133 to 641 cfs) during at least three months, does not exceed 641 cfs for more than 45 days during the season, and is not less than 133 cfs for more than 45 days during the season.
- These freshwater inflows are expected to include wastewater and agricultural return flows, and rainfall runoff.

The Lower Rio Grande BBEST acknowledges the following aspects of this recommendation:

- These inflows are less than current inflows into the LLM.
- Extensive environmental analysis described in Chapter 9 suggested that negative impacts to seagrasses are occurring from increased nutrient loading as total inflows rise above 40,000 acre-ft per month. The upper limit for the wet season flow recommendation of 38,152 acre-ft per month derived from the natural flow analysis is very close to this 40,000 acre-ft value. This convergence of values tends to reinforce the upper flow limit in our recommendation as an important inflow threshold to be maintained for protecting LLM seagrasses from increasing nutrient loading effects.
- Although there are not enough data to identify a specific inflow and nutrient loading regime that will protect the LLM, analysis suggests there will be less impact with lower inflows and nutrient loading.
- The Arroyo Colorado provides estuarine habitat that is uncommon in this area of the coast. The lower limits of the flow recommendations are intended to help protect the ecological benefits resulting from freshwater inflow into the Arroyo Colorado tidal.
- Substantial reduction in nutrient loading from wastewater and agricultural return flows and nonpoint source pollution may increase protection of seagrass communities with little reduction of freshwater inflow below current levels.
- During significant rainfall events, there is little that can practically be done in the short-term to reduce freshwater inflows to the LLM. Although tropical storms and hurricanes can produce rainfall runoff that lowers salinity and impacts seagrass, the BBEST does not believe it is necessary to divert rainfall runoff from the LLM.
- Except during periods of rainfall runoff nearer the coast, a majority of the freshwater inflow to the LLM passes through the Arroyo Colorado gage at Harlingen. During the period from 1999-2008, the proportion of freshwater inflow to the LLM that passed the Arroyo Colorado gage at Harlingen was approximately 63% for median flow conditions across all contributing subbasins. This value is an approximation using median flow conditions only and should not be directly applied at the Harlingen gage without additional analysis. Additional suggested work includes incorporating a longer period of record and the inclusion of uncertainty estimates for all flow values from all contributing subbasins. The proportion of inflow to the LLM

that passes the Harlingen gage varies due to many factors including: seasonal changes in return flows downstream of the gage and in other subbasins, the percentage of instream flows being generated by return flows, the percentage of runoff induced by rainfall over the study area subbasins, and the percentage of runoff induced by rainfall upstream of the study area and subsequently routed through the study area by the flood protection system It is suggested that these factors be investigated more thoroughly in future work plans if the inflow recommendations are adopted and implemented.

- Environmental flow regulations developed through the Senate Bill 3 process are intended to help guide issuance of water rights permits and not to limit flows from permitted wastewater discharges or from agriculture return flows for which volumes are not typically regulated.

In summary, the BBEST believes the LLM will be a sound environment with substantially less freshwater inflow and nutrient loading than it currently receives. Although these recommendations do not support development of environmental flow standards that would provide more water to the LLM, these recommendations are offered by the BBEST in the hope that stakeholders and the regulatory communities explore strategies to reduce wastewater flows and nutrient loading to the LLM.

10.2. Inflow Recommendation for the Rio Grande Estuary

BBEST recommendations for flow regimes of the Rio Grande Estuary are based primarily on two hydrodynamic analyses:

1. Environmental Flow Recommendation for the Rio Grande tidal (as measured at the Brownsville gage):

Minimum Flows: Minimum flow of 60 cfs at all times to maintain a salinity transition zone that supports the vegetative communities that transition along the length of the estuary and helps keep the mouth of the river open. It is 25% greater than the 45 cfs identified (Ernest et al. 2007) as necessary to keep the mouth open and it is higher than the average flow of 39 cfs into the tidal reach for the 28 days prior to the mouth closing in February 2001.

Pulse Flows to Keep the Mouth Open: Daily average flow of 175 cfs at least once every 2 months (based on flows during 1999, which had lower total inflow than all but one other year during the period of record from 1934 to 2010), when there were 7 pulse periods with at least one day of daily average flow exceeding 175 cfs.

Daily Average Flows: Daily average flow of 880 cfs at least once each year (based on the November 3, 2002 flow of 915 cfs which was part of a wet period that helped naturally reopen the river mouth by November 7, 2002). No pulse flows of this magnitude occurred from February 4, 2001 through November 3, 2002, during which period the river mouth was closed (except when artificially opened in late July 2001).

The blockage of the river mouth in 2001 due to drought and low-flow sediment deposition raised awareness of the need to maintain sufficient flow to keep the river mouth open to the Gulf. Two subsequent studies evaluated relationships between flow, velocity, and maintenance of flow to the Gulf of Mexico. The special Sandia Laboratories study (Sandia Laboratories 2003) supported by the IBWC concluded that a velocity of > 0.3 m per sec (or 1 ft per sec) from the Rio Grande is required to overcome long-shore current sediment transport. When this velocity is translated into an actual flow volume, it equates to ca 250 cfs when a channel mouth cross section 5 feet deep and 50 feet wide is considered. Discharge of 45 cfs at the river's mouth was estimated to provide the peak shear stress necessary to prevent sediments from blocking the mouth of the river (Ernest et al. 2007). This hydraulic function has serious ramifications for the issue of faunal ingress and egress to the estuarine habitat within the Rio Grande. If the mouth were to remain closed for an inordinate period or during the wrong season, the estuary habitat would be inaccessible to larval or juvenile fauna needing to migrate into the estuary according to their life cycle requirements. Conversely, adult fauna would be trapped and prevented from leaving the closed river in order to spawn.

2. Hydrologic stream flow data documents the highly pulsed, episodic nature of inflows to the estuary (IBWC 2010). Under very reduced flows, this could produce excessive salinity levels in the upper reaches of the estuary. Based on results of TPWD survey data from the late 1990s, the City of Brownsville Water Permit for the Brownsville-Matamoros Weir contains a flow restriction for water diversion at the El Jardin site. When conductivity rises to a value of 2,250 uS cm^{-1} at river mile 23.6, then water cannot be diverted unless flows are 25 cfs or higher. This conductivity level is the highest value recorded in recent years during extremely low flow periods, which were reached when the river mouth became plugged. In a recently completed monitoring study over the period 2000 – 2009 (Machin 2009), it was shown that low river flows will in fact produce these elevated bottom salinities at mile 23.6; thus diversions at El Jardin may need to be curtailed at even higher flows than 25 cfs. The BBEST recommends maintaining this 25 cfs flow minimum, but cautions that an even higher flow threshold could be necessary as a result of further monitoring and data analysis.

The BBEST makes these environmental flow recommendations with the knowledge that flows in the Rio Grande basin are over-appropriated. The BBEST also acknowledges that the complex interactions of physical and biological factors may cause the river mouth to close at flows greater than these recommendations or may allow the mouth to remain open at flows less than these recommendations. However these environmental flow recommendations are intended to emphasize the importance of maintaining a connection between the river and the Gulf to the ecological functions of the Rio Grande tidal. These values will serve as a starting point for future analysis and consideration of strategies to protect and restore ecological health in the Rio Grande estuary.

Section 11 Adaptive Management

11.1. Purpose

The Rio Grande 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 Lower Rio Grande 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).

11.2. Future Research and Monitoring Needs

A table of information of needs identified by the BBEST follows. The following paragraphs describe the general sections of the table.

<u>Number</u>
This column assigns a number to each research or monitoring need for ease of identification and future reference.

Priority
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.

Description of the Information Needed
This column identifies the question that needs to be answered to achieve the work plan's purpose.

Monitoring, Special Study, Research, or Modeling
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.

Schedule
A schedule is to be determined on the basis of prioritization of work plan activities by the Rio Grande 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 2023 to allow review and revision of reports, and development of BBASC recommendations to the TCEQ. By 2023, the BBASC may provide the TCEQ and the Environmental Flows Advisory Group a report, summarizing:

- 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
- Suggestions for future monitoring, studies, and activities.

In some cases, monitoring, research and modeling activities may continue past 2023.

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 2023. The BBASC may wish to stay informed of and coordinate with the Senate Bill 1 process in the interim.

Organizations Involved
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 International Boundary and Water Commission, 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. The Arroyo Colorado Watershed Partnership, Nueces River Authority, water providers, and water users may be involved. Some nonprofit organizations including the

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 information sought in the work plan. In the Lower Rio Grande, particularly important universities include the University of Texas Pan American at Edinburg, University of Texas at Brownsville, 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.

The Rio Grande is the international border between the U. S. and Mexico and its water is managed by both countries under international treaties and agreements. It is important as time and resources permit to engage Mexico and the state of Tamaulipas in future evaluation of environmental flows in the lower Rio Grande. The BBEST recommends the BBASC explore engagement with Mexico as its work plan is carried out in the future.

Funding

Funding is expected to limit implementation of the work plan. Three approaches may provide funding for tasks:

- Collaboratively incorporate work plan tasks into existing, funded, monitoring programs with related objectives. Some BBASC members represent organizations conducting monitoring and they could take leadership roles in guiding this merger of monitoring efforts.
- Seek new sources of funding for tasks, including legislatively allocated funds, and state and federal grants.
- 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 understanding of relationships between flow and ecological health of streams and bays. In the lower Rio Grande basin, the primary complicating factor is the intensive management of water in the Rio Grande. Flow in the Rio Grande is controlled for the primary purposes of providing water for agricultural, municipal, and industrial uses. Major reservoirs in the watershed substantially reduced flooding and sediment transport that historically moved the river back and forth within its coastal basin and produced resacas. Flood control efforts in the basin divert much of the flooding that still occurs away from the Rio Grande basin towards the north to the Laguna Madre through the Main Floodway. The Arroyo Colorado above its tidal reach has grown from what was probably an ephemeral stream to a substantial perennial stream where flow almost always exceeds 100 cfs due to irrigation return flows and municipal and industrial wastewater discharges.

The Lower Laguna Madre was a semi-enclosed basin with little or no freshwater inflow except during flooding. It was not uncommon for salinities to exceed 100 psu and for fish kills to occur caused by hypersalinity. Channelization for navigation has increased circulation with the Gulf and diversion of floods and return flows have modified the salinity regime to the extent that the Lower Laguna Madre has salinity comparable to the Gulf of Mexico and never approaches the hypersalinity experienced over 60 years ago.

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:

- Changes in agricultural, industrial, and municipal use of surface and ground water.
- The relatively long life spans of some species that will be analyzed. Some riparian tree species may live over one hundred years.
- Changes in waste loading from municipal, agricultural, industrial, and nonpoint sources of pollution.
- Noxious species like water hyacinth, Hydrilla, tilapia, and Asiatic clams outgrow native species, modify flow, and impact healthy sediment transport.
- Changes in land cover/land use by cities, industries, or agricultural which modify drainage and flows.

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 ensure 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 11.1. Future Research and Monitoring Needs

Number	Priority	Needs
Rivers and Streams		
1		Describe relationships between flow and physical, chemical, and biological structure and function of the Rio Grande and Arroyo Colorado 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 lower Rio Grande 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 the Rio Grande and Arroyo Colorado. 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 2012 through 2023 with earlier data. A 2023 work plan report could summarize results of monitoring and studies conducted in the basin 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 the Rio Grande between Brownsville and Falcon Lake and the Arroyo Colorado upstream of Harlingen. Another important component of this effort would be to characterize the water quality of gaged and ungaged inflows into the LLM as nutrient levels appear to be as important as salinity in determining the health of the LLM. 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.
Rivers and Streams		
2		Describe ecological services provided by resacas. Resacas provide ecologically valuable aquatic habitat in the lower Rio Grande basin. Little is known about the ecological structure and function of resacas and particularly the relation of their environmental health to flow. It is important to study how the different flow regimes support environmental health in these perennial pools. This could be a special study conducted on at least three resacas, one in an urban area, one in a minimally disturbed area like a park or preserve, and one in an area of predominantly agricultural land use. Resacas would be chosen based on part on the ability to characterize water flowing into and through them. This sampling would focus on fish, benthic macroinvertebrates, riparian plants, and as resources permit, wildlife using the riparian zone. Water chemistry would be monitored in conjunction with biological monitoring and continuous recording

Number	Priority	Needs
		water quality meters might be installed.
3		Describe how surface flow patterns and quantities are changing compared to the period of record patterns. Include consideration of possible future flows and diversions. Because flow in the lower Rio Grande basin is managed to a large degree for human water uses, it may be valuable to evaluate how shifts in water use from agricultural to municipal and industrial use, changes in agricultural and municipal conservation practices, and impacts of future water plans may affect flow in the Rio Grande and Arroyo Colorado. Flow patterns may also be influenced by several different global climate drivers, e.g. Southern Pacific Oscillation, and North Atlantic Oscillation.
Rivers and Streams		
4		Identify water development activities planned for the future, and how they might influence flows in the Rio Grande, Arroyo Colorado, and resacas and physical and hydrologic connections between them. 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 municipal 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. As necessary, field studies would be conducted to provide needed information.
Rivers and Streams		
5		Identify key flow-dependent ecosystem processes and structure associated with a sound ecological environment in resacas, the lower Rio Grande, and the Arroyo Colorado. Aquatic 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 an aquatic ecosystem without adequate understanding of such processes can be problematic. 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 at least 3 representative resacas, the Rio Grande between Brownsville and Falcon Lake, and the Arroyo Colorado upstream of Harlingen. 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, and invasive

Number	Priority	Needs
		species effects on interspecific competition.
6		Since the lower Rio Grande comprises a “pulsed” flow system in an arid environment, additional modeling studies are needed to relate inflow dynamics to the geomorphology issue of flow regimes needed to maintain the opening of the River to the Gulf of Mexico. Current, preliminary information is still very tentative, and does not adequately address the size of the channel mouth to be maintained, effects from upstream flow attenuation factors, and annual flow pulses. This work would build on existing data, but certainly would require additional careful field monitoring of flow conditions at the River mouth and upstream conditions.
7		To understand better the relationship between Rio Grande flows and the estuarine salinity gradient and salt wedge dynamics, modeling studies using TxBLEND (or other suitable hydrodynamic model) should be completed. Recent river surveys have identified a potentially critical transition zone for freshwater and estuarine vegetation, and for nutrient (especially nitrogen) cycling; thus the modeling analysis would help to explain and validate these ecological dynamics.
8		The Rio Grande bears a great similarity to tidal rivers in other parts of the world flowing through arid country, and emptying directly into the sea. Thus, studies and data from such rivers in Africa, Australia, Mexico, and even the Mediterranean may provide useful information for lower Rio Grande water management. As mentioned earlier, impacts from global warming and climate change are also now superimposed on such tidal river estuaries and their flow dynamics. While it is difficult to identify all relevant case studies, certainly those situations involving increased nutrient loadings accompanied by decreased flows from diversions/impoundments close to the river mouth (e.g. analogous to the Brownsville weir) are good examples. Methods that identify and then prevent/eliminate nutrient discharges into a low-flowing estuary would be especially applicable to the restoration and maintenance of the lower Rio Grande.
9		Implement a program to evaluate effectiveness of strategies to protect and/or restore ecological structure and function in areas where flows are highly regulated. Strategies may be implemented to protect or restore ecological structure and function. These strategies should be evaluated to determine if they can effectively preserve important ecological characteristics in systems where flow is highly managed for human uses.
Bays		
10		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 the Rio Grande estuary, Bahia Grande, San Martin Lakes,

Number	Priority	Needs
		South Bay, the Arroyo Colorado tidal, and the Lower Laguna Madre. This is an overarching goal that would be accomplished by combining information collected from 2012 through 2023 with earlier data. The 2023 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 the Lower Laguna Madre. However, the BBEST did not conduct in-depth analysis of freshwater inflows and environmental health in other related bays systems.
Bays		
11		Study methods for determining environmental flow regimes for estuaries in arid watersheds. Most estuaries in Texas exhibit an increase in salinity from freshwater, to brackish, and then to near Gulf of Mexico salinities near the passes to the Gulf. These estuaries experience transitions in sediments and nutrients that are representative of this mixing between riverine and Gulf waters. The Lower Laguna Madre has not had those characteristics in the past but has been changing from a hypersaline estuary to one with salinities representative of the Gulf of Mexico. 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 with limited Gulf mixing. New techniques would be evaluated and applied as appropriate.
12		Implement a program to evaluate effectiveness of strategies used in areas where there may be too much freshwater for an environmentally sound 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.
13		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

Number	Priority	Needs
		maintain supply of freshwater inflow to the estuary.
14		Implement a program to evaluate the synergistic effects between nutrients and salinity on LLM seagrasses. While experimental manipulations of salinity and nutrients have been performed for a number of seagrass species, these factors have not been examined in an interactive manner, and never for *H. wrightii*, a major species in the LLM. Furthermore, while studies on the salinity tolerance of numerous seagrass species have been conducted, all have been limited to the effects on the above-sediment fraction and their responses. There are no studies which address the effects of hyper- or hyposaline changes to the root/rhizome fraction which determines the long-term survival of these plants.
15		Conduct more extensive monitoring and analyses of sources of nutrient loadings to the LLM and its secondary waterbodies as a first phase of designing/developing an effective nutrient loading management plan for the LLM. As part of the BBEST analysis of factors causing seagrass impacts, a major potential factor was attributed to nutrient loading contained in inflows, particularly nitrogen. However, it has been difficult to unequivocally determine the source and quantities of nitrogen nutrients, in particular the quantities entering from ungaged runoff vs. point discharges. The Water Balance project initiated by the BBEST has provided some definite data over the last 9 year period which strongly suggests that agricultural runoff could be a major contributor of nutrients at certain seasons, while wastewater return flows are a constant amount year-round. However, we do not know at this point the relative types or amounts of nutrients contained in these flows, and secondly how they differ by subwatersheds. A careful holistic subwatershed study is needed to get an accurate evaluation of the latter situation. Only in this way will it be possible to design and then begin to implement an effective nutrient loading management plan for the LLM.
16		Continue to monitor, but with increased intensity and coverage, changes in seagrass distribution and species in the LLM. Although LLM seagrasses have been monitored regularly over ca 50 years, this has mostly occurred at 10-year intervals. The LLM system is extremely dynamic and seagrass changes quickly, both in coverage and species composition, in response to environmental conditions. It is recommended that an intensive sampling design be established, similar to the Chesapeake Bay monitoring program, so that critical fixed sites are established for annual field verification. System-wide monitoring on a random basis can also be done, but because of costs, this would not necessarily be done every year. Not only would seagrass vegetation be included, but other parameters such as continuous underwater light, tissue N:P composition, macroalgae and epiphytes, should also be measured.

11.3. 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 creation. 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, International Boundary and Water Commission, Nueces River Authority, Arroyo Colorado Watershed Partnership, Texas Stream Team volunteer monitors, University of Texas - Pan American, University of Texas at Brownsville, 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.

11.4. 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 lower Rio Grande 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 2023. 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.

11.5. 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. Ecological baseline condition would be a set of parameters and their values which the work group identifies as characteristic of an acceptably sound environment for each water body. Examples of ecological baseline conditions may include number of fish species, width of riparian plant zone, dissolved oxygen levels above 5 mg/l, etc. Other ecological components that may be part of the ecological baseline condition may include presence of aquatic species that do not tolerate environmental disruptions (e.g., fish, benthic macroinvertebrates including mussels, aquatic and riparian vegetation), relative abundance of certain species, food web composition, reproductive behavior, area of water-dependent wetlands, such as marshes and habitat availability. 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.

The sound environment baselines for each water body would be completed by 2017. 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."

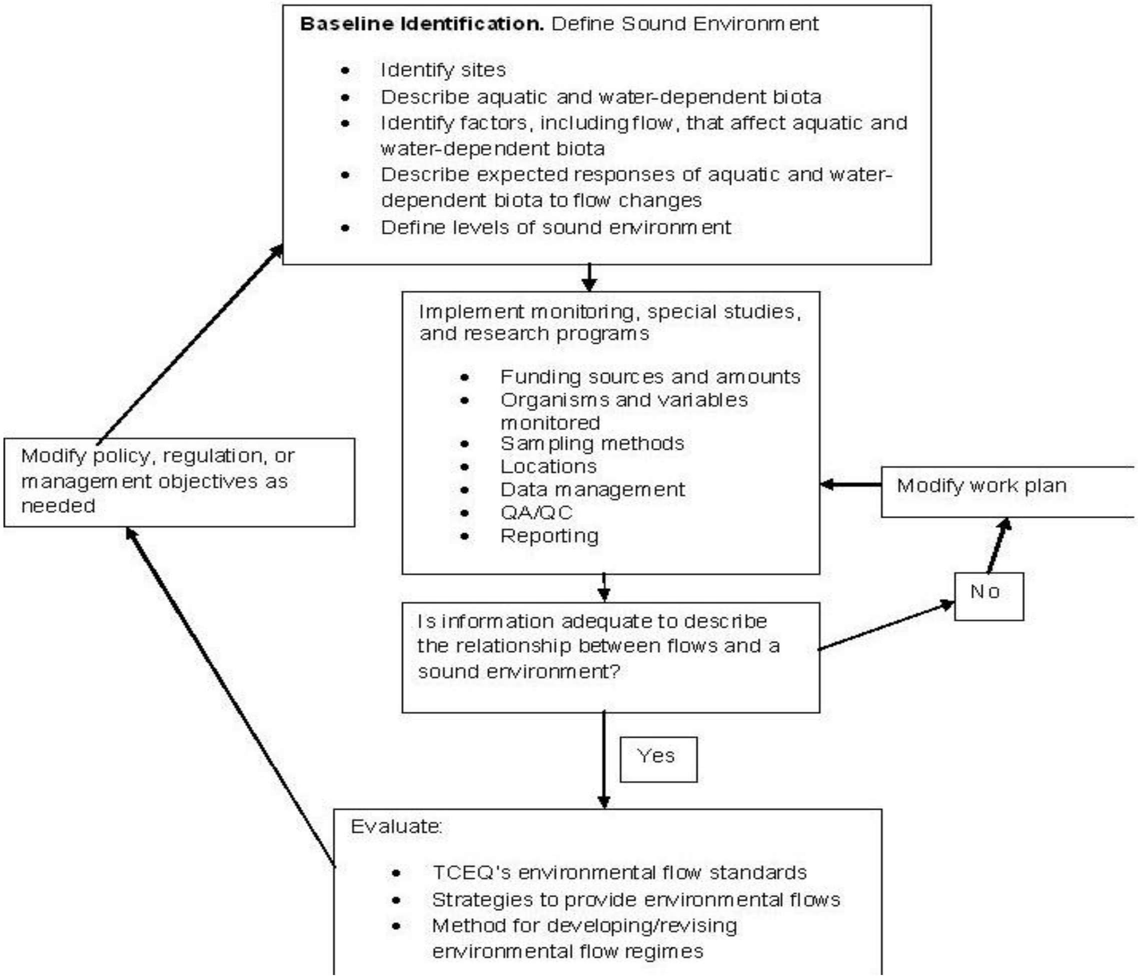


Figure 11.5.1. Adaptive Management Plan Flow Chart

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Environmental Flows Recommendations Report

Final Submission to the Environmental Flows Advisory Group, Rio Grande Basin and Bay Area Stakeholders Committee, and Texas Commission on Environmental Quality

Upper Rio Grande Basin and Bay Expert Science Team

July 2012

Cover Photo:

The Lower Canyons of the Rio Grande. View is looking downstream towards Big Canyon.

Photo credit: Jeff Bennett, National Park Service

Upper Rio Grande

Basin & Bay Expert Science Team

July 12, 2012

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

Tony Reisinger, Chair
Rio Grande, Rio Grande Estuary, and Lower Laguna Madre
Basin & Bay Area Stakeholder Committee

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

Pursuant to its charge under Senate Bill 3 of the 80th Texas Legislature, the Upper Rio Grande Basin & Bay Expert Science Team (URG BBEST) hereby submits its Environmental Flows Recommendations Report for your consideration.

Respectively Submitted,

Kevin Urbanczyk, Ph.D., Chair

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Upper Rio Grande Acknowledgements

The Upper Rio Grande Basin & Bay Expert Science Team respectfully and gratefully acknowledge the invaluable technical and logistical support provided by the following organizations and very capable individuals:

- U.S. Geological Survey Grand Canyon Monitoring and Research Center_– Jack Schmidt, Ronald Griffiths, and Thomas Sabol
- U.S. Geological Survey_– Bruce Moring and David Topping
- U.S. Fish and Wildlife Service_– Aimee Roberson
- Trungale Engineering and Science_– Joe Trungale
- The Nature Conservancy – John Karges, Corbin Neil, Jason Wrinkle, and Scott McWilliams
- Texas Water Development Board_– Ruben Solis, Mark Wentzel, Nolan Raphelt, Gayla Ray, Dave Flores, Mike Vielleux, Caimee Schoenbaechler, and Tony Connel
- Texas State University–San Marcos: Timothy Bonner and Thomas Hardy
- Texas Parks and Wildlife Department_– Ken Saunders, Gary Garrett, Dan Opdyke, Megan Bean, David Bradsby, and Steve Boles
- Texas Commission on Environmental Quality_– Cory Horan, Chris Loft, Gregg Easley, and Christine Kolbe
- Texas AgriLife Research
- Texas Agrilife Extension Service
- Sul Ross State University and the Rio Grande Research Center_– Chris Jackson, Rusty Woodburn, Kris Farmer, and Leslie Hopper
- National Park Service_– Joe Sirotnak, Raymond Skiles, and Mark Wondzell
- International Boundary and Water Commission – Elizabeth Verdecchia

This report may be cited as follows:

Upper Rio Grande Basin and Bay Expert Science Team. 2012. Environmental Flows Recommendations Report. Final Submission to the Environmental Flows Advisory Group, Rio Grande Basin and Bay Area Stakeholders Committee and Texas Commission on Environmental Quality.

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Common Abbreviations

AF	acre-feet
AMIS	Amistad National Recreation Area
ARS	Agriculture Research Service
BBASC	Basin and Bay Area Stakeholder Committees
BBEST	Basin and Bay Expert Science Team
BBNP	Big Bend National Park
BMP	best management practice
BOD	biological oxygen demand
Ca	calcium
cfs (ft^3/s)	cubic feet per second
CILA	Comisión Internacional de Límites y Aguas , Mexican Section, International Boundary and Water Commission
Cl	chloride
CMM	Coordinated Monitoring Meeting
cms	cubic meters per second
CONANP	Comisión Nacional de Áreas Naturales Protegidas , Mexican Commission for the Protection of Natural Areas
CRP	Texas Clean Rivers Program
CSREES	USDA Cooperative State Research, Education and Extension Service
CWA	Federal Clean Water Act
DEM	Digital Elevation Model
DO	dissolved oxygen
EFAG	Environmental Flows Advisory Group
EPA	United States Environmental Protection Agency
EQIP	Environmental Quality Incentives Program
ETPA	Edwards-Trinity Plateau aquifer
FM	Farm to Market Road
FOTG	Field Office Technical Guide
FWTRWPG	Far West Texas Regional Water Planning Group
GPS	global positioning system
HEC-RAS	Hydrologic Engineering Centers River Analysis System
HDFR	High Dam Flow Releases
HEFR	Hydrology-based Environmental Flow Regime
HSC	Habitat Suitability Criteria
HUC	Hydrologic Unit Code
I/E	information and education
IBI	Index of Biotic Integrity
IBWC	International Boundary and Water Commission, US Section
IHA	Indicators of Hydrologic Alteration
LPRB	Lower Pecos-Red Bluff
mg/L	milligrams per liter
MX	Mexico
Na	sodium
NM	New Mexico, USA

NPS	National Park Service
OFCUF	Oil Field Cleanup Fund
ppm	parts per million
PRAC	Pecos River Advisory Committee
PRBAP	Pecos River Basin Assessment Project
PRCC	Pecos River Compact Commission
PRISM	Parameter-elevation Regressions on Independent Slopes Model
Q	Discharge (volume rate of water flow)
QA/QC	Quality Assurance/Quality Control
RGBI	Rio Grande Basin Initiative
RGSM	Rio Grande Silvery Minnow
RIGR	Rio Grande Wild and Scenic River
RRC	Railroad Commission of Texas
SAC	Science Advisory Committee
SB3	Senate Bill 3
SEE	Sound Ecological Environment
SO4	sulfate
SOC	Species of Concern
SWCD	Soil and Water Conservation District
TCEQ	Texas Commission on Environmental Quality
TCRP	Texas Clean Rivers Program
TDS	total dissolved solids
TECO	Texas Extension Counties Online System
TFS	Texas Forest Service
TIFP	Texas Instream Flow Program
TMDL	Total Maximum Daily Load
TNC	The Nature Conservancy
TPWD	Texas Parks and Wildlife Department
TPWT	Trans Pecos Water and Land Trust
TSSWCB	Texas State Soil and Water Conservation Board
TWDB	Texas Water Development Board
TWRI	Texas Water Resources Institute
URG	Upper Rio Grande
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture
USGS	United States Geological Survey
USGS-GCMRC	USGS Grand Canyon Monitoring and Research Center
USIBWC	International Boundary and Water Commission, United States Section
USU	Utah State University
UT	Utah, USA
WHIP	Wildlife Habitat Incentives Program
WPCD	Water and Power Control District
WPP	watershed protection plan
WQMP	water quality management plan
WUA	Weighted Usable Area
WY	Wyoming, USA

Glossary of Terms

Adaptive management—An iterative and structured decision making process that seeks to address uncertainty through system monitoring.

Aggradation—the raising or elevating of a bottomland surface through the process of alluvial deposition; conceptually it is the vertical component of accretion and is most frequently applied to sediment deposition on a channel bed, bar or other near-channel surfaces, flood plain, or, less often, low-lying alluvial terrace (Osterkamp, 2008).

Appropriation—A specified amount of water set aside by Congress, other legislative body or state or provincial water regulatory authority to be used for a specified purpose at a specified place, if available.

Aquatic life—All organisms living in or on the water.

Base flow—Average stream flow in the absence of significant precipitation or runoff events. Also known as "normal flow".

Bed load—Material moving on or near the streambed.

Bosque—A Spanish term for "woodlands", the name refers to areas of gallery forest found along riparian floodplains of stream and river banks, primarily in the southwestern United States.

Channel—That cross section containing the stream that is distinct from the surrounding area due to breaks in the general slope of the land, lack of terrestrial vegetation, and changes in the composition of the substrate materials. The portion of the river bottomland that conveys water at all discharges

Connectivity—Maintenance of lateral, longitudinal, and vertical pathways for biological, hydrological, and physical processes.

Discharge—The rate of stream flow or the volume of water flowing at a location within a specified time interval. Usually expressed as cubic meters per second (cms) or cubic feet per second (ft^3/s). Commonly referred to as "Q".

Diversion—A withdrawal from a body of water by human-made contrivance.

Drainage area—The total land area draining to any point in a stream. Also called catchment area, watershed, and basin.

Flood—Any flow that exceeds the bankfull capacity of a stream or channel and flows out on the floodplain.

Floodplain—(1) Land beyond a stream channel that forms the perimeter for the maximum probability flood. (2) A relatively flat strip of land bordering a stream that is formed by sediment deposition.

Flow—(1) The movement of a stream of water or other mobile substance from place to place. (2) Discharge.

Flow regime—The distribution of annual surface runoff from a watershed over time such as hours, days, or months (See also Hydrologic regime).

Fluvial—Pertaining to streams or produced by river action.

Gradient—The rate of change of any characteristic, expressed per unit of length. (See Slope) May also apply to longitudinal succession of biological communities.

Ground water—In general, all subsurface water that is distinct from surface water; specifically, that part which is in the saturated zone of a defined aquifer.

High flow pulse—A short-duration, high flow within the stream channel that occurs during or immediately following storm events and serves to flush fine sediment deposits and waste products, restore normal water quality following prolonged low flows, and provide longitudinal connectivity for species movement along the river.

Hydrograph—A graph showing the variation in discharge over time.

Hydrologic regime—The distribution over time of water in a watershed, among precipitation, evaporation, soil moisture, ground water storage, surface storage, and runoff.

Hyporheic zone— the area below and adjacent to the stream through which surface water and ground water are readily exchanged and mixed, having a strong influence on stream biogeochemistry

Index of biotic integrity—A numerical gauge of the biological health of stream fish communities based on various attributes of species richness, species composition, trophic relations, and fish abundance.

Instream flow—The rate of flow in a natural stream channel at any time of year.

Main Stem—The main channel of a river, as opposed to tributary streams, and oxbow lakes or floodplain sloughs.

Mussel—Freshwater clam.

Natural flow—The flow regime of a stream as it occurs under completely unregulated conditions; that is, a stream not subjected to regulation by reservoirs, diversions, or other human works.

Overbank flow—An infrequent, high flow event that overtops the river banks, physically shapes the channel and floodplain, recharges ground water tables, delivers nutrients to riparian vegetation, and connects the channel with floodplain habitats that provide additional food for aquatic organisms.

Pool—A part of the stream that is deeper than other parts of the stream and where the water is not visibly flowing downstream.

Reach—A comparatively short length of a stream, channel, or shore. One or more reaches compose a segment.

Riffle—A relatively shallow reach of stream in which the water flows swiftly and the water surface is broken into waves by obstructions that are completely or partially submerged.

Riparian/ riparian zone—as applied to the study of fluvial systems, is an ecological term referring to that part of the fluvial landscape inundated or saturated by flood flows; it consists of all surfaces of active fluvial landforms up through the flood plain including channel, bars, shelves, and related **riverine** features such as **oxbow lakes**, oxbow depressions, and natural **levees**. Particularly in arid and semiarid (water-deficient) environments, the riparian zone may support plants and other biota not present on adjacent, drier uplands (Osterkamp, 2008).

Riparian vegetation—Vegetation that is dependent upon an excess of moisture during a portion of the growing season on a site that is perceptively more moist than the surrounding area.

Sediment—Solid material, both mineral and organic, that is in suspension in the current or deposited on the streambed.

Sediment load—A general term that refers to material in suspension and/ or in transport. It is not synonymous with either discharge or concentration.

Segment—A relatively long section of a river, exhibiting relatively homogeneous conditions of hydrology, channel geomorphology, and pattern.

Sound Ecological Environment (SEE)—An environment that sustains the full complement of the current suite of native species in perpetuity, or at least support the reintroduction of extirpated species, 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.

Stream—A natural water course of any size containing flowing water, at least part of the year, supporting a community of plants and animals within the stream channel and the riparian vegetative zone.

Streambed—The bottom of the stream channel; may be wet or dry.

Subsistence flow—The minimum stream flow needed during critical drought periods to maintain tolerable water quality conditions and provide minimal aquatic habitat space for the survival of aquatic organisms.

Suspended sediment—Particles that are suspended in the moving water column for long distances downstream. Much of this material settles out when water movement slows or ceases.

Tributary—A stream feeding, joining, or flowing into a larger stream.

Water resources—The supply of ground water and surface water in a given area.

Water right—A legally protected right to use surface or ground water for a specified purpose (such as crop irrigation or water supply), in a given manner (such as diversion or storage), and usually within limits of a given period of time. While such rights may include the use of a body of water for navigation, fishing, hunting, and other recreational purposes, the term is usually applied to the right to divert or store water for some out-of-stream purpose or use.

Watershed—See Drainage area.

INTRODUCTION

by Bob Brandes

Section 11.02362(b) (3) of Senate Bill 3 (SB3) as enacted by the 80th Texas Legislature in 2007 identifies the river basin and bay system consisting of the Texas portions of the Rio Grande, the Rio Grande estuary, and the Lower Laguna Madre (collectively the Texas Rio Grande system) as a priority system for the purpose of developing environmental flow regime recommendations and adopting environmental flow standards. This report presents the findings and recommendations of the SB3 Rio Grande Basin and Bay Expert Science Team (BBEST) regarding these environmental flow requirements. Because of distinct differences in the aquatic environments across the Texas Rio Grande system, the associated different needs with regard to protecting environmental flows, and the unique water rights, water availability and institutional aspects of this system, this SB3 work has been conducted by two subgroups of the BBEST, a Lower Rio Grande BBEST and an Upper Rio Grande BBEST.

The Texas Rio Grande system as defined by SB3 covers a large geographical area characterized by extremely varied climatic and hydrologic conditions and correspondingly varied aquatic biological resources extending from the humid subtropical coastal environment on the lower end to the semi-arid middle basin and finally to the upper basin Big Bend desert region. In total, this system covers approximately 70,000 square miles within Texas, and the Rio Grande itself extends over 1,200 river miles along the international border between the United States and Mexico from near El Paso, Texas to the Gulf of Mexico. On this segment of the river, there are two major international reservoirs, Amistad Reservoir just upstream of Del Rio, Texas, and Falcon Reservoir downstream of Laredo, Texas, both of which are jointly operated by the United States and Mexico Sections of the International Boundary and Water Commission (IBWC). Water users in Texas are the sole beneficiaries of the United States share of water from these two reservoirs, and releases are made for Texas users at the request of the Texas Rio Grande Watermaster under the Texas Commission on Environmental Quality (TCEQ).

Downstream of Fort Quitman, Texas, to the mouth of the Rio Grande at the Gulf of Mexico, the flows in the Rio Grande are divided between the United States and Mexico by the provisions of the 1944 Treaty between the two countries, with portions of the inflows from some of Mexico's tributaries assigned to the United States. The IBWC performs daily accounting of inflows and ownership of the waters flowing in the Rio Grande for this segment of the river. Upstream of Fort Quitman, the Convention of 1906 defines the ownership of flows in the Rio Grande between the United States and Mexico. The Rio Grande Compact between the Texas, New Mexico and Colorado divides the inflows to the upper portion of the Rio Grande among these states. These multiple institutional arrangements and the various agencies and entities involved in their implementation can complicate the management of the flows in the river for purposes of environmental protection. For example, as noted in Section 11.02362(m) of SB3, it is specifically acknowledged that "For the Rio Grande below Fort Quitman, any uses attributable to Mexican water flows must be excluded from environmental flow regime recommendations".

There are over 1,500 surface water rights within the Texas Rio Grande system that authorize the diversion of about 3.5 million acre-feet of water per year for a variety of uses including domestic, municipal, industrial, mining and irrigation. Water rights on the middle and lower portions of the Rio Grande below Amistad Reservoir are supplied with stored water from Amistad and Falcon Reservoirs, to the extent it is available, and these water rights are subject to a class-based system of water rights administration that prioritizes the available supplies for these water rights based on their type of use, with domestic, municipal and industrial uses assigned the highest priority.

Currently, the combined authorized annual diversion from Amistad and Falcon Reservoirs for these middle and lower Rio Grande water rights is about 2.15 million acre-feet per year, whereas the combined firm annual yield of these reservoirs is only about 1.05 million acre-feet per year, which creates a situation of substantial over-appropriation and periodic shortages for many of the lower-priority water rights, i.e., irrigation and mining. Other water rights in the Texas Rio Grande system that do not rely on Amistad and Falcon Reservoirs for their supplies are subject to the prior appropriation doctrine for the allocation of available stream flows during dry periods. Under this doctrine, the older water rights are allocated available stream flows first before the more junior priority rights, which again results in significant supply shortages for many water rights.

Because of the significant over-appropriation of available surface water supplies in the Texas Rio Grande system, the TCEQ, which is the water rights regulatory agency for Texas, generally considers that no unappropriated water is available within the system for the issuance of new water rights permits. Since the environmental flow standards adopted by the TCEQ under authority of SB3 apply only to new permits or certain water rights amendments issued by the TCEQ on or after September 1, 2007, there appears to be little or no need for specific environmental flow regime recommendations from the BBEST or environmental flow standards from the TCEQ <u>solely</u> for new appropriations of water within the Texas Rio Grande system.

Still, there is need to understand the aquatic biological resources that exist and have existed within key portions of the Texas Rio Grande system and their relationships to instream flows. For example, in the upper Big Bend portion of the Rio Grande basin, efforts are underway to acquire existing water rights that then can be dedicated to protecting environmental flows – the question is how much water is needed. The timing and magnitude of releases from Luis L. Leon Reservoir on the Rio Conchos in Mexico upriver from Presidio to meet treaty delivery requirements to the United States also could potentially be adjusted to maximize the beneficial effects of various flow patterns on maintaining channel features and biological integrity downstream along the Rio Grande, but more information on the flow patterns needed to accomplish these purposes is needed. In the lower basin, studies are underway to assess the role of marsh grasses in the Laguna Madre for supporting a wide variety of marine organisms and processes, and one of the key aspects of this research is the importance of freshwater inflows from the Arroyo Colorado for maintaining conditions conducive to these marsh grasses.

Recognizing: (1) that no new water rights permits would likely be issued by the TCEQ within the Texas Rio Grande system, (2) that there are specific needs in some portions of the Texas Rio Grande system for pursuing SB3 environmental flow studies to investigate environmental flow requirements, and (3) the fact that initial funding for the BBEST's work was limited and of short duration, the Basin and Bay Area Stakeholders Committee (BBASC) for the Texas Rio Grande system determined at the outset of the Rio Grande SB3 process that the scope of activities of the BBEST should be limited to a manageable portion or portions of the system area so that this work could reasonably be accomplished within the given timeframe and funding. To this end, the BBASC, through consensus action, identified the Rio Grande basin upstream of Amistad Reservoir and below Fort Quitman, including the Pecos and Devils river basins, as the <u>Upper Rio Grande BBEST Study Area</u>, and the segment of the Rio Grande below Falcon Dam, the Rio Grande estuary, the Arroyo Colorado and the Lower Laguna Madre as the <u>Lower Rio Grande BBEST Study Area</u>.

The work of these two BBEST subgroups is reported in this document as separate sections with separate recommendations.

Executive Summary

The Upper Rio Grande BBEST (URG BBEST) study area includes the Rio Grande basin upstream of Amistad Reservoir and below Presidio, including the Pecos and Devils river basins. This report is written to provide a summary of the best available science regarding this reach of the Rio Grande and its tributaries. It includes river-specific definitions of a Sound Ecological Environment (SEE) and discussion of whether such an environment exists for specific river and tributary segments. It also includes environmental flow regime recommendations to sustain the SEE consistent with the Texas 80th legislature Senate Bill 3 Environmental Flows process.

We conclude that the "Lower Canyons" reach of the Rio Grande, the Lower reach of the Pecos river and the Devils river currently support a sound ecological environment and make specific flow recommendations to sustain or improve this status. We also conclude that the "Parks" reach of the Rio Grande and the upper Pecos between Red Bluff reservoir and Independence Creek are not sound and make variable recommendations to improve or at minimum to not degrade the environment in these reaches. Recommendations for the Rio Grande and the Pecos are written as to not exceed the limitations of the 1944 Treaty with Mexico or the Pecos River Compact.

We follow previous BBEST's in recommending flow regimes in terms of four primary environmental flow components (subsistence flows, base flows, high flow pulses and overbank flows) derived from both analyses of historical hydrology and overlays of available water quality, biology and geomorphology information. The URG BBEST developed environmental flow regime recommendations for a total of thirteen locations in three Upper Rio Grande sub-basins: the Rio Grande, Pecos River and Devils River. The approach to development of flow recommendations varied somewhat across these three sub-basins.

The hydrology of the upper Rio Grande is determined by inflows from the Rio Grande upstream from Presidio, TX, inflows from the Rio Conchos in Chihuahua, MX, and other large desert ephemeral tributaries in both countries. Stream flow is primarily comprised of runoff produced by monsoon rains during the summer months, tropical storms and hurricanes from both the Pacific Ocean and the Gulf of Mexico, and ground water inputs from adjacent aquifers. The Rio Grande also transports extremely high sediment loads, and channel morphology changes rapidly as dictated by the magnitude, duration, and source areas of flood flows, and the quantity of sediment input by ephemeral tributaries. Thus, flow recommendations for the Rio Grande sub-basin rely upon historic hydrologic analysis, with a strong emphasis placed upon study of sediment transport and analysis of geomorphology for the Rio Grande for high flow pulses and, on water quality and biology for base flows and subsistence flow.

The hydrology of the Pecos River is primarily driven by groundwater inputs from the Pecos Valley and Rustler Aquifers as well as other local springs from undetermined aquifer sources. Extensive ground water pumping from the Pecos Valley Aquifer occurs for irrigated agriculture. High-flows are derived from regional frontal storms and convective storms during the monsoon season. Water availability and water quality are the two most dominant environmental concerns for the Pecos River, and directly control the health of the aquatic and riparian ecosystem. To address these concerns within this report, several analyses were conducted to determine environmental flow recommendations for six locations in the Pecos River sub-basin. HEFR analyses were used to describe all aspects of the historical flow regime. The evaluation of existing data and information combined with the URG BBEST analysis concluded the upper Pecos River to be unsound and unable to sustain a sound ecological environment, therefore the flow regime recommendations for the upper gages are considered initial recommendations to maintain existing conditions. Recommendations for flows to restore the soundness of this reach are not offered, however the URG BBEST has laid out adaptive management steps to develop future flow recommendations, should such become priority. For the lower Pecos River and Independence Creek, which the URG BBEST determined sound, the flow regime recommendations are intended to maintain the current ecological conditions. To refine hydrology-based flow recommendations, a biological overlay consisting of flow-instream habitat modeling for 10 focal fish species was incorporated. This methodology was also used to develop base-flow recommendations for one lower Pecos River gage and for Independence Creek. Thereafter a water quality overlay was applied to evaluate and refine subsistence flow recommendations.

The Devils River sub-basin is characterized by groundwater inputs governing the low flows of the river, and frontal storms and convective storms during the monsoon season driving high flows. The Devils River is considered pristine with exceptional water quality and an abundant and diverse aquatic and riparian ecosystem. We make environmental flow recommendations for two locations in the Devils River sub-basin. We began by using HEFR analyses to characterize the historical stream-flow record. A biological overlay consisting of habitat modeling for 10 focal fish species are used to evaluate the base-flow component of the hydrology-based flow regime and refine the base flow recommendations for one of the two Devils River gages. A water quality overlay was employed for the evaluation of the subsistence flow recommendations, but no modifications to the hydrology-based subsistence flows were necessary

The URG BBEST flow regime recommendations were develop using the best available science; however there are many areas in which more information is needed to develop and strengthen aspects of the flow regimes. To accomplish this, adaptive management recommendations including improved stream gage maintenance, future studies regarding geomorphology and sediment transport, biology, and water quality are offered in order to better understand the instream flow – SEE relationship.

Section 1. Preamble

1.1 Senate Bill 3 Environmental Flows Process

Senate Bill 3 (SB3) of the 80th Texas Legislature established statutory framework and 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 Upper Rio Grande Basin and Bay Expert Science Team (URG BBEST) and is may serve as a useful technical resource to the SB3 timely submitted in the midst of the SB3 environmental flows process to serve as a useful technical resource.

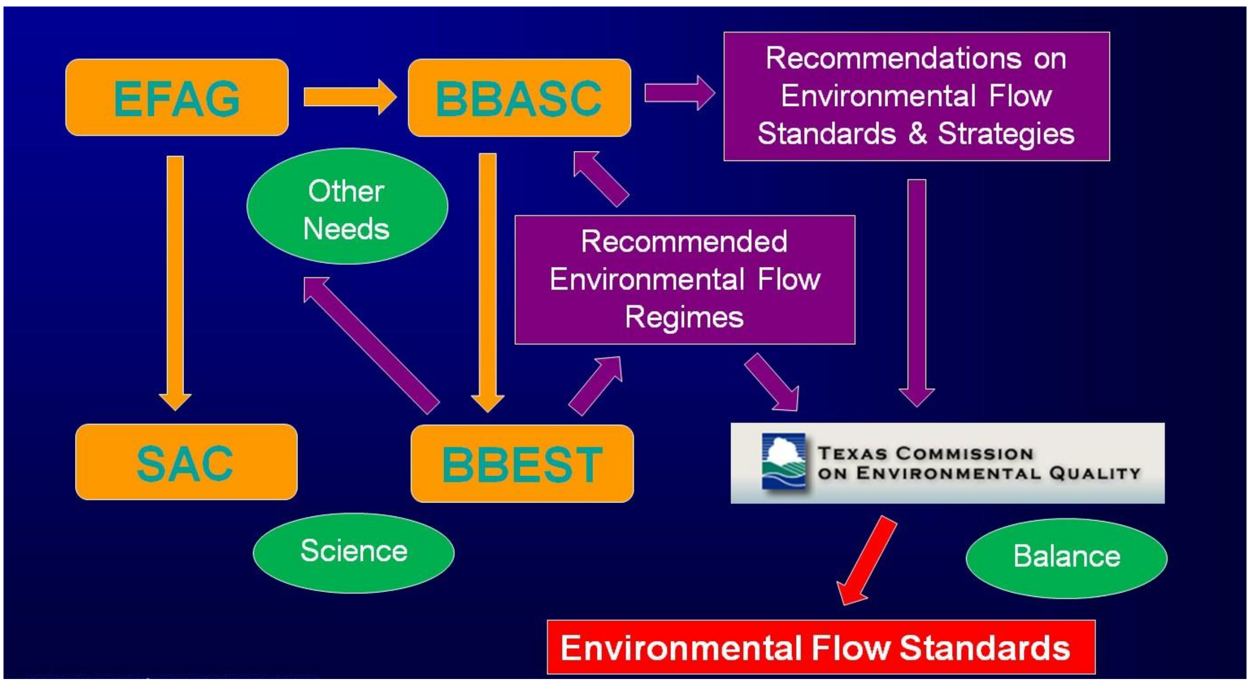


Figure 1.1-1. SB3 Environmental Flows Process.

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 BBEST's and BBASC's. 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 BBEST's, work plans for adaptive management, methods for evaluating interrelationships between environmental flow regimes and water supply projects, and consideration of attainment frequencies and hydrologic conditions. This guidance has been relied upon by the Upper Rio Grande 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)

BBASC's must reflect a fair and equitable balance of interest groups concerned with particular river basins and bay systems. Interest groups represented on BBASC's include: agriculture, recreation, municipalities, soil and water conservation districts, refining industry, chemical manufacturing, electricity generation, commercial fishing, public interests, regional water planning, ground water conservation districts, river authorities, and environmental groups. BBASC's, in turn, appoint BBEST's comprised of technical experts with knowledge of particular river basin and bay systems and/or development of environmental flow regimes. The Upper Rio Grande BBASC is comprised of 18 members. On April 21, 2010, the Upper Rio Grande BBASC acted to appoint 6 scientists as members of the Upper Rio Grande BBEST. Information regarding the Upper Rio Grande 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, BBASC's 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.
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 Upper Rio Grande Basin and Bay Expert Science Team (Upper Rio Grande BBEST)

1.2.1 Membership

The Upper Rio Grande BBEST is comprised of 6 members appointed by the Upper Rio Grande BBASC. Due to scheduling conflicts and other commitments, one original member chose to withdraw in March 2011 and was subsequently replaced by the Upper Rio Grande BBASC. Active membership of the Upper Rio Grande BBEST is summarized below along with administrative and subcommittee assignments.

Kevin Urbanczyk	— Chair
Zhuping Sheng	— Vice-Chair, Pecos River Subcommittee
Jeff Bennett	— Rio Grande Subcommittee
David Dean	— Rio Grande Subcommittee
Gary Bryant	— Pecos River Subcommittee
Ryan Smith	— Devil's River Subcommittee

1.2.2 Upper Rio Grande 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 and to maintain the productivity, extent, and persistence of key aquatic habitats in and along the affected water bodies.

1.3 Sound Ecological Environment – Upper Rio Grande BBEST

Senate Bill 3 (SB 3) defines an environmental flow regime as:

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

SB3 did not define Sound Ecological Environment, but the SAC and other groups have provided definitions. The following is an interpretation from SAC (2006) with additions from the Upper Rio Grande BBEST.

A sound ecological environment is one that:

- sustains the full complement of the current suite of native species in perpetuity, or at least support the reintroduction of extirpated species,
- sustains key habitat features required by these species,
- retains key features of the natural flow regime required by these species to complete their life cycles, and
- sustains key ecosystem processes and services, such as elemental cycling and the productivity of important plant and animal populations.

The streams of the upper Rio Grande, including the Pecos and Devils Rivers as well as major tributaries like Alamito and Terlingua Creeks have changed in a variety of ways and extents in the years since major reservoirs were constructed and major water diversions began. For the purposes of this report it is assumed that the key ecosystem processes, services, habitat features and biological communities and species were in dynamic equilibrium with any changes attributable to natural environmental fluctuations and that the large changes in water quality, quantity, or species composition and distribution subsequent to major water development can be attributed to anthropogenic causes. We note, as have other BBEST's, that the adjective "sound" can be interpreted in many ways. In our view, "sound" does not equate to "natural', "pristine", or "in a condition similar to that before major diversions". However, in as much as it is the ecosystem services that support stakeholders (i.e. water quality and water supply, native species) and maintain, to a reasonable level, the physical, chemical, and biological attributes, "sound" will equate to active and functioning processes such as sediment and solute transport, habitat maintenance, persistent base flows, and elemental cycling.

There is not a single measure to test for soundness. Rather a test for soundness necessarily requires a review of a suite of measurements to assess the key features of a sound environment. These measures include flow data, water quality standards, fish and other biological surveys, sediment transport, flood frequency patterns, indices of biologic integrity and species occurrence, abundance, and diversity.

Many of the rivers and streams, riparian, wetland ecosystems (water bodies) of our assigned area exist wholly on private land and are not serviced by any state or federal monitoring systems. Given the paucity of data for these streams it is impossible to make a thorough determination of soundness in all places. For the purposes of this report, we will focus on the following stream segments: Rio Grande downstream of the confluence with the Rio Conchos at Presidio, Texas and above Amistad Reservoir, as well as two gaged tributaries: Alamito and Terlingua Creeks, Pecos River from the New Mexico state line to Amistad reservoir and one of its tributaries Independence Creek, and the Devils River from the headwaters to Amistad Reservoir (see **Figure 1.3-1**).

The Upper Rio Grande BBEST feels that the water bodies of our assigned area are “sound” with two large exceptions;

1) The Pecos River from the New Mexico state line to the confluence with Independence Creek and
2) The Rio Grande upstream of La Linda, Coahuila Mexico.

The Rio Grande exhibits a gradient of salinity, nutrient, and organic enrichment (Porter and Longley, 2011) downstream from the confluence with the Rio Conchos to Amistad Reservoir. This gradient is dependent on managed releases from the dams along the Rio Conchos and surface runoff from local tributaries and varies from year to year. The nature and extent of this gradient is the controlling factor in determining a boundary between an upstream unsound reach and a reach downstream that is ecologically sound. Given the variations in water flow and inputs, it is difficult to assign a boundary that will be meaningful in the years to come, but for the purposes of this report we will designate the boundary at La Linda, Coahuila, Mexico (see Section 3.6.3).

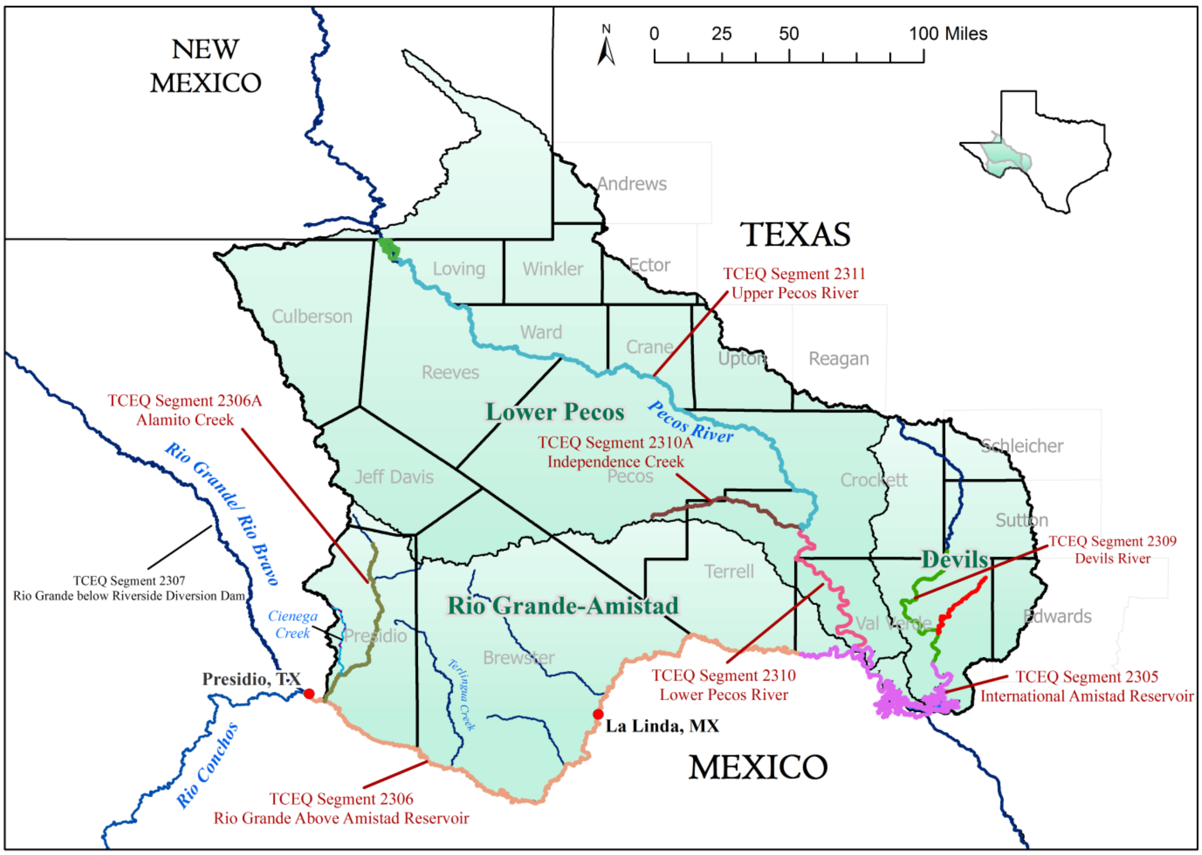


Figure 1.3-1. TCEQ stream segments in the Upper Rio Grande Basin.

1.3.1 SEE: Rio Grande, from the confluence with the Rio Conchos to Amistad Reservoir

The reach between Presidio Texas and Amistad Reservoir, designated water quality segment 2306 by the Texas Commission of Environmental Quality, flows through a small agricultural area near Redford, Texas and Mulato, Chihuahua, Mexico, and through a network of state and federally protected areas, including 4 units protected by Mexico (see **Figure 2.1-1**), encompassing nearly 3.3 million acres. This reach of the Rio Grande can be divided into two parts: a lower reach below La Linda that is significantly influenced by ground water contributions and an upper part that is not.

Sustains the full complement of the current suite of native species in perpetuity

Eight of 41 native fish have been extirpated or are extinct from the Big Bend Reach of the Rio Grande (see Section 3.6.3.2) (Hubbs et al., 2008). A recent mussel survey by the National Park Service (NPS) found only dead shells of three of five species that are believed to exist in the area with no individuals found in the upper reach and increasing numbers moving downstream. The invasive red eared slider is displacing and hybridizing with the native Big Bend Slider. This is in contrast to the recent and early success of the reintroduction of the Rio Grande Silvery Minnow (RGSM). Quarterly monitoring for the RGSM occurs at five sites in Brewster County. It is reasonable to suggest that this success is attributable to concurrent timing between the initial release and the channel reset flows of late 2008 (see Section 4.1.1). It is notable that of the 304 miles of river between the Rio Conchos and Amistad Reservoir, biological sampling is guided by the greater ease of access in the upper reach than in the lower reach, and thus the same level of sampling effort is not conducted everywhere. Monitoring of the RGSM through the next phase of channel sedimentation and narrowing that occurs after large floods will remain an important element of adaptive management programs. The overall trend is a decline in native species diversity. This criterion is not met for the reach above La Linda.

Sustains key habitat features required by these species

Dean and Schmidt (2011) have documented channel sedimentation, narrowing, and a loss of exposed gravel bars and multithreaded sections for the segment of the Rio Grande within Big Bend National Park (BBNP). The same has been documented for the El Paso to Presidio reach (Everitt, 1993). Dean and Schmidt (2011) further documented that channel reset events where significant channel widening occurs, like the one in 2008, only partially recover channel features and that channel narrowing re-occurs rapidly; the overall trend is an alteration of channel and habitat features from a wide multi-threaded channel with shallow and sparsely vegetated banks to a narrow, deeper channel with steeper heavily vegetated banks. As the channel accumulates sediment, its conveyance capacity is decreased and flooding frequency increases.

Downstream of La Linda, the Rio Grande enters a reach typified by deep canyons and spring fed base flows. Steeper tributaries deliver a coarser sediment load. A riverine ecosystem dominated by sediment transport gives way to one where geology may play a more important role. The impact of sediment accumulation on the reach below Boquillas Canyon has not been studied and is not well understood. In some locations channel and habitat features appear to be in decline, while in others this trend has not been documented.

Given the long term trend documented by Dean and Schmidt (2011) this criterion is not met for the reach above Boquillas Canyon.

Retains key features of the natural flow regime, such as water quality, required by these species to complete their life cycles.

Segment 2306, like 2307 above it, is an impaired water body, failing water quality standards for chloride, sulfate and total dissolved solids (TDS). In 2010, segment 2306 was included in the state's list of impaired water bodies, (TCEQ, 2010, 303D). The TCEQ averages all measurements across the reach; water quality measurements taken in the upper portion of the reach are consistently above acceptable limits while measurements taken in the lower reach are consistently within an acceptable range and yet the reach average violates the standards. The overall trend is increasing salinity at 3 of the 4 continuous monitoring stations operated by the Texas Clean Rivers Program (TCRP) (Bennett, et al 2012).

Ground water contributions to the Rio Grande from Cretaceous limestone aquifers in the lower end of the reach sustain aquatic habitats during dry years and mitigate water quality impairment (Bennett and Cutillo, 2007). Thermal springs occur along the Rio Grande from below Mariscal Canyon in Big Bend National Park to below Foster's Weir and just above Amistad Reservoir. Ground water contributions can account for as much as 2/3 of the flow at Foster's Weir and the river entering the reservoir during low flow conditions.

Given the long term trend in declining water quality in the upper reach this criteria is not met for the reach between the Rio Conchos and the TCRP station at Rio Grande Village.

<u>Sustains key ecosystem processes and services, such as elemental cycling and the productivity of important plant and animal populations.</u>

Quantitative studies of algal communities within the Rio Grande were completed by Porter and Longley in 2011. These studies revealed that the reach between Presidio and Castolon was dominated by brackish water species of algae indicating eutrophic to hypereutrophic conditions. The reach between Castolon and La Linda was a transition zone dominated by algal communities indicating mesotrophic or eutrophic conditions. Downstream of La Linda algal assemblages indicated improving water quality. These observations are congruent with the TCRP assessment in 2008 that lists the upper segments of this reach as impaired for contact recreation due to bacterial levels. The same assessment found increasing ammonia levels at one station. Eutrophic conditions indicate that elemental cycling is not in balance with nutrient inputs. Given the current condition and trends this criterion is not met above La Linda.

1.3.2 Alamito Creek

<u>Adapted from</u>: Far West Texas Water Planning Group. 2011. Far West Texas Water Plan.

http://www.twdb.state.tx.us/wrpi/rwp/3rdRound/2011_RWP/RegionE/

Alamito Creek extends from its confluence with the Rio Grande upstream to north of Marfa in Presidio County. A high quality tributary, Cienega Creek extends from its confluence with Alamito Creek upstream to its headwaters also in Chinati Mountains State Natural Area. Springs north of the Big Bend Ranch State Park form the headwaters of both creeks. Segments of these two streams on public land and on land held by the Trans Pecos Water and Land Trust are designated ecologically significant in the state water plan.

<u>Sustains the full complement of the current suite of native species in perpetuity</u>

Alamito Creek is recognized as a high quality ecoregional stream with exceptional aquatic life and high aesthetic value. The stream contains a diverse benthic community of macroinvertebrates and fishes (Bayer et al., 1992; Linam et al., 1999). Unique communities of threatened or endangered species include: Concho pupfish (Federal Species of Concern/State Threatened), Chihuahua shiner (Federal Species of Concern/State Threatened), Mexican stoneroller (Federal Species of Concern/State Threatened) (Bayer et al., 1992). Cienega Creek is an intact desert spring ecosystem displaying overall habitat value. Unique communities of threatened or endangered species include: Big Bend mud turtle and various endangered desert fishes.

The Dixon Water Foundation recently donated a tract of land approximately 35-40 miles south of Marfa in Presidio County to the Trans Pecos Water and Land Trust (TPWT), a non-profit 501.c.3 corporation. The 1,061-acre donated property, designated as the Trans Pecos Water Trust Alamito Creek Preserve, includes a 3.5-mile riparian zone of Alamito Creek and a shorter segment of Matonoso Creek. The southern downstream boundary of this property is located where TX 169, also known as Casa Piedra Road, bridges Alamito Creek. The 3.5- mile segment of Alamito Creek within the Preserve boundary is recommended by the Far West Texas Regional Water Planning Group (FWTRWPG) as an "Ecologically Unique River and Stream Segment.

This criterion is met for Alamito Creek.

<u>Sustains key habitat features required by these species</u>

Alamito Creek runs on the surface for most of the TPWT Preserve stretch. There are pools with year round populations of endemic fish, amphibians and aquatic invertebrates. Alamito Creek supports an extensive cottonwood bosque. Ash and willow species are present. There is very little tamarix/salt cedar. The segment offers superb wildlife habitat, natural diversity, and perennial stream flow, deserving recognition as an ecologically unique stream segment. This criterion is met.

<u>Retains key features of the natural flow regime, such as water quality, required by these species to complete their life cycles.</u>

A large concrete dam is located on Alamito Creek just south of Marfa, Texas and was built to create San Esteban Reservoir in the early part of the last century. Though the reservoir rarely holds water, the dam is intact and effectively disconnects the upper portion of Alamito Creek with the lower reach. Large stands of cottonwoods, willows and ash in the ecologically significant reach indicate a relatively intact hydrology.

<u>Sustains key ecosystem processes and services, such as elemental cycling and the productivity of important plant and animal populations.</u>

No information is available for this stream segment.

1.3.3 Pecos River

The Pecos River, TCEQ water quality segments 2311 (from Red Bluff Reservoir to the confluence with Independence Creek) (**Figure 1.3-1**) and 2310 (from the confluence with Independence Creek to Amistad Reservoir),

<u>Sustains the full complement of the current suite of native species in perpetuity</u>

The fish communities of the Pecos River in Texas have been highly altered. The reach from the Red Bluff Reservoir to Independence Creek (segment 2311) has lost 16 of its 35 native species (Hoagstrom 2003) and most fishes that persist are tolerant of high salinity and low water quality. Many of these species losses are directly related to flow impacts, particularly the flow regulation by Red Bluff Reservoir. Some species losses in both reaches are due to hybridization and competition with introduced species (Wilde and Echelle 1992, Hoagstrom 1994, Hoagstrom 2003). Because of the highly altered fish community, this criterion for a sound ecological environment is not met for the upper reach of the Pecos.

The fish community of the reach below Independence Creek (segment 2310) exhibits similar declines with 18 of its 39 native species persisting (Hoagstrom 2003). Many of these species losses are also related to flow impacts and hybridization and competition with introduced species (Wilde and Echelle 1992, Hoagstrom 1994, Hoagstrom

2003). While this lower reach is a much different environment than it was before water development and has also seen a loss or significant decline of most large river fishes, it does maintain a thriving, albeit different, fish community. The lower reach is now primarily a ground water, spring-fed stream with a fish community similar to Independence Creek with the large river fishes that do remain in highly reduced abundances. Primarily due to ground water input, this reach maintains healthy and stable biological communities and still supports several rare species. We consider this lower reach to meet this criterion for a sound ecological environment.

The fish community of Independence Creek, a primary tributary of the lower Pecos River, is largely intact with only a few species declining or extirpated due to hybridization or other factors separate from flow regulation and impacts. We consider this criterion to be met for Independence Creek. Information is insufficient to evaluate this criterion for other tributaries of the Pecos such as Live Oak Creek.

<u>Sustains key habitat features required by these species</u>

The water development of the Pecos River has also had major effects on the river's channel and the instream, riparian and floodplain habitat features that it provides. The upper and lower reaches have always been somewhat different, with the lower portion intersecting the Edwards Plateau. The Upper Pecos has seen major changes from its historical deep, swift flow with steep, unstable banks and shifting sandy bed to its current narrow, muddy channel with highly reduced flow. This reach does not meet this criterion for a sound ecological environment. However, the lower Edwards Plateau influenced reach retains more of its historical characteristics, which is partly responsible for it maintaining a more healthy fish community. The lower reach does meet this criterion for a sound ecological environment.

<u>Retains key features of the natural flow regime, such as water quality, required by these species to complete their life cycles.</u>

The Pecos River from Red Bluff Dam to Independence Creek (segment 2311) can be divided into three ecological sections. The first section, from Red Bluff Dam to Ward II turnout, is managed by the Red Bluff Water Power Control District. Varying management strategies have been utilized in the past some of which have totally dried the river bed but very little water ever passes Ward II turnout (**Figure 2.6-8** and **Figure 2.6-10**). In this section of the river, high flow pulse flows events are diverted by the seven irrigation districts. This criterion is not met in the upper reach.

Section 2, from Ward II turnout to Iraan, receives high salinity ground water from the Pecos Valley Aquifer. Total dissolved solids for base flows are > 15,000 ppm TDS in the aquifer which feeds the springs into this segment of the Pecos River (**Figure 2.7-2**). During the summer months TDS can exceed 30,000 ppm in the vicinity of Iraan. In this section of the river, the majority of overland flows are intercepted by Ward II and Pecos II and III irrigation districts. Therefore, storm water events which would cause pulse flow events never make it to the Pecos River. Key features of the natural flow regime are not met in this section of the river.

From Iraan to the confluence of Independence Creek the River is spring fed by fresh water from the Edwards Aquifer. This water dilutes the TDS concentration in the river until it reaches the confluence with Independence Creek. Storm events in Tunas sub-basin and Pecos sub-basin enter the river as do storm events in Comanche Creek and Landreth Draw. Therefore, overland flows in this section do create pulse flows which contribute to the improved water quality and habitat. However the low base flows and the low water quality keep this section of the river from meeting the criteria of retaining a natural flow regime required by these species to completer their life cycles.

Downstream from the confluence of Independence creek (segment 2310), flow and water quality are drastically improved. Below Independence Creek, river flow increases 42% and the sodium concentration decreases 50%. Water quality improves to the vicinity of 2,000 ppm TDS (Miyamoto et al. 2006). Below Independence Creek, the river has storm event flows from Comanche Creek, Landreth Draw, Tunas sub-basin, Pecos sub-basin, and Independence Creek sub-basin. This provides the natural flow regime to maintain a sound ecological environment for the smaller native fishes which currently exist in the river. To maintain this sound ecological environment, overland flow must be protected to support sufficient channel flow for smaller fishes and ground water flows must be protected to provide base and subsistence flow. If the spring flows are not protected, the river will not sustain a sound ecological environment for even the smaller fishes.

<u>Sustains key ecosystem processes and services, such as elemental cycling and the productivity of important plant and animal populations.</u>

To our knowledge, there has not been a large amount of research on ecosystem processes on the Pecos River. We also do not know of studies of important processes like sediment transport and sediment budget, ecosystem productivity, etc. There have been studies of riparian vegetation, insect, bird, and herpetofaunal communities in the area of Independence Creek Preserve, which indicate a high degree of health and intactness. The critical process for the ecological health of the Pecos is ground water contributions in lower portion of TCEQ segment 2311 and the entirety of Segment 2310. For the purposes of this report, we have determined that segment 2310 is ecologically sound based wholly on occurrence of high quality ground water input. We consider it highly unlikely that this criterion is met for the upper reach, but that it is met, in its current state of “soundness”, in the lower reach.

1.3.4 SEE: Independence Creek

Independence Creek, unclassified TCEQ water quality segment 2310A,

<u>Sustains the full complement of the current suite of native species in perpetuity</u>

Nearly all of the 29 native fishes of Independence Creek are currently extant with good population sizes. Only one species, the Pecos pupfish (*Cyprinodon pecosensis*) has been extirpated, due to hybridization with the introduced sheepshead minnow (*Cyprinodon variegatus*) (Wilde and Echelle 1992). Independence Creek supports 2 listed species [proserpine shiner *Cyprinella proserpina* (State-Threatened) and Rio Grande darter *Etheostoma grahami* (State-Threatened)] and several other rare fish (e.g., headwater catfish *Ictalurus lupus* and manantial roundnose minnow *Dionda argentosa*). All currently extant Independence Creek fishes have stable populations (Kelsch and Hendricks 1990, Hoagstrom 2003, Bonner et al. 2005, Watson 2006), though at least two are threatened by hybridization, the headwater catfish by channel catfish (*Ictalurus punctatus*) (Wilde and Echelle 1992) and the plains killifish (*Fundulus zebrinus*) by introduced Gulf killifish (*Fundulus grandis*) (Hoagstrom 1994). Independence Creek serves as a refuge for Pecos River fishes during periods of environmental stresses such as poor water quality (Rhodes and Hubbs 1992).

Sustains key habitat features required by these species

Independence Creek does currently sustain key habitat features required by the native species. Again, any habitat impacts are not likely due to flow alteration, but to watershed impacts and other factors. Similar to the Devils River, large floods seem to severely impact instream habitats, with the post-flood channel tending to be wider, shallower with a higher abundance of gravels (Watson 2006), though this does not seem to severely impact the post-flood fish community. The Independence Creek watershed sustains grazing which was heavier in the past, but the effects of this grazing on watershed hydrology have not been investigated. There has been some development of Independence Creek for irrigation, particularly in the area of Caroline Springs now contained in The Nature Conservancy's (TNC) Independence Creek Preserve. But, diversions are now very small and are made primarily to water wetland habitats.

Retains key features of the natural flow regime, such as water quality, required by these species to complete their life cycles.

Independence Creek does currently retain all aspects of its natural flow regime on which species' life histories depend. There is currently no flow regulation of Independence Creek, so there has been little to no management of or impacts to high flow events. Base flow has not been highly altered by minimal irrigation in the watershed, but is the aspect of the flow regime most likely to be affected in the future, primarily by aquifer pumping. Trends in base flow should be examined in more detail using annual summaries and other parameters in future work.

Sustains key ecosystem processes and services, such as elemental cycling and the productivity of important plant and animal populations.

A large amount of research on ecosystem processes in Independence Creek was in evidence at the time of this. Published studies of important processes like sediment transport and sediment budget, ecosystem productivity, etc. were not located. Studies of riparian vegetation, insect, bird, and herpetofaunal communities have been conducted in the area of Independence Creek Preserve, which indicate a high degree of health and intactness.

1.3.5 Devils River

The Devils River, TCEQ water quality segment 2309, flows approximately 66 miles through Val Verde County in south central Texas. There are no major diversions on the river and only one continuous monitoring station. The lower 21 miles of this reach are impounded by Amistad Reservoir. It is widely recognized as the state's most unsoiled stream in terms of water quality.

Sustains the full complement of the current suite of native species in perpetuity

Nearly all of the 33 native fishes of the Devils River are currently extant with good population sizes. Only one species, the blotched gambusia (*Gambusia senilis*) has been extirpated, likely due to construction of Amistad Reservoir (Hubbs et al. 2008). The Devils River supports 4 listed species [Devils River minnow *Dionda diaboli* (Federal, State-Threatened), Proserpine shiner *Cyprinella proserpina* (State-Threatened), Rio Grande darter *Etheostoma grahami* (State-Threatened), and Conchos pupfish – Devils River subspecies *Cyprinodon eximius ssp.* (State-Threatened)] and several other rare fish (e.g., headwater catfish *Ictalurus lupus*, manantial roundnose minnow *Dionda argentosa* and Tex-Mex Gambusia *G. speciosa*). The construction of Amistad Reservoir seems to have not only extirpated blotched gambusia, but also severely reduced another species (Conchos pupfish) (Davis 1980a, Hubbs and Garrett 1990) and may have reduced or eliminated some larger bodied large river fishes. The

Conchos pupfish was nearly extirpated, but was re-established in the upper river (Dolan Falls area) from a downstream population (Hubbs and Garrett 1990). All currently extant imperiled fishes have stable populations (Kelsch and Hendricks 1990, Garrett et al. 1992, Cantu and Winemiller 1997, Robertson and Winemiller 2003, Kollaus and Bonner 2012). There have been several exotic species introduced into the Devils River, some of which may affect native fishes (Lopez-Fernandez and Winemiller 2005). Also, several reservoir fishes (e.g., striped bass) now occur in the river as they move upstream from Amistad Reservoir. There is no ongoing fish community monitoring as part of a Clean Rivers Program, but the Devils River was used as a reference stream for development of regional fish IBI's (Bayer et al. 1992, Linam et al. 2002) and all recent studies indicate that the fish communities are highly intact.

The freshwater mussel community of the Devils River seems to be mostly intact. There have been few recent surveys, but *Popenaias popeii* was recently rediscovered in the Devils River. The aquatic reptiles and amphibians of the Devils River also seem to be largely intact (Bailey et al. 2008). The Rio Grande cooter is a species of conservation concern that seems to have stable population in the Devils River. However, more survey attention and information on the current status of species such as Rio Grande cooter and springs salamander (*Eurycea sp*., spring-dwelling species, not in river itself) is needed. All recent studies of benthic macroinvertebrates indicate that the insect communities of the Devils River are also highly intact.

Overall, most of the native species of the Devils River are sustained by the current flow regime. The few species losses and declines that have taken place in the Devils seem to be due not to flow effects, but to downstream reservoir construction and other human activities. This criterion is met for the Devils River.

<u>Sustains key habitat features required by these species</u>

The Devils River does currently sustain key habitat features required by the native species. Again, any habitat impacts are not likely due to flow alteration, but to watershed impacts and other factors. Periodic large floods have major effects on instream habitats, with the post-flood channel tending to be wider, shallower with a higher abundance of gravels (Harrell 1978). It is not known whether this has been exacerbated by land uses. There is some suggestion of impacts from heavy grazing of the Devils watershed in the early and middle part of the 20th century. While not having been heavily studied, the Devils River channel has not sustained heavy alteration such as the Rio Grande. The biggest impact to the Devils River has been Amistad Reservoir which cuts off access to downstream habitats. This criterion is met for the Devils River.

<u>Retains key features of the natural flow regime, such as water quality, required by these species to complete their life cycles.</u>

The Devils River does currently retain all aspects of its natural flow regime on which species' life histories depend. There is currently no flow regulation in the Devils River, so there has been little to no management of or impacts to high flow events. Base flow has not been highly altered, and is the aspect of the flow regime most likely to be affected in the future, primarily by aquifer pumping. Trends in base flow need to be analyzed in more detail using annual summaries and other parameters. The Devils River meets all current water quality standards (De La Cruz 2004) and is often put forward as one of the standards for high water quality in Texas. This criterion is met for the Devils River.

<u>Sustains key ecosystem processes and services, such as elemental cycling and the productivity of important plant and animal populations.</u>

To our knowledge, there has been little research on ecosystem processes in the Devils. There have also been no studies of important processes like sediment transport, ecosystem productivity, etc. There have been studies funded by The Nature Conservancy of riparian vegetation, insect, bird, and herpetofaunal communities in the area of Dolan Falls Preserve, which indicate a high degree of health and intactness. This criterion is met for the Devils River.

1.4 Introduction to Environmental Flows Recommendation Report

The remainder of the Environmental Flows Recommendations Report of the Upper Rio Grande BBEST is comprised of four major sections and supporting appendices. Section 2 provides an overview of the geologic, physiographic, climatic, and biophysical characteristics of the upper Rio Grande basin and sub-basins and their respective current conditions. Section 3 describes the in-stream flow analyses conducted for each sub-basin including the bio-physical overlays used to guide the flow analyses and recommendations. Section 4 provides the environmental flow recommendations for each river, and Section 5 outlines the adaptive management actions that may be taken to improve the understanding of biophysical processes and future environmental flow recommendations for each sub-basin.

The river segments under review in this report span two ecoregions that include diverse geologic and physiographic characteristics, climatic and hydrologic regimes, and different environmental and land use histories. Thus, the environmental processes that occur within each are unique with respect to the natural variability guiding these processes as well as the land use histories and the degree of hydrologic development that has occurred. Previous scientific investigations conducted within the URG basin are equally diverse and range from detailed geomorphic investigations, habitat modeling, and water quality monitoring, to areas where little to no scientific investigations have been conducted. The diverse physical and hydrologic environments and the different levels of scientific understanding necessitate a unique suite of methods and biophysical overlays to be used for each river segment. It is the URG BBEST's opinion that applying standardized methodologies and analyses to each portion of the URG basin would be a disservice to the unique nature of each river segment. For the above reasons, fundamentally different approaches were used to guide the environmental flow analyses included within this report.

Methods for environmental flow analyses are the most unique on the Rio Grande because of the rapid rates of geomorphic change that occur from year to year. An extensive geomorphic overlay is used for the Rio Grande because the rapidly changing geomorphic template is viewed by regional environmental managers as the one of the most important factors affecting the aquatic and riparian health of this river. Water quality is the other primary overlay used for the Rio Grande because portions of the river are often listed as impaired by the TCEQ. For the Pecos and Devils Rivers, environmental flow recommendations primarily consist of historic hydrologic .analyses using Hydrology-based Environmental Flow Regimes (HEFR), along with low flow biological overlays pertaining to fish habitat, as well as water quality. These differences are highlighted below and more fully described in Sections 2 and 3.

1.4.1 Rio Grande, Alamito, and Terlingua Creeks

Stream flow of the upper Rio Grande river segment (318 miles between Presidio, TX and Amistad Reservoir, **Figure 2.1-1**) is determined by inflows from the Rio Grande upstream from Presidio, TX, inflows from the Rio Conchos in Chihuahua, MX, and other large desert ephemeral tributaries in both countries. Within these areas, stream flow is comprised of runoff produced by monsoon rains during the summer months, tropical storms and hurricanes from both the Pacific Ocean and the Gulf of Mexico, and ground water inputs from adjacent aquifers.

Over 80% of Rio Grande stream flow is derived from the Rio Conchos and other Mexican tributaries, and thus, climatic conditions and hydrologic conditions in the Rio Conchos headwaters high in the Mexican Sierra Madre Occidental, and Mexican water development directly influence the hydrologic regime of the Rio Grande. The Rio Grande also transports extremely high sediment loads, and channel morphology changes rapidly as dictated by the magnitude, duration, and source areas of flood flows, and the quantity of sediment input by ephemeral tributaries. Significant ground water inputs begin approximately 148 miles downstream from Presidio, TX, and augment low flow and improve the water quality. Few studies regarding the aquatic ecology of the Rio Grande have been conducted; however, it is believed that native aquatic species are strongly affected by the rapid geomorphic changes and longitudinal differences in water quality.

Based on the above characteristics, environmental flow recommendations for the Upper Rio Grande rely heavily upon geomorphology, and water quality overlays, and to a lesser extent, biological overlays. HEFR analyses are used to help characterize past hydrologic trends, and are supplemented by additional hydrologic analyses. The geomorphology overlay, and the understanding of historic hydrologic trends in driving geomorphic process is used to provide recommendations with regards to high flow pulses, because high flows (or lack thereof) dictate the rate, magnitude, and trajectory of geomorphic change. The water quality overlay and biological overlay is used to provide recommendations with regards to the low-flow regime.

The environmental flow recommendations for Alamito and Terlingua Creeks are entirely obtained by HEFR analyses. These creeks have changed little over that last century, and there have been few studies from which to incorporate bio-physical overlays. These creeks may potentially be affected by ground water pumping in the future; however, there is little understanding of current land use trends with regards to the biological health and physical characteristics of these creeks.

1.4.2 Pecos River and Independence Creek

The hydrology of the Pecos River is primarily driven by ground water inputs from the Pecos Valley and Rustler Aquifers as well as other local springs. Extensive ground water pumping from the Pecos Valley Aquifer occurs for irrigated agriculture. High-flows are derived from regional frontal storms and convective storms during the monsoon season.

Water availability and water quality are the two most dominant environmental concerns for the Pecos River, and directly control the health of the aquatic and riparian ecosystem. To address these concerns within this report, we use several analyses in determining environmental flow recommendations for six locations in the Pecos River sub-basin. HEFR analyses are used to describe all aspects of the historical flow regime. Because we consider the upper Pecos River to be unsound, the flow regime recommendations for the upper gages (Pecos River at Orla, Pecos and Girvin) are considered initial recommendations to maintain current conditions. We do not offer recommendations for flows to restore the soundness of this reach, but do lay out adaptive management steps to develop this. For the lower Pecos River, which we consider to be sound, our flow regime recommendations are intended to maintain the current ecological conditions. To refine our hydrology-based flow recommendations, we incorporate a biological overlay consisting of flow-instream habitat modeling for 10 focal fish species to develop base-flow recommendations for one gage in the lower Pecos River (Pecos River at Brotherton Ranch near Sheffield). We then employ a water quality overlay to evaluate subsistence flow recommendations.

Independence Creek is the most important freshwater tributary to the lower Pecos River. Independence Creek is spring fed and pristine supporting a diverse suite of bird and fish species and we consider it to be sound ecological environment. Because of the ecological importance of Independence Creek to the region, a biological overlay consisting of flow-instream habitat modeling for 10 focal fish species was developed to refine the hydrology-based environmental flow recommendations.

1.4.3 Devils River

Hydrology of the Devils River is similar to that of the Pecos with ground water inputs governing the low flows of the river, and frontal storms and convective storms during the monsoon season driving high flows. The Devils River is considered pristine with exceptional water quality and an abundant and diverse aquatic and riparian ecosystem and we consider it to support a sound ecological environment.

For environmental flow recommendations, HEFR analyses are used to characterize the historical stream-flow record of two locations on the Devils River. A biological overlay consisting of habitat modeling for 10 focal fish species is used to evaluate the base-flow component of the hydrology-based flow regime and refine the base flow recommendations for one of the two Devils River gages (Devils River near Juno). A water quality overlay is employed for the evaluation of the subsistence flow recommendations, but no modifications to the hydrology-based subsistence flows were necessary.

Section 2. Overview of the Upper Rio Grande & Current Conditions

2.1 Geographic coverage of the Upper Rio Grande Sub-basin

As discussed in the previous section, the Upper Rio Grande BBEST covers the Rio Grande sub-basin (segment from the Confluence of the Rio Grande and the Rio Conchos to above Amistad Reservoir), the Pecos River sub-basin (segment from the Red Bluff Reservoir to its confluence with the Rio Grande), and the Devils River sub-basin and associated watersheds (**Figure 2.1-1)** (SAC, 2009; TCEQ et al. 2008). They are located in the Trans-Pecos region, also known as Far West Texas and the Big Bend Country, consisting of the Chihuahuan Desert and isolated mountain ranges. The environmental flow assessments used 3 selected gage stations along a 318 mile long segment of the Rio Grande, 4 gage stations along a 398 mile long segment of the Pecos River and 2 gage stations along a 67 mile long segment of the Devils River. Additional stream flow data included in the Rio Grande geomorphic and water quality overlays is obtained from two additional gaging stations (USGS near Castolon #08374550, and USGS near Rio Grande Village #08375300) that have short records and thus are not used in the environmental flow recommendation. The total drainage area is approximately 35,322 square miles (10,360 for the sum of Alamito, Terlingua, Maravillas, and Rio Grande; 20,700 for Lower Pecos; 4,262 for the Devils). The work of URG BBEST encounters 20 counties; Andrews, Brewster, Crane, Crockett, Culberson, Ector, Edwards, Jeff Davis, Loving, Pecos, Presidio, Reagan, Reeves, Schleicher, Sutton, Terrell, Upton, Val Verde, Ward, Winkler, across three water planning regions, Far West Texas Region (Region E) (FWT Water Planning Group, 2011), Region F (Region F Water Planning Group, 2010), and Plateau Region (Region J) (Plateau Water Planning Group, 2011; TWDB, 2012) (see **Figure 2.7-1** and **Figure 2.7-2**).

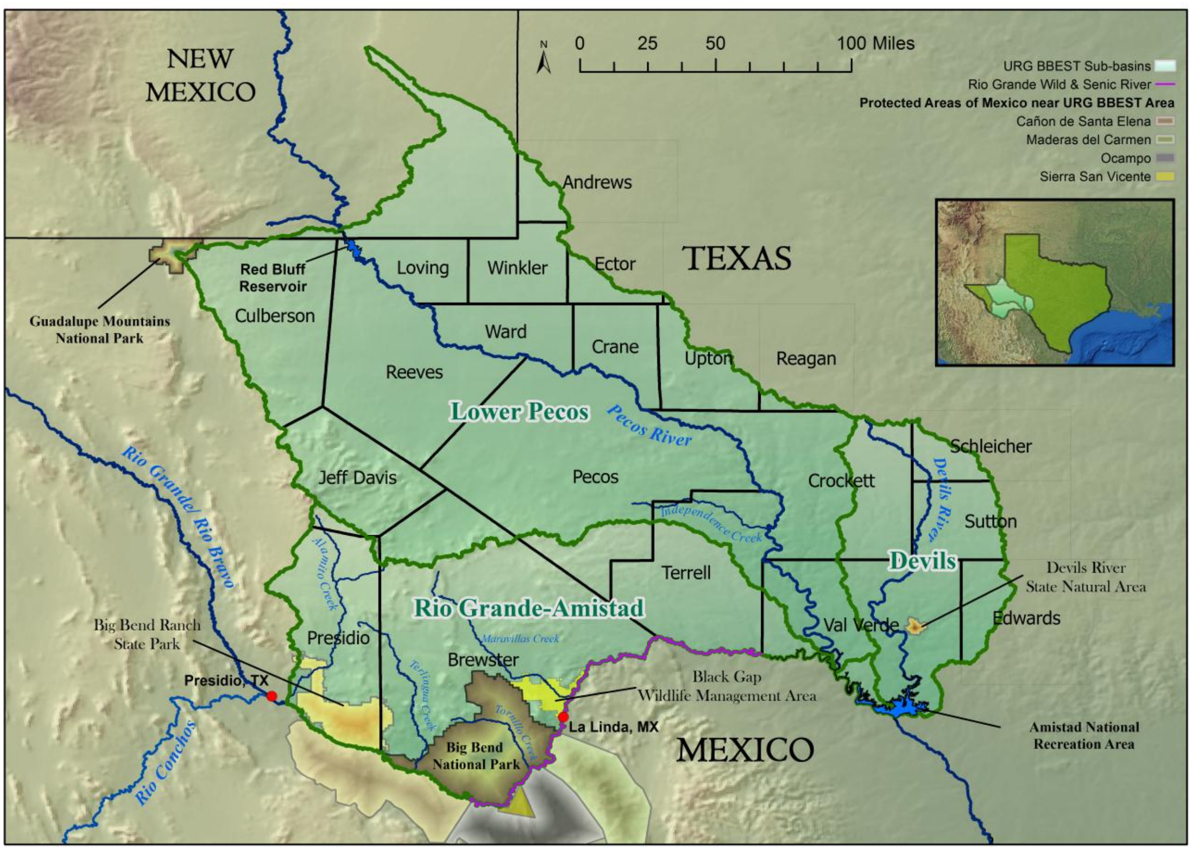


Figure 2.1-1. Location of Upper Rio Grande BBEST sub-basins.

2.2 Ecoregions; Edwards Plateau and Chihuahuan Desert

All the following information is summarized from the ECOREGIONS OF TEXAS (publication AS -199) authored by Glenn Griffith, Sandy Bryce, James Omernik, and Anne Rogers (Griffith, et al. 2007) for the Texas Commission on Environmental Quality in December, 2007. The State of Texas is comprised of 56 level IV ecoregions reflecting the ecological and biological diversity of the State of Texas. The term ecoregion attempts to categorize areas with similar type, quality and quantity of environmental resources, disturbance response, and management requirements. Within this categorization are the Chihuahuan Desert and Southern Texas Plains ecoregions which contain the Upper Rio Grande basin in southwest Texas (**Figure 2.2-1**). In this region, the Rio Grande is comprised of three unique drainage basins: the Rio Grande comprising the southern border of Big Bend National Park, Pecos River basin downstream from the park boundary, and the Devils River basin from Lake Amistad. The Chihuahuan Desert ecoregion contains the stretch of the Rio Grande bordering Big Bend National Park and the Pecos River. The Devils River is in the northeastern corner of the Southern Texas Plains ecoregion and more specifically, the Semiarid Edwards Plateau.

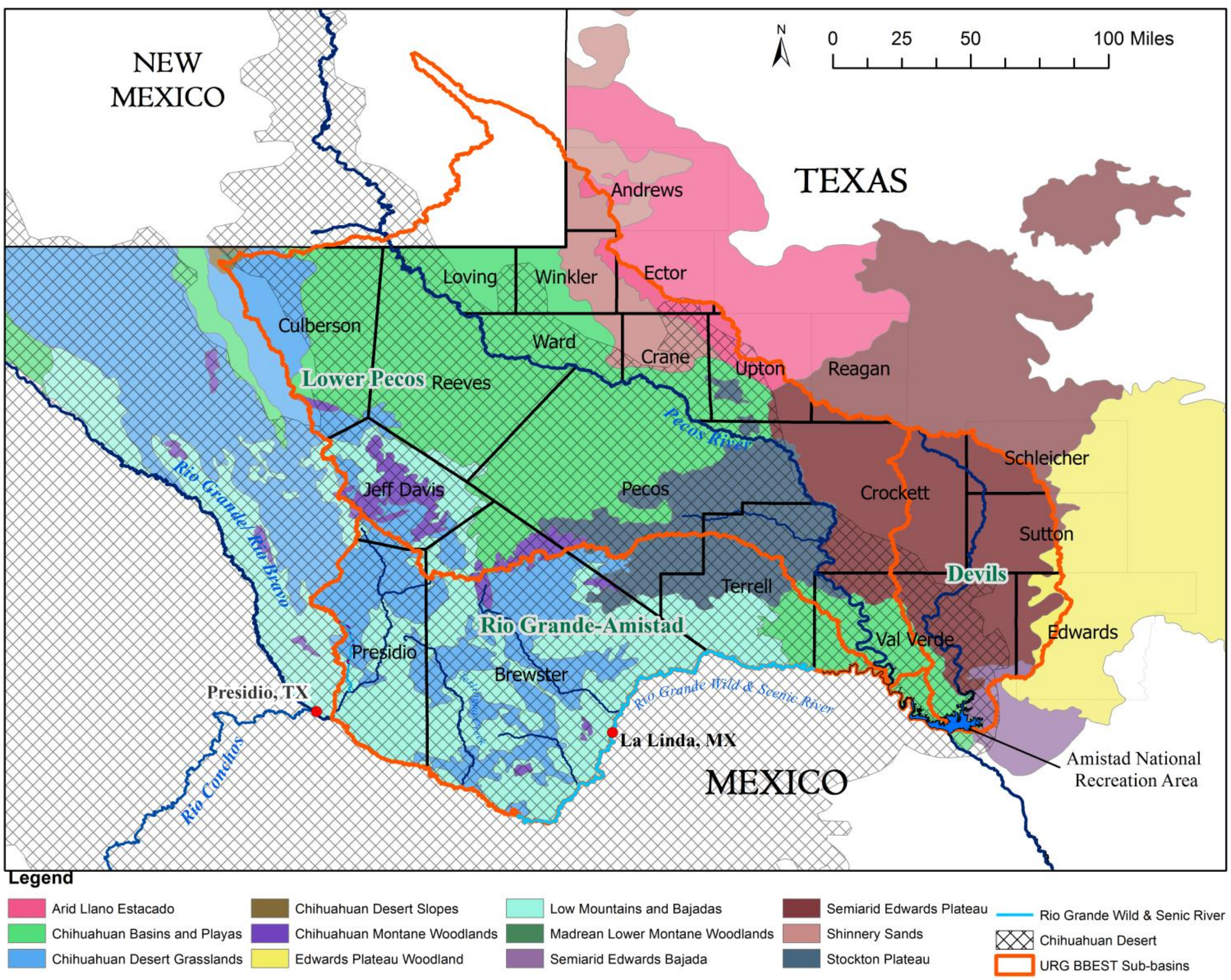


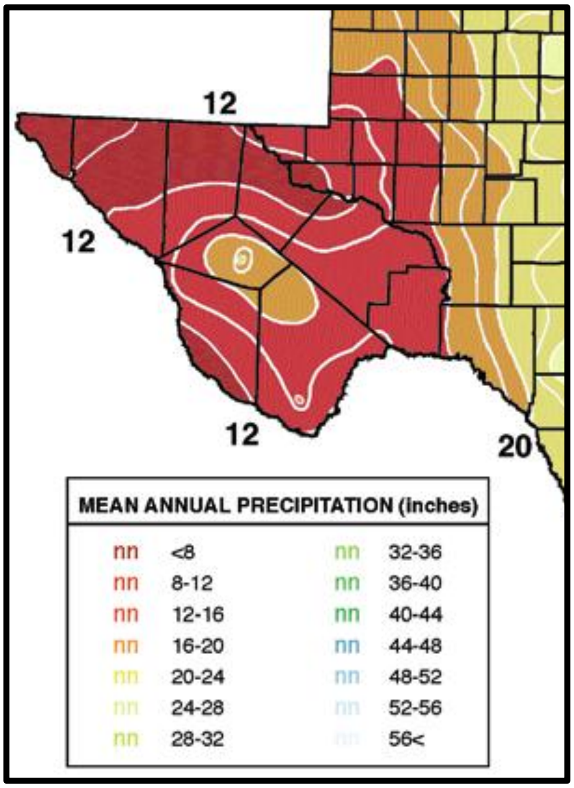
Figure 2.2-1. Ecoregions within the URG BBEST sub-basins (Omernik, 2004).

The Chihuahuan Desert ecoregion is comprised of alternating mountains and basins. The mountains consist of faulted limestone reefs, volcanic basalt, rhyolite, and tuff extrusive rocks with woodlands (oak, juniper, Texas madrone, bunchgrasses, and pinyon), coniferous forest (Douglas-fir, ponderosa pine, and Arizona cypress), and grasses such as gramas and bluestems. The basins are formed by deep depressions or sediment filled grabens, alluvial basins (Rio Grande Basin), or internally drained (Salt Basin) dominated by semi–desert grasslands, arid shrublands, and ephemeral streams. This ecoregion is further broken down into Chihuahuan Basin and Playas (1200 to 4500 feet in elevation, 8 to 14 inches annual precipitation, and 67ºF to 97ºF average low/high temperature); Chihuahuan Desert Grasslands (2000 to 6000 feet in elevation, 10 to 18 inches annual precipitation, and 62ºF to 90ºF average low/high temperature); Low Mountains and Bajada (2000 to 6000 feet in elevation, 9 to 17 inches annual precipitation, and 65ºF to 92ºF average low/high temperature); and Chihuahuan Montane Woodlands (4800 to 8378 feet in elevation, 18 to 26 inches annual precipitation, and 58ºF to 90ºF average low/high temperature).

The semiarid Edwards Bajada of the Southern Texas Plains ecoregion is at a lower elevation than the Chihuahuan Desert ecoregion (**Figure 2.2-1**), and forms the northwest boundary and historically supported grasslands and savanna vegetation but as a result of anthropogenic impacts has become dominated by honey mesquite and black brush. This ecoregion is comprised of alluvial and slope wash deposits from the Edwards Plateau. This ecoregion supports a network of springs and streams originating from deep “cool” water aquifers beneath the Edwards Plateau. The Rio Grande Floodplain ecoregion consist mainly of Holocene alluvium or Holocene and Pleistocene terraces with hyperthermic soils. Vegetation on the floodplain along the Rio Grande in this upper reach may include honey mesquite, salt-cedar, black willow, black mimosa, and common and giant reed. This region ranges in elevation from 880 to 1780 feet receiving 19 to 22 inches of precipitation annually, and experiences average temperatures ranging from 74ºF to 96ºF.

2.3 Climate of the Upper Rio Grande BBEST Area

The URG BBEST area is located in a Subtropical Steppe and Arid climate of the Trans-Pecos Region and is typified by semi-arid to arid conditions (Larkin and Bomar, 1983; Nielsen-Gammon, 2008). During fall, winter, and spring, it experiences the clearest days statewide. It is also the driest, receiving an average annual rainfall of less than 16 inches (410 mm) or less (TECO, 2008; TWDB, 2012). The wettest months in this region occur during the summer. In general the precipitation decreases westward across the area except in mountain ranges. Precipitation increases with the elevation within the mountain range as shown in **Figure 2.3-1**.



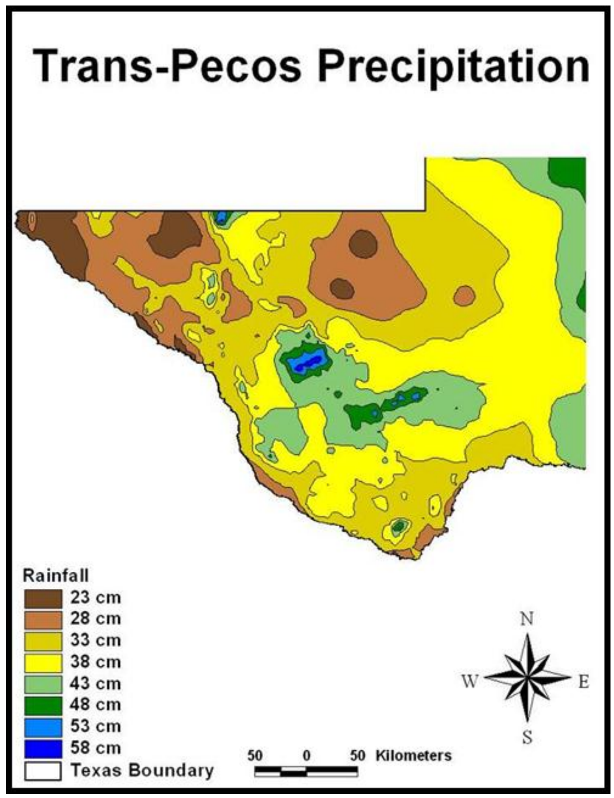


Figure 2.3-1. Mean annual precipitation and elevation/ precipitation relationships in the Trans-Pecos, TX (TECO, 2008).

Based on monthly and annual precipitation at county quadrangles, No. 604, 605, 705, 706, and 803 through 806 (**Figure 2.3-2**) from 1940 through 2010 compiled by the National Weather Service and by the Texas Water Development Board (TWDB, 2012), annual mean precipitation varies from 11.77 inches at the quadrangle 604 to 21.28 inches at the quadrangle 803.

Based on gross lake surface evaporation data at county quadrangle, No. 604, 605, 705, 706, and 803 through 806 from 1954 through 2010 (TWDB 2012), annual mean evaporation varies from 55.01 inches at the quadrangle 804 to 71.57 inches at the quadrangle 605.

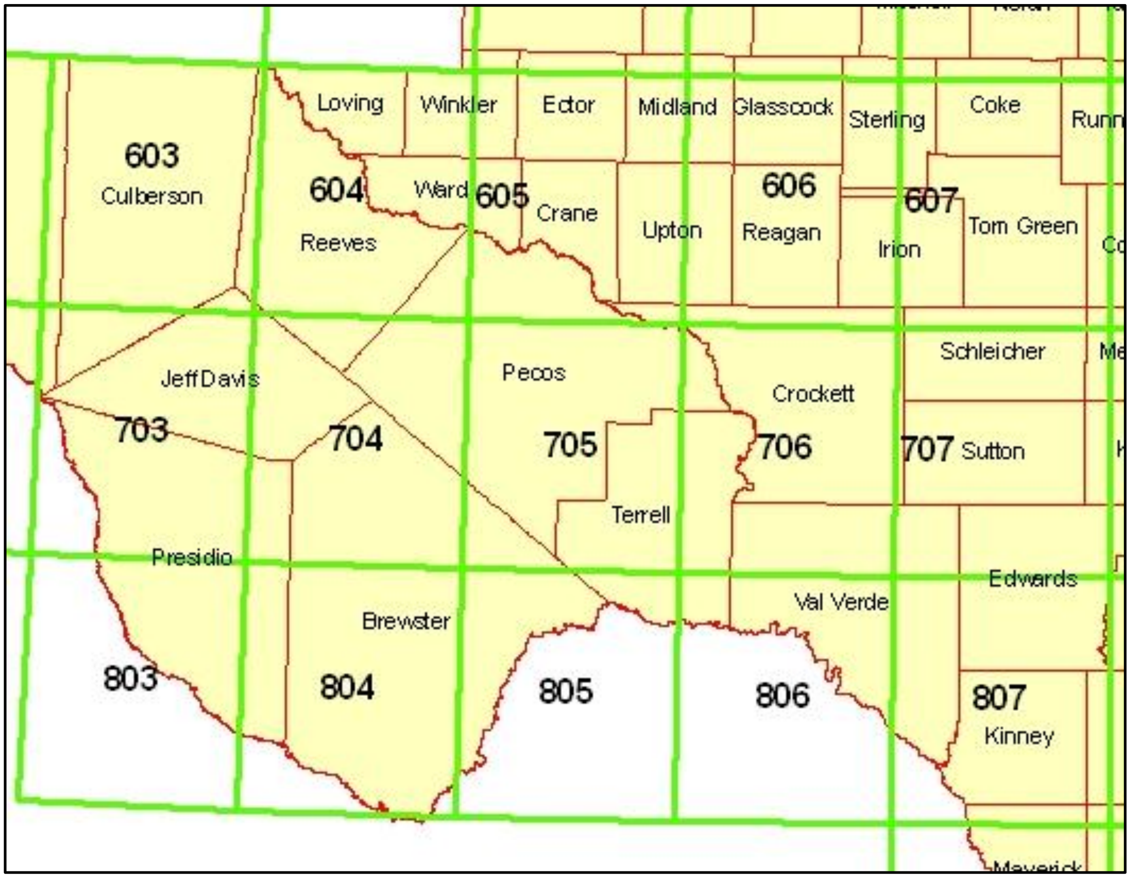


Figure 2.3-2. County quadrangles (modified from TWDB, 2012)

Annual precipitation and lake evaporation calculation at selected quadrangles are summarized in **Table 2.3-1**.

Table 2.3-1. Summary of annual lake evaporation and precipitation in URG area

ID	Annual Lake Evaporation (inch)				Annual Precipitation (inch)			
	Min	Max	Median	Mean	Min	Max	Median	Mean
604	48.43	93.1	67.06	68.18	2.8	25.33	10.49	11.77
605	48.45	97.34	71.79	71.57	5.64	29.37	12.36	13.67
705	44.17	89.25	63.68	64.33	4.09	28.85	12.82	13.81
706	43.94	94.2	63.53	64.21	6.76	34.91	19.01	19.16
803	39.67	80.44	54.22	55.54	3.82	67.03	13.53	21.28
804	38.98	81.74	53.23	55.01	6.21	40.35	13.81	15.11
805	47.45	81.75	63.89	64.5	4.69	26.51	11.5	11.9
806	47.91	81.85	67.67	67.79	4.38	28.96	16.13	16.95

The coldest temperatures in URG area are observed in the Davis Mountains (**Figure 2.3-3**). The temperature variations are shown with maps of January normal minimum temperature and July normal maximum temperature (**Figure 2.3-4**). Typical daily minimum temperatures in January vary from 28°F to 35°F. The maximum temperatures in July vary from 84°F to 96°F. Hotspots are found along the Rio Grande and Pecos River, while the coolest summertime temperatures are found in the mountains of West Texas (Nielsen-Gammon, 2008).

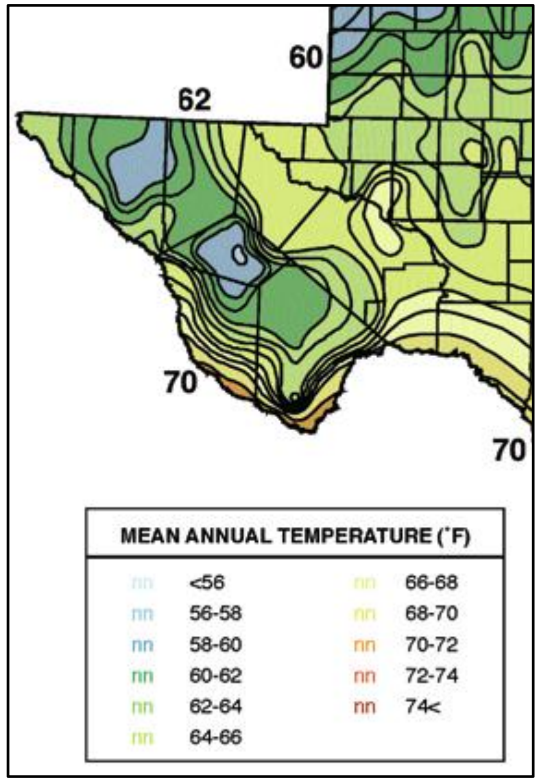


Figure 2.3-3. Average Annual Temperature (TECO, 2008).

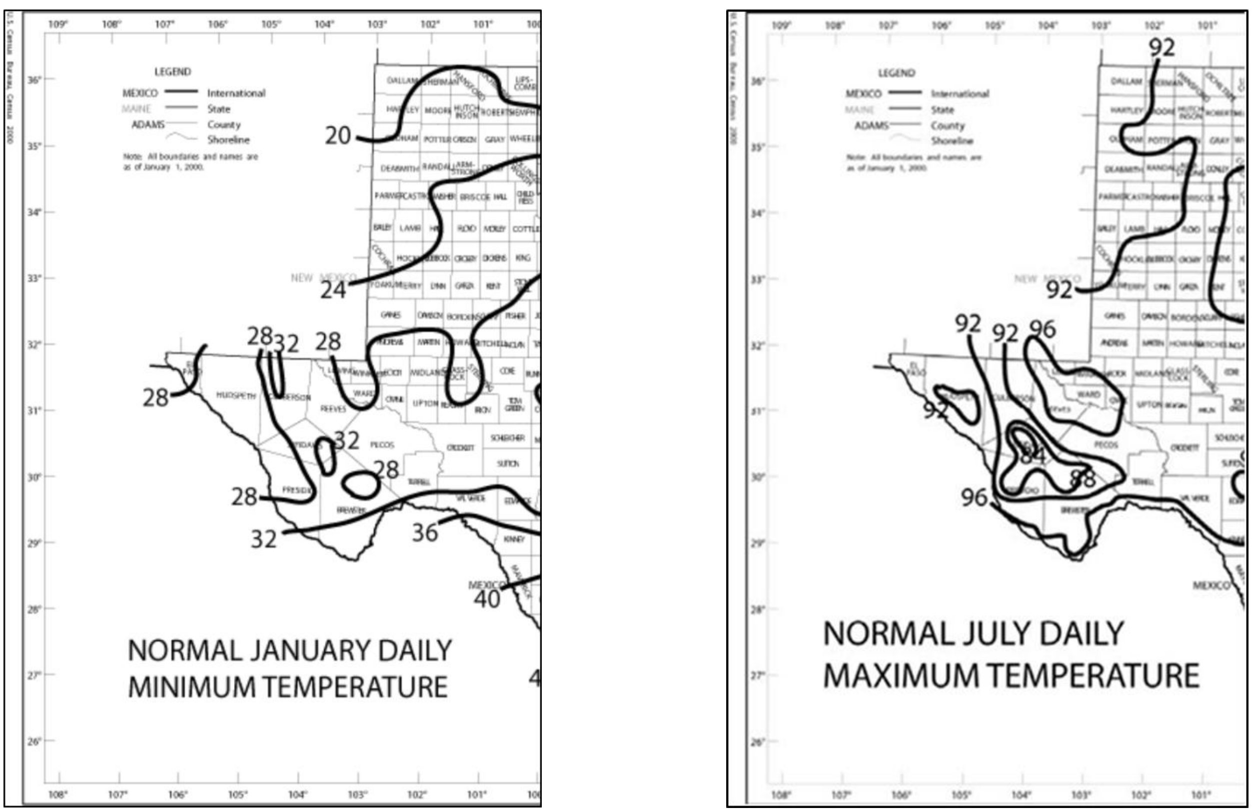


Figure 2.3-4. Normal January and July daily minimum temperatures (°F), 1971-2000. Redrawn after graphics created Feb. 20, 2004 by the PRISM Group, Oregon State University, http://prismclimate.org (modified from Nielsen-Gammon, 2008).

2.4 Geology

The Rio Grande flows through the Trans-Pecos region of Texas which encompasses many snapshots of North American geologic history. Precambrian crystalline metamorphic rocks are exposed in the Franklin Mountains, Van Horn Mountains, and Sierra Diablo Mountains. Xenoliths of these rocks recovered from volcanic rocks in the Davis Mountains, Bofecillos Mountains, and Chisos Mountains provide strong evidence that almost all of Trans-Pecos Texas is underlain by Precambrian rocks similar to those that crop out at the surface. Cambrian to Pennsylvanian rocks crop out in the Franklin Mountains, Marathon Basin, Solitario, and at Persimmon Gap. These rocks represent a transgressive, then regressive marine sequence that was caught between the North American continent and another unidentified continent during the Pennsylvanian Period and intensely deformed and thrust on to North America, forming the Marathon-Ouachita Mountains. The foreland basin of these mountains became the Permian Basin, and the carbonate rocks associated with this intracratonic sea now crop out in the Guadalupe, Glass, Apache, Van Horn, and Sierra Diablo mountain ranges. A depositional hiatus from the Triassic to Mid-Cretaceous was followed by the deposition of Mid- to Late-Cretaceous limestone that covers much of central and west Texas and frequently hosts important aquifers. From the Late Cretaceous to the Early Tertiary, these rocks were locally deformed during the Laramide Orogeny, which can be seen in the Del Norte-Santiago Mountains, Mariscal Mountain, the Terlingua-Fresno Monocline, and in the Chihuahua Tectonic Belt. Laramide compression was followed by a long period of large-scale ignimbritic volcanism in Trans-Pecos Texas. As compression continued to wane, ignimbritic volcanism yielded to smaller-scale effusive volcanism that was coupled with extensional tectonics, resulting in Rio Grande Rift / Basin and Range structures and related mountain ranges in the Trans-Pecos. Between these ranges, which include the Franklin, Hueco, Guadalupe, Delaware, Sierra Diablo, Sierra Vieja, and Van Horn mountains, large basins formed that filled with thick sequences of gravel and sand eroded from the adjacent mountains (Urbanczyk et al., 2001).

Down river from Big Bend National Park, the Rio Grande flows through the easternmost limits of both the Rio Grande Rift and Laramide deformation. Evidence of this can be found in the form complex structures including thrust faults, monoclines and broad folds in the Lower Canyons reach (see map). Also in this reach, the river has carved canyons into rocks of Edwards / Trinity (Cretaceous) association in the uplifted Stockton Plateau. Significant spring inflow from Creteaceous aquifers begins in the eastern part of Big Bend National Park and reaches a maximum in the Lower Canyons reach. These springs emerge from the Edwards-Trinity Plateau Aquifer (ETPA) which, combined with the Pecos Valley Aquifer occupies an area of 44,000 square miles in west central Texas (Anaya and Jones, 2009).

2.5 Regional aquifers

The western half of Texas experiences low rainfall, a high frequency of drought, and possesses few major rivers. Consequently, the people and natural resources of the region rely on ground water to a great extent. The hydrogeologic centerpiece of the aquifers of west Texas is the Edwards-Trinity Plateau Aquifer (ETPA). A second major aquifer, the Pecos Valley Aquifer, is located within the upper reach of the Pecos River (Anaya and Jones, 2009). Five minor aquifers interact directly or indirectly with the river reaches within the URG area and include the West Texas Bolsons (Wade et al., 2011), Igneous Aquifer, Capitan Reef Complex, Rustler Aquifer, and the Marathon Aquifer, (George et al., 2011).

The Edwards-Trinity (Plateau) Aquifer is a major aquifer extending across much of the southwestern part of the state (**Figure 2.5-1**). The water-bearing units are composed predominantly of limestone and dolomite of the Edwards Group and sands of the Trinity Group. Although maximum saturated thickness of the aquifer is greater than 800 feet, freshwater saturated thickness averages 433 feet. Water quality ranges from fresh to slightly saline; with total dissolved solids ranging from 100 to 3,000 milligrams per liter (mg/L), and water is characterized as hard within the Edwards Group. Water typically increases in salinity to the west within the Trinity Group. Elevated levels of fluoride in excess of primary drinking water standards occur within Glasscock and Irion counties. Of ground water pumped from this aquifer, more than two-thirds is used for irrigation, with the remainder used for municipal and livestock supplies. Water levels have remained relatively stable because recharge has generally kept pace with the relatively low amounts of pumping over the extent of the aquifer. The regional water planning groups, in their 2006 Regional Water Plans, recommended water management strategies that use the Edwards Trinity (Plateau) Aquifer, including the construction of a well field in Kerr County and public supply wells in Real County (George et al. 2011).

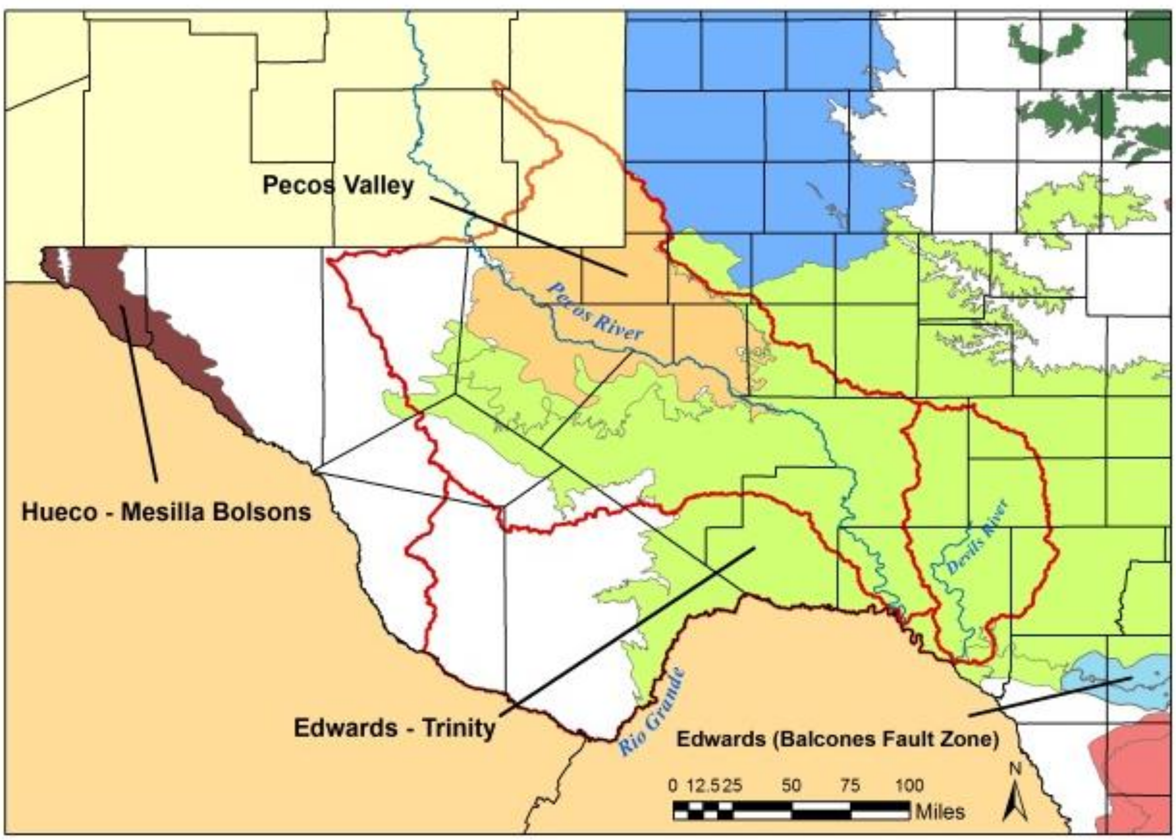


Figure 2.5-1. Major aquifers in the Upper Rio Grande BBEST area (modified from George et al., 2011).

The Pecos Valley Aquifer is a major aquifer in West Texas. Water-bearing sediments include alluvial and windblown deposits in the Pecos River Valley. These sediments fill several structural basins, the largest of which are the Pecos Trough in the west and Monument Draw Trough in the east. Thickness of the alluvial fill reaches 1,500 feet, and freshwater saturated thickness averages about 250 feet. The water quality is highly variable, the water being typically hard, and generally better in the Monument Draw Trough than in the Pecos Trough. Total dissolved solids in ground water from Monument Draw Trough are usually less than 1,000 mg/L. The aquifer is characterized by high levels of chloride and sulfate in excess of secondary drinking water standards, resulting from previous oil field activities. In addition, naturally occurring arsenic and radionuclides occur in excess of primary drinking water standards. More than 80% of ground water pumped from the aquifer is used for irrigation, and the rest is withdrawn for municipal supplies, industrial use, and power generation. Localized water level declines in south-central Reeves and northwest Pecos counties have moderated since the late 1970s as irrigation pumping has decreased; however, water levels continue to decline in central Ward County because of increased municipal and industrial pumping. The Region F Regional Water Planning Group recommended several water management strategies in their 2006 Regional Water Plan that would use the Pecos Valley Aquifer, including drilling new wells, developing two well fields in Winkler and Loving counties, and reallocating supplies (George et al., 2011).

In the URG BBEST area there are five minor aquifers, which are connected hydrologically with three rivers in one way or another. They include West Texas Bolsons Aquifer, Igneous Aquifer, Captain Reef Complex Aquifer, Rustler Aquifer, and Marathon Aquifer (**Figure 2.5-2**).

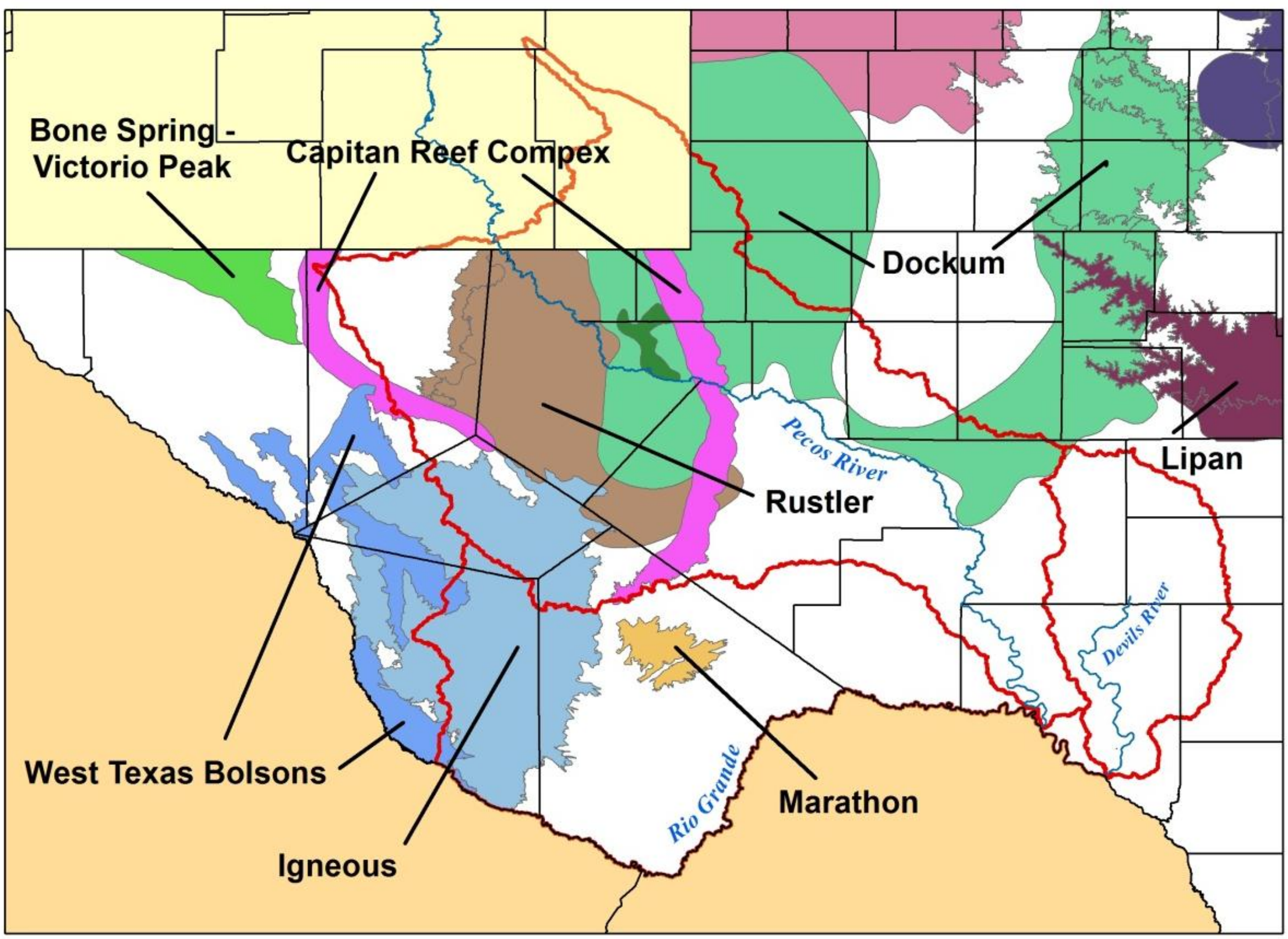


Figure 2.5-2. Minor aquifers in the URG BBEST area (modified from George et al., 2011).

The West Texas Bolsons Aquifer is a minor aquifer located in several basins, or bolsons, in Far West Texas. The aquifer occurs as water-bearing, basin-fill deposits as much as 3,000 feet thick. It is composed of eroded materials that vary depending on the mountains bordering the basins and the manner in which the sediments were deposited. Sediments range from the fine grained silt and clay of lake deposits to the coarse-grained volcanic rock and limestone of alluvial fans. Freshwater saturated thickness averages about 580 feet. Ground water quality varies depending on the basin, ranging from freshwater, containing less than 1,000 (mg/L) of total dissolved solids, to slightly to moderately saline water, containing between 1,000 and 4,000 (mg/L) of total dissolved solids. Ground water is used for irrigation and livestock throughout the area and for municipal supply in the cities of Presidio, Sierra Blanca, Valentine, and Van Horn. From the 1950s to the present, water levels have been in decline in the West Texas Bolsons Aquifer, with the most significant declines occurring south of Van Horn in the Lobo Flats area and to the east in the Wild Horse Basin area. The Region E Planning Group, in its 2006 Regional Water Plan, did not recommend any water management strategies using the West Texas Bolsons Aquifer (George et al., 2011; Wade et al., 2011).

The Igneous Aquifer is located in Far West Texas and is designated as a minor aquifer. The aquifer consists of volcanic rocks made up of a complex series of welded pyroclastic rock, lava, and volcaniclastic sediments and includes more than 40 different named units as much as 6,000 feet thick. Freshwater saturated thickness averages about 1,800 feet. The best water-bearing zones are found in igneous rocks with primary porosity and permeability, such as vesicular basalts, interflow zones in lava successions, sandstone, conglomerate, and breccia. Faulting and fracturing enhance aquifer productivity in less permeable rock units. Although water in the aquifer is fresh and contains less than 1,000 mg/L of total dissolved solids, elevated levels of silica and fluoride have been found in water from some wells, reflecting the igneous origin of the rock. Water is primarily used to meet municipal needs for the cities of Alpine, Fort Davis, and Marfa, as well as some agricultural needs. There have been no significant water level declines in wells measured by the TWDB throughout the aquifer. The Far West Texas Water Planning Group, in its 2006 Regional Water Plan, did not recommend any water management strategies using the Igneous Aquifer (George et al. 2011).

The Capitan Reef Complex Aquifer is a minor aquifer located in Culberson, Hudspeth, Jeff Davis, Brewster, Pecos, Reeves, Ward, and Winkler counties. It is exposed in mountain ranges of Far West Texas; elsewhere it occurs in the subsurface. The aquifer is composed of as much as 2,360 feet of massive, cavernous dolomite and limestone. Water-bearing formations include the Capitan Limestone, Goat Seep Dolomite, and most of the Carlsbad facies of the Artesia Group, including the Grayburg, Queen, Seven Rivers, Yates, and Tansill formations. Water is contained in solution cavities and fractures that are unevenly distributed within these formations. Water from the Capitan Reef Complex Aquifer is thought to contribute to the base flow of San Solomon Springs in Reeves County. Overall, the aquifer contains water of marginal quality, yielding small to large quantities of slightly saline to saline ground water containing 1,000 to greater than 5,000 mg/L of total dissolved solids. Water of the freshest quality, with total dissolved solids between 300 and 1,000 mg/L, is present in the west near areas of recharge where the reef rock is exposed in several mountain ranges. Although most of the ground water pumped from the aquifer in Texas is used for oil reservoir flooding in Ward and Winkler counties, a small amount is used to irrigate salt-tolerant crops in Pecos, Culberson, and Hudspeth counties. Over the last 70 years, water levels have declined in some areas as a result of localized production. The Far West Texas Regional Water Planning Group (FWTRWPG), in its 2006 Regional Water Plan, recommended several water management strategies for the Capitan Reef Complex Aquifer, including redeveloping an existing well field, desalinating the water, and transporting it to El Paso County (George et al., 2011).

The Rustler Aquifer is a minor aquifer located in Brewster, Culberson, Jeff Davis, Loving, Pecos, Reeves, and Ward counties. The aquifer consists of the carbonates and evaporites of the Rustler Formation, which is the youngest unit of the Late Permian Ochoan Series. The Rustler Formation is 250 to 670 feet thick and extends down dip into the subsurface toward the center of the Delaware Basin to the east. It becomes thinner along the eastern margin of the Delaware Basin and across the Central Basin Platform and Val Verde Basin. There it conformably overlies the Salado Formation. Ground water occurs in partly dissolved dolomite, limestone, and gypsum. Most of the water production comes from fractures and solution openings in the upper part of the formation. Although some parts of the aquifer produce freshwater containing less than 1,000 mg/L of total dissolved solids, the water is generally slightly to moderately saline and contains total dissolved solids ranging between 1,000 and 4,600 mg/L. The water is used primarily for irrigation, livestock, and waterflooding operations in oil-producing areas. Fluctuations in water levels over time most likely reflect long-term variations in water use patterns. The regional water planning groups in their 2006 Regional Water Plans did not propose any water management strategies for the Rustler Aquifer (George et al., 2011).

The Marathon Aquifer is located within the Marathon Basin in north central Brewster County and is composed of a series of highly folded and faulted Paleozoic formations including the Gaptank Formation, the Dimple Limestone, the Tesnus Formation, the Caballos Novaculite, the Maravillas Chert, the Fort Pena Formation, and the Marathon Limestone. The Marathon Limestone is the most productive of the group, although there are very few wells and consequently very little information to evaluate properties of the aquifer. Most of the ground water production occurs at depths of less than 1000 feet; well depths are commonly less than 250 feet (Ashworth, personal communication; Smith, 2001). Shallow wells are generally produce from alluvial deposits on top of the bedrock and are under water table conditions while deeper portions of the aquifer are under artesian pressure. Ground water flow is likely to the south east toward the Rio Grande. Several significant springs occur south of Marathon, including Peña Colorada Springs near a county park (Brune, 1981) Total dissolved solids range from 500 to 1000 mg/L. Primary use is for supply to the town of Marathon, other domestic supply and agriculture. Well yields range from 10 to 300 gallons per minute (TWDB website, accessed 6/22/2012).

2.6 Physiography and Geomorphic History of Sub-basins

2.6.1 Geology, Physiography, and Geomorphic History of the Rio Grande

The upper Rio Grande described in this study extends from the confluence of the Rio Grande and Rio Conchos 304 miles downstream to Amistad Reservoir (**Figure 2.1-1**). Today, the Rio Grande in this region is predominantly single-threaded and flows through wide alluvial valleys in structural basins and narrow canyons cut through intervening ranges. Some of the canyons are very narrow, and the channel banks are bedrock. In wider canyons, alluvium forms the channel banks. Channel slope ranges from approximately 0.0005 in the alluvial valleys to 0.002 in the canyons. The bed of the Rio Grande is composed of sand and gravel. Gravel is most predominant at the mouths and downstream from ephemeral tributaries. There is also a large supply of silt and clay, and thick muddy deposits (>1 m) may consist along the channel margins or in low velocity pools. The channel banks are predominantly very fine sand and mud.

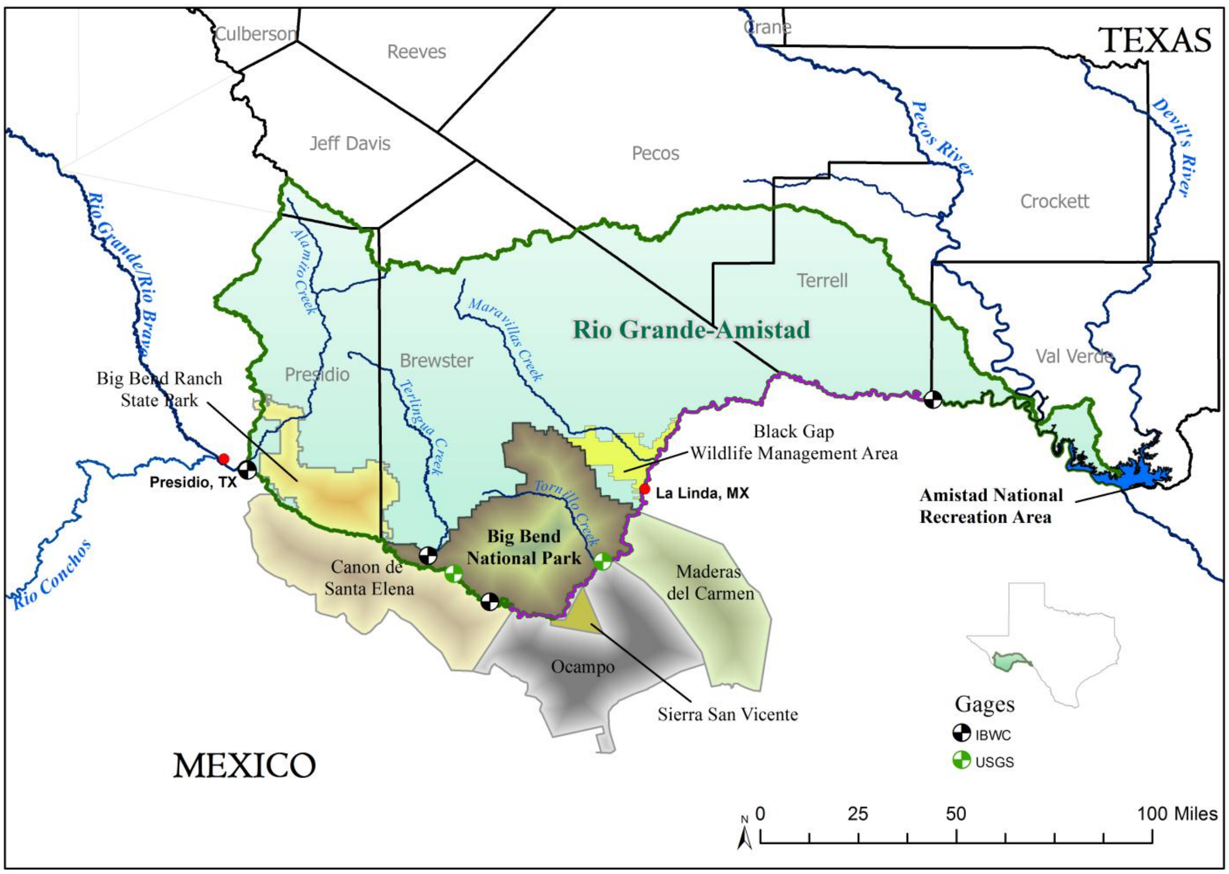


Figure 2.6-1. Location of the Upper Rio Grande Basin below the confluence with the Rio Conchos.

The early 20th century Rio Grande was wide, meandering, multi-threaded, and prone to avulsion (Mueller, 1975; Everitt, 1993; Stotz, 2000; Dean and Schmidt, 2011). These geomorphic characteristics were a result of a highly variable flow regime consisting of intense flooding followed by extremely low flows, and large sediment loads contributed by the surrounding desert landscape. High flows occurred for nearly 5 months of the year; beginning with the spring snowmelt in northern New Mexico and southern Colorado, and ended with the last monsoon rains in late summer and early fall (**Figure 2.6-2**). Stream flow remained low during the remainder of the year. Sediment loads were contributed by the upper Rio Grande and Rio Conchos as well as the numerous ephemeral tributaries that drain the sparsely vegetated Chihuahuan Desert (Schmidt et al., 2003, Dean and Schmidt, 2011). The combination of the extended high flows and large sediment supply produced a dynamic river that changed course from year to year and had an extremely diverse physical template that contained numerous migrating in-channel bars, side-channels, and backwaters.

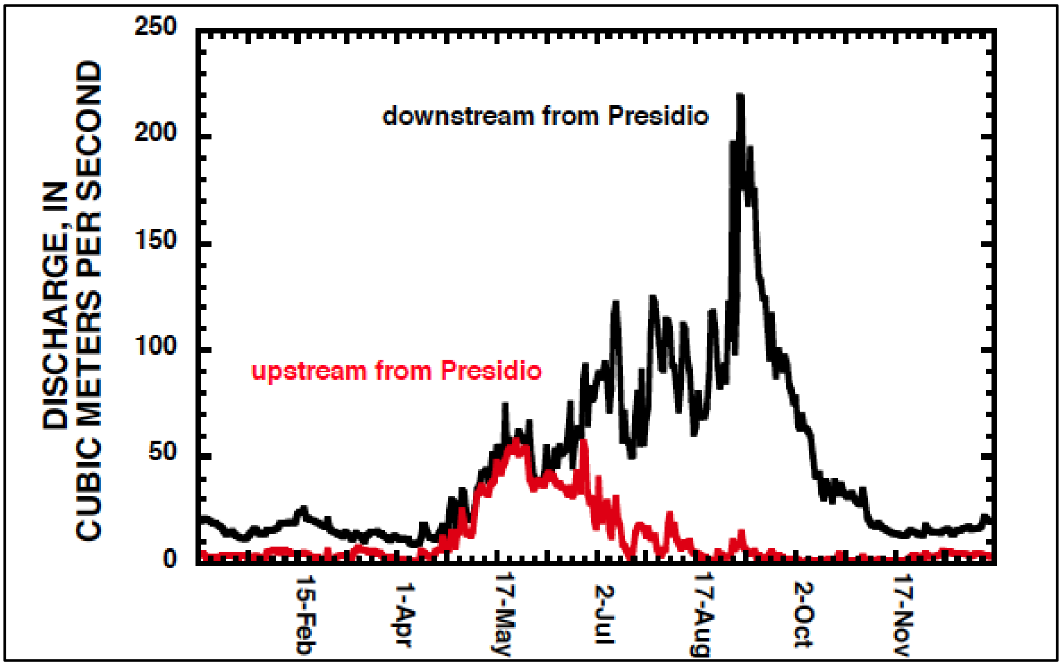


Figure 2.6-2. Median hydrographs of the Rio Grande near Presidio upstream and downstream from the Rio Conchos for the period 1900 to 1914.

By the mid-1900's, water development on the upper Rio Grande and the Rio Conchos caused drastic reductions in stream flow (Everitt, 1993; Schmidt et al., 2003; Dean and Schmidt, 2011). Operations of Elephant Butte and Caballo Dams in New Mexico, and irrigation diversions in the El Paso–Juarez valley completely eliminated the natural spring snowmelt flood of the upper Rio Grande (Schmidt et al., 2003). Virtually no flow now passes beyond Fort Quitman, TX (Everitt, 1998). Today, more than 90% of the present stream flow of the lower Rio Grande comes from the Rio Conchos, and stream flow from the Rio Conchos has also greatly declined (Schmidt et al., 2003; Dean and Schmidt; 2011).

Declines in mean and peak stream flow, and a relatively unchanged sediment supply, has resulted in progressive channel narrowing over the last sixty years. Channel narrowing has occasionally been interrupted by large, long duration floods in excess of 35,000 ft^3/s. We refer to these floods as channel resetting floods because they erode accumulating sediment, scour vegetation, and push the morphology of the channel back towards its historic form. In the early 1900s, floods of this magnitude occurred approximately once every 4 or 5 years. Since 1950, however, floods of this size have occurred just five times. Following each of these floods, channel narrowing has resumed and each subsequent channel resetting flood has failed to reset the channel to widths following the previous reset (**Figure 2.6-3**) (Dean and Schmidt, 2011). Between the 1940s and 2008, the channel of the Rio Grande narrowed by over 50% (**Figure 2.6-3, Figure 2.6-4**).

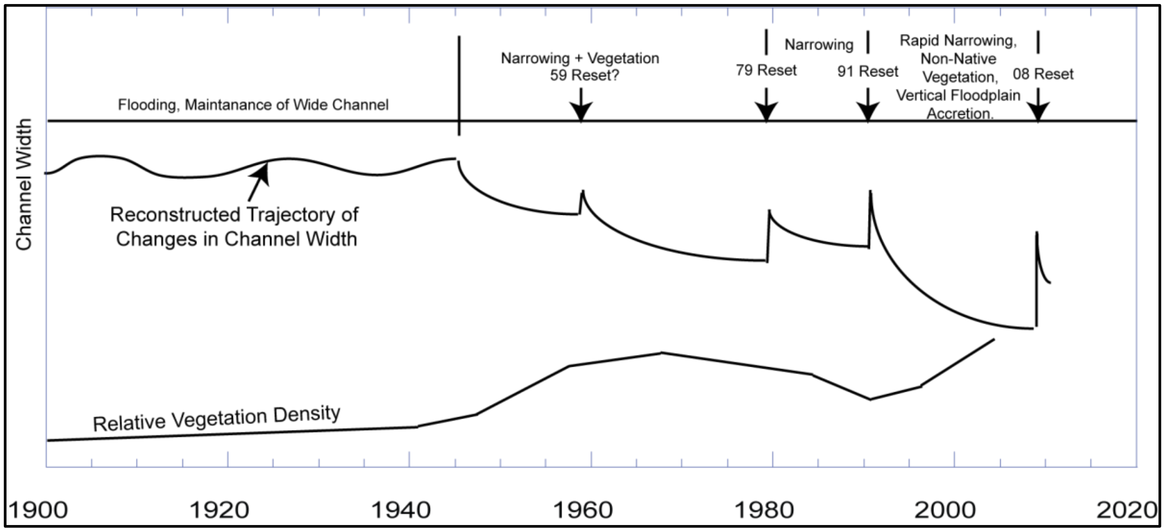


Figure 2.6-3. Reconstructed model of changes in channel width and vegetation density since 1900. Modified from Dean and Schmidt (2011).

Non-native vegetation has exacerbated the processes of channel narrowing. Since the early 1900s, non-native tamarisk and giant cane have become dominant species along the river corridor (Everitt, 1998; Moring, 2002). The invasion of the channel by these species during drought exacerbates processes of channel narrowing by stabilizing banks, increasing channel margin roughness, and inducing additional sediment deposition (Tal and Paola, 2007; Pollen-Bankhead et al., 2009). For example, during the low flow years between 1992 and 2008, sediment accumulation and non-native vegetation establishment within the active channel caused the channel to narrow by 36% to 52% (Dean and Schmidt, 2011; Dean et al., 2011a). Non-native vegetation establishment during these years resulted in the conversion of 39% to 77% of active channel bars to floodplains as measured in three study reaches (Dean and Schmidt, 2011; Dean et al., 2011a) (**Figure 2.6-3, Figure 2.6-4**).

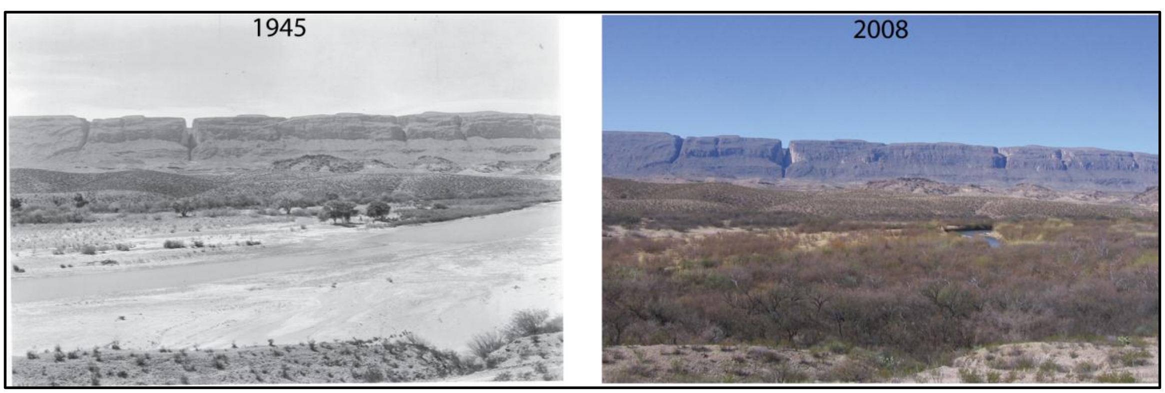


Figure 2.6-4. Historic ground photographs from 1945 and 2008 depicting the magnitude of geomorphic change on the Rio Grande in the Big Bend region, and the expansion of riparian vegetation, much of which is non-native.

Channel narrowing is of great concern to the native and endemic ecosystem of the lower Rio Grande (Heard et al., 2012). As channel narrowing occurs, ecologically important habitat such as backwaters and side-channels fill with sediment and are abandoned. Thus, the environmental flow analyses herein aim to determine the flows necessary to shift the present ecosystem towards a condition (**Figure 2.6-5**) more like that of the early to mid-1900s, because this is a period when a sound ecological environment (see Section 1.3) is believed to have persisted. In the definition of “sound”, geomorphic attributes/processes are responsible for both sediment transport and habitat maintenance, and thus, an emphasis is placed on characterizing the flows that would rejuvenate and maintain the key geomorphic attributes of a sound ecological environment.

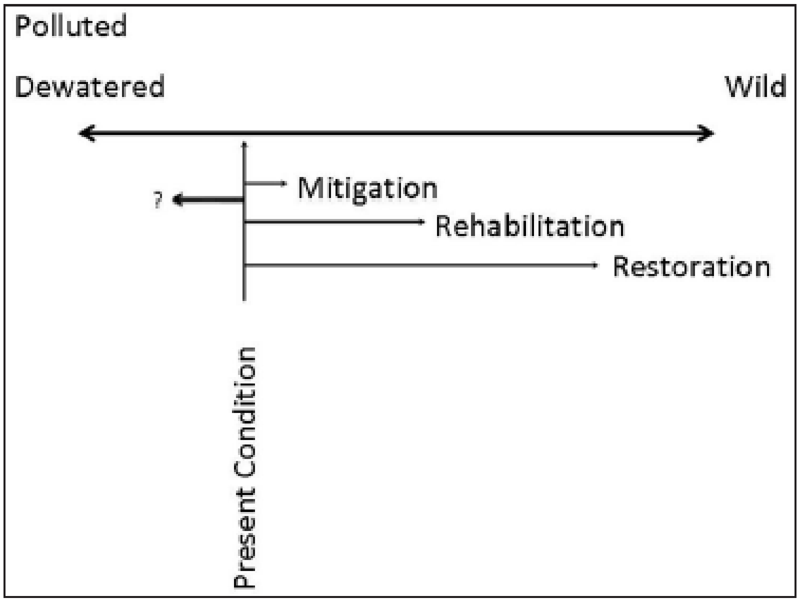


Figure 2.6-5. Conceptual diagram illustrating the continuum between wild conditions and potentially severely degraded conditions of river systems. Each part of today's Rio Grande exists somewhere on this continuum. Small degrees of change are typically referred to as mitigation, whereas attempts to significantly shift the ecosystem towards the formerly wild conditions are called rehabilitation. (adapted from Schmidt, 2010).

2.6.1.1 Ground water and low flows in the Rio Grande

The western half of Texas experience low rainfall, high frequency of drought, and few major rivers. Consequently, the people and natural resources of the region rely heavily upon ground water resources. The hydrogeologic centerpiece of the aquifers of west Texas is the Edwards-Trinity Plateau Aquifer (ET). A significant portion of the flow of the Rio Grande, Pecos, and Devils Rivers is derived from this aquifer. Two other aquifers are associated with surface water in the study area: the Cenezoic Pecos Alluvium, and the Ogallala.

Ground water contributions to the Rio Grande from the ET sustain aquatic habitats during dry years and mitigate water quality impairment (Bennett and Cutillo, 2007). Thermal springs occur along the Rio Grande from below Mariscal Canyon in Big Bend National Park to below Foster's Weir and just above Amistad Reservoir.

We examined IBWC gage data on the Rio Grande for low flow periods in 2001, 2002, 2003, and 2005. Net spring discharges along the reach can range from 196 ft^3/s to 266 ft^3/s. Ground water contributions can account for as much as 2/3 of the flow at Foster's Weir and the river entering AMIS during low flow conditions (**Figure 2.6-6**). An analysis of stream flow for selected low flow periods suggest that ground water contributions may range between 142,000 and 192,000 acre feet annually. Between the IBWC gages near Johnson Ranch and Foster's Weir, gains in flow account for 23% of the mean annual flow for the period 1961 to 1985 (Saunders, 1987). In addition, some spring flow may be lost to the channel and would not be included here. The importance of spring flow to the aquatic recourses of the Rio Grande is site specific.

Ground water is generally better quality than surface water in the Rio Grande and therefore the addition of ground water improves the water quality in the river. The gain loss study described here was initiated to better quantify ground water contribution and add to a growing data set documenting the natural resource value of Rio Grande springs. Water quality and discharge data are plotted in (**Figure 2.6-7**).

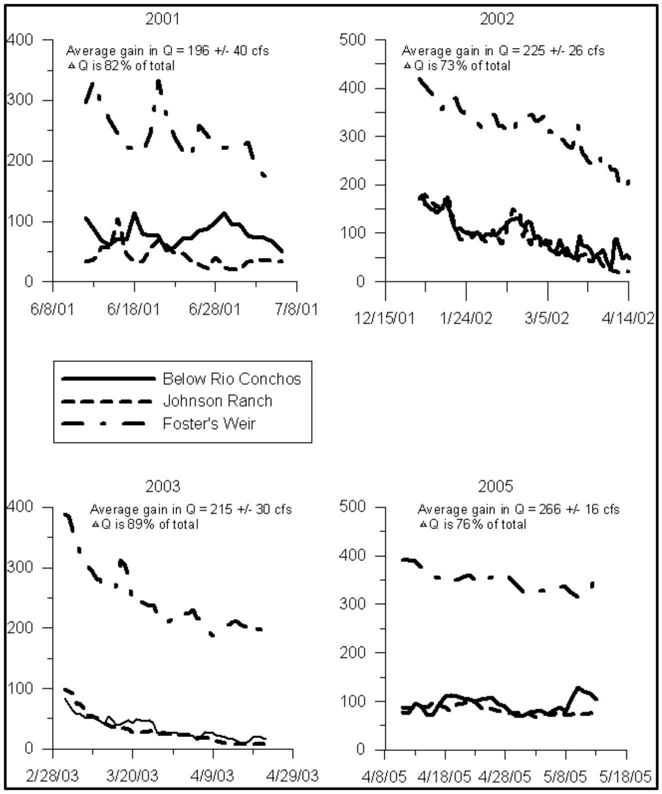


Figure 2.6-6. Average gain in Q (discharge). From Bennett et al., 2009.

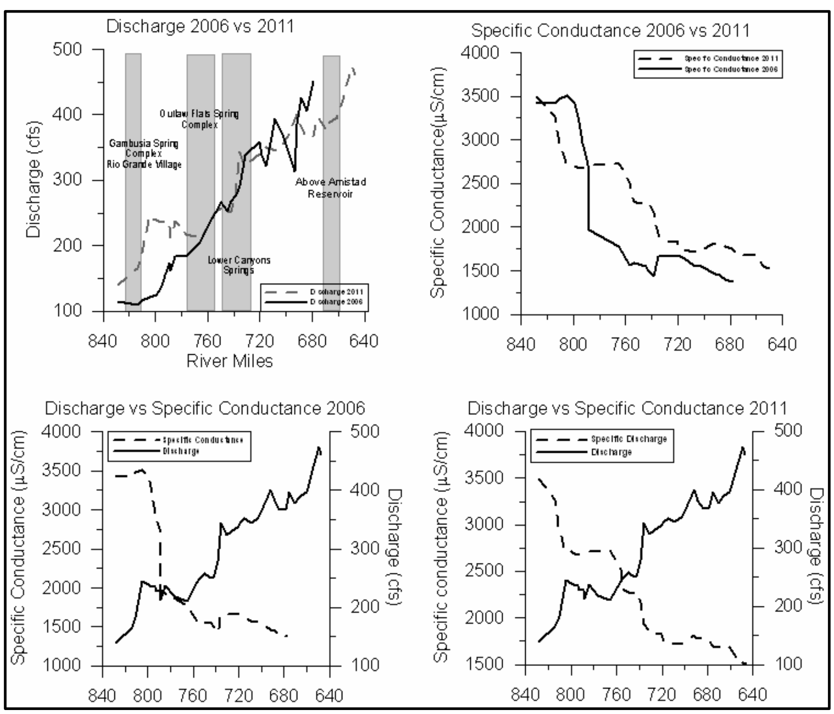


Figure 2.6-7. Longitudinal trends in discharge and specific conductance for years 2006 and 2011. From Bennett et al. 2012.

2.6.1.2 Alamito and Terlingua Creeks

Alamito and Terlingua Creeks are two of the largest tributaries to the Rio Grande within the geographic scope of this report. The confluence of Alamito Creek and the Rio Grande is approximately 11 km downstream from the Rio Conchos (approximate IBWC river mile 947). Terlingua Creek joins the Rio Grande in the western portion of Big Bend National Park at IBWC river mile 885. Each of these creeks flow perennially at their downstream ends. Perennial flow is provided by springs and ground water inputs. In the upstream portions of these watersheds, stream flow is ephemeral.

The hydrology of Alamito and Terlingua Creeks is extremely flashy. Monsoon rains and convective thunderstorms can cause large flash floods. The largest flood measured at on Alamito Creek was 12,395 ft^3/s, and the largest flood measured on Terlingua Creek was 17,198 ft^3/s. Base flows are often less than 5 ft^3/s. Both creeks have extremely high sediment loads during floods and are braided in plan form. In some areas the braid plains of these creeks exceed 1,500 ft. in width. The braided geomorphic form of these rivers reflects the high variability between base flow and flood flow, and the high sediment loads transported during high-flow pulses.

Both Alamito and Terlingua Creeks are remote. Development is minimal and consists of mining with several bentonite mines in the Terlingua Creek drainage and zeolite mines in Alamito Creek. The primary land use within each drainage is ranching. Aerial photos reveal a great deal of manipulation of surface flow with large diversions and terracing. A large concrete dam exists on Alamito Creek near Marfa, TX that was designed as a resort property in the early part of the last century. Though intact, the dam no longer functions as designed.

2.6.2 Pecos River

The Pecos River enters Texas just east of the 104th meridian and continues to flow 418 winding miles through semi-arid West Texas before entering the Rio Grande (**Figure 2.6-8**). The river creates the eastern boundary of the most mountainous and arid region of Texas, known as the Trans-Pecos. It also forms the boundaries of Loving, Ward, Reeves, Pecos, Crane, Crockett, and Terrell counties. Andrews, Brewster, Culberson, Ector, Jeff Davis, Presidio, Reagan, Upton, and Winkler counties are also included in the Pecos River watershed (**Figure 2.6-8**). The Pecos River watershed in Texas is bound by Texas' Colorado River Basin to the northeast and by the Rio Grande watershed on the south and west. As the largest river subwatershed flowing into the Rio Grande, the 10 million-acre Pecos River watershed in Texas plays a significant role, both biologically and hydrologically, in the future of the Rio Grande Basin. The flows of the once great Pecos River have dwindled to a mere trickle due to many causes, some natural but most are due to anthropogenic factors.

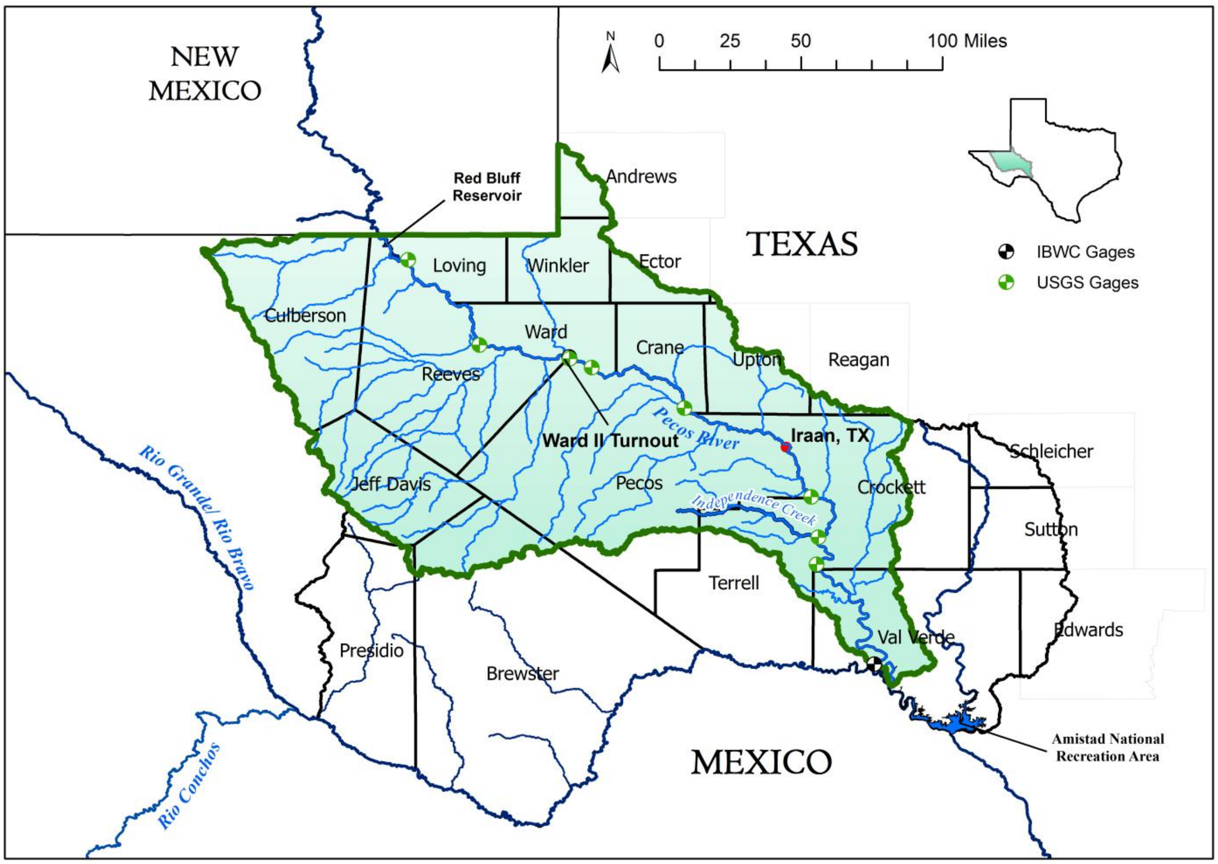


Figure 2.6-8. The boundary of the Pecos River Basin in Texas.

The soils of the Pecos River watershed consist mostly of well-drained Aridisols and Entisols that support sparse desert shrubs. The drainage basin near Red Bluff Reservoir consists of gypsic soils, such as the Reeves and Holloman soil series. The majority of Reeves and Pecos counties consist of either shallow Aridisols (Del Norte, Nikel, and Reakor) or calcareous silty clay loam, such as a Hoban series. The soils in the east bank of the river are predominantly Simona and Sharvana series, both of which are shallow calcareous soils developed over caliche and have moderate permeability. The soils along the Pecos River are alluvial, namely Pecos, Patrole, Toyah, and Gila series that have textures ranging from silty to loamy. Arno series, also alluvial, is the only series along the river that has montmorillonitic clayey textures with low permeability (Miyamoto et al., 2005).

The topography of the Pecos Basin varies greatly. The northern part of the river in New Mexico includes mountain pastures and reaches elevations of 13,000 feet above sea level. In Texas, the elevation shifts from 2,700 feet above sea level at Red Bluff Reservoir to 1,050 feet above sea level at the mouth of the Pecos. The river passes through a deep canyon (walls as high as 200 feet or more in some places) in its lower reaches before merging with the Rio Grande in Val Verde County.

The river and its watershed have long served as a vital source of life in the Trans-Pecos Region. Archeological evidence collected in the watershed has verified that humans have relied on the watershed as a source of food, water, and shelter for thousands of years. Numerous Native American tribes and peoples have also been identified as inhabitants of the Pecos River watershed and, undoubtedly, depended on the waters of the river and springs in the watershed to sustain themselves (Jensen, 2006).

Salinity in the Pecos has long been a known water quality concern and led to people establishing numerous water wells capable of providing better quality water. In some cases, people have referred to the Pecos as the "dirty river," the "salty river" or the "pig river" (Daggett, 1985; Dearen, 2000; Williams, 1982). Salinity levels in the Pecos are commonly above 6,000 mg/L at the Texas-New Mexico state line, often exceed 12,000 mg/L near Girvin, and usually decline to about 2,000 mg/L after Independence Creek converges with the river (Miyamoto et al., 2005). Elevated salinity levels in the Pecos have multiple detrimental effects. The salts limit the types of crops that can be grown and irrigated with river waters and can negatively impact the productivity of crops that can tolerate the salinity levels present. Increased salinity is also detrimental to downstream activities and uses. The Pecos River greatly influences the water quality of Amistad International Reservoir, located just below the confluence of the Pecos and the Rio Grande. Miyamoto et al. (2006) indicated that the Pecos River contributes 9.5 % of the annual inflow into Lake Amistad and 26 % of the annual salt load. For a month in 1998, salinity of Amistad exceeded 1,000 ppm, the maximum limit for drinking water, and has since fluctuated below that level. This exceedance greatly concerns those who depend on Amistad as a source of drinking water and should be strongly considered when managing salinity across the watershed. To successfully maintain the salinity levels of the reservoir below 1,000 ppm will require management to control salt loading from the Pecos to the Rio Grande. Reducing salinity in the upper segments of the Pecos in Texas will also make river flows more suitable for livestock use and irrigation of croplands.

Despite the overall contributions of salts into the Pecos and the potential impacts that can be seen downstream, some segments of the river have relatively good water quality. Salinity levels in the upper portion of the river can be restrictive for the majority of agricultural production and are definitely not suitable for human consumption. Downstream to Iraan, the river is dominated by fresh water spring flow and, as a result, is of much better quality than the upstream portions of the river. These inflows result in a significant dilution effect that greatly improves the quality of the water before it enters the Rio Grande.

Encroaching woody plant species have also drastically altered the Pecos River watershed. Historical accounts indicate that grasses were the dominant vegetation in the watershed and any type of woody plant was scarce at best. The establishment of vast cattle ranches and subsequent over grazing have undoubtedly influenced the shift from grassland to woodland in upland and riparian areas. Salt cedar (*Tamarix spp*.) practically took over riparian areas in the watershed and created monocultures along almost every waterway. Originally introduced to the watershed in the early 1900s to control stream bank erosion, this plant has taken over and formed dense stands along the river banks and floodplain (Jensen, 2006). In many cases, salt cedar pulls water from shallow water tables near the river, diverting river flow into these water tables. Based on this information, salt cedar removal is seen as a viable option to increase flows in the river by increasing local water table levels. Removing this noxious plant will also help in re-establishing native riparian vegetation. Upland brush and other non-grass species have also changed the face of the watershed. Areas that were once short-grass prairies are now dominated by mesquite, greasewood, creosote bush, prickly pear, and many other species that have a competitive advantage over native grass species. Proper control practices and long-term management can effectively restore these grasslands to a semi-native state that is more productive and produces cleaner, more available water in the watershed.

National Land Cover Dataset information from 2001 was used to delineate land uses and land coverages for the Pecos River watershed. Primary land uses and land cover were divided into seven major categories. Rangeland is by far the dominant land cover in the watershed and accounts for approximately 68% of the land area. Grassland is the second most prominent land cover found in the watershed accounting for about 28% of the watershed area. Uses for these land covers include primarily livestock and wildlife grazing. The remainder of the watershed (4%) is split between many different land uses and land covers. The largest of these are quarries (2.2%), combined forest (1%), urban (0.37%), agriculture (0.26%), water (0.08%) and wetlands (0.0087%). These seven land uses and land covers account for 99.9% of the watershed; the remaining 0.1% is dispersed over 43 other land use and land cover categories.

Farming has historically been very important to the economy of communities in the Pecos River watershed in Texas. The Torres Irrigation Company began using the waters of the Pecos River in 1870 to support irrigation in Pecos County in 1870. This effort watered 480 acres that produced 12,000 bushels of corn that year (Williams, 1975). In 1877, the Pecos River Irrigation Company was incorporated to take water from the Pecos River and develop irrigation on 320 acres (Bogener, 2003; Daggett, 1985; Dearen, 2000; Williams, 1982; Bogener, 1993). By 1914, work had started or had been completed on 10 irrigation projects stretching from Arno (near the Texas-New Mexico state line) to Girvin about 150 river miles downstream (Lingle & Linford, 1961). On paper, more than 173,000 acres of irrigable land were included in these 10 projects, but less than 30,000 acres were actually cultivated (Jensen, 2006). Some crops grown in the Pecos watershed of Texas throughout the early 1900s included cantaloupes, alfalfa, vegetables, grapes, orchard crops, and strawberries (Newman & Dale, 1993).

The Texas Water Development Board (TWDB) reported in 2001 that irrigated acreage rose to 233,578 acres in 1958 and peaked at nearly 260,000 acres in 1964 because of widespread ground water pumping. Irrigated acreage began to decline in the 1970s because of rising costs to pump ground water from greater depths and because less water was flowing in the Pecos River. Currently, irrigated acreage has increased slightly in the region with data from 2000 showing 73,171 acres in the Pecos watershed.

These data also reveal trends in ground water and surface water uses for agricultural irrigation since the 1950s. For example, ground water pumping for irrigation totaled more than 684,972 acre-feet (AF) in 1958, peaked at 777,785 AF in 1964, and has generally declined ever since. In 2000, ground water pumping totaled 176,541 AF (TWDB, 2001).

Irrigation water use from the Pecos River and other surface waters has largely been confined to a few counties. The volume of surface water used for irrigation (ranging from a low of 1,415 AF in 1969 to a high of 35,189 AF in 1958) is only a small percentage (less than 5 %) of overall agricultural water use in the region.

Total water use for agricultural irrigation in the region peaked in 1964 at 835,412 AF and declined to a low of 193,163 AF in 1989; however, the most recent data from 2000 showed that agricultural water use totaled 202,221 AF in 2000. Increasing costs to pump ground water from increasing depths has caused some decline while a general decrease in the number of acres farmed in the watershed has significantly reduced the demand as well.

Surface water is scarce in the Pecos watershed of Texas. The Pecos River is the main source of perennial surface water in the upper end of the watershed and has been known to go dry in some places. Numerous springs in the watershed also provide perennial sources of surface water that bolster the flow of the Pecos. In Texas, Salt Creek provides readily observable surface flow and high salt loading in the Upper Pecos while Independence Creek provides high-quality water to the river in the Lower Pecos. The remaining tributaries in Texas are intermittent and typically only carry flow during high volume rain events (Belzer, 2007).

Across the basin, surface water and ground water resources are highly connected and can significantly influence each other. Many areas of the Pecos are known to lose large amounts of stream flow to shallow water tables and aquifers near the river. Although this water is "lost" from the river's flow, it often flows parallel to the river and can re-enter the channel further downstream. The river also has a significant connection to ground water resources further away from the river. Springs, such as Caroline Springs that supplies about 25% of Independence Creek inflow, arise in the watershed and can be significant sources of inflow to the Pecos. According to Gunnar Brune's comprehensive description of the springs of Texas (2002), the Pecos Basin originally contained more than 50 flowing springs. Some of these springs stopped flowing during the "drought of record" that lasted in Texas throughout most of the 1950s. According to local experts (Karges, 2006), as few as eight springs may still flow in Reeves and Loving counties. Some of the springs in the Pecos watershed include:

- Kokernot Spring (Brewster County)
- Live Oak Springs and Cedar Springs (Crockett County)
- Rustler Springs (Culberson County)
- Madera Springs, Phantom Lake Springs, and Seven Springs (Jeff Davis County)
- Comanche Springs, Diamond Y Springs, Leon Springs, Pedro Ureta Springs, Santa Rosa Springs, and San Pedro Springs (Pecos County)
- Giffin Springs, Sandia Springs, San Solomon Springs (Reeves County)
- Red Bluff Springs (Loving County)
- Caroline Springs, Cedar Springs, Geddes Springs, King Springs, Myers Springs, and Vanderbeek Springs (Terrell County)

There are several significant ground water resources along the Pecos River, including the Pecos Alluvium, Dockum, Capitan Reef, Rustler, Igneous, and Edwards-Trinity Plateau aquifers (**Figure 2.5-1** and **Figure 2.5-2**). The Pecos Valley Aquifer is the principal aquifer in the Texas portion of the river and consists of up to 1,500 feet thick alluvial sediments. This aquifer was once used for irrigating large areas of cropland in the Pecos Valley of Reeves County. During the peak irrigation era of the 1950s, pumping from wells was estimated to have reached as much as 730,000 AF/year. Pumping from this alluvium declined drastically after the 1960s, and water tables have dropped as much as 200 feet according to a TWDB report (Ashworth, 1990). However, recent data shows that water tables west of the Pecos rose as much as 30 feet between 1989 and 1998 while areas east of the river have declined by 40 feet or more (Boghici, 1999). Perched water tables near the Pecos River are usually between 10 feet and 20 feet below the surface, and deepen to 50 feet away from the river. Water table depth fluctuates depending on the flow of the Pecos (TWDB, 2001). TWDB 2006 data reports that the depth-to-ground water in Pecos and Reeves counties averages 125 feet and ranges from 12 feet to 1,492 feet with the greatest depth occurring where cones of depression have developed as a consequence of ground water pumping for agriculture and other purposes (Miyamoto et al., 2005). Mills (2005) suggests that ground water inflows to the Pecos River between Red Bluff and Girvin averaged 30,000 AF/year before large-scale irrigation projects were developed. **Figure 2.6-9** depicts the location of ground water wells within the Pecos basin.

Declining ground water levels in these aquifers have caused the reversal of flow paths in some locations. This reversal results in lower quality water in the river flowing into the aquifers instead of the higher quality aquifer water flowing into the river. Essentially, the river is contaminating nearby aquifers with lower quality water, which only intensifies the need to improve the river's water quality. Pumping paired with rampant salt cedar growth in the watershed has undoubtedly exacerbated this phenomenon. Decreasing the influences of these impacts will have a positive impact on restoring hydrologic function along the river and water quality of the river.

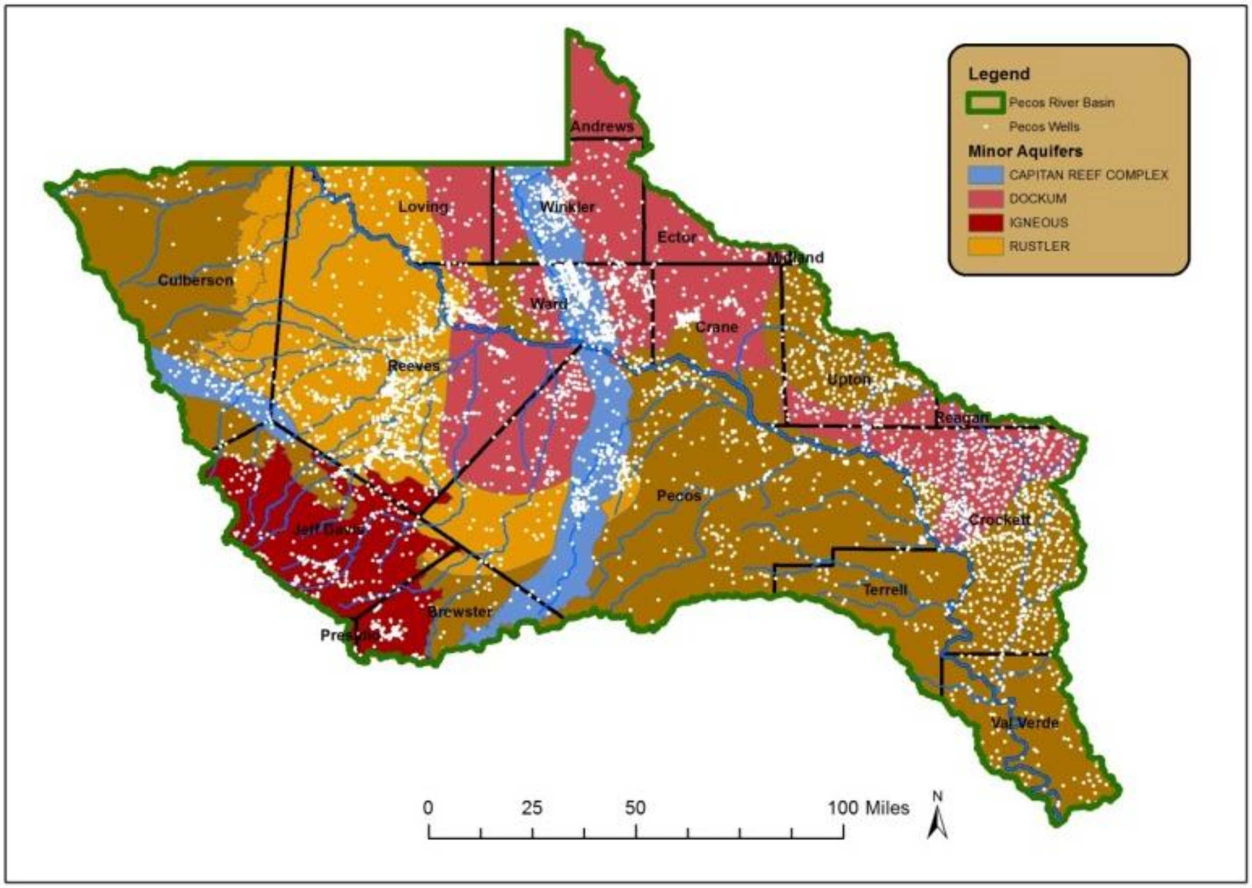


Figure 2.6-9. Ground water wells within the Pecos River Basin.

Throughout the river's course across West Texas, the Pecos River undergoes a drastic transformation that results in a river that looks and is completely different in its upper, middle and lower reaches. The upper 11.75 miles of the Pecos River, between the Texas and New Mexico State Line and the Red Bluff dam, makes up the Red Bluff Reservoir. The upper 102 miles of the river is an irrigation canal for the Red Bluff Water Power Control District. The next 90.25 miles of river bed is an irrigation canal for the Red Bluff distribution system. At the end of the 102 miles is a concrete dam with no outlet (**Figure 2.6-10**).

Figure 2.6-10: Concrete dam at Ward II Turnout (G. Bryant photo) and aerial view (Google Earth, 2/7/2011).

Unless the dam is overtopped there is no water passing through the dam in a normal year. This dam is at the Ward II Turnout. (31°22'50.40" N, −103°02'10.95" W) The irrigation canals border the next 80 river miles so runoff from the basins enter the irrigation canals instead of the river (**Figure 2.6-11**, see below). The irrigation districts intercept storm events from the Delaware, Lower Pecos – Red Bluff, Salt Draw, Toyah, Barilla Draw, Coyanosa – Hackberry, and the majority of the Landreth-Monument draw sub basins (approx. 12,500 sq. miles).

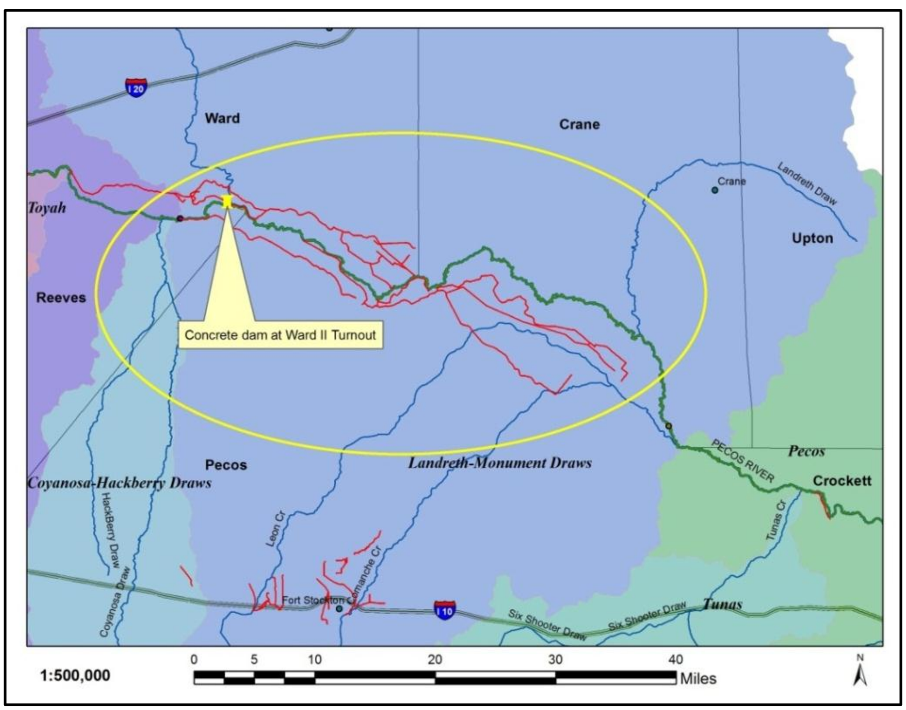


Figure 2.6-11. Detail of irrigation canals along the Pecos River (shown in red).

For the next 187 river miles, the river flows through Pecos Valley sediments and does have contribution from storm events from the basin. Overland flows from Tunas and portions of Landreth-Monument Draws sub basins (3,500 sq. miles) enter into the river in this stretch.

Below Sheffield and I-10, the Pecos, Independence Creek, Howard Draw, and Lower Pecos sub basins flow into the Pecos River (4,773 sq. miles). The river begins to transform into a predominantly spring fed river with greatly improved water quantity and quality as compared to the upper portion. The inflow of Independence Creek adds a vital source of fresh water that doubles the flow of the river and reduces the salinity by one half or more.

The U.S. Geological Survey (USGS) has delineated watersheds throughout the country based on surface hydrologic features, which are much smaller than the larger river watersheds. In Texas, the Pecos River watershed has been divided into 11 separate cataloguing units (8-digit) that were determined based on major tributaries that flow to the river (**Figure 2.6-12**). These cataloguing units, as defined by the USGS, will be used to divide the Pecos watershed into sub watersheds to facilitate focused water quality management. Most of the tributaries within these sub watersheds are dry creek beds throughout most of the year and only contribute measurable flow to the Pecos during heavy rainfall events (Belzer, 2007).

Table 2.6-1. Pecos River Sub Watersheds in Texas.

Hydrologic Unit Code (HUC)	Sub Watershed Name	Area (mi^2)
13070001	Lower Pecos – Red Bluff *	2,492
13070002	Delaware *	787
13070003	Toyah	1125
13070004	Salt Draw	1,959
13070005	Barilla Draw	707
13070006	Coyanosa – Hackberry Draws	1,480
13070007	Landreth – Monument Draws *	6,337
13070008	Pecos	1,916
13070009	Tunas	967
13070010	Independence Creek	771
13070011	Howard Draw	1,092
13070012	Lower Pecos	994

* This HUC is not entirely in Texas

There are ten springs located within the watershed including Comanche, Cottonwood, Diamond Y, Horseshoe, Monument, Rustler, Salt, Santa Rosa, Screw Bean and Toyah (http://www.esg.montana.edu). Diamond Y Spring Preserve is owned and managed by The Nature Conservancy (TNC) and provides important habitat for two species of rare desert fishes listed as federally endangered species: the Leon Springs pupfish (*Cyprinodon bovines*) and the Pecos Gambusia (*Gambusia nobilis*). Diamond Y is also home to the federally threatened, rare, salt-tolerant Pecos sunflower (*Helianthus paradoxus*). Red Bluff Reservoir is located on the main stem of the Pecos just below the state line and Imperial Reservoir is located in northern Pecos County.

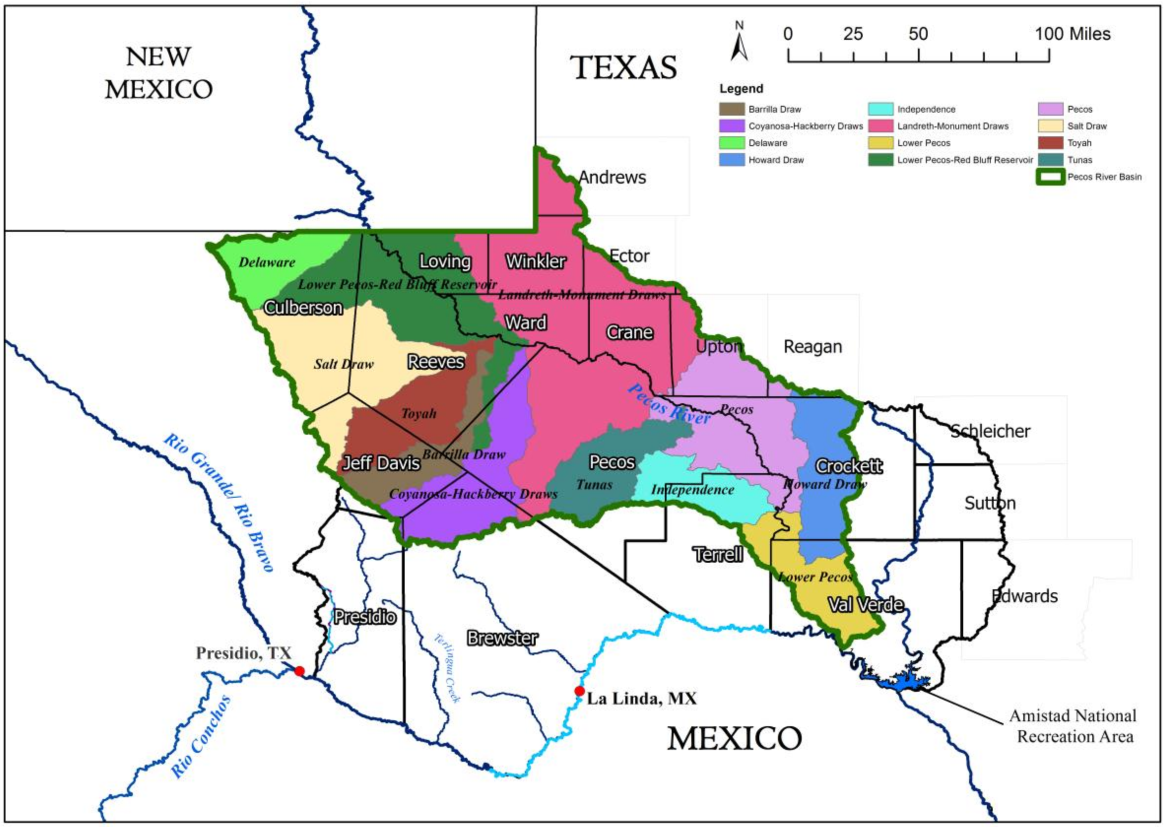


Figure 2.6-12: Pecos River Sub Watersheds (8-digit HUCs) in Texas

The Pecos River flows through the entire LPRB. Salt Creek, which travels through Culberson County and drains into the Pecos in Reeves County. The salt inflow from Salt Creek is estimated at 45,700 tons per year at the annual flow of 3.3 million cubic meters and markedly increases the salinity of Pecos River flows directly below Red Bluff Reservoir (Miyamoto et al., 2005). This segment of the Pecos is also listed as impaired by the Texas Commission on Environmental Quality (TCEQ) for having depressed DO levels within the stream.

The Pecos and Lower Pecos subwatershed covers 2,910 square miles and include Crane, Crockett, Pecos, Reagan, Terrell, Upton, and Val Verde counties in Texas. Elevations range from 1,166 feet to 3,240 feet and the terrain becomes deep canyon lands carved by the Pecos River in the southern end of the watershed (http://www.esg.montana.edu). The Pecos River is the only perennial surface water resource and its mouth is located at the southern end of the watershed where it converges with the Rio Grande in Amistad National Recreation Area.

This segment of the river, above Independence Creek, is also listed by the TCEQ as having depressed DO levels. The confluence of Independence Creek with the Pecos, the most significant freshwater contribution to the Pecos River in Texas, is located in the Lower Pecos subwatershed. Maintaining the integrity of this valuable resource will remain critical to Pecos River water quality. Independence Creek is discussed further in its corresponding subwatershed section.

Independence Creek subwatershed covers 771 square miles and is located in Pecos and Terrell counties. Elevations in the watershed range from 1,861 feet to 3,599 feet (http://www.esg.montana.edu). Independence Creek is the largest freshwater tributary of the Pecos River in Texas and drastically improves both water quality and quantity in the river. Below the confluence of the Pecos and Independence Creek, the river's flow volume increases by 42 %

and total dissolved solids decrease by 50 % (http://www.nature.org). This virtually transforms the Pecos, providing the water necessary to support both recreation and healthy populations of aquatic species.

The Chandler family and TNC have permanently protected approximately 20,000 acres along Independence Creek through conservation easements and are committed to maintaining the ecological integrity of this resource. Caroline Spring, located on the Nature Preserve, produces 3,000 gallons to 5,000 gallons of fresh water per minute and contributes approximately 25% of Independence Creek's flow (http://www.nature.org).

For the purposes of the Environmental Flows Report, it is advantageous to divide the river the same as the TCEQ water quality segments. Segment 2310 is referred as the Lower Pecos and 2311 is referred to as the Upper Pecos. The Lower Pecos reaches from the confluence of Independence Creek to Amistad Reservoir and has been determined to be a Sound Ecological Environment by the Upper Rio Grande BBEST team. The Upper Pecos River reaches form the TX-NM line to the confluence of the Pecos River and Independence Creek. The Upper Pecos River has been determined as an Unsound Ecological Environment.

The purpose of the BBEST is to determine the flow required to maintain a sound ecological environment or determine the flow required to create a sound ecological environment. In the lower Pecos, the BBEST has done exactly that. These recommendations are based on historical flow assessments based on the HEFR modeling programs, water quality data, biological overlays and geomorphological characteristics and requirements of the river.

However, the Upper Pecos cannot be evaluated in this manner. The upper river has a dissolved oxygen (DO) water quality impairment and an extremely high total dissolved solid content which has altered the biological community so the majority of the native fishes of the river no longer inhabit the river or have been hybridized with salt tolerant invasive species.

There are three USGS flow gages in the Upper Pecos which record water flow in the river but the flow is for managed water data and have never reported natural flow patterns. All three of the gages were installed after the construction of Red Bluff Reservoir. The gage at Orla is nine river miles below Red Bluff Reservoir. Basically this gage reports the opening and closing of the gates at Red Bluff Reservoir. Modeling can be done on the data from the gage but it in no way represents any type of a natural flow pattern.

Above, the Pecos gage, four irrigation district canals divert water from the river. Water is purchased from Red Bluff Water Power Control District and delivered to the lower irrigation districts. These four irrigation districts remove the allotted water from the river. If there is a storm event which creates pulse flows in the river, the first water which is laden with salt and debris is allowed to flow downstream. The rest of high flow is diverted to the irrigation canals where it freshens the irrigation water but does nothing for the river. The irrigation districts refer to this as "free" water.

Below the Pecos gage are two more diversions for the next three irrigation districts. The standard operating procedures are the same which results in basically all the water being removed from the river at the last irrigation diversion, Ward II.

Paralleling the river from Orla to 80 miles below the Ward II turnout, are irrigation canals which catch any runoff from the surrounding watershed. This is important because this runoff would naturally create pulse flows to transport sediment and create biological habitat imperative to a healthy river. This water would also freshen the saline waters of the river and dilute the current salt concentrations.

Between the Ward II turnout and Girvin, there are springs which contribute water to the river. However, the water is between 12,000 and 15,000 ppm tds. This water slowly flows across the Girvin gage and to Iraan. During the summer months, this water can reach salt concentration of 30,000 ppm due primarily to evaporation. The winter water quality will remain in the 15,000 to 18,000 ppm range. Once the water reaches Iraan, the water is mixed with fresh water spring flow and increases in quantity and quality. It isn’t until the water reaches the confluence of Independence Creek and the flow increases 42% and the salt concentration decreases by 50% (Miyamoto 2008).

The most practical way to determine a subsistence flow for the Upper Pecos is to begin releases from Red Bluff Reservoir and monitor the water at Iraan. Once the flows have sufficient DO then this will be the subsistence flows. The base flows would then be calculated as percentages based upon the subsistence flows. Pulse flows would have to be based on rainfall in each of the basins as each of the basins in the upper reaches of the Pecos are intercepted by irrigation district diversion districts and collect “free“ water and the storm water doesn’t create pulse events which are necessary to transport sediment and maintain the channel habitat for the biology of the river. Basin analyses would have to be conducted to determine the amount of rainfall in each basin and then correlated with the runoff curves for individual events based on soil and vegetation types. These pulse flows would then need to be simulated by releases from Red Bluff Reservoir. Analyses would also need to be conducted to determine the probabilities of rainfall across multiple basins in order to create the high pulse flows.

Imperative to any attempt to reestablish environmental flows in the Upper Pecos is the potential to pollute the Lower Pecos and Amistad Reservoir. In 1998, a storm event occurred which increased flow in the Pecos River and produced salinity levels in Amistad Reservoir above the 1,000 ppm drinking water standards (Miyamoto 2006). All practical testing of flow enhancements should be aware of the effects on the entire water system of the Rio Grande.

These analyses are beyond the time and financial scope of this report.

2.6.3 Devils River Sub-Basin

The Devils River sub-basin covers approximately 4,300 square miles, encompassing all or part of 5 counties in South-Central/South-West Texas (**Figure 2.6-13**). The sub-basin is bordered by the Colorado River Basin to the north, the Nueces River Basin to the east and other sub-basins of the Rio Grande Basin to the south and west. The permanent surface water of the Devils River extends for approximately 71 km. (45 mi.) entirely within Val Verde County from its headwaters at Pecan Springs to the weir dam at Pafford's Crossing at the upper end of the Devils River arm of Lake Amistad. An additional 34 km. (21 mi.) of the Devils River from Pafford's Crossing, where the downstream most IBWC stream flow gaging station (08-4494.00) is located, to its confluence with the Rio Grande is now inundated by Lake Amistad. Just above Dolan Falls, spring-fed Dolan Creek is the largest tributary along the river. There are also numerous smaller tributaries and many seeps and basal springs along the river. The discharge of the Devils River, as measured at the IBWC gaging station at Pafford's Crossing, averages 362 ft³/s, with a maximum of 122,895 ft³/s and a minimum of 54 ft³/s.

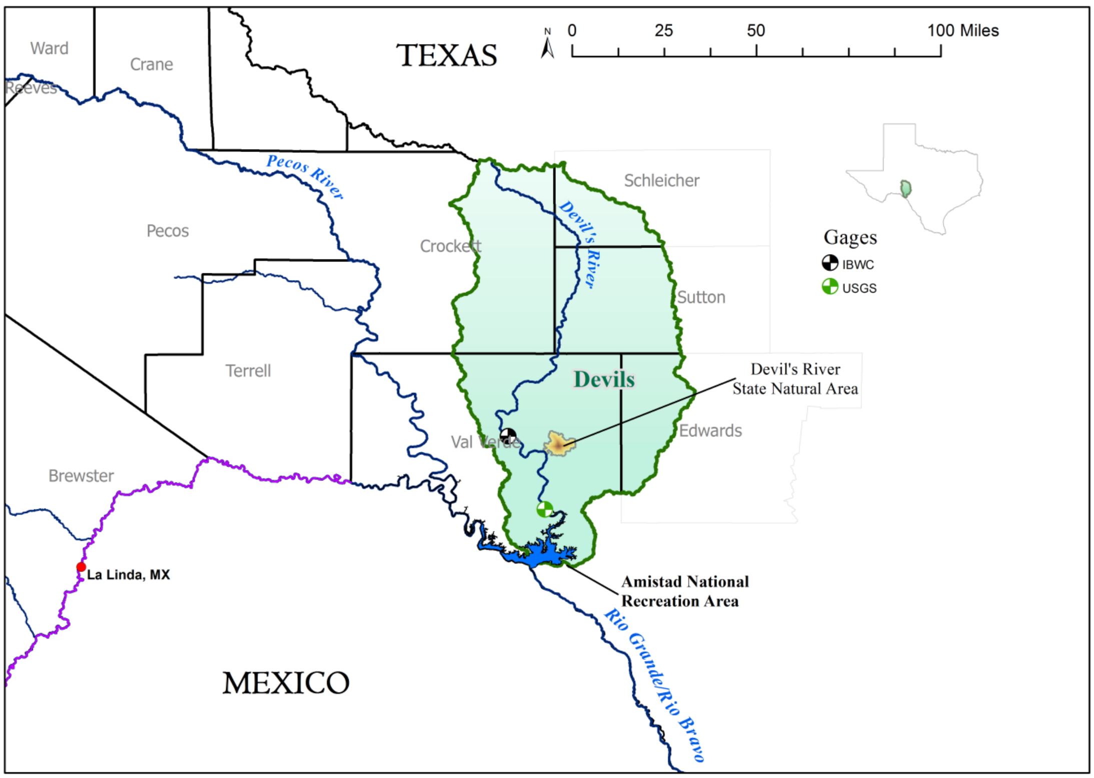


Figure 2.6-13. Location of the Devils River Basin and gaging stations.

The Devils River is recognized as one of the most pristine aquatic systems in the state (De La Cruz 2004) and is often considered the benchmark for surface water quality in Texas. The river flows through an arid landscape dominated by mesas, steep cliffs and canyons and is generally characterized by long, flat-water pools punctuated by shallow riffles and stair-step cascades. All this flow is channelized within fluted limestone bedrock.

The Devils River sub-basin is remarkable in its biodiversity; occurring at the ecological transition zone at the confluence of three ecoregions (Edwards Plateau, Tamaulipan Thornscrub, and Chihuahuan Desert), as well as supporting the high species richness associated with a riparian community occurring in an otherwise arid ecosystem. It is a cross-section of both eastern and western species and has a high number of localized endemic species, particularly in the aquatic realm. Because of all these factors, the Devils River is a major conservation priority.

The species richness resulting from the convergence of ecoregions is further augmented by the aquatic communities associated with the Devils River, Dolan Creek, and Dolan Springs. These waters are home to numerous endemic and rare species, including the Devils River minnow (*Dionda diabola*), Rio Grande darter (*Etheostoma grahami*), proserpine shiner (*Cyprinella proserpina*), Conchos pupfish (*Cyprinodon eximius*), Dolan Falls salamander (*Eurycea sp*. 10) and Rio Grande cooter (*Pseudemys gorzugi*).

The diverse habitats in the conservation area support a variety of terrestrial species of conservation concern, including breeding black-capped vireos (*Vireo atricapilla*), the largest known population of Texas snowbells (*Styrax platanifolius ssp. texana*), and small populations of Tobusch fishhook cactus (*Sclerocactus brevihamatus var. tobuschii*), all three federally endangered species. Also found here are several endemic and peripheral species, such as the Devils River blackhead snake (*Tantilla cucullata*), ringed kingfisher (*Ceryle torquata*) and rufous-capped warbler (*Basileuterus rufifrons*, not confirmed breeding). Common black-hawks (*Buteogallus anthracinus*) and zone-tailed hawks (*Buteo albonotatus*) nest here, and the Devils River provides a critical north-south corridor for myriad species of migratory songbirds, waterbirds, shorebirds, and raptors. Monarch butterflies (*Danaus plexippus*) also utilize the Devils River riparian zone on their migratory journey. Other terrestrial fauna include white-tailed deer (*Odocoileus virginianus*), black-tailed jackrabbits (*Lepus californicus*), cottontails (*Sylvilagus auduboni, S. floridianus*), gray foxes (*Urocyon cinereoargenteus*), raccoons (*Procyon lotor*), ringtails (*Bassariscus astutus*), beavers (*Castor canadensis*), bobcats (*Lynx rufus*), and occasional transitory mountain lions (*Felis concolor*) and black bears (*Ursus americanus*).

There are multiple conservation and managed lands in the Devils River sub-basin, the primary public land being the 7,689-ha (19,000-ac) Devils River State Natural Area (DRSNA) in the middle portion of the basin. There is also a second, recently purchased 17,000 acre section of the DRSNA under development near the bottom of the Devils River sub-basin immediately around the Pafford's Crossing weir dam. The DRSNA is used for canoeing, kayaking, hiking, camping, and mountain biking. There is also a National Park Service managed Amistad National Recreational Area adjacent to Amistad Reservoir.

The Devils River sub-basin is also a location with extensive private conservation partnerships. The Nature Conservancy owns and manages the Dolan Falls Preserve, a 1,943 ha (4,800 ac) property adjacent to the upper SNA section. This preserve serves as the nucleus for the Conservancy's work with private landowners along the Devils River. As a result of these partnerships over 28,000 ha (70,000 ac) are under conservation easement. Many partnership lands contain some of the important springs maintaining the Devils River base flow, such as Snake Spring, the headspring of Dolan Creek.

In addition to its biological diversity, this area is rich in artifacts of ancient Native American people. Pictographs dating back 5,000 years are found on the surface of many cliff shelters and overhangs at the heads of canyons and along rimrock ledges, with younger pictographs (post-European contact) at the base of the limestone cliffs at Dolan Springs. Prehistoric Indian rock middens in the area may be as much as 10,000 years old. The historic rock art of the Dolan Falls area is widely recognized and appreciated by members of the anthropological community.

Since the late 1800s, this area has been used for cattle, sheep and goat ranching. Changes in the market have led to a general decline of livestock ranching in the area, and today an increasing percentage of the income generated on these lands is from game hunting. Exotic game animals, most notably aoudad or Barbary sheep (*Ammotragus lervia*) have been introduced for hunting, with mixed results from an economic and ecological perspective. Other past and continuing land uses in the area are primarily recreational, including fishing, swimming, and canoeing.

In the middle 1900's hydroelectricity generated from the Devils River was a major power source for southwest Texas. Central Power and Light developed three hydroelectric plants along the Devils River in the late 1920's: The Devils Lake Hydro Plant, Lake Walk Hydro Plant, and Steam Plant. These plants provided a significant amount of power to southwestern Texas and fueled much of the development of the Del Rio area. These structures are now inundated under Lake Amistad.

2.6.3.1 Physiography

The Devils River sub-basin occurs at the confluence of three ecoregions: the Edwards Plateau, South Texas Brush Country, and Chihuahuan Desert (**Figure 2.2-1**) and the physiography and vegetation reflect this. The Devils River watershed is characterized by high topographic relief with broad flat mesas in the areas of highest elevation, dropping off steep cliffs and slopes to the river valley bottom. The Devils River is highly constrained by its valleys, but the channel does contain broad flat bedrock shelves with vibrant floodplain and riparian communities on its margins. The riparian corridor along the Devils River is typical of western Edwards Plateau riparian communities, including trees such as willow (*Salix spp*.), sycamore (*Platanus occidentalis*), Plateau live oak (*Quercus fusiformis*), Berlandier ash (*Fraxinus berlandieri*), and little walnut (*Juglans microcarpa*). Uplands characteristic of the Edwards Plateau may be dominated by Ashe juniper (*Juniperus ashei*) and various oak species, and grasslands of the curly mesquite-sideoats grama series (*Hilaria berlandieri-Bouteloua curtipendula*). The slopes have plant communities representative of the three ecoregions that intersect here (Tamaulipan Thornscrub, Chihuahuan Desert and Edwards Plateau), including a variety of chaparral shrubs and succulents such as cenizo (*Leucophyllum frutescens*), guajillo (*Acacia berlandieri*) and other acacias, coyotillo (*Karwinskia humboltiana*), lechuguilla (*Agave lechuguilla*), and sotol (*Dasylirion texanum*). In addition, Dolan Falls Preserve harbors the only known U.S. population of Mexican white oaks (*Quercus polymorpha*) and a population of Anacacho orchid (*Bauhinia lunarioides*) trees.

2.6.3.2 Relationship to Aquifers

The Devils River sub-basin is characterized by clear, clean, perennially flowing streams that are highly dependent on ground water-fed base flow. The river's permanent flowing reach arises from headwater springs emanating from the Edwards-Trinity Aquifer and is augmented by several more zones of input from this aquifer as it flows southward. The headwater source of the Devils River is Pecan Springs, a complex of springs at which the river's surface flow becomes permanent and contiguous. Downstream from the headwaters, the known remaining springs are: Hudspeth, Huffstutler, Phillips, Finnegan, Dolan and Snake Springs on Dolan Creek, and Gillis (Willow), Indian, Slaughter Bend, Smith, Swann-Shelton, and Big Satan Springs on the mainstem (Brune 2002). All of these springs and most others in the sub-basin appear to be contact springs or seep springs, although there are a few artesian springs. Each contributes appreciable volume to the river and Lake Amistad. Historic springs include several above the present headwater spring complex that are either completely depleted or only express surface flow following very high watershed rainfall and subsequent recharge, or perhaps even from recharge pulses outside the watershed. These springs are Beaver (which failed between 1971 and 1976), Juno Headwater, Stein, and San Pedro Springs (each of which apparently was extinguished by 1971, [Brune 2002]).

The Devils River sub-basin falls within the upper permeable units of the Edwards-Trinity (Plateau) Aquifer (**Figure 2.5-1**). The Edwards Group in this sub-basin is made up of the following hydrogeologic units: Fort Lancaster and Fort Terrett Formations (Comanche Shelf); Devils River Formation (Devils River Trend); and West Nueces, McKnight, and Salmon Peak Formations (Maverick Basin) (Reeves and Small 1973, Barker et al. 1994, Barker and Ardis 1996, Anaya 2004). Each of these provinces represents a specific environment of deposition and has its own unique geologic formations with discreet hydraulic characteristics. The major depositional provinces (Comanche Shelf, Devils River Trend, and Maverick Basin) and structural features (e.g., Carta Valley Fault Zone) may be the major controls on ground water flows (Barker and Ardis, 1996).

The primary importance of ground water to the Devils River flow underscores the importance of ground water management to maintenance of sufficient instream flow in the sub-basin. Impacts to the sound ecological environment of the Devils River will not only come from surface water withdrawals, but also from excessive ground water pumping. It will be important to consider instream flow and/or springflow standards in ground water management, e.g., in setting desired conditions for the aquifer and in drought management plans. This will also be important as San Antonio and other cities to the east and north look to eastern Val Verde County aquifers as additional sources for municipal water supply. This is doubly important because Val Verde County ground water is the water supply for the city of Del Rio and the air force base.

2.6.4 Amistad Reservoir

Amistad Reservoir is a very prominent feature in the Devils River sub-basin as it impounds the lower 21 miles of the river to its confluence with the Rio Grande. In high lake stands, the upstream end of the reservoir pool is at the Pafford's Crossing weir dam on the new Devils River State Natural Area. Amistad Reservoir provides flood control and water supply, primarily for downstream agricultural users in the lower Rio Grande Valley. Throughout the basin, the rivers are used for water supply and recreational purposes. There are currently no surface water rights within the Devils River watershed. Diversions from the Devils River are thus restricted to domestic and livestock use at river front properties, typically from shallow wells. Use of ground water in the Devils River Basin in Val Verde County is currently unregulated; however, part of the basin lies within Kinney County and as such may be subject to regulation by the Kinney County Ground water Conservation District. To date, the Kinney Ground water Conservation District has focused on the eastern portion of that county, outside the Devils River basin.

2.7 Regional Water Planning (Regions E,F,J)

2.7.1 2012 State Water Plan

Texas State Water Plan updated and published in 2012 assessed water demands and water supplies for next 50 years for 16 regions (TWDB, 2012). The URG BBEST's work is closely related to three regional water plans, including Regions E (FWTRWPG, 2011), Region F (Region F Water Planning Group, 2010), and Plateau Region (Region J) (Plateau Water Planning Group, 2011). Each regional water plan is designed to meet the regional needs for water during times of drought. Each planning group evaluates population projects, water demand projections, and existing water supplies that would be available during times of drought. By comparing water demands and supplies, water user groups that will not have enough water during time of drought will be identified. Strategies for addressing such water shortage are recommended in the water plan. During the planning process, the planning group also assessed risks and uncertainties, and evaluated potential impacts of water management strategies on the regional water, agricultural and natural resources. One of the potential future planning issues identified in the Texas State Water Plan is impacts to water availability from new environmental flow standards (TWDB, 2012).

2.7.2 Unique Stream Segments

The Texas Water Development Board (TWDB) regional water planning guidelines require that a regional water plan include recommendations for regulatory, administrative, and legislative changes that will facilitate water resources development and management:

"357.7(a) Regional water plan development shall include the following… regulatory, administrative, or legislative recommendations that the regional water planning group believes are needed and desirable to facilitate the orderly development, management, and conservation of water resources and preparation for and response to drought conditions in order that sufficient water will be available at a reasonable cost to ensure public health, safety, and welfare; further economic development; and protect the agricultural and natural resources of the state and regional water planning area. The regional water planning group may develop information as to the potential impact once proposed changes in law are enacted." (TWDB, 2001).

The guidelines also call for regional water planning groups to make recommendations on the designation of ecologically unique river and stream sites and unique sites for reservoir development. In each regional water plan, unique stream segments are identified and recommended by the State Legislature and stakeholders. Following sections summarize those unique stream segments that are related to this project.

2.7.2.1 The Rio Grande

In region E water plan, the planning group recognizes the significance of the 196-mile Rio Grande Wild and Scenic River segment that was designated by Congress in 1978 under the Wild and Scenic River Act (16 USC 28 §1274) and encourages the proper conservative management of this region (**Figure 2.7-1**). The segment is covering the United States side of the river, extending from river mile 842.3 above Mariscal Canyon downstream to river mile 641.1 at the Terrell-Val Verde County line. The International Boundary and Water Commission later revised the beginning and ending river miles to 853.2 and 657.5 respectively. The upper 69-mile section of this corridor lies within the Big Bend National Park, however the National Park Service administers the entire 196-mile designated section. For purposes of the Far West Texas Regional Water Plan (FWTRWPG, 2011), the Planning Group officially recommends that only the part of the federally designated Rio Grande that is bordered by the Big Bend National Park be considered under the guidelines of "Ecologically Unique River and Stream Segments". The following river segment characterization is principally contained with the National Parks Service / Rio Grande Wild and Scenic River Final General Management Plan and Environmental Impact Statement (http://www.nps.gov/rigr/parkmgmt/upload/RIGR_gmp-eis.pdf).

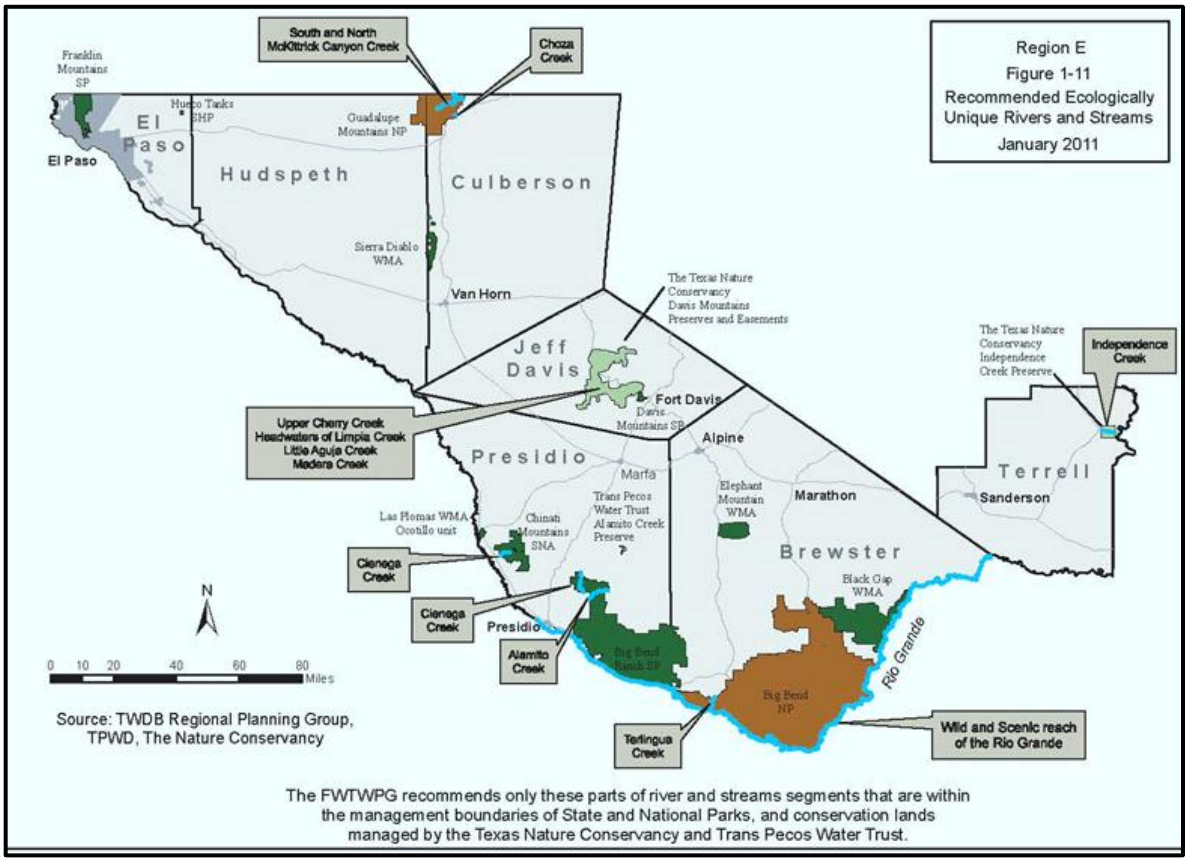


Figure 2.7-1: Region E, Recommended Ecologically Unique Rivers and Streams (TWDB, 2011)

The Rio Grande Wild and Scenic River (RIGR) was designated for the following purposes:

- To preserve the free-flowing condition and essentially primitive character of the river (expect as provided by treaty)
- To protect the outstanding scenic, geologic, fish and wildlife, recreational, scientific, and other similar values of the river and its immediate environment
- To provide opportunities for river-oriented recreation that is dependent upon the free- flowing condition of the river and consistent with the primitive character of the surroundings.

The Rio Grande Wild and Scenic River is significant as part of a valuable and largely intact ecological system representing major riparian and aquatic habitat associated with the Chihuahuan Desert. Spectacular river canyons, the primitive character of the river, and its international flavor combine to form a stimulating environment for high quality scenic and recreational experience. Protecting and managing this outstanding natural resource extends a valuable opportunity for international cooperation between the United States and Mexico.

The designated Wild and Scenic stretch of the Rio Grande begins in Big Bend National Park, opposite the boundary between the Mexican states of Chihuahua and Coahuila. It then flows through Mariscal and Boquillas Canyons in the national park. Downstream from the park, it extends along the state-managed Black Gap Wildlife Management

Area and several parcels of private land in the Lower Canyons. The wild and scenic river segment ends at the county line between Terrell and Val Verde Counties. The National Park Service's jurisdiction on the Rio Grande Wild and Scenic River downstream from the park boundary includes only the river area from the United States/Mexico international boundary in the middle of the deepest channel to the gradient boundary at the edge of the river on the United States side. The gradient boundary, as recognized by the State of Texas, is defined as located midway between the lower level of the flowing water that just reaches the cut bank and the higher level of it that just does not overtop the cut bank. The riverbed of the Wild and Scenic River downstream from the park is the property of the State of Texas.

The following sections are classified as wild: Talley to Solis, which includes Mariscal Canyon; the entrance to Boquillas Canyon to the exit of Boquillas Canyon; and Reagan Canyon to San Francisco Canyon (the bulk of the "Lower Canyons"). The remainder of the Wild and Scenic River is classified as scenic. The area is an outstanding example of Chihuahuan Desert wildlife in Texas. This isolated area represents a rapidly dwindling, irreplaceable natural resource. The riparian corridor, containing more vegetative growth and a reliable water supply, attracts many wildlife species.

Forty-six known species of fish inhabit the Big Bend area; 34 of these are native. Shiners and daces are the most abundant fishes in the Rio Grande. Larger fish found here are the long-nose gar, channel catfish, blue catfish, and European carp. Six native fish species have been extirpated in recent decades because of the effects of dams, habitat modification, and competition from at nonnative species (FWTRWPG, 2011). Native freshwater mussels have virtually disappeared from this area. Some historic species no longer can be found, and the more persistent Texas hornshell and Salina Mucket have not been found alive in recent years. Other aquatic species may be in danger of extirpation. Reductions in water quality and quantity adversely affect these and other aquatic species. At least 12 nonnative fish species are prominent in the Rio Grande, however, at present there is insufficient information about the distribution and spread of exotic species.

Birds are the most frequently seen animals along the river. Common resident species seen or heard along the river include yellow-breasted chat, black phoebe, white-winged dove, canyon wren, and roadrunner. Ravens, turkey vultures, and various raptors regularly soar overhead. Peregrine falcons (*Falco peregrinus*) use high cliff faces for nesting in Santa Elena, Mariscal, and Boquillas canyons. Reptiles include lizards, snakes, and both terrestrial and aquatic turtles. Several amphibian species also are present.

2.7.2.2 The Pecos River

In the Region E water plan, the planning group identified and designated Independence Creek as ecologically unique segment (**Figure 2.7-1**). It is a large spring-fed creek in northeastern Terrell County. It is the most important and one of the few remaining freshwater tributaries of the lower Pecos River. The Texas Nature Conservancy owns and manages the 19,740-acre Independence Creek Preserve. Caroline Spring, located at the Texas Nature Conservancy's Preserve headquarters, produces 3,000 to 5,000 gallons per minute and comprises about 25% of the creek's flow. Independence Creek's contribution increases the Pecos River water volume by 42% and reduces the total dissolved solids, thus improving water quantity and quality. The Preserve hosts a variety of bird and fish species, some of which are extremely rare. Caroline Spring, along with the entirety of the Independence Creek Preserve, is a significant piece of West Texas natural heritage. That portion of Independence Creek that flows through the Preserve continues to be recommended as an "Ecologically Unique River and Stream Segment". Caroline Spring is recognized as a "Major Spring" (FWTWRPG, 2011).

In the Region F water plan, Texas Parks and Wildlife Department (TPWD, 2004) identified 20 segments as ecologically significant, among which five are closely related to the Pecos River.

1. Salt Creek, Confluence with Pecos River upstream to Reeves/ Culberson County line in Reeves County;
2. Toyah Creek, Confluence with Pecos River upstream to FM 1450 In Reeves County;
3. The Pecos River, Val Verde/ Crockett County line upstream to FM 11 bridge on Pecos/ Crane County line across several counties;
4. Diamond Y Draw, Headwaters to confluence with Pecos River in Pecos County;
5. Live Oak Creek, Headwaters to confluence with Pecos River in Crockett County.

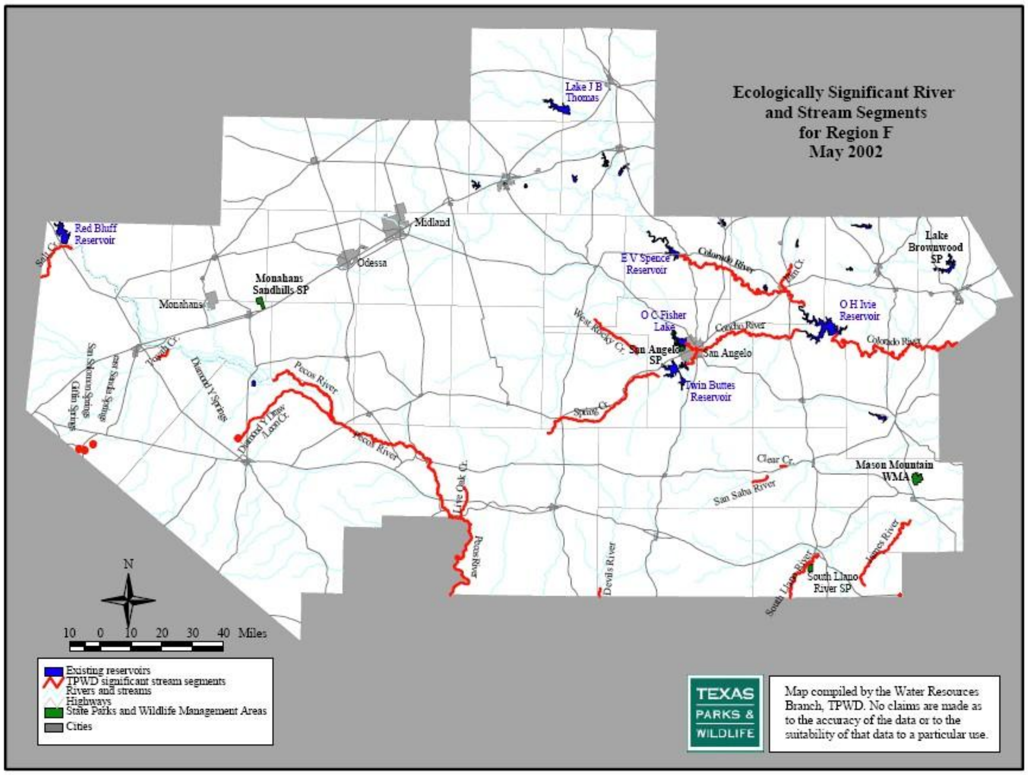


Figure 2.7-2: Texas Parks and Wildlife Department Ecologically Significant River and Stream Segments in Region F

In previous planning cycles, the Region F Water Planning Group (2010) decided not to recommend any river or stream segments as ecologically unique because of unresolved concerns regarding the implications of such a designation. The Texas legislature has since clarified that the only intended effect of the designation of a unique stream segment was to prevent the development of a reservoir on the designated segment by a political subdivision of the state. However, the TWDB regulations governing regional water planning require analysis of the impact of water management strategies on unique stream segments, which implies some level of protection beyond the mere prevention of reservoir development. Considering the remaining uncertainty for designation and the regional consensus that there are no new reservoirs recommended for development, the Region F Water Planning Group did not recommend the designation of any river or stream segment as ecologically unique (Region F Water Planning Group, 2010).

2.7.2.3 Devils River

In Region J (Plateau Water Regional Planning Group, 2011), TPWD provided a list of stream segments that were identified as meeting ecologically unique criteria, including the Devils River. For each segment, TPWD lists qualities of each segment that support the stream's candidacy. These qualities may include but are not limited to biological function, hydrological function, location with respect to conservation areas, water quality, the presence of state or federally listed, threatened, or endangered species, and the critical habitat for such species.

The Devils River, from a point 0.4 miles downstream of the confluence of Little Satan Creek in Val Verde County upstream to the Val Verde/Sutton County line (within TNRCC classified stream segment 2309), is recommended for ecologically unique segment by TPWD. The Devils River serves following functions. (a) Biological function, National Wild and Scenic Rivers System nominee for outstandingly remarkable fish and wildlife values (NPS, 1995); (b) Riparian conservation area, Devils River State Natural Area High water quality/exceptional aquatic life/high aesthetic value – ecoregion stream (Bayer et al., 1992); high water quality and exceptional aquatic life use (TNRCC, 1996); exceptional aesthetic value (NPS, 1995); (c) Threatened or endangered species/unique communities - Devils River minnow (Federally Endangered/ State Threatened), Conchos pupfish (Species of Concern/State Threatened) (Hubbs et al., 1991); proserpine shiner (Species of Concern/ State Threatened), Rio Grande darter (Species of Concern/ State Threatened) (Bayer et al., 1992; Hubbs et al., 1992); largest known population of Texas snowbells (Federally Endangered/ State Endangered) (J. Poole, 1999, pers. comm.).

The Plateau Water Regional Planning Group recognized the importance of preservation of this natural environment and the uniqueness of this Region as the Region's economy is closely tied to these natural resources. Throughout the planning period the planning group has followed a policy of always considering the impact that their decisions have on the area's ecological resources. However, because the subsequent ramifications of designation are not fully understood, the planning group had chosen to refrain from recommending specific segments for designation as "ecologically unique". The Water Planning Group strongly asserts that all river and stream segments in the Plateau Region are vitally important and their flows constitute a major consideration in adoption of the regional water plan (Plateau Water Regional Planning Group, 2011).

2.8 URG Study Area Unique Issues

2.8.1 United States – Mexico Water Treaty (1944)

The 1944 International Treaty addresses the waters in the international segment of the Rio Grande from Fort Quitman, Texas to the Gulf of Mexico. The Treaty allocates water in the River based on percentage of flows in the River from each country's tributaries to the Rio Grande. The 1944 Treaty also stipulates that one third of the flow of the Rio Conchos in Mexico is allotted to the United States. The Rio Conchos is by far the largest tributary of the Rio Grande. The treaty requires that the combined flow of the Rio Conchos and five other tributaries (San Diego, San Rodrigo, Escondido, Salado Rivers and Las Vacas Arroyo) shall have an annual average of not less than 350,000 acre-ft. The IBWC/CILA is responsible for implementing the treaties between the United States and Mexico. As of the printing of this Plan in 2012, Mexico was current on its obligations (Far West Texas Water Plan, 2011).

2.8.2 Pecos River Compact

The major purposes of the Pecos River Compact among the State of New Mexico, the State of Texas and the United States are to provide for the equitable division and apportionment of the use of the waters of the Pecos River; to promote interstate comity; to remove causes of present and future controversies; to make secure and protect present development within the states; to facilitate the construction of works for, (a) the salvage of water, (b) the more efficient use of water, and (c) the protection of life and property from floods. Under this Compact, New Mexico shall not deplete by man's activities the flow of the Pecos River at the New Mexico-Texas state line below an amount which will give to Texas a quantity of water equivalent to that available to Texas under the 1947 condition. The beneficial consumptive use of water salvaged in New Mexico through the construction and operation of a project or projects by the United States or by joint undertakings of Texas and New Mexico, is hereby apportioned 43% to Texas and 57% to New Mexico. The beneficial consumptive use of water which shall be non-beneficially consumed, and which is recovered, is hereby apportioned to New Mexico but not to have the effect of diminishing the quantity of water available to Texas under the 1947 condition. Any water salvaged in Texas is apportioned to Texas. Beneficial consumptive use of unappropriated flood waters is hereby apportioned 50% to Texas and 50% to New Mexico. Moreover, the Compact requires that the nothing shall be construed as:

a) Affecting the obligations of the United States under the Treaty with the United Mexican States (Treaty Series 994); and
b) affecting any rights or powers of the United States, its agencies or instrumentalities, in or to the waters of the Pecos River, or its capacity to acquire rights in and to the use of said waters. These rules have great impacts on the acquisition of water rights to maintain environmental flows.

2.8.3 Pecos River Watershed Protection Plan

The Watershed Protection Plan for the Pecos River in Texas (WPP) prepared by Texas AgriLife Extension Service, Texas AgriLife Research, the U.S. Section of the International Boundary and Water Commission, the Texas Water Resources Institute and the Texas State Soil and Water Conservation Board, is a plan to restore water quality in the river and generally improve watershed health (Gregaory and Hatler, 2008). The WPP assesses water quality and quantity concerns and other natural resource issues across the entire Pecos River watershed in Texas, and provides practical, landowner-supported solutions to address these concerns. The overall goal of the WPP is to sustain a landowner-driven process to promote voluntary best management practices throughout the watershed that will improve water quality and overall health of the watershed.

The WPP includes an extensive overview of the watershed and the physical characteristics that define the watershed. The WPP identifies concerns, information on the causes and sources, critical areas for management, estimated load reductions, management measures, and assistance needed. Some of major concerns listed in the WWP are summarized as below: Salinity management, biological diversity, water quantity, golden algae, DO, sediment, oil and gas production, nutrients and chlorophyll-a. The WPP also addressed technical and financial assistance, implementation schedule, public education and outreach, and monitoring programs. Following sections are summarized from the WPP.

Salinity: The sources of elevated salinity in the Pecos River are irrigation return flows flowing across naturally occurring salt deposits across the Permian Basin then returning to the river and saline ground water entering the river in several locations. Human influences and activities can alter the effects of natural sources of salt on the river's salinity. These sources occur in New Mexico and Texas, yet both influence the quality of water in Texas. Two critical areas for management and further investigation are the ground water intrusion points near Malaga, NM and Imperial, TX. A pilot project conducted near Malaga, NM in the 1960s verified that a 25% load reduction in salinity is feasible through pumping a saline aquifer and harvesting the salt. Although highly saline inflows have been noted near the Imperial area, specific information about the intrusion point and salinity of these inflows is currently unknown. Further information will be needed prior to implementing management measures in this area.

Salt cedar (*Tamarix spp.*) removal and subsequent water salvage also has the ability to decrease salinity. Decreases in salinity will be inversely related to increases in stream flow because of salt cedar removal. Previously treated salt cedar and planned salt cedar treatment also have the ability to influence in-stream salinity concentrations if salvaged water materializes as stream flow.

Biological Diversity: Biological diversity refers to a variety of features in the watershed that can include aquatic, riparian, and upland vegetation; aquatic life species; and wildlife species. The changes in these aspects of the watershed are due primarily to human influences occurring over the last 150 years. The combination of overgrazing in the late 1800s, extensive droughts, the introduction of the invasive species salt cedar, and the increased use of water from the river and aquifers have been the driving factors in changing the biological diversity. Critical areas for improving biological diversity have been identified in three primary areas: riparian brush control and revegetation, upland brush management, and aquatic habitat improvement. Specific management measures recommended to achieve biological diversity restoration are widespread salt cedar control followed by prescribed burns to remove debris and promote natural revegetation, controlling other invasive species in riparian areas such as giant cane and willow baccharis, conducting upland brush control and implementing improved land management practices, and working to improve aquatic habitat.

Estimated changes in biological diversity are extensive and it will take many years to fully realize these changes. Over 2,000 acres of invasive salt cedar trees remain to be treated in the riparian corridor along with undocumented new growth and regrowth from previously treated salt cedar. Chemical treatment paired with biological control is not anticipated to eradicate this invasive species but rather to prevent it from consuming thousands of acres as it has in the past. Aquatic habitat, also expected to improve over an extended period, will be dependent upon many of the management measures implemented throughout the watershed.

Water Quantity: Water quantity issues are always a concern in a desert environment. Causes of water shortages in the river are a combination of climate and increased water consumption throughout the watershed. Critical areas for managing water quantity are improving on-farm irrigation and delivery of irrigation water, promoting water conservation throughout the watershed, controlling invasive plant species, and promoting new management practices to enhance existing land stewardship. Estimated improvements in water quantity are primarily derived from irrigation efficiency improvements, reservoir release modifications, and salt cedar control. Irrigation efficiency of 95% to 97% can be achieved using drip irrigation technology, thus making a 20% savings realistic as compared to surge flow irrigation. Reservoir releases currently lose more than 50% of the released water, and research shows that these losses could be reduced to around 35%. Lastly, salt cedar removal is anticipated to salvage 0.5 to 1 acre-foot of water per acre of salt cedar treated and this salvaged water should supplement shallow water tables or stream flow.

Dissolved Oxygen: Improving DO levels in the river between Pecos and Girvin is one of the primary objectives of the WPP. Maintaining sufficient DO levels in the river is critical to the survival of aquatic life and an indicator of overall river health. The critical area for improving DO levels in the river is the stretch between Business 20 near Pecos downstream to US 67 near Girvin. Data collected in this area over a three-year period resulted in this reach of the river being listed as impaired on the 2008 303(d) List for not meeting current water quality standards. Depressed DO can stem from a variety of causes and sources such as low flows, high nutrients and algal growth, higher salinity, and increased biological oxygen demand; however, these have not been fully evaluated for the Pecos River. Planned work will use computer-based modeling to evaluate the influence of environmental parameters on in-stream DO levels. Without a sound understanding of the causes leading to low DO levels, appropriate management measures cannot be recommended; however, increasing the agitation of the river, decreasing water temperatures and salinity in the river, decreasing the amount of dead organic matter in the river, and reducing nutrient loading into the river will all positively affect DO levels in the river.

Sediment: Sediment loading in the Pecos River is not a major problem in most areas; however, planned salt cedar debris removal activities will increase the risk of excessive sediment until vegetation is re-established. Establishing healthy ground cover in upland and riverbank areas will have the greatest positive impact on sediment levels and may increase available grazing in the watershed. Critical areas where erosion potential will need to be managed are in areas where salt cedar debris is burned. Sediment loading to the river will be reduced by 6,192 tons if all treatable areas are sprayed, burned, and subsequently revegetated.

Oil and Gas Production: The long-standing influence of the oil and gas industry in the Pecos River watershed has led to many landowner concerns about potential industry-related water quality impacts. Some landowners have reported abandoned wells, leaking wells, and/or improper brine disposal in their land or adjacent lands, all of which could pose significant threats to water quality. The critical area to watch for these activities and issues is in the upper portion of the watershed (above I-10) where exploration and drilling began almost 100 years ago and the bulk of today's oil and gas production in the region still occurs. One management measure recommended in the WPP is to document the date and location of abandoned wells, leaking wells, and/or improper brine disposal and report them to the Railroad Commission of Texas (RCC) or to the Pecos River Watershed Coordinator. Once problem areas are identified, solutions with industry and state and federal agencies can be achieved.

Nutrients and chlorophyll-a: Several segments of the Pecos River and Red Bluff Reservoir have elevated nutrient levels and are listed as concerns on the 2008 Texas Water Quality Inventory. Critical areas for implementing nutrient management measures are in the upper portions of the watershed in Texas and in irrigated agriculture areas in New Mexico. The elevated nutrients in Red Bluff Reservoir indicate that excessive levels of nutrients are being delivered in the river from New Mexico. Management techniques and educational activities recommended in the WPP will help address this issue. Management measures specific to nutrients are primarily education based. Educational programs and workshops will teach participants about proper nutrient management and will lead to reduced nutrient levels in the river. Coordinating with New Mexico is also a key to effectively managing nutrient levels in Texas.

Section 3. Instream Flow Analysis

3.1 Introduction

The guiding principle applied to the Upper Rio Grande BBEST instream flow analyses and associated methodologies is the concept of the "Natural Flow Regime”, which stresses the importance of the dynamic processes that occur over a range of flows that help maintain the physical, biological, chemical, and ecological integrity of river systems (Poff, et al.,1997).

The natural flow regime paradigm incorporates five critical components of flow that 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). The five components represent attributes of the entire range of both flood flows and low flows. Along with the over–arching physical characteristics of each river basin, the flow regime is the single-most important variable in controlling physical, biologic, and chemical processes. Additionally, these processes feedback upon each other, and thus, changes to one aspect of the flow regime may cause cascading effects throughout the river system. For further discussion on the interrelationships between the physical, biologic, and ecologic processes (**Figure 3.1-1**), refer to the above publications, TIFP 2008 and previous BBEST reports including the Nueces Environmental Flow Recommendations Report (Section 3; 2011).

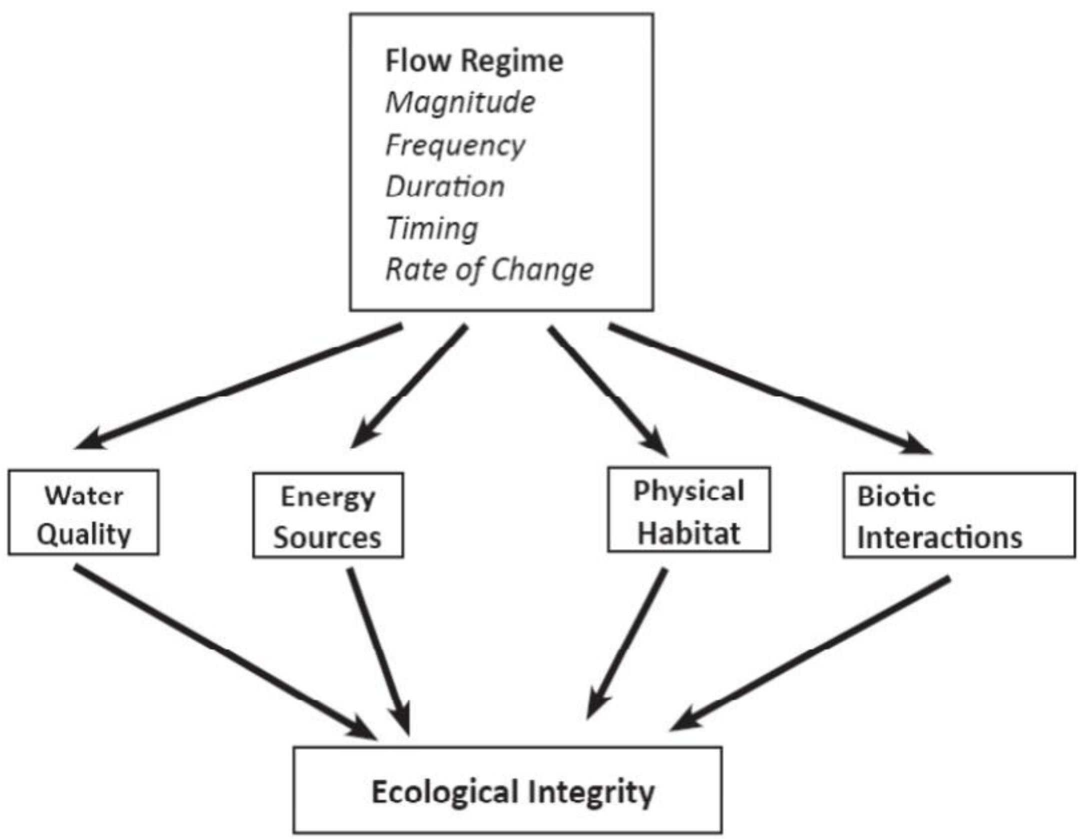


Figure 3.1-1. The five components of the natural flow regime that directly and indirectly affect the ecological integrity of river ecosystems (adapted from Poff, et al., 1997) and taken from Nueces BBEST Environmental Flow Recommendations Report (2011).

As a tool for characterization of flow regimes within Texas rivers, the SAC (2009) adopted the HEFR Methodology which employs statistical calculations based on historic mean daily discharges in order to quantify attributes of four portions of the flow regime: subsistence flows, base flows, high flow pulses, and overbank flows. For each of these flow regime components, HEFR was designed to assist in characterizing their attributes in terms of magnitude, duration, timing, and frequency. For environmental flow recommendations within this report, HEFR results are then integrated with overlays of biology, water quality, and geomorphology in order to tailor HEFR outputs and fulfill the requirement of achieving a sound ecologic environment for each river segment. 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 3.1-1** summarizes the ecological functions of various flow components for perennial and intermittent locations in the upper Rio Grande basin, taking into consideration the unique physical characteristics of the basin and its biota.

Table 3.1-1. General flow components for the stream segments of the Upper Rio Grande Basin.

Component	Hydrology	Geomorphology	Biology	Water Quality
No-Flow Periods	Flow ceases between perennial pools	Encroachment of vegetation	Generally stressful for fish communities	Temperatures rise and oxygen levels decrease. These condition sometimes cause fish kills
Subsistence Flows	Infrequent low flows	Increased deposition of fine and organic particles, encroachment of vegetation	Provide restricted aquatic habitat limit connectivity	Elevate temperature and constituent concentrations Maintain adequate levels of dissolved oxygen
Base Flows	Average flow condition, including variability	Maintain soil moisture and ground water table Maintain a diversity of habitats, Exports or transports sediment?	Provide suitable aquatic habitat, Provide connectivity along channel corridor	Provide suitable in-channel water quality
High Flow Pulses	In channel short duration, high flows	Deposit sediment, development of inset flood plains; Prevent encroachment of riparian vegetation	Serve as recruitment events for organisms; Provide connectivity to near-channel water bodies	Restore in-channel water quality after prolonged low flow periods. Episodic in nature and associated with fish kills (anecdotal, no real investigation of this yet)
Overbank flows	Infrequent high flows that exceed the channel	Provide lateral channel movement and floodplain maintenance; Recharge floodplain water table; form new habitats; flush organic material into channel; Deposit nutrients in floodplain	Provide new life phase cues for organisms; Maintain diversity of riparian vegetation; Provide conditions for seedling development; Provide connectivity to floodplain	Restore water quality in floodplain water bodies
Channel Maintenance	For most streams, channel maintenance occurs mostly during pulse and overbank flows	Long-term maintenance of existing channel morphology	Maintains foundation for physical habitat features instream	Water quality condition like those during pulse overbank flows

Environmental flow analyses 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; b) hydrology-based tools are applied to extract statistics descriptive of flows and flow regime components at the selected locations; and c) biological, water quality, and geomorphology, 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 4.

The stream segments for which we provide environmental flow recommendations for in this report have all experienced a wide range of scientific attention varying from little to no scientific work concerning some ecosystem processes, and extensive work concerning other processes. However, there have generally been few, if any, scientific investigations or monitoring efforts designed to relate physical or biological processes to the flow regime. Although we incorporate the best available scientific data to inform our recommendations, very few data collection or monitoring efforts were conducted with the specific purpose for informing management decisions regarding the establishment of in-stream flows. As a reflection of the different levels of scientific attention, and the different initial purposes of scientific data collection, the datasets included herein as part of the biologic, water quality, and geomorphic overlays are extremely disparate and are at times difficult to use to specifically adjust HEFR output numbers. For example, the physical processes that occur on some streams, most notably, the Rio Grande, are extremely dynamic and have received a considerable degree of scientific investigation, whereas the physical processes that occur on the Devils and Pecos rivers are not understood. For the reasons described above, the overlays included within the individual flow recommendations for each river vary widely in scope, and are used to much different degrees depending on the stream. In order to benefit future environmental flow recommendation efforts, we outline many adaptive management actions in section 5 that could potentially provide for more scientifically robust recommendations.

3.2 Geographic Scope

3.2.1 Streamflow gaging stations

A total of 20 gaging stations were evaluated within the Upper Rio Grande BBEST work area, including 7 gaging stations for the Rio Grande, 10 for the Pecos River and 3 for the Devils River. Thirteen of these gages were chosen for development of environmental flow regime recommendations, 5 for the Rio Grande, 6 for the Pecos River and 2 for the Devils River. These gage stations are shown in **Figure 3.2-1**. The characteristics of gage stations are listed in **Table 3.2-1**. and gage descriptions are included in Sections 3.2.1.1, 3.2.1.2 and 3.2.1.3.

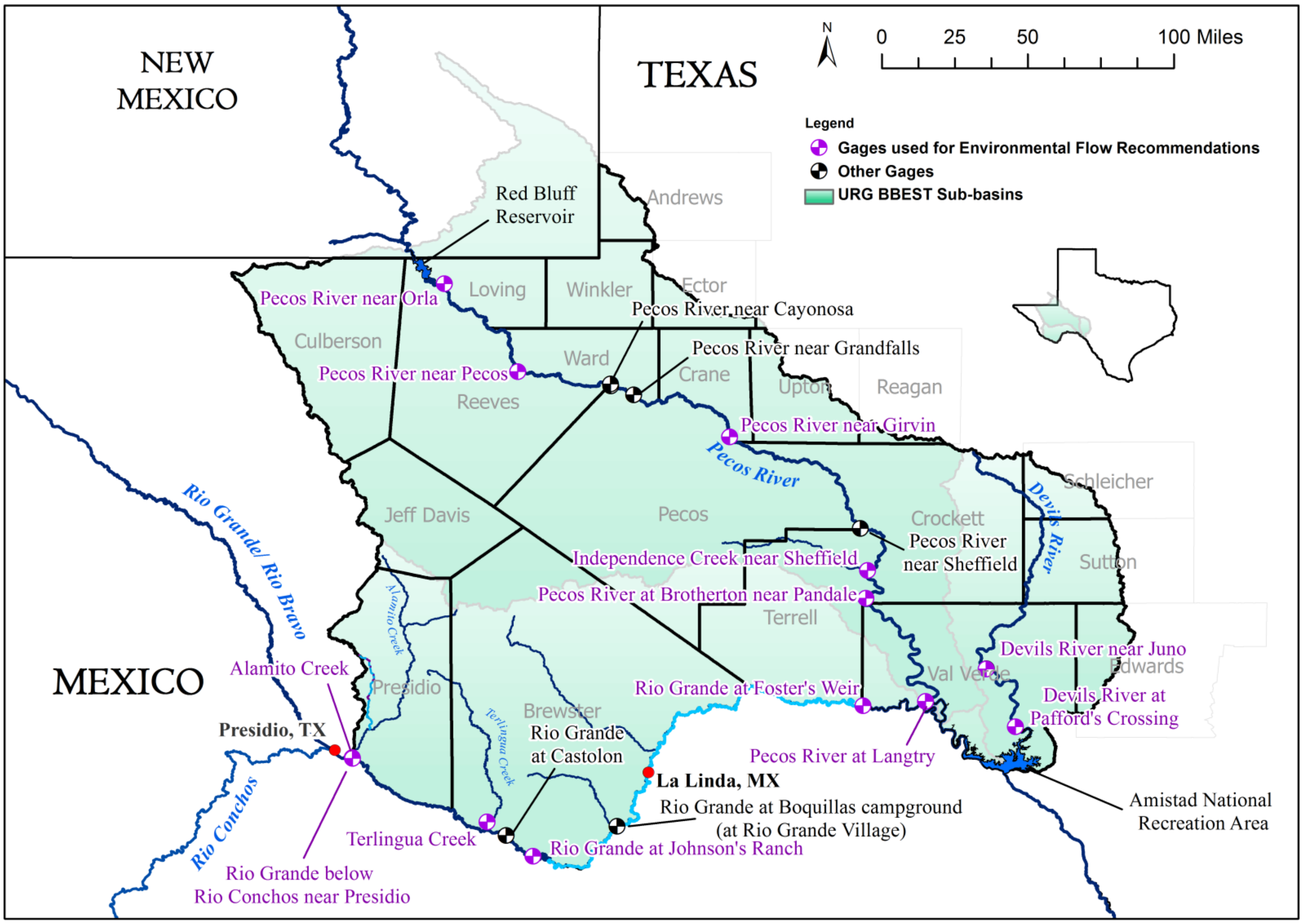


Figure 3.2-1. Gaging stations for the Rio Grande, Pecos, and Devils Rivers in the Upper Rio Grande BBEST sub-basin.

Table 3.2-1 Upper Rio Grande BBEST – Streamflow Gage Selection. Highlighted rows indicate gages used in making Environmental Flow Recommendations (Section 4).

Upper Rio Grande BBEST - Streamflow Gage Selection										
Sub-Basin	Agency	Gage Number	Hydrologic Unit Code	Gage Name	Lat/Long (NAD27)	Datum of Gage (ft)	Drainage Area in sq mi (contributing)	Period of Record		
								Begin Date	End Date	Earliest Full Year
Rio Grande	IBWC	08-3740.00		Alamito Creek	Latitude 29°31'15", Longitude 104°17'15"			1/1/1932	Current	1932
Rio Grande	IBWC	08-3742.00	13040203	Rio Grande bl Rio Conchos nr Presidio	Latitude 29°31'10", Longitude 104°17'10"	2,527.99 NGVD 29	66,203	1/1/1931	Current	1931
Rio Grande	IBWC	08-3745.00		Terlingua Creek	Latitude 29°31'10", Longitude 104°17'10"			1/1/1932	Current	1932
Rio Grande	USGS	08-3745.50	13040205	Rio Grande at Castolon	Latitude 29°08'16", Longitude 103°31'28"	3,000.00 NGVD 29		8/3/2007	Current	2008
Rio Grande	IBWC	08-3750.00	13040205	Rio Grande at Johnson's Ranch	Latitude 29°02'05", Longitude 103°23'30"	2045.30 NGVD 29	67,760 (39,720)	4/1/1936	Current	1937
Rio Grande	USGS	08375300	13040205	Rio Grande at Boquillas Cpgd (at Rio Grande Village)	Latitude 29°11'00", Longitude 102°58'30"	1,800.00 NGVD 29		8/3/2007	Current	2008
Rio Grande	IBWC	08-3772.00	13040212	Rio Grande at Foster's Weir	Latitude 29°46'50.00", Longitude 101°45'20"	1,157.17 NGVD 29	80,742	9/1/1961	Current	1962
Pecos	USGS	08412500	13070001	Pecos River near Orla	Latitude 31°52'21", Longitude 103°49'52"	2,730.86 NGVD 29	25,070 (21,229)	6/1/1937	Current	1938
Pecos	USGS	08420500	13070001	Pecos River near Pecos	Latitude 31°26'11", Longitude 103°28'01"	2,552.88 NGVD 29	26,236 (22,100)	1/1/1902	Current	1902
Pecos	USGS	08437710	13070001	Pecos River at RR 1776 near Grandfalls	Latitude 31°22'00", Longitude 103°00'20"	2,440.00 NGVD 29	34,740 (27,685)	7/13/2007	Current	2008
Pecos	USGS	08438100	13070001	Pecos River near Grandfalls	Latitude 31°19'18", Longitude 102°53'33"	2,410.00 NGVD 29	34,896 (27,810)	1/1/1916	3/31/1926	1916
Pecos	IBWC	08437710	13070001	Pecos River near Cayonosa	Latitude 31°22'31", Longitude 103°00'25"	2461.00		9/22/2004	Current	2005
Pecos	USGS	08446500	13070001	Pecos River near Girvin	Latitude 31°06'47", Longitude 102°25'02"	2,269.00 NGVD 29	37,300 (29,560)	9/1/1939	Current	1940
Pecos	USGS	08447000	13070001	Pecos River near Sheffield	Latitude 30°39'34", Longitude 101°46'11"	2,026.30 NGVD 29	40,685 (31,850)	10/1/1921	Current	1922
Pecos	USGS	08447020	13070001	Independence Creek near Sheffield	Latitude 30°27'07", Longitude 101°43'58"	1,883.00 NGVD 29	763	1/17/1974	Current	1975
Pecos	USGS	08447300	13070008	Pecos River at Brotherton Rh nr Pandale	Latitude 30°18'50.4", Longitude 101°44'29.6"	1,739.02 NGVD 29	42,169 (33,334)	7/15/2007	Current	2008
Pecos	IBWC	08-4474.10	13070008	Pecos River at Langtry	Latitude 29°48'10", Longitude 101°26'45"	1,739.02 NGVD 29	44,015(35,179)	7/1/1967	Current	1968
Devils	USGS	08449000	13040302	Devils River near Juno	Latitude 29°57'48", Longitude 101°08'42"	1489.7 NGVD 29	2,766	6/1/1925	9/30/1973	1926
Devils	IBWC	08-4490.00	13040302	Devils River at Baker's Crossing near Juno	Latitude 29°57'49", Longitude 101°08'39"	**1801.00**		7/17/2008	Current	2009
Devils	IBWC	08-4494.00		Devils River at Pafford's Crossing	Latitude 29°40'35", Longitude 101°00'00"		3,960	1/1/1960	Current	1960

3.2.1.1 Rio Grande Gaging Stations

In order from upstream to downstream, the stream-flow gages that exist or have existed on the Rio Grande are listed below:

IBWC #08-3740.00 – Alamito Creek – 1932 to present

The gage at Alamito Creek is located approximately 0.2 miles upstream from its confluence with the Rio Grande. The gage is situated on the left edge of the creek. The creek at this location is braided and the braid plain is approximately 125 ft. wide. The gage resides downstream of a wider braided section that is greater than 800 ft. wide.

Figure 3.2-2. Alamito Creek upstream from the FM 170 bridge.

IBWC #08-3472.00 – Rio Grande below Rio Conchos – 1900 to present

The Rio Grande below Rio Conchos gage is located 9 miles downstream from the Rio Conchos and just downstream of the confluence with Alamito Creek. The gage is near the beginning of a bedrock narrow on the downstream end of the Presidio Bolson This gage has a cableway and is located immediately upstream of a weir that controls the water surface at the gage. The left bank at the gage consists of sloping concrete. The gage cross section spans a wide flat floodplain approximately 750 feet wide that resides within a bedrock canyon. The floodplain vegetation is predominantly bermuda grass (*Cynodon dactylon*) with tamarisk (*Tamarix spp.)* existing on the wider portions of the floodplain.

Figure 3.2-3. Photos of the Rio Grande below Rio Conchos gage. Both photos taken from left bank and flow is from right to left.

IBWC #08-3745.00 – Terlingua Creek – 1932 to present

Terlingua Creek joins the Rio Grande 73 miles downstream from the Rio Conchos. The gage on Terlingua Creek is located approximately 2.5 miles upstream of its confluence with the Rio Grande. Terlingua Creek is located within western BBNP, and the gage is situated within a bedrock notch approximately 220 feet wide. Terlingua Creek is a braided gravel-bed stream and contributes large loads of both coarse and fine sediment (cobbles to clay) to the Rio Grande. Vegetation along the creek consists of tamarisk, seep-willow (*Baccharis salicifolia*), cottonwood (*Populus spp*.), and mesquite (*Prosopis spp*.).

Figure 3.2-4. Photo of the Terlingua Creek gage and cableway. Photo is taken from left bank and flow if from right to left.

TCEQ CAMS # 720, USGS #0837455 – Rio Grande near Castolon, TX – 2007 to present

The Rio Grande near Castolon gage is located approximately 80 miles downstream from the Rio Conchos near Cottonwood Campground in BBNP. The gage does not have a cableway, and it is funded by the TCEQ and maintained by USGS. The gage is located immediately upstream of a large meander-bend. The river is laterally unconfined and flows through a wide alluvial valley. Vegetation consists of tamarisk, mesquite, giant cane (*Arundo donax*), seep-willow, and bermuda grass. The gage was destroyed by the 2008 flood and was out of operation between Sept. 18, 2008 and Nov. 8, 2008. This gage was not chosen for development of flow recommendations.

Figure 3.2-5. Photo of the Rio Grande near Castolon gage. Photo is taken from left bank and flow is from right to left.

IBWC #08-3750.00 – Rio Grande at Johnson's Ranch – 1936 to present

The Rio Grande at Johnson's Ranch is located approximately 98 miles downstream from the Rio Conchos. The gage resides within a small canyon approximately 315 feet wide. The gage is mounted on bedrock cliff, and a floodplain is inset into the canyon wall on the right side of the river. Although the gage is situated within bedrock, the river generally flows through a wide alluvial valley. Vegetation is dominated by tamarisk, giant cane, and bermuda grass.

Figure 3.2-6. Photo looking downstream at the Johnson's Ranch gage.

TCEQ CAMS # 721, USGS #0837530 – Rio Grande at Rio Grande Village, Big Bend NP, TX – 2007 to present

The Rio Grande at Rio Grande Village gage is located approximately 148 miles downstream from the Rio Conchos. The gage resides at the downstream end of Hot Springs Canyon near Daniel's Ranch. The gage does not have a cableway, and it is funded by the TCEQ and maintained by USGS. The left bank consists of a mixed bedrock and colluvial hillslope. The right bank consists of alluvium. Downstream of this gage, the river flows through a wide alluvial valley before entering Rio Grande Village on the Texas side. The Mexican community of Boquillas is approximately three miles downstream. This gage was not chosen for development of flow recommendations.

Figure 3.2-7. Photo taken above Rio Grande at Rio Grande Village gage. Gage house is in the bottom center on the hillslope above the irrigation pump house. Gage cross section is at the bottom edge of the photo.

IBWC #08-3772.00, TCEQ CAMS # 759, – Rio Grande at Fosters Ranch – 1961 to present

The Rio Grande at Foster's Ranch gage is located upstream of Amistad Reservoir just east of the Terrell-Val Verde county line. This gage has a cable way over a weir. The CAMS station is funded by TCEQ and maintained by USGS. The right bank is alluvium and the left bank has been altered to buttress the weir with heavy rock with a concrete stairway.

Figure 3.2-8. Foster's Weir.

3.2.1.2 <u>Pecos River Gaging Stations</u>

USGS 08412500 – Pecos River near Orla – 1938 to present.

The Pecos River near Orla gage is located at the Farm Road 652 Bridge. The river here flows through a wide alluvial floodplain.

Figure 3.2-9. Photo of the Pecos River near Orla gage. Both Pictures were taken from the right bank. Flow is from left to right. Photo credit: Zhuping Sheng, Texas AgriLife Research.

USGS 08420500 – Pecos River near Pecos – 1902 to present.

The Pecos River near Pecos gage is located at the Business Route Interstate 20 Bridge. The river here flows through a wide alluvial floodplain.

Figure 3.2-10. Photo of the Pecos River near Pecos gage. The Picture was taken from the right bank. Flow is from left to right. Photo credit: Zhuping Sheng, Texas AgriLife Research.

USGS 08446500 – Pecos River near Girvin – 1940 to present.

The Pecos River near Girvin gage is located 8 river miles upstream of the U.S Highway 67 bridge. The river here flows through a wide alluvial floodplain.

Figure 3.2-11. Photos of the Pecos River near Girvin gage. Both Pictures were taken from the left bank. Flow is from right to left. Photo credit: Gary Bryant, Texas AgriLife Extension Service.

USGS 08447020 – Independence Creek near Sheffield – 1975 to present.

The Independence Creek near Sheffield gage is located on Independence Creek just above the confluence of Independence Creek and the Pecos River. The river here flows through a wide gravelly bottomed floodplain.

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Figure 3.2-12. Photos of the Independence Creek gage. The pictures were taken from the center of the Creek and the left bank. Flow is away from the photographer. Photo credit: TPWD and TNC.

USGS 08447300 – Pecos River at Brotherton Ranch near Pandale – 2008 to present.

The Pecos River near Girvin gage is located 19 river miles downstream of the confluence of the Pecos River and Independence Creek. The river here flows through a wide bedrock channel with steep canyon walls.

Figure 3.2-13. Photo of the Pecos River at Brotherton Ranch near Pandale gage. The pictures were taken from the center of the river. Flow is moving away from the photographer. Photo credit: TPWD.

IBWC 08-4474.10 – Pecos River near Langtry – 1968 to present.

The Pecos River near Langtry gage is located 13 river miles upstream of the U.S Highway 90 bridge. The river here flow through a wide bedrock channel with steep canyon walls.

Figure 3.2-14. Photos of the Pecos River near Langtry gage. The picture was taken from the right bank. Flow is from left to right. Photo credit: Zhuping Sheng, Texas AgriLife Research.

3.2.1.3 Devils River Gaging Stations

IBWC #08-4490.00, USGS 08449000, TCEQ CAMS 0768 – Devils River at Baker's Crossing near Juno/Devils River near Juno – 1926-1949 and 1963-1972 (USGS), 2005 to present (IBWC), 2008-present (TCEQ-water quality)

The Devils River at Baker's Crossing near Juno gage is located downstream of the state Highway 163 bridge roughly 10 miles downstream from the headsprings of the Devils River and 35 miles upstream of the Pafford's Crossing gage. The river here has a wide bedrock channel with little floodplain and is constrained by steep canyons.

Figure 3.2-15. Photos of the Devils River near the Juno/Baker's Crossing gage. Both photos taken from left bank and flow is from right to left. Photo credit: Christine Kolbe, TCEQ.

IBWC #08-4494.00 – Devils River at Pafford's Crossing – 1960 to present (IBWC)

The Devils River at Pafford's Crossing gage is located at the Pafford's Crossing weir dam roughly 4 miles upstream from the upper end of the Devils River arm of Lake Amistad. This gage is approximately 45 miles downstream from the headsprings of the Devils River and 21 miles upstream of the confluence with the Rio Grande, now under Lake Amistad. The river here has a wide, flat bedrock channel and a well-developed, but narrow floodplain that is constrained by steep canyons. The gage exists within the Amistad National Recreation Area managed by the National Park Service.

Figure 3.2-16. Photo of the Devils River at the Pafford's Crossing gage. Photo is taken from right bank and flow is from left to right. Photo credit: US Geological Survey.

3.3 Hydrology-based environmental flow regime methods

Based on data availability and requirements for flow regime assessment, a total of thirteen sites were selected for HEFR assessment. There are five sites along the Rio Grande, namely Rio Grande below Rio Conchos, Johnson's Ranch, Fosters weir, Alamito Creek, and Terlingua Creek. There are six sites along the Pecos River, Pecos River near Orla, Pecos River at Pecos, Pecos River near Girvin, Independence Creek at Sheffield, Pecos River at Brotherton near Pandale, and Pecos River at Langtry. There are two sites along the Devils River, namely Devils River at Pafford Crossing and Devils River at Juno.

The general approach for the hydrologic assessment is to assign each day of the hydrologic record to a specific flow component. Hydrographic separation uses a time-series record of stream flow to derive a base flow signature. The method for assessing the variations in hydrology in conjunction with HEFR analyses is the Indicators of Hydrologic Alteration (IHA).

The IHA method separates the flow data into five fundamental characteristics of hydrologic regimes: the magnitude, time, frequency, duration, and rate of change in water conditions. Before running an analysis, environmental flow component parameters were established for each stream gage including high and low flow separation, high flow pulse and flood definition, and extreme low flow conditions (**Figure 3.3-1**).

All flows that are below the 25th percentile of daily flows for the period of record are classified as low flows and only provide the ecological functions associated with base flows. The 25th percentile is the lower limit for high flow pulses. Similarly, all flows that exceed the 75th percentile of daily flows for the period of record are classified as high flows and only provide ecological functions associated with high flow pulses. The 75th percentile is the upper limit for base flows. Specific calibration parameters were established for the identification of high flow pulses between the 25th and 75th percentile levels. High flow pulses start when flow increases by more than 50% per day and end when flow decreases by less than 10% per day.

Overbank flows were defined in IHA as an initial high flow with a peak flow greater than 99.8% of the daily flows for the period; however, some of the resulting data was revised to best fit each river system. The overbank threshold for each river changes over time. In particular, flooding on the Rio Grande is difficult to predict based on IHA parameters because the stream channel has been drastically altered over the past half century (see Section 3.6.1.1 and 3.6.1.3).

Extreme low flows or subsistence flows represent infrequent, naturally occurring low flow events. They were classified in IHA as an initial low flow (base flow) below 10% of daily flows for the period.

HEFR models require a continuous period of record for calculation. Three of the selected gages have missing data. The gages at Rio Grande below Rio Conchos, Independence Creek, and Devils River near Juno have gaps of 17, 17, and 14 years, respectively. In order to use all available records, the dates were rearranged to create a consecutive time line. For example, a gap in data occurs from 1914 to 1931 for the Rio Grande below Rio Conchos gage. Measured data on March 1, 1931 was assigned to March 1, 1914 to create a continuous data run without seasonal shifting. Similar shifts were performed for Independence Creek and the Devils River near Juno. The results of shifting the dates can lead to a sporadic increase or decrease in flow and possible fluctuations between high flow pulses and base flow, but this type of event is insignificant during long periods of record.

Originally, a HEFR analysis was run for the full period of record at each gage; however, specific adjustments were made to change the seasons and periods of record to better inform the results. The seasons and periods of record chosen are described below.

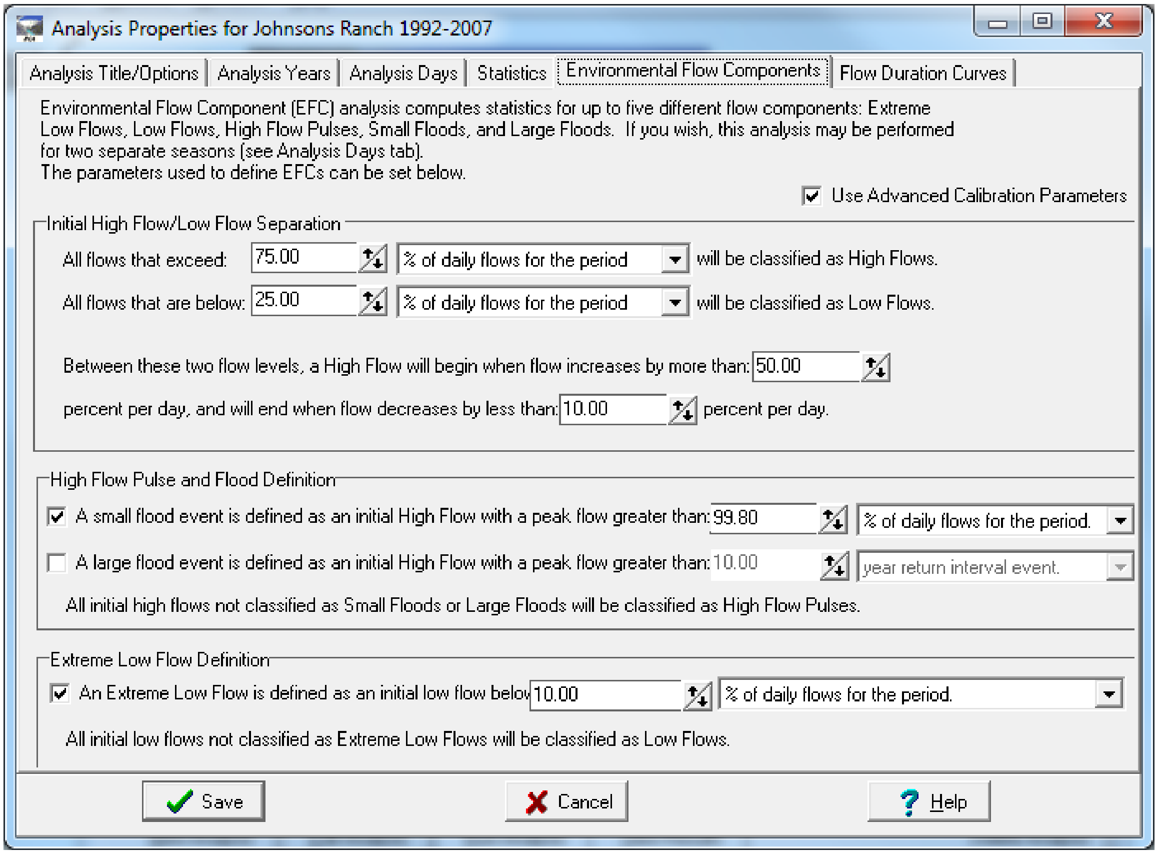


Figure 3.3-1. An IHA analysis showing the revised environmental flow components.

3.3.1 Flow Components

Subsistence Flows

Subsistence flows are infrequent low flows that result in deposition, encroachment of vegetation, restricted aquatic habitat, elevated temperatures and constituent concentrations, and maintain adequate levels of dissolved oxygen. Subsistence flows were calculated in HEFR by averaging the lowest 5% of base flows for non-zero flows only. A calculated subsistence flow is created for each seasonal analysis. The results can be redefined based on further consideration of geomorphology, biology, and water quality data as is the case for the gages at Rio Grande below Rio Conchos near Presidio and Rio Grande at Johnson's Ranch.

Base Flows

Base flow is the average flow condition for the river. It maintains the ground water table and provides soil moisture, flow variability, diversity of habitats, suitable aquatic habitats, connectivity along channel corridors, and suitable in-channel water quality. Base flow recommendations levels for HEFR analyses use 25th, 50th, and 75th percentiles. These base flow components are separated into dry, average, and wet periods, respectively. HEFR divides these components based on reservoir capacity. The percentile values provide variability within and between years in base flow conditions and vary by season.

High Flow Pulses

High flow pulses provide a short duration, high flow increment. They benefit the geomorphology of streams by transporting sediment downstream, preventing the encroachment of riparian vegetation, and rejuvenating habitat. They also provide recruitment events and purges for organisms, connectivity to near-channel water bodies, and restoration of in-channel water quality after low flow periods.

High flow pulses in HEFR were divided into frequencies. This approach defines the high flow pulse episodic events by evaluating the duration (days), volume (acre-ft), and peak flow (ft^3/s). The URG BBEST decided on five sets of frequencies for high flow pulses: 1 per 2 years, 1 per year, 1 per 2 seasons, 1 per season, and 2 per season. Not all sets of frequencies were used for environmental flow recommendations, and those instances are fully described in Section 4.

In some cases, it is difficult for IHA hydrographic separation method to distinguish multiple episodic events. If flow remains above the 75^{th} percentile for all flows or if flow from a storm event decreases sharply and abruptly increases from a subsequent storm event, IHA is unable to distinguish the two events. However, HEFR is able to make the distinction using the multipeaks multiplier option. It is designed to split the long high flow pulses into multiple discrete episodic events for statistical calculations. This setting measures any sharp increase in flow, greater than 50% of the flow, directly after an episodic event, so it causes the termination of the first episodic event and the initiation of the new episodic event. The multipeaks multiplier option was set at 2.

Overbank Flows

Overbank flows, a sub-set of high flow pulses, were created for infrequent elevated flows that exceed the channel capacity. They provide lateral channel movement, floodplain maintenance, recharge of floodplain water tables, formation of new habitats, distribution of organic material into the channel, deposition of nutrients in the floodplain, new life phase cues for organisms, diversity of riparian vegetation, conditions for seedling development, connectivity to floodplain, and restoration of water quality to floodplain waters. Overbank flow frequencies are set at 1 per 5 years for all HEFR analyses. The multipeaks multiplier was also set at 2.

3.3.2 Seasons

An integral part of base flow separation for HEFR is defining the seasonal variations. West Texas differs from the rest of the state because of the arid climate; therefore, seasons were defined accordingly. HEFR analyses were analyzed for three seasons: 1) winter months (November – February) when stream flow is typically on a declining trajectory following the monsoonal high flows, and when few precipitation inputs occur, 2) Spring (March – June) when stream flow is often at its lowest levels, but which also overlaps with the historic spring snowmelt flows from the upper Rio Grande, 3) Monsoon season (July – October) when stream flow is high due to the accumulation of water from changes in atmospheric circulation and precipitation.

3.3.3 Period of Record

HEFR results can change significantly if separate time frames are used for the analyses. The URG BBEST chose the period of record for each gage based on careful consideration of historical impacts such as upstream impoundments, human interactions, biology, and climate variability. **Table 3.3-1** describes the historical data analyzed by HEFR for each stream flow gage. A more in-depth discussion of the period of record chosen for the Rio Grande gages is given in sections 3.6.1.2.

Table 3.3-1. Streamflow gage period of record.

Sub-Basin	Site Name	Period of Record
Rio Grande	Alamito Creek	1/1/1932 to 12/31/2009
Rio Grande	Rio Grande below Rio Conchos near Presidio	1/1/1901 to 2/28/1914 and 3/1/1931 to 12/31/1967
Rio Grande	Terlingua Creek	1/1/1932 to 12/31/2009
Rio Grande	Rio Grande at Johnson's Ranch	1/1/1936 to 12/31/1967
Rio Grande	Rio Grande at Foster's Weir	1/1/1962 to 12/31/2009
Pecos River	Pecos River near Orla	1/1/1938 to 12/31/2009
Pecos River	Pecos River near Pecos	1/1/1902 to 12/31/1935
Pecos River	Pecos River near Girvin	1/1/1939 to 12/31/2011
Pecos River	Independence Creek near Sheffield	1/1/1975 to 6/30/1985 and 7/1/2000 to 12/31/2009
Pecos River	Pecos River near Langtry	1/1/1967 to 12/31/2010
Devils River	Devils River near Juno	1/1/1936 to 2/28/1949 and 3/1/1931 to 12/31/1972
Devils River	Devils River at Pafford's Crossing	1/1/1960 to 12/31/2009

3.4 Biological Overlay Methods

There are multiple aspects of the relationships of Upper Rio Grande basin flow regimes to the biology and ecology of its rivers. These include dependencies of instream, riparian and floodplain biological communities to subsistence, base, high flow pulses and overbank flows. Many of these key functions and their relationships to the various environmental flow components are outlined in **Table 3.1-1**. These relationships also vary among the three Upper Rio Grande sub-basins and the specific approaches to describing them and utilizing available information in a biological overlay are described in sub-basin specific sections below (Section 3.6.3 Rio Grande sub-basin, Section 3.7.3 Pecos River sub-basin and Section 3.8.3 Devils River sub-basin). We also include recommendations in Section 5 on adaptive management for additional biological overlay items that we were not able to accomplish with available time and data.

3.4.1 Fishes of the Upper Rio Grande Basin and Instream Habitat Modeling in the Pecos and Devils River Sub-basins

One important aspect of the flow biology of Upper Rio Grande Basin rivers is the maintenance of instream habitats for fishes, primarily by base flows and subsistence flows. This is an important factor for all rivers of the basin, but particularly with the ground water fed streams of the Pecos and Devils River sub-basins. To ensure that we make flow recommendations that would be expected to maintain sufficient instream habitat for these locations, we modeled flow-habitat relationships using available fish habitat utilization data and river cross-section data gathered as part of the BBEST process. This section outlines the methods used to accomplish this, including compiling a list of Rio Grande basin fishes, selecting focal species for habitat analysis and our modeling approach and methods.

A fish species list for the upper Rio Grande Basin was compiled using literature (Hoagstrom 2003, Kollaus and Bonner 2012, Harrell 1978, Cantu and Winemiller 1997, Suttkus and Jones 2006, Valdes Cantu and Winemiller 1997, Bonner et al. 2005, Watson 2006, Moring 2005), the Fishes of Texas Database (vouchered museum collections; http://www.fishesoftexas.org/about), existing taxonomic works (Texas Freshwater Fishes, http://www.bio.txstate.edu/~tbonner/txfishes/), and TPWD collections (Garrett 2000-2004, Bean 2012). After correcting for taxonomic synonyms, a total of 73 fish species (54 for the Rio Grande, 50 for the Pecos and 45 for the Devils) were recorded for the basin from these sources (**Table 3.4-1**). Native status and distribution is difficult to determine for many species; presumed native status is noted for each species in each of the three upper Rio Grande sub-basins.

Table 3.4-1. Fish species list for the Upper Rio Grande Basin BBEST area. shown are the sub-basins in which each species occurs; with each species noted as Native or Introduced in the indicated sub-basin. Focal species for flow-habitat modeling (see text for description) are in bold. Et = extirpated from Texas, E = presumed extinct and R=reintroduced.

Scientific name	Common name	Rio Grande	Pecos River	Devils River
Scaphirhynchus platorynchus	Shovelnose Sturgeon	Native-Et		
Atractosteus spatula	Alligator Gar	Native-Et	Native	Native
Lepisosteus oculatus	Spotted Gar	Native	Native	Native
Lepisosteus osseus	Longnose Gar	Native	Native	Native
Anguilla rostrata	American eel	Native-Et	Native-Et	Native-Et
Dorosoma cepedianum	Gizzard Shad	Native	Native	Native
Dorosoma petenense	Threadfin Shad	Introduced		Introduced
Campostoma anomalum	Central Stoneroller		Native	Native
Campostoma ornatum	Mexican Stoneroller	Native		
Cyprinella lutrensis	Red Shiner	Native	Native	

Scientific name	Common name	Rio Grande	Pecos River	Devils River
Cyprinella lutrensis blairi	Maravillas Red Shiner	Native-E		
Cyprinella proserpina	**Proserpine Shiner**		Native	Native
Cyprinella venusta	Blacktail Shiner	Introduced	Introduced	Native
Cyprinus carpio	Common Carp	Introduced	Introduced	Introduced
Dionda argentosa	**Manantial Roundnose Minnow**		Native	Native
Dionda diaboli	**Devils River Minnow**			Native
Dionda episcopa	Roundnose Minnnow	Native		
Hybognathus amarus	Rio Grande Silvery Minnow	Native-R	Native-Et	
Macrhybopsis aestivalis	Speckled Chub	Native	Native	
Notropis amabilis	**Texas Shiner**		Native	Native
Notropis braytoni	**Tamaulipas Shiner**	Native	Native	
Notropis buchanani	Ghost Shiner		Native	
Notropis chihuahua	Chihuahua Shiner	Native		
Notropis jemezanus	Rio Grande Shiner	Native	Native	
Notropis orca	Phantom Shiner	Native-E	Native-E	
Notropis simus pecosensis	Pecos Bluntnose Shiner		Native-Et	
Notropis simus simus	Bluntnose Shiner	Native-E		
Notropis stramineus	**Sand Shiner**		Native	Native
Pimephales promelas	Fathead Minnow	Introduced	Introduced	
Pimephales vigilax	Bullhead Minnow	Introduced	Native	Native
Rhinichthys cataractae	Longnose Dace	Native		
Carpiodes carpio	River Carpsucker	Native	Native	Native
Cycleptus elongatus	Blue Sucker	Native	Native	
Ictiobus bubalus	Smallmouth Buffalo	Native	Native	Native
Ictiobus niger	Black Buffalo	Introduced		
Moxostoma austrinum	West Mexican Redhorse	Native		
Moxostoma congestum	**Gray Redhorse**	Native	Native	Native
Astyanax mexicanus	**Mexican Tetra**	Native	Native	Native
Ameiurus melas	Black Bullhead			Native
Ictalurus furcatus	Blue Catfish	Native	Native	Native
Ictalurus lupus	Headwater Catfish	Native-Et	Native	Native
Ictalurus punctatus	Channel Catfish	Native	Native	Native
Ictalurus sp.	Chihuahua catfish	Native		
Pylodictis olivaris	Flathead Catfish	Native	Native	Native
Menidia beryllina	Inland Silverside	Introduced	Introduced	Introduced
Fundulus grandis	Gulf Killifish		Introduced	
Fundulus zebrinus	Plains Killifish	Introduced	Native	
Lucania parva	Rainwater Killifish		Native	
Gambusia affinis	Western Mosquitofish	Native	Native	Native
Gambusia amistadensis	Amistad Gambusia	Native-E		
Gambusia gaigei	Big Bend Gambusia	Native		
Gambusia geiseri	Largespring Gambusia		Introduced	Introduced
Gambusia senilis	Blotched Gambusia			Native-Et
Gambusia speciosa	Tex-Mex Gambusia			Native
Cyprinodon eximius	Conchos Pupfish	Native		Native

Scientific name	Common name	Rio Grande	Pecos River	Devils River
Cyprinodon pecosensis	Pecos Pupfish		Native	
Cyprinodon variegatus	Sheepshead Minnow		Introduced	
Morone chrysops	White Bass	Introduced		Introduced
Morone saxatilis	Striped Bass	Introduced		Introduced
Lepomis auritus	Redbreast Sunfish		Introduced	Introduced
Lepomis cyanellus	Green Sunfish	Native	Native	Native
Lepomis gulosus	Warmouth	Native	Native	Native
Lepomis macrochirus	Bluegill	Native	Native	Native
Lepomis megalotis	**Longear Sunfish**	Native	Native	Native
Lepomis microlophus	Redear Sunfish	Introduced		Introduced
Lepomis miniatus	Redspotted Sunfish			Native
Micropterus dolomieu	Smallmouth Bass	Introduced		Introduced
Micropterus salmoides	**Largemouth Bass**	Native	Native	Native
Pomoxis annularis	White Crappie		Introduced	
Etheostoma grahami	**Rio Grande Darter**	Native	Native	Native
Aplodinotus grunniens	Freshwater Drum	Native	Native	Native
Cichlasoma cyanoguttatum	**Rio Grande Cichlid**	Native	Native	Native
Oreochromis aureus	Blue Tilapia	Introduced	Introduced	Introduced
	Total Introduced	13	10	10
	Total Native, Extant	32	36	33
	Total Native, Extinct	4	1	0
	Total Native, Extirpated	4	3	2
	Reintroduced	1	0	0
	Total	**54**	**50**	**45**

3.4.1.1 Focal Fish Species Selection

One key decision point discussed by the BBEST 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 highly diverse in upper Rio Grande basin streams 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 therefore 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 and experts from TPWD and Texas State University evaluated and selected candidate focal species such that several different habitat types were represented, most habitat types were represented by multiple species, and the diversity of life-history variation in fish species was well represented. We selected 10 focal species for each of our habitat modeling sites (our approach to site selection is described below in Section 3.4.1.3), though the species were not the same across sites (**Table 3.4-2**). **Table 3.4-2** indicates the habitat usage of each selected focal species; we included at least two species with a primary or secondary preference for each mesohabitat type. 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.

All of the selected focal species are consistent components of the basin's fauna and encompass the key ecological and life-history gradients present at the three sites identified for analyses. Some species of ecological significance such as Conchos pupfish (*Cyprinodon eximius*) at the Devils River and various *Gambusia* species at each site were not included in this analysis because they are not highly flow-dependent, at least in terms of habitat parameters (depth, velocity) that our modeling approach analyzes. It is also important to note that other species of ecological importance were excluded when sufficient data on habitat affinities were not available. The most notable species in this category is headwater catfish (*Ictalurus lupus*) which does have habitat flow dependencies, but for which data are limited primarily because of unknown genetic purity of specimens collected in habitat studies though we were able to include it for one of the three sites.

Table 3.4-2. Focal species for flow-habitat modeling, which sites they are focal species at and their mesohabitat affinities. Primary and secondary mesohabitat preferences are indicated by large X's and dark shading and small x's and light shading, respectively.

Focal Species	Devils	Indy	Pecos	Riffle	Shallow Run	Deep Run	Shallow Pool	Deep Pool
Manantial roundnose minnow	Yes	Yes	Yes	x	X	x		
Devils river minnow	Yes					X		
Proserpine shiner	Yes	Yes	Yes	x	X	x		
Texas shiner	Yes	Yes	Yes		x	X	x	
Tamaulipas shiner			Yes		X	x		
Sand shiner	Yes	Yes			X	X	X	
Headwater catfish		Yes				X	x	x
Gray redhorse	Yes	Yes	Yes			X	x	x
Mexican tetra	Yes	Yes	Yes		X	X		
Largemouth bass	Yes	Yes	Yes			x	x	X
Longear sunfish	Yes	Yes	Yes		x	x	X	x
Rio Grande darter	Yes	Yes	Yes	X	X			
Rio Grande cichlid	Yes	Yes	Yes					X

3.4.1.2 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. Datasets utilized were Kollaus and Bonner (2012) for the Devils River, Bean (2012) for the Devils River and lower Pecos River, and Watson (2006) for Independence Creek. We also used data for gray redhorse (*Moxostoma congestum*) from the Blanco River (Bean et al. 2007) because sufficient data were not available from our sites and the Blanco River was judged to be the river most similar to our sites that had additional data available. We considered using a site-specific approach to developing HSC's, i.e., develop separate HSC's for each species at each site using only habitat utilization data from that site. However, we decided to develop one set of HSC's for each species using all data from the three sites due to concerns about site-specific data from the lower Pecos River not being from the same site as the field cross-section measurements and the desire to have the same approach at each site (i.e., not doing site-specific at only two of the three sites). As mentioned above, we also needed to add additional data for gray redhorse to have a sufficient dataset to develop HSC's. This was the only species for which we used data outside of the three sites and outside of the upper Rio Grande basin.

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%, 75 %, 90 %, and 95 % of the data at the 0.95 confidence level. Tolerance limits for the central 50 % 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 % tolerance limits and the 75 % tolerance limits was given a suitability of 0.5. Data between the 75 % tolerance limits and the 90 % tolerance limits was given a suitability of 0.2, and the data between the 90 % tolerance limits and the 95 % tolerance limits received a suitability of 0.1. data points falling outside the 95 % tolerance limits were considered outliers and given a suitability of zero.

BBEST members, agency staff, other experts and our contractor then reviewed and refined the initial NPTL results to adjust for bias and other factors affecting the habitat utilization data. 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., largemouth bass) we extended the range of 0.5 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 riffle-oriented species such as Rio Grande darter (*Etheostoma grahami*) silt was given a suitability of 0. Final HSC's for all focal species are in **Appendix 3.4**.

3.4.1.3 Fish Habitat Availability and Suitability Modeling

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

1. Do the hydrology-based flow regime recommendations maintain sufficient instream habitat quality, quantity and diversity that provide a sound ecological environment?
2. If they do not, what aspects of the flow regime need to be adjusted or modified to recommend flows that will maintain instream habitats?
3. Does the flow-habitat analysis provide any justification for simplifying the flow regime (i.e., reducing number of base flow tiers) or provide any reason not to simplify when there are other reasons to consider simplification?

The focus of this assessment was amount and quality of habitat provided during base and subsistence flows. 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 HEFR outputs). Ultimately, we did use the analysis to modify some aspects of the HEFR-derived flow recommendations. Also, one of our three sites did not have a sufficient period of record for a rigorous HEFR run, so we used the habitat modeling along with some general hydrology analysis to generate the base flow portion of the flow regime for this site.

Throughout this section, we frequently refer the reader to **Appendix 3.4** which is the final report from our contractor (Joe Trungale, Trungale Engineering and Science) 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 analysis subsequent to the report and modifications to HEFR-derived flow recommendations.

<u>Site Selection</u>

We selected three sites for analysis, the Devils River near Juno, the Pecos River at Brotherton Ranch near Pandale and Independence Creek near Sheffield. These three sites were selected for three primary factors: 1) these streams are primarily ground water-fed streams where instream habitats maintained by baseflow are of primary importance to maintaining a sound ecological environment, 2) there were site-specific habitat utilization data available from these sites, and 3) we had access at these three sites to take field measurements required as input for the habitat models. No sites in the Rio Grande sub-basin were included in this analysis either because this modeling approach is not the best method to model habitat due to the continually shifting nature of the river channel (Rio Grande mainstem sites) or because a combination of lack of fish habitat utilization data and unsure access (tributary sites). However, there is an ongoing habitat study utilizing a different approach on the mainstem of the Rio Grande (Bruce Moring, U.S. Geological Survey) focused on Rio Grande silvery minnow and we comment on preliminary results of this study in the Rio Grande sub-basin section.

<u>Modeling Method</u>

We did not have previous habitat modeling or hydraulic models for the upper Rio Grande 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 subcontract the model development. We decided to use a modified PHabSim method (see **Appendix 3.4**). 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.

<u>Field Work</u>

The field data on cross-sections were gathered by staff of the TPWD River Studies Program, TWDB and Sul Ross State University. 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

It was not possible to get multiple repeated field measurements of hydrology and hydraulics to strengthen the stage-discharge rating and the hydraulics model due to time limitations. Obtaining additional sets of field measurements of hydraulics should be a priority for adaptive management (see Section 5) 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 3.4**. 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 3.4** 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 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 analysis for all species at all cross-sections and 3 subsets: riffle, run, and pool. For evaluation and refinement of the flow regimes we used both the totals for all cross-sections and subsets, with emphasis on the riffle and run subsets. **Table 3.4-3** indicates which cross-section subsets were utilized for decision-making for each focal species. For species with multiple subsets indicated, the large X's indicate which cross-section subsets were emphasized.

Table 3.4-3. Focal species for flow-habitat modeling and the cross-section subsets for analysis and decision-making.

Focal Species	Riffle	Run	Pool
Manantial roundnose minnow	X	x	
Devils river minnow		X	
Proserpine shiner	X	x	
Texas shiner		X	
Tamaulipas shiner	x	X	
Sand shiner		x	X
Headwater catfish		X	
Gray redhorse		X	
Mexican tetra		x	X
Largemouth bass			X
Longear sunfish			X
Rio Grande darter	X	x	
Rio Grande cichlid			X

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 used both WUA and percent of maximum WUA, but used percent of maximum WUA to make decisions about maintenance of suitable habitat. 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 decision was to include all of the flows that could be characterized as 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. These flows were 172 ft^3/s for the Devils River near Juno and 52 ft^3/s for Independence Creek near Sheffield. Because the Pecos River at Brotherton Ranch near Pandale did not have HEFR flows, we could not use this approach to set its upper bound. Because the magnitude of flows at this site is roughly similar to the Devils River near Juno, we also used the 172 ft^3/s number as the upper end for the Pecos River. These flows correspond approximately to the 95th, 98th and 97th percentiles of flow for the Devils River, Independence Creek and Pecos River, respectively. The hydrographic separation in the 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 exceedance 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 3 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, 0.5-0.75 suitable, and 0.75-1.0 optimal to evaluate potential minimum thresholds of 0.5 and 0.75. A variety of minimum quality thresholds have been utilized by other scientists. The 0.5 and 0.75 (or the very similar 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 an example plot of four ranges of habitat quality (<0.5, 0.5-0.75, >0.75 and total) for one selected focal species is included in each site's results description. Tables summarizing the analysis using the 0.5 threshold are presented in Sections 3.7.3 and 3.8.3. 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 %, 70 %, 75 % and 90 %. We decided to use 75 % to evaluate each focal species' habitat and both 75 and 90 % to evaluate species of conservation concern. We designated Devils River minnow, manantial roundnose minnow, Proserpine shiner, Tamaulipas shiner, headwater catfish and Rio Grande darter as the species conservation concern for this analysis. They were chosen because they are federal or state listed (threatened or endangered) species and/or (if not listed) they are species of some conservation concern where maintenance of flow-dependent habitat plays a particularly important role in the species conservation. Specifics of the criteria were as follows:

- For species of conservation concern listed above: the Base-Low range needed to maintain at least 75 % in at least one season in the cross-section subset(s) representing the species' primary habitat preference(s) and the Base-Medium needed to maintain at least 90 %, also in the cross-section subset(s) representing the species' primary habitat preference(s).
- For other species: the Base-Medium numbers needed to maintain at least 75 % in at least one season in the cross-section subset(s) representing the species' primary habitat preference(s).

The habitat preferences used to define the focal cross-section subsets for each species are presented in **Table 3.4-3**. Because one of the functions of subsistence flows is to provide at least a minimal amount of instream habitat we also applied a 20 % of maximum threshold for subsistence flows.

Time Series Analysis and Attainment Frequencies

We used the historical record of flows at the three habitat modeling sites and 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 derive historical attainment frequencies of the 75 and/or 90 % of maximum WUA thresholds for each species at each site. While the BBEST did not also use this analysis to examine example flow regime applications, this could be used by the BBASC, TCEQ or other decision-makers to evaluate the effects of potential flow standards and/or water management decisions. For example, one might determine that a given reduction (e.g., 10%) in the frequency of attaining our minimum thresholds due to a management scenario being considered would be the maximum sustainable to maintain a sound ecological environment. We present this analysis in the form of both graphs and tables for all three sites, but it is noted that the numbers are based on a very short period of record (5 years) for the Pecos site.

In generation of habitat attainment frequencies we only used the range of flows for which habitat modeling was done (i.e. 1 to 500 ft^3/s). 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 500 ft^3/s 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 500 ft^3/s and not for the entire period of record.

Uncertainty and limitations of flow-habitat analysis

There are several areas of uncertainty in this flow-habitat analysis which affect its strength and may limit the conclusions that can be drawn from this assessment. One primary area of uncertainty that should be addressed in adaptive management is the modeling of hydraulics. Due to low flow conditions and the short timeline to complete this work, we only have field data on depth and velocity from a single low flow between our subsistence and base flow recommendations. As a result, our contractor was not able to evaluate the accuracy of the model's extrapolations to higher flows. More measurements of discharge and water surface elevation at our sites would also allow development of site-specific stage-discharge ratings. This analysis relied on USGS ratings from the gage locations which were proximal to the habitat study sites. However, the assumption that channel geometry and pattern of response of water surface elevation to changing flows is a potential source of error and uncertainty and may affect modeling results (see **Appendix 3.4** for more discussion of this issue). A priority adaptive management item would be to obtain more field hydraulics measurements at higher flows, ideally at least in the middle and upper range of base flow recommendations, and to adjust hydraulics models accordingly.

A second area of uncertainty is the development of habitat suitability criteria. We had sufficient habitat data from our sites for most of our focal species. However, we did have some species (e.g., headwater catfish, gray redhorse) with limited data and also did not have data for different life history stages (i.e., juvenile vs. adults). 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 refine the criteria to include multiple life history stages and to include spawning habitats for species with life histories particularly vulnerable to flow alteration. For example, spawning habitats may be of particular concern for some species and for others juveniles and adults use distinctly different habitats.

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.

Another obvious limitation to our analysis is that instream habitats were modeled only for fishes. Additional modeling for mussels, benthic macroinvertebrates or other flow-sensitive biota would strengthen our certainty that our flow recommendations would maintain the full suite of biota and a sound ecological environment. Including other taxa in this analysis would only require gathering habitat utilization data or deriving suitability criteria from published literature.

The transferability of this analysis to other sites in the upper Rio Grande basin cannot be explicitly reviewed because we do not have modeling data for other sites. However, the overall conclusions regarding the maintenance of instream habitats by hydrology-based flow regimes are reasonably consistent across the three study sites (see description of analysis results in Sections 3.6.3 and 3.7.3). This provides some degree of confidence that the hydrology-based flow regimes derived from least altered periods of flow record would also maintain habitats in other sites. An additional work plan item would be to expand this analysis to other sites where maintenance of instream habitats is a primary concern in maintaining a sound ecological environment. This should include consideration of this analysis at Alamito and Terlingua Creeks in the Rio Grande sub-basin and potentially sites in the upper and middle Pecos River.

Results

Site-specific results of flow-habitat analysis are presented and briefly summarized with site-specific conclusions in Sections 3.6.3 for the Pecos River and Independence Creek and in Section 3.7.3 for the Devils River. 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 three seasons) of subsistence flows and the three levels of base flows.

3.5 Water Quality Impairments in the Upper Rio Grande of West Texas

The Texas Commission on Environmental Quality is responsible for assessing water quality for the State's water bodies. Formerly called the *Texas Water Quality Inventory and 303(d) List*, the Texas Integrated Report (IR) describes the status of Texas' surface waters based on data collected during the most recent seven-year period. The Texas IR satisfies the requirements of the Federal CWA Sections 305(b) and 303(d). The TCEQ produces a new report every two years in even-numbered year. The IR identifies water bodies not meeting criteria set by the Texas Surface Water Quality Standards (TSWQS) in support of various designated uses such as aquatic life use, contact recreation, and public water supply (see **Table 3.5-1**). These water bodies are then included in the 303(d) List of Impaired Water Bodies. The Texas IR must be approved by the EPA before it is final.

To address surface waters not meeting water quality standards, each water body on the 303(d) List is placed into one of three subcategories that define specific management strategies. The three categories are,

- Category 5a – A Total Maximum Daily Load (TMDL) is underway, scheduled, or will be scheduled.
- Category 5B – A review of the TSWQS for the water body will be conducted before a TMDL is scheduled.
- Category 5c – Additional data and information will be collected before a TMDL is schedule.

The 2010 Texas 303(d) List is divided by river basin and stream segments. Given that each basin or segment flows through a unique landscape, water quality standards vary accordingly. For instance, the Pecos River in Texas traverses the Rustler Formation which formed in an evaporative basin and consequently has higher chloride and sulfate concentrations due to natural inputs. **Table 3.5-1** summarizes water quality standards and designated uses for each segment in the BBEST Rio Grande Instream Flow Study area.

Table 3.5-1. Water quality standards and designated uses for segments in the Upper Rio Grande

Segment Name	Segment Number	Designated Uses	TDS (mg/L)	Chloride (mg/L)	Sulfate (mg/L)	DO (mgL)	Water Temperature (°F)	Indicator Bacteria (#/100 mL) Geomean
Upper Pecos	2311	High ALU; PCR	15,000	7000	3500	5.0/3.0 (5c)	92	Enterococcus 33
Lower Pecos	2310	High ALU; PS; PCR	4000	1700	1000	5.0/3.0	92	*E. coli* 126
Devils River	2309	Exceptional ALU; PS; PCR	300	50	50	6.0/4.0	90	*E. coli* 126
Upper Rio Grande	2307	High ALU; PS; PCR	1500 (5c)	300 (5c)	550	5.0/3.0	93	*E. coli* 126 (5c)
Middle Rio Grande	2306	High ALU; PS; PCR	1550 (5c)	300 (5c)	570 (5c)	5.0/3.0	93	*E. coli* 126
Designated Uses:	ALU= aquatic life use (24-hour average/minimum); PS= public water supply; PCR=primary contact recreation							

3.6 Rio Grande

3.6.1 Hydrology-Based Environmental Flow Regimes

For the Rio Grande below the Rio Conchos, the Rio Grande at Johnson's Ranch, and the Rio Grande at Foster's Weir, we performed HEFR analyses to help guide our understanding of the historic flow regime. However, we employ a number of other hydrologic analyses to describe hydrologic processes that are overlooked by HEFR analyses. For the Rio Grande, high flow pulses and overbank flows are specifically important because these are the flows that guide the direction and rate of geomorphic change. Base flows and subsistence flows are also key features of the flow regime because these flows directly relate to the available aquatic habitat and water quality. Thus, the Rio Grande environmental flow recommendations include hydrologic analysis, a geomorphology and water quality overlay. The geomorphology overlay relates to the high-flow pulse and overbank flow recommendations, and the water quality overlay informs our base flow and subsistence flow recommendations. There are also some scientific data pertaining to aquatic habitat for native fish species, however, these studies are ongoing and thus do little to inform and decisions related to adjustments to HEFR outputs. Biological surveys of fish and mussels populations can also assist with determinations of ecological soundness.

For Alamito and Terlingua Creeks, HEFR analyses were performed to understand the variability between low flows (base and subsistence) and high flows (high flow pulses and overbank flows) and the magnitude of the high flow pulses and overbank flows. Little is known about the physical, biological, or chemical processes that occur in these creeks, therefore, we rely specifically on HEFR analyses for environmental flow recommendations. It must be noted here that the HEFR prescribed "overbank flow" term is not directly applicable to Alamito and Terlingua Creeks. These creeks are braided, and thus, channel bank delineation is a subjective process, and specifying discharges that inundate these banks is difficult. Thus, in the context of these creeks, "overbank flow" simply refers to large flows of a 1-5 year recurrence interval.

3.6.1.1 <u>Instream flow regimes and flow regime components</u>

An initial flow table describing instream flow components was presented in **Table 3.1-1**. However, flow components of the Rio Grande can be further classified based on the discharge, duration, source area of runoff, and the geomorphic processes that occur. Thus, modifications to the general flow component table (**Table 3.1-1**) based specifically for the Rio Grande are described below and summarized in **Table 3.6-1**.

1) Subsistence flows – Minimum stream flow to maintain tolerable water quality. Subsistence flows are generally maintained by ground water in puts in the lower reach. In the upper reach, subsistence flows are dependent on return flows.
2) Base flows – long duration low flows with discharge maintaining either a flat or gently sloping trajectory. Base flows are generally driven by a combination of ground water inputs and irrigation or municipal return flow from the lower Rio Conchos, or the Presidio irrigation district. Base flows transport little or no sediment.
3) High flow dam releases (HFDR) – HFDR are generally higher than 350 ft^3/s, most often in the range of 1,500 to 5,000 ft^3/s and occur when water is released from Luis L. Leon Dam on the Rio Conchos. HFDR can occur any time of the year and are generally for the sole purpose of delivering water to Amistad Reservoir. HFDR occasionally occur, however, when reservoir storage needs to be created behind Luis L. Leon Dam in anticipation of high flow inputs from the upper Rio Conchos basin. Dam releases occur for long durations, generally 5 days or more, and rarely overtop the banks of the channel on the Rio Grande. These floods transport fine sediment

(Dean et al., 2011b, unpublished data), yet little data exists as to whether these flows are capable of reorganizing gravel deposits on the channel bed.

4) Flash floods – These floods are short duration and variable in discharge. Discharge may be anywhere between 200 and 20,000 ft^3/s or more, and these floods last from less than 12 hours to a few days. Flash floods generally occur on ephemeral tributaries during monsoon season, and contribute a large proportion of sediment to the Rio Grande. Because of the short duration and high sediment loads of flash floods, they are ineffective at eroding banks and reorganizing material on the channel bed, and instead, cause channel narrowing and vertical floodplain accretion because sediment is deposited in low-velocity areas along the channel margins, on top of channel bars, or on the floodplain (Dean and Schmidt, 2011; Dean et al., 2011a).
5) Channel resetting floods – These flows occur during the monsoon season and originate in the Rio Conchos watershed, are greater than 35,000 ft^3/s, and occur for longer than a week in duration. These floods were common in the early part of the 20^{th} century, however, now they only occur when tropical storms in the Sierra Madre Occidental deliver large amounts of precipitation to the Rio Conchos watershed and overwhelm the capacity of Rio Conchos reservoirs. Since the 1950s, these floods have only occurred 5 times (1958, 1978, 1990, 1991, and 2008) and are referred to as "channel resetting" floods because they erode accumulating sediment, uproot channel margin vegetation, and cause channel widening throughout the length of the river corridor

The flows that constitute the present flow regime described above have shown to be ineffective at maintaining a sound ecological environment above La Linda, MX because this regime has failed to maintain key habitat such as gravel bars free of fine sediment, backwaters and side-channels, and has failed to sufficiently transport enough sediment downstream to prevent progressive channel narrowing. The primary cause of this is because there has been a shift in the ratio of large, long-duration floods that move sediment and erode accumulating sediment, to short-duration flash floods that contribute sediment and cause channel narrowing and vertical floodplain accretion. The frequency of short-duration flash floods is governed by the storm frequency over ephemeral watersheds, and is thus a given boundary condition of both the present and the past stream flow regimes. The frequency of long-duration high flows (i.e. HFDR and channel-resetting floods) is also determined by climatic conditions throughout the basin, but it is also governed by the degree of water impoundment and irrigation diversions upstream. Given that long-duration high flows also constitute the portion of the present flow regime that is known to provide key geomorphic and ecological services, such as sediment transport and habitat rejuvenation, a large portion of our environmental flow analyses for the Rio Grande focuses on these types of flows. High flows also promote sound ecological function downstream from La Linda, MX, however, ground water inputs are also an important component to the ecological environment, and thus, the downstream reach will be discussed in a different manner.

HEFR analyses segregate flows into four categories: overbank flows, high flow pulses, base flows, and subsistence flows. For the Rio Grande, subsistence flows and base flows are the same as those described above. High flow pulses and overbank flows, however, include high flow dam releases, flash floods, and channel resetting floods. For the purposes of HEFR analyses in this study, we characterize channel-resetting floods as overbank flows that occur for long durations, and characterize HFDR and flash floods as high flow pulses which may be short or long in duration, yet do not significantly inundate the floodplain. The above flows are summarized in **Table 3.6-1**, which is adapted from the flow component table in Section 3 and specifically tailored to the hydrology of the Rio Grande. This table specifically outlines different types of flow components. Additional discussion of physical processes associated with these flows are included in the geomorphological overlay.

Table 3.6-1. Rio Grande flow regime components, HEFR classifications, and associated riverine processes.

Rio Grande Flow Regime Component	HEFR Classification	Ecologic Processes	Physical Processes	Other Characteristics
Subsistence flows	Subsistence flows	Maintain tolerable water quality, maintain critical habitats, provide longitudinal connectivity	Encroachment of vegetation	
Base flows	Base flows	Provide longitudinal connectivity, allow persistence of isolated low-flow refugia	Maintain soil moisture and ground water table Maintain a diversity of habitats. Little to no sediment transport occurs	Discharge determined by ground water inputs.
High flow dam releases	High-flow pulses	Provide migration and spawning cues for some species, provide access to spawning habitats, support growth, survival, and reproduction of aquatic organisms , reconnect isolated habitats	Evacuate fine sediment (sand, silt, clay) from the channel bed and channel margins, potentially shape physical habitat features on the reach scale	Generally long duration flows that fill a significant portion of the active channel, but are not overbank. Maintain water table levels in adjacent alluvial aquifers.
Flash Floods	High-flow pulses	Serve as recruitment events for organisms; Provide connectivity to near-channel water bodies	Contribute large amounts of fine and coarse sediment. Fine sediment travels for short distances depending on the rate of flow attenuation, and gets deposited on bars and along the channel margins. Coarse sediment (gravel, cobbles) is deposited at tributary mouths which causes aggradation of the channel bed in those localities.	Short duration floods originating in ephemeral tributaries; Episodic in nature and anecdotally associated with fish kills (no investigation of fish kills has been initiated)
Channel resetting floods	Overbank floods	Provide migration and spawning cues, scour vegetation, provide spawning and nursery areas for fish and other biota, provide lateral exchange of organic material and nutrients between river and floodplain, facilitate exchange of nutrients, sediments, organics, and woody debris	Channel widening, channel migrations, bank erosion, floodplain scour, gravel mobility, reorganize reach scale channel features such as bars, riffles, and pools, evacuate fine sediment	Long duration floods that inundate the floodplain and recharge water table in alluvial aquifers. Short duration overbank effects fail to achieve the physical processes described here, and cause channel narrowing and vertical floodplain accretion.

For base-flows and subsistence flows, our environmental flow analyses focus on water quality data and some biological data. The Texas Commission of Environmental Quality recently listed Rio Grande stream segment 2306 (Rio Grande from Presidio to Amistad Reservoir) as impaired for sulfate, total dissolved solids (TDS), and chloride. This listing was determined by averaging all water quality data throughout the reach, even though water quality significantly improves downstream from La Linda, MX. Discussions are currently under way within the TCEQ to split the segment based on water quality differences within the segment.

Investigations to determining the role of ground water in maintaining water quality with in the Rio Grande conducted by the National Park Service and Sul Ross State University show improvements in water quality downstream from Presidio, TX, at low flows, (Bennett and Cutillo, 2008). Biological investigations into associations between algal communities and water quality are congruent with these studies (Porter and Longley,2011) Water quality studies, TCEQ impairment listing show that a sound ecological environment does not exist upstream from La Linda, MX.

HEFR analyses for Alamito and Terlingua Creeks are used for specifying environmental flows for each flow component. There are water quality concerns for both of these creeks pertaining to high mercury levels (Smith et al., 2010), however, much of this mercury is naturally derived from cinnabar deposits at the base of the Del Rio formation. Mercury mining during the 19th and 20th centuries have undoubtedly caused increases in mercury levels found in the creeks, however, there is little information as to how concentrations vary with stream flow or other processes that affect mercury levels in these creeks. Therefore, a water quality overlay is not included, but is discussed in the adaptive management section.

3.6.1.2 Period of Record

Over the last century, there has been a general trend of declining stream flow on the Rio Grande, although this trend was interrupted by large runoff in the 1980s and early 1990s (**Figure 3.6-1**). These general patterns are caused by cyclical climatic periods of wet years and drought, the ever-increasing irrigation withdrawals upstream of this study reach, and the control of flood flow by large dams upstream. The largest dams include La Boquilla Dam (closed 1916), Francisco I. Madera (closed 1947), Luis L. Leon Dam (closed 1967), all on the Rio Conchos, and Elephant Butte Dam on the Rio Grande (closed 1916).

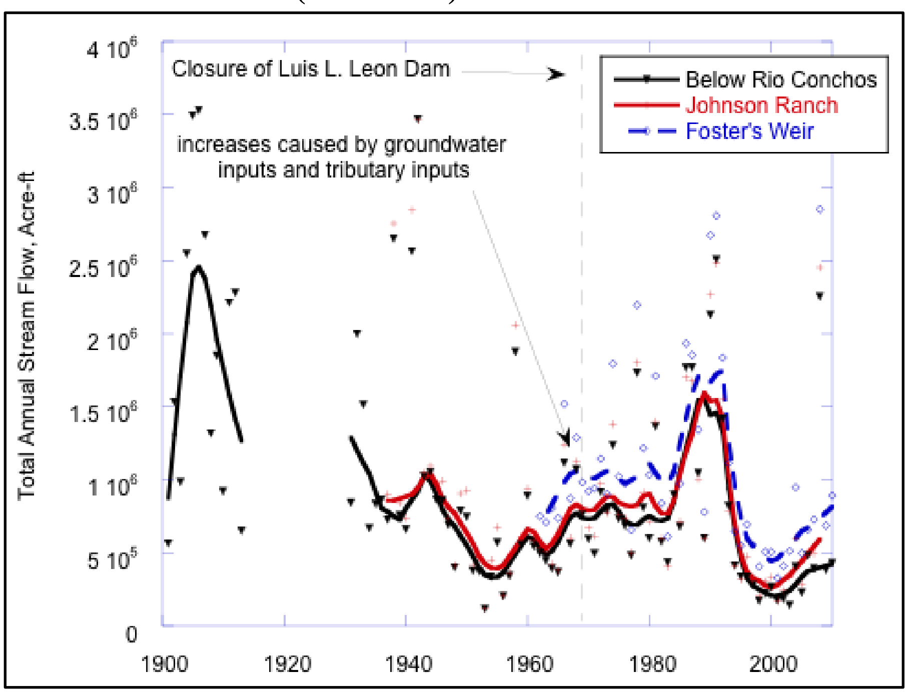


Figure 3.6-1. Total annual stream flow volume for the Rio Grande below the Rio Conchos, Johnson's Ranch, and Foster's weir. 10-year running averages are shown.

The driest periods on record occurred in the late 1940s and 1950s, and the late 1990s and 2000s. Both periods were typified by regional drought, and the later period was additionally affected by withdrawals for irrigated agriculture. The onset of large-scale ecosystem changes began in this initial drought period of the late 1940s and

1950s (Dean and Schmidt, 2011). Total stream flow increased in the 1970s and 1980s, however, the closure of Luis L. Leon Dam in 1967 effectively removed all flood flows originating in the Rio Conchos headwaters from the Rio Grande hydrology. The exceptions were the largest floods occurring during tropical storms when reservoir capacity was exceeded (1978, 1990, 1991, and 2008) (**Figure 3.6-2**). Thus, after the closure of Luis L. Dam, there was a shift in the ratio of large, long-duration floods coming from the Rio Conchos to short-duration flash floods from ephemeral tributaries.

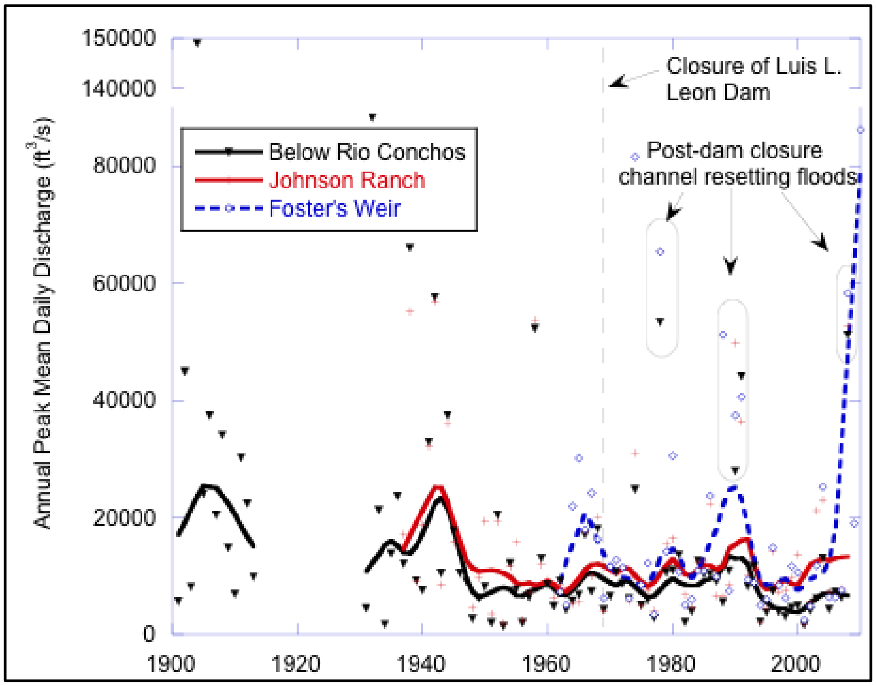


Figure 3.6-2. Annual peak mean daily discharge for the Rio Grande below the Rio Conchos, Johnson Ranch, and Foster's weir. 10-year running averages are shown.

The hydrologic shift in flood source is apparent when flood magnitude and flood duration are analyzed in concert. To investigate this pattern, we calculated the annual cumulative discharge that exceeded 15,467 ft^3/s (i.e. ft^3/s*days >15,467), which is the average annual flood over the period of record for the Rio Grande below the Rio Conchos gage (**Figure 3.6-3**). Thus, small spikes on this graph depict flows that exceeded this threshold for short periods of time, and large spikes depict flows that exceeded this threshold for long periods of time. This graph shows that since the closure of Luis L. Leon Dam, only the largest floods driven by tropical storms in the Rio Conchos basin exceed this threshold for any significant duration. The plot shows that downstream of the confluence of the Rio Conchos, runoff from many ephemeral tributaries can still produce floods that exceed this threshold, although they are short lived. Average floods from ephemeral tributaries in the upper section of the study reach rarely, if ever, exceed the discharge of 15,467 ft^3/s.

Based on the patterns described above, the period of record for HEFR analyses at the below the Rio Conchos gage and the Johnson's Ranch gage consists of all data prior to the closure of Luis L. Leon Dam, in 1967. This period is believed to correspond to the above vision of a sound ecological environment, because it included an ecologic assemblage containing the full suite of native species, and a physical template that consisted of a large width to depth ratio, the presence of numerous in-channel bars, backwaters, and side-channels. All of these geomorphic features are deemed necessary for the survival of the native aquatic species. For the gage at Foster's weir, the entire dataset from 1962 to present was used partly, because there is a lack of data prior to the closure of Luis L. Leon Dam, and partly because ground water inputs and occasional moderate to large floods from tributaries alleviate the problems of fine sediment loading, and water quality that occur in the upstream section of the reach.

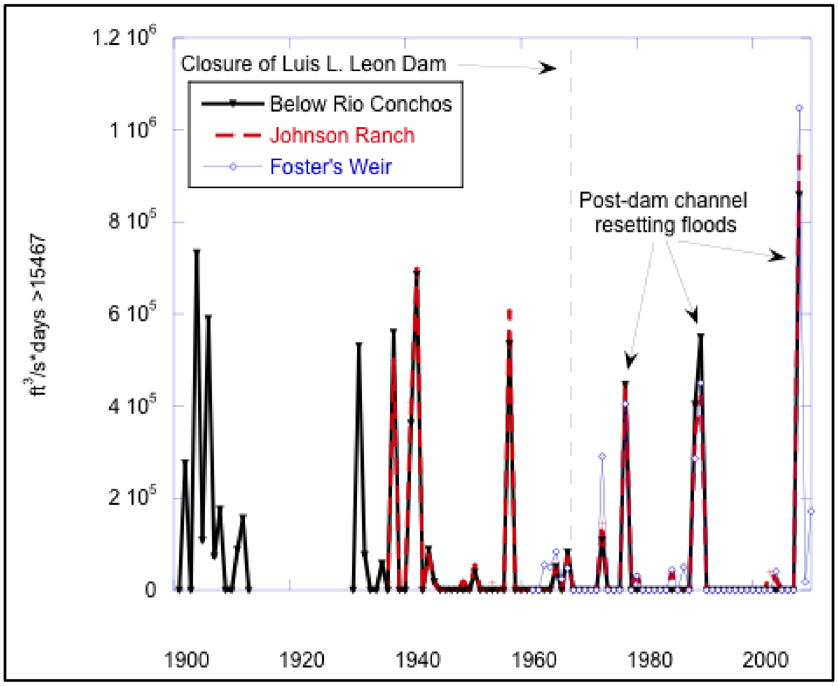


Figure 3.6-3. Plot showing ft³/s days greater than the average annual flood at the Rio Grande below the Rio Conchos of 15,467 ft³/s. This metric combines both flood magnitude and duration. Note that downstream from the Rio Conchos, there are occasional moderate to large floods that occur at the Johnson's Ranch and Foster's weir gage caused by tributary inputs.

HEFR analyses for Alamito and Terlingua Creeks use the entire periods of record, from 1932 to present. Analyses were conducted in this manner because there is little knowledge concerning historical variation or historical anthropogenic impacts to stream flow during this period.

3.6.1.3 <u>HEFR application</u>

HEFR analyses provide a reasonable approach for identifying past hydrologic trends. On dynamic systems where geomorphic and ecologic conditions rapidly change, however, results from HEFR analyses may be unreasonably applied without sound understanding of the physical and ecological processes that occur. For the Rio Grande, we describe the results of the HEFR analyses for overbank and high-flow pulses, and contrast those results with the present understanding of the geomorphic processes that are known to occur. Summaries of the results from the HEFR analyses are shown in **Table 3.6-2**. This table shows the discharge and duration statistics for the below Rio Conchos and Johnson Ranch gages prior-1967, and for the Foster's Weir gage between 1962 and 2010. We also included HEFR analyses for the Johnson Ranch gage between 1980 and 1989, which was a period characterized by high stream flow, and 1992-2007, which is the driest period of record. Additionally, in parentheses, are the 5-year, 2-year, and 1-year discharges and the flow duration calculated from the mean daily discharge data for the same periods. The 5-year, 2-year, and 1-year were calculated using the Weibull plotting position of the annual peak mean daily discharge data. These data are included in **Table 3.6-2** because they provide a means for comparing the HEFR analyses to other simple statistics typically used in hydrologic analyses. The below discussion of HEFR results and additional hydrologic analyses focus on the Rio Grande below the Rio Conchos and Johnson's Ranch gages because these gages exist in a reach deemed unsound. Stream flow is much higher at the Foster's Weir gage because of ground water inputs and additional flash floods from large ephemeral tributaries.

Table 3.6-2. HEFR results for Rio Grande at the below Rio Conchos, Johnson's Ranch, and Foster's Weir gages for selected time periods.

Gage	HEFR Overbank flow, 1 per 5 year (mean daily data comparison)	HEFR high flow pulse, 1 per 2 year (mean daily data comparison)	HEFR high flow pulse 2, 1 per year (mean daily data comparison)
Rio Grande below Rio Conchos (1900-1967-pre-dam)	34,010 ft³/s (32,327)	17,090 ft³/s (10,488)	9,500 ft³/s (1,441)
	21 to 79 days (0.7)	13 to 48 days (8.1)	9 to 31 days (85.3)
Rio Grande below Rio Conchos (1980-1989)	12610 ft³/s (12,164)	10,310 ft³/s (10,312)	8,970 ft³/s (<2,140)
	9 to 69 days (0.2)	7 to 58 days (0.6)	7 to 52 days (62.8)
Rio Grande below Rio Conchos (1992-2007)	9,076 ft³/s (7,881)	7,310 ft³/s (4,738)	5,721 ft³/s (<1,733)
	7 to 41 days (0.5)	6 to 37 days (4.6)	6 to 32 days (20.2)
Rio Grande at Johnson's Ranch (1936-1967 – pre-dam)	30,690 ft³/s (22,521)	15,720 ft³/s (11,737)	9,500 ft³/s (<1,938)
	16 to 57 days (1.5)	10 to 37 days (5.9)	7 to 26 days (46.8)
Rio Grande at Johnson's Ranch (1980-1989 – wet)	18,190 ft³/s (15,327)	12,400 ft³/s (10,128)	9,747 ft³/s (<4,626)
	12 to 86 days (0.4)	9 to 67 days (1.1)	8 to 57 days (12)
Rio Grande at Johnson's Ranch (1992-2007 - dry)	14,270 ft³/s (12,996)	11,160 ft³/s (9,323)	8,052 ft³/s (<1,861)
	6 to 24 days (0.3)	6 to 21 days (1.3)	5 to 17 days (24)
Rio Grande at Foster's Weir (1962-2010)	24,190 ft³/s (25,249)	12,710 ft³/s (10,912)	9,394 ft³/s (<2,458)
	13 to 61 days (0.86)	8 to 38 days (4.3)	6 to 30 days (50.1)
*Note: numbers in parentheses are flood recurrence intervals and flow duration statistics for same periods. Flood statistics are discharges of 5, 2, and 1-year recurrence intervals calculated using the Weibull plotting position for peak mean daily discharges for the indicated periods. Flow duration statistics are in days			

The results of the HEFR analyses show similar findings to those presented in **Figure 3.6-1-Figure 3.6-3**, with significant reductions in stream flow occurring after the closure of Luis L. Leon Dam in the upstream half of the study reach. Even during the wet decade of the 1980s, the 1 per 5 year and 1 per 2 year floods are significantly less than prior to 1967. Comparisons of HEFR results for the periods before 1967 and during 1992-2007 are even more striking. Prior to 1967 at the below Rio Conchos, HEFR analyses show a 1 in 5 year flood to be 34,010 ft³/s , while the 1992 to 2007 1 in 5 year flood was 9,076 ft³/s. At the Johnson Ranch gage, the 1 in 2 year flow was 15,720 ft³/s prior to 1967, with a duration of 10 to 37 days. Between 1992 and 2010, a flow of this magnitude was exceeded just three times, one of which was the 2008 channel-resetting flood. With the exception of the 2008 flood, a flow of 15,720 was only exceeded for a total duration of 3 days during this period.

Comparison of the HEFR analyses and the additional statistics regarding flood flow magnitudes and durations show that HEFR analyses over-predict both the flood magnitude and duration of the overbank and high flow pulses. The greatest differences are for the 1 per year high flow pulses. The HEFR 1 per year pulse if often 4 to 8 times greater than the 1-year recurrence interval flood based on the peak mean annual discharge data. For example, during the driest period of record at the Johnson's Ranch gage (1992-2007), HEFR results show a 1-per year high flow magnitude of 8,052 ft^3/s, whereas the 1-year flood from the peak mean annual discharge data is less than 1,861 ft^3/s. Based on flow duration analyses using the mean daily discharge data, the HEFR 1 per year high flow magnitude of 8,052 ft^3/s only lasted approximately 1.8 days; much smaller than the 5 to 17 days obtained from the HEFR regression statistics. For these reasons, the HEFR results are helpful for understanding historic hydrologic trends, however, we believed that HEFR inaccurately represents some aspects of the high-flow regime.

The difference between the pre-1967 HEFR analyses and flood statistics from the 1992-2007 HEFR results and flood statistics exemplifies the magnitude of hydrologic alteration that has occurred over the last 50 years. Thus, even though the pre-1967 hydrologic data correspond to a sound ecological environment, the simple comparison of the present and past flow regimes highlights that recommending environmental flow targets outlined by the pre-1967 HEFR results is completely unreasonable, and potentially impossible. Instead, the results of the pre-1967 HEFR analyses should be viewed as the flows required for complete geomorphic restoration of the upper Rio Grande. Below we discuss the key physical riverine processes that are understood, and rely heavily upon our geomorphic understanding to guide our environmental flow recommendations for high-flow pulses and overbank flows.

HEFR analyses for Alamito and Terlingua Creeks show that stream flow of Terlingua creek is generally higher than Alamito Creek for all flow components. Subsistence flows for Terlingua Creek range from 1.1 to 1.4 ft^3/s, and are 0.71 ft^3/s for Alamito Creek. The 1 in 5 year flow for Terlingua creek is 5,933 ft^3/s and is 2,469 ft^3/s for Alamito Creek. The 1 in 5 year flow for Terlingua creek is roughly half of the long-term 2 year flood on the Rio Grande.

3.6.2 Water Quality Overlay

The Rio Grande in west Texas is divided into two segments, the Upper Rio Grande, Segment 2307, is from El Paso to the confluence with the Rio Conchos. The Middle Rio Grande runs from the confluence with the Rio Conchos to the upstream end of Amistad Reservoir just below Foster's Weir.

Irrigation withdrawal in the Upper Rio Grande Basin coupled with long-term drought throughout northern Mexico and the southern Rockies has put pressure on an already over-appropriated basin. The end result is increasing dissolved solids concentrations in the Rio Grande above Amistad Reservoir (Segment 2306). Spring-water inflow has maintained reduced TDS concentrations in the lower portion of Segment 2306 (Lower Canyons Reach). However, the lack of consistent flow in the upper half of Segment 2306 (Park Reach) and input from Segment 2307 and possibly the Rio Conchos has resulted in increasing and variable dissolved solids concentrations. Segment 2307 has been listed as impaired for bacteria, chloride, and total dissolved solids since 1996.

Historically, Segment 2306 has fully supported the assigned water quality standards for TDS, chloride, and sulfate because of spring flow. The TSWQS require the averaging of chloride, sulfate, and TDS data across the entire segment. Higher salinity levels in the upper portion are masked when data from the lower portion of Segment 2306 are included in the average. However, an increasing trend in dissolved solids concentrations has resulted in this water body failing to attain the water quality standards for TDS, chloride, and sulfate for the first time. Segment 2306 was included on the 2010 303(d) Impaired Waters List for chloride, sulfate and total dissolved solids in 2010.

For this reason the TCEQ is currently considering creating a new stream segment in the TSWQS to better reflect water quality and flow in these two stream reaches. The data review is still ongoing. The recommended segment boundaries are,

- “Rio Conchos confluence in Presidio County to Tornillo Creek in Brewster County" — flow is highly dependent on dam releases and experiences periods of very low flow.
- “From Tornillo Creek in Brewster County to Ramsey Canyon in Val Verde County” —stable base flow is maintained by spring input.

An indication of the potential effects of elevated dissolved solids was observed downstream of Santa Elena Canyon. Several toxicity tests were run on samples collected downstream of Santa Elena Canyon. In 1995, a sample collected by TCEQ downstream of Santa Elena Canyon caused sub-lethal effects on the water flea *Ceriodaphnia dubia*. In 2001-2002 a toxicity project conducted by TCEQ collected four samples at Santa Elena Canyon that also caused sub-lethal effects on *C. dubia*. The suspected cause was elevated dissolved solids but this was not confirmed. This location was also noted in the biological summary as having a benthic community dominated by a single tolerant species of black fly.

Other parameters included in the TSWQS for Segment 2306—pH, temperature, and DO—meet water quality standards and are considered fully supporting in the 2010 Texas IR.

Figure 3.6-4 illustrates a relationship between flow and total dissolved solids for four stations along the Rio Grande. Regression equations best explain the observed variability for the stations below the Rio Conchos and above the reach with significant spring flow. Generally speaking high flows are associated with more dilute waters.

Figure 3.6-5 depicts TDS through time for the same four stations showing an increasing trend. The modeled relationship best explains the variability for the stations below the Rio Conchos and above the spring fed reach. For the upper three stations, TDS concentrations are about the standard.

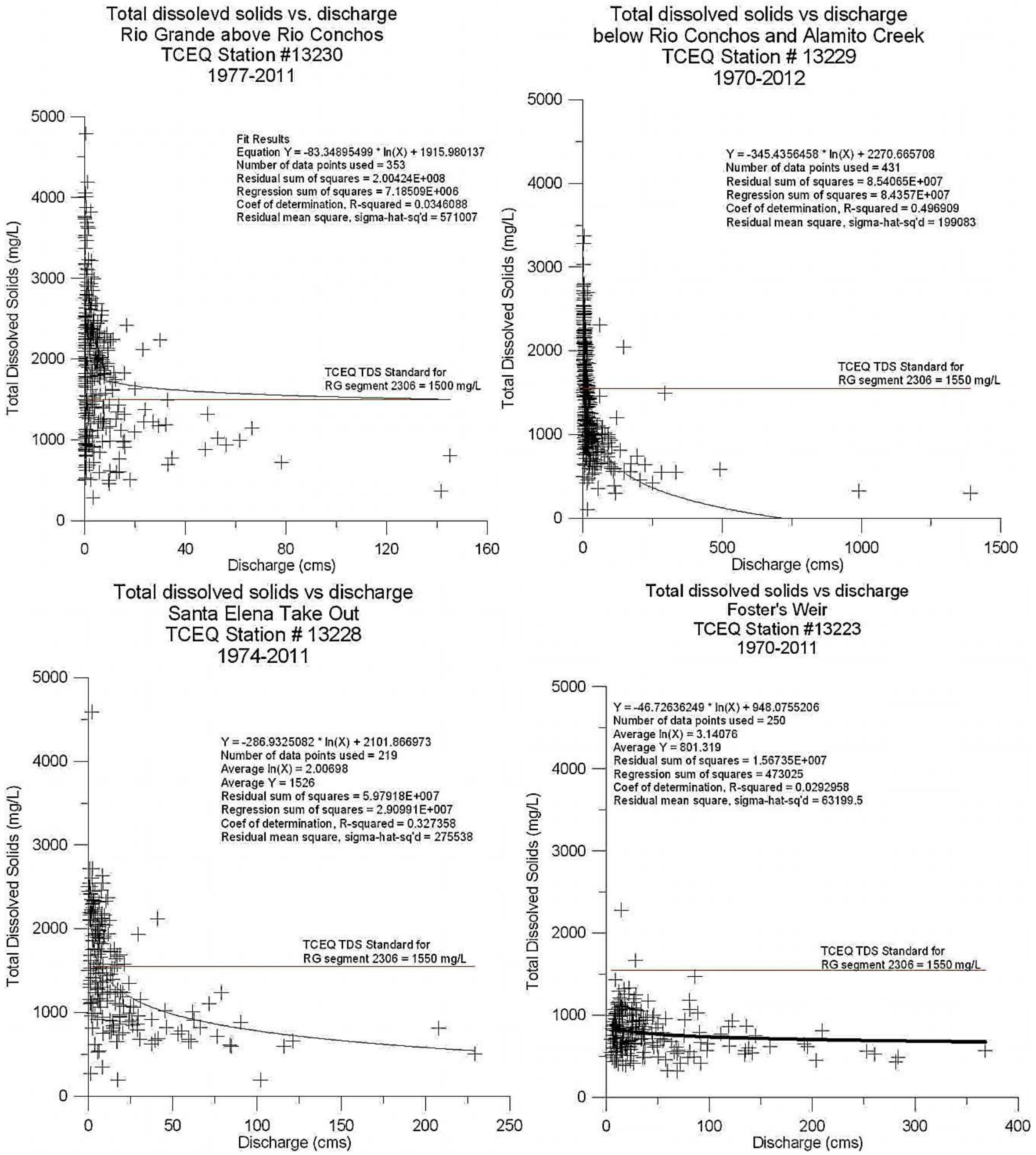


Figure 3.6-4. Total dissolved solids are plotted against flow for four stations along the Rio Grande, from Bennett et al., 2012.

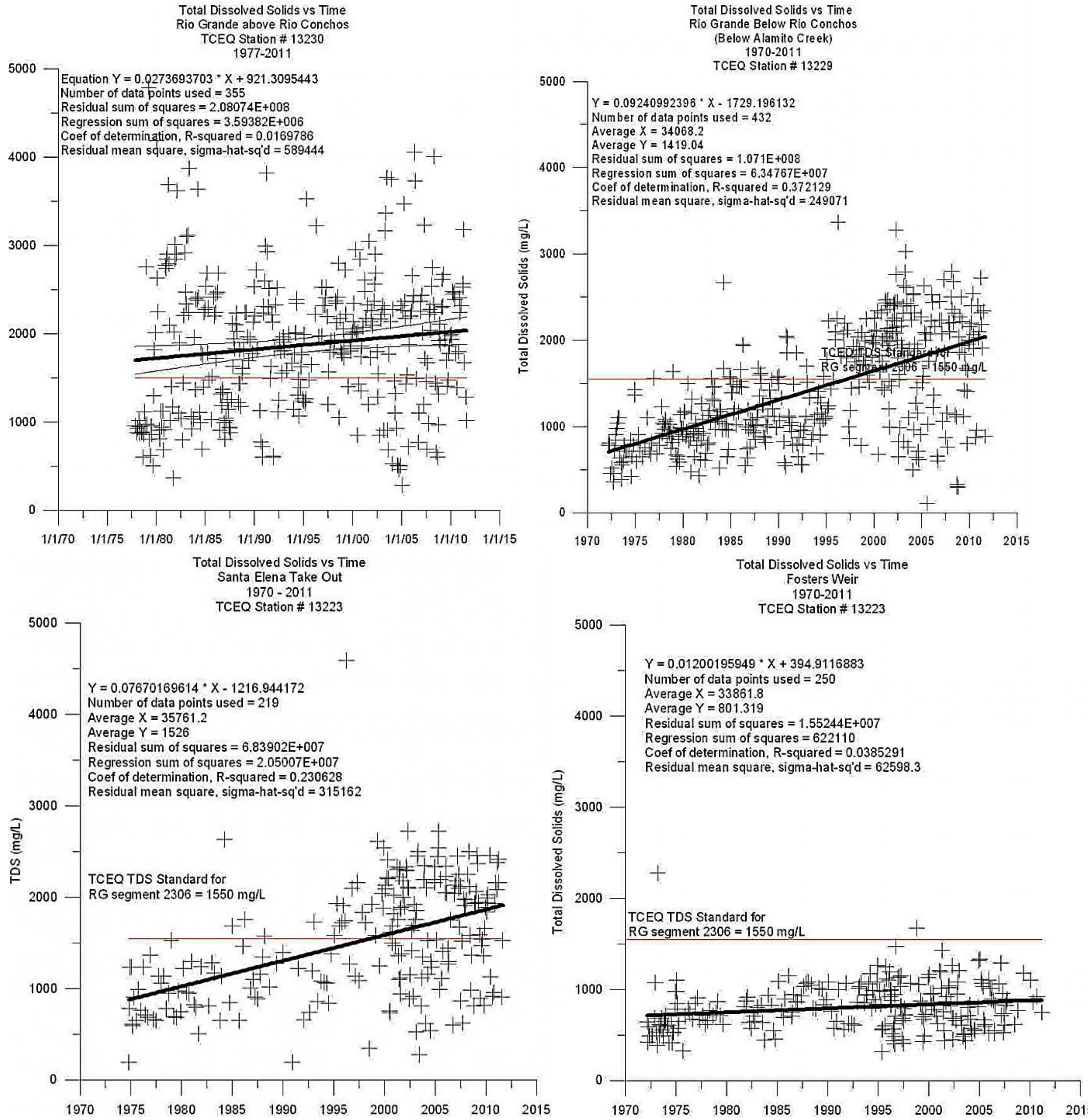


Figure 3.6-5. TDS plotted through time for four stations: Rio Grande above Rio Conchos, Rio Grande below Rio Conchos , Rio Grande at Santa Elena Take Out, and Rio Grande at Foster's Weir, from Bennett et al., 2012.

3.6.3 Biology Overlay

Biological data used in the preparation of this report was gathered from various sources including published peer reviewed articles, agency reports, conference proceedings, and regional, state and federal environmental databases. These data are used to evaluate the condition and extent of aquatic communities (fish, benthic macroinvertebrates, and freshwater mollusks) in a hydrologic context whenever possible.

The URG is one of the most remote stream segments in Texas and is therefore one of the least studied segments. This segment is defined as 2306 in the Texas Surface Water Standards (TSWQS). At 318 miles, with significant geochemical, hydrological and ecological gradients, this segment can be described as two different stream reaches. For the purposes of the report, the Lower Canyons Reach (La Linda, MX to the headwaters of Amistad Reservoir) has stable base flows provided by ground water inputs and increased flood pulses due to larger watershed inputs. The Parks Reach (Rio Conchos to La Linda, MX) is highly dependent on dam releases which results in a more regulated hydrograph. The Parks Reach is vulnerable to periods of very low flow and sections that go dry under certain conditions. The TCEQ is currently considering creating a new stream segment in the TSWQS to better reflect water quality and flow in these two stream reaches. The boundary between the two new stream segments may not coincide with the two reaches described here.

The biological information used in the report is focused primarily on the upper 140 miles of river. The URG BBEST has determined that the upper reach above La Linda, Coahuila, MX is unsound due to water quality issues, an absence of native mussel populations, and a depauperate benthic macroinvertebrate population. The upstream portion is partly lined by state and federal park lands and is accessible by roads. The downstream reach is not serviced by any paved roads between La Linda, MX and Amistad Reservoir, a distance of over 100 river miles. Few backcountry roads exist within this reach with the exception of roads within the Black Gap Wildlife Management Area just downstream of La Linda and an access road to Foster’s Weir just upstream of Amistad Reservoir. Any studies conducted within this lower reach are generally dependent on boat travel.

3.6.3.1 Background

The Rio Grande can be divided into two branches. The northern branch drains the southern Rocky Mountains in Colorado and New Mexico and much of the western half of New Mexico. The northern branch is affected by hydrologic modifications intended to divert water for irrigation and municipal uses. The Water Convention of May 21, 1906 provided for the distribution of water to the US and Mexico within the international reach of the Rio Grande between the El Paso-Juarez Valley and Fort Quitman, TX. Water diversions in El Paso and Juarez typically block the majority of flow from the northern branch. These diversions and long-term drought throughout northern Mexico, the desert southwest, and the southern Rockies in the U.S. continues to put extreme pressure on an already over-appropriated basin.

The southern branch drains the Sierra Madres Occidental in Chihuahua, MX. This branch can provide greater than 80% of the flow entering the URG reach via the Rio Conchos.

Consequently, primary focus of this report is to summarize the available biological data and to develop a biological context to be used in conjunction with hydrological based methods for developing instream flow recommendations.

3.6.3.2 Hydrology, Geomorphology and Habitats.

Because of upstream diversions and flow controls, the Big Bend reach of the Rio Grande is plagued by a cyclic accumulation of sediment which fills backwater areas, side channels, pools, and gravel bars with fine sediment all resulting in the narrowing of the river channel. In addition, more subtle shifts in grain size from fine sand and small gravel to large gravel and cobble in riffles and rapids is impacting habitat use and availability for imperiled native species (Heard et al, 2012, Garrett, unpublished report). Channel narrowing is occasionally interrupted by long-duration floods induced by tropical storms, often called “reset events” (see Section 2.6.1). In between reset events the available aquatic habitat constantly changes with the accumulation of sediment and the resulting reduction in channel width. The development of floodplains inset into the channel cover near shore habitats, steepen banks and decrease width-to-depth ratios. Large gravel and cobble substrates, especially in riffles and at tributary mouths, have replaced small gravel and sand. The channel narrowing process is amplified by the exotic giant cane (*Arundo donax*) and saltcedar (*Tamarix* spp.) which line the banks and invade the channel, anchoring sediment and making it even harder for the river to flush sediment downstream.

Fish abundance and distribution respond to variations in flow and habitat availability (Poff, et al, 1997). The USGS completed a biological assessment (Moring, 2002) in which five study reaches were established on the Rio Grande in and near Big Bend National Park. Moring interpreted differences in stream habitat condition and riparian vegetation as being related to differences in surface geology among the five reaches. In the most upstream reach, Colorado Canyon in Big Bend Ranch State Park, igneous rock predominates and stream-bed material is larger. Steeper and rockier banks provide for less diverse and dense riparian vegetation than the other four reaches that were bounded by limestone or Quaternary gravel terraces. Habitat variables such as slope, sinuosity, velocity, depth, width and riparian vegetation were measured and reported. Of the five sites, only one, Santa Elena, is associated with a large tributary and Moring reported the greatest number of fish species and individuals at this site, illustrating the importance of tributary flows on hydrologic variability and maintenance of habitat heterogeneity. Replicated sampling and mapping of these areas through the following decade would likely have revealed intra-site variability related to channel sedimentation and narrowing. A more recent USGS study of habitat associated with the reintroduction of the Rio Grande Silvery minnow is not yet complete.

Heard et. al, (2012) reported that imperiled species only comprise 4% of the total fish community, a drastic decline in relative abundance for these species. Heard found strong associations for speckled chub (*Macrhybopsis aestivalis*) and Rio Grande shiner (*Notropis jemezanus*) with riffle and run habitats with gravel substrates and relatively swift current with little silt. Also associated with these types of habitats were blue sucker (*Cycleptus elongates*), Tamaulipas shiner (*Notropis braytoni*), and longnose dace (*Rhinichthys cataractae)*. The loss of sand and gravel riffles and backwaters has been shown to negatively affect many species and it is likely the cause for the potential loss of some species (Saunders, personal communication).

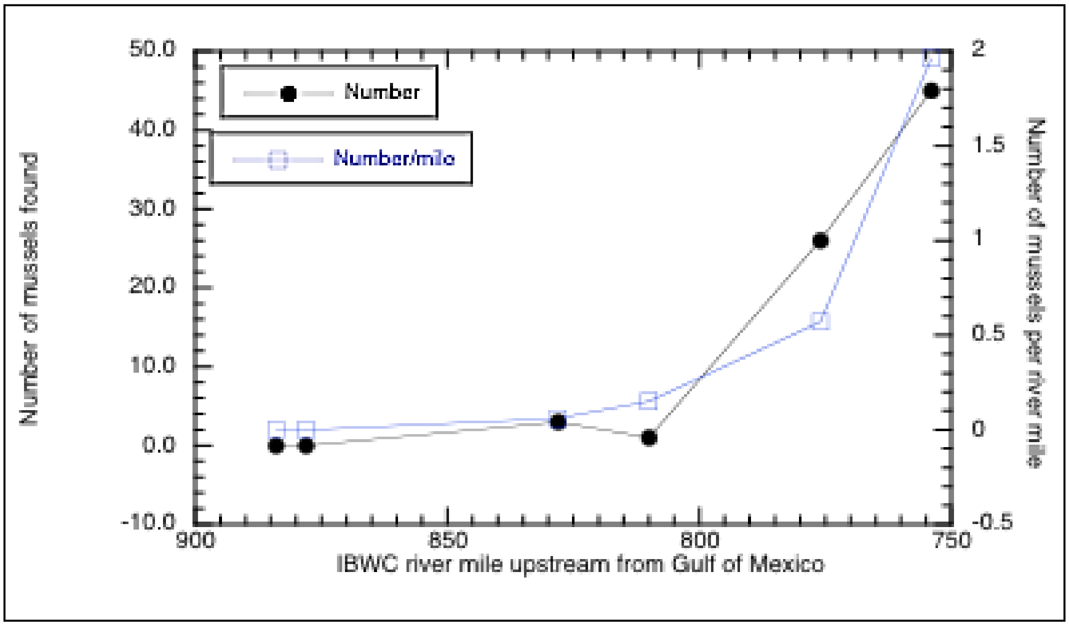


Figure 3.6-6. Results from a mussel survey conducted in 2005 depicting downstream increase in abundance. Reported river mile is at the downstream end of each sampling reach.

Table 3.6-3. Mussel data from NPS survey (Renfro, 2005)

Reach	Number of mussels found	Mussels/ river mile
Lajitas to Santa Elena Take Out	0	0.00
Santa Elena take Out to Cottonwood Campground	0	0.00
Cottonwood Campground to Solis	3	0.06
Solis to Rio Grande Village	1	0.15
Rio Grande Village to La Linda	26	0.57
La Linda to Taylor's Farm	45	1.96

3.6.3.3 Benthic Macroinvertebrates

The first published, and broadly focused survey of upper Rio Grande invertebrates were conducted by Davis and published in 1980. Davis found increasing diversity and number of taxa and decreasing redundancy moving downstream. He also found improvement in ecological richness between a station above the confluence with the Rio Conchos and just below. Davis attributes these changes to improving water quality and substrate.

More recent studies indicate a lower diversity of benthic macro invertebrates in the area downstream of Santa Elena Canyon and the area of Rio Grande Village when compared to upstream and downstream monitoring sites (IBWC, 1994, 1998, Moring 2002). Several studies found the benthic community in these areas dominated by a single tolerant species of black fly. Available data scored using the benthic index of biotic integrity and compared to the TSWQS the aquatic life use (ALU) at Santa Elena Canyon ranges from limited to high. The designated ALU is high in the TSWQS. The limited and intermediate ALU scores indicate very low abundance or absence of sensitive species, moderate to low diversity and species richness, and a moderately to severely imbalanced trophic structure. Unpublished field observations made during sample collection indicates improving conditions moving downstream.

Freshwater mussels are widely recognized as one of the most-rapidly declining groups in North America. They are important elements of aquatic ecosystems and appear to be most impacted by changes in water quality and habitat in part due to their sensitivity to environmental degradation. Historically, 16 species of unionids occurred in the Rio Grande drainage. Howells reports that only six native species had been found alive in the decade previous to his publication in 2001. Moring (2002) found only exotic bivalves in a biological assessment of the Rio Grande in BBNP. A more recent (2005) mussel survey by the National Park Service (NPS) found only empty shells representing three of the four species believed to exist in the area with no individuals found in the upper reach and increasing in number moving downstream (**Table 3.6-3**, **Figure 3.6-6**). The condition and location of these shells indicate that these species are still living within the Big Bend Reach. In 2008, state directed sampling within the Big Bend Reach from Terrell County downstream to Val Verde County found native unionids only at John's Marina near Dryden.

Table 3.6-4. List of native mussel species with status.

Scientific name	Common name	Status
Cyrtonaias tampicoensis	Tampico Perlymussel	Native,
Potamilus salinasensis	Salina Mucket	Native
Popenaias popeii	Texas Hornshell	Native
Truncilla cognate	Mexican fawnsfoot	Native-Et
Corbicula fluminea	Asiatic Clam	Introduced
Spahaerium Sp	Fingernail Clam	Introduced

3.6.3.4 Ichthyofauna

Eight of fifty-three species of fish have been identified in the Big Bend Reach of the Rio Grande as threatened (Hubbs et al, 2008). Five species are extirpated, two species are extinct, and 13 are introduced (Hubbs et al., 2008). Within Big Bend National Park several studies report intact populations relative to other reaches upstream and downstream (Heard et al., 2012). Yet these same studies note multiple extirpations of native fish, competition with invasive species and persistent water quality and quantity issues (Moring, 2002, Heard, 2012). Although several lists of sampled and extirpated fish are available (Garrett, 2002, Moring, 2002, and Heard 2012), the lack of replicated sampling and comparable sampling methods makes it difficult to develop a current or historic status of fish fauna. However, several patterns emerge from a review of available published studies.

Declines in three major Rio Grande families are apparent. Cyprinidae, Ictaluridae, and Catostomidae all show marked declines. By 2002, Rio Grande Cyprinids show a marked decline while increasing in other Texas streams. Ictalurids (catfish) have declined by two–thirds during period of collection. Catostomids (suckers) have declined by eight-fold within the Rio Grande (Garrett, 2002).

The Rio Grande silvery minnow (*Hybognathus amarus*), speckled chub (*M. aestivalis*), Rio Grande shiner (*N. jemezanus*) and blue sucker (*C. elongatus*) have been extirpated from numerous reaches of the river (Anderson et al 1995; Platania and Altenbach 1998). Calamusso et al 2005 postulated that declines in many of these species might also be associated with the increase of generalist species such as red shiner (*Cyprinella lutrensis*), fathead minnows (*Pimephales promelas*), gizzard shad (*Dorosoma cepedianum*) and western mosquitofish (*Gambusia affinis*). Dudly and Platania (2007) indicated declines in pelagic spawning species might be due to fragmentation of habitat (low flows, channel alteration) with a few populations remaining only in long fragments (>100 km).

The Chihuahua shiner (*Notropis chihuahua*), a species that prefers clear cool waters often associated with springs and underlying sand and gravel substrates, has also declined and specimens were collected below Terlingua Creek in 2006 near Johnson Ranch (Heard et al 2012) but since sampling conducted in 2009 through 2012 as part of Rio Grande silvery minnow monitoring efforts yielded no specimens (Edwards unpublished monitoring data, Saunders, personal communication).

In 1940, Hubbs identified the Rio Grande Shiner (*N. jemezanus*) as characteristic of the Rio Grande and its tributaries in New Mexico, Texas and Northeastern Mexico. Trevino and Robinson (1959) reported the species was well distributed throughout the middle Rio Grande down to the mouth. This distribution has dramatically reduced with very few specimens collected over the last ten years (personal com. Saunders). This species is usually found in large rivers with sand and gravel substrates and little silt accumulation. This species is considered threatened due to its low frequency of occurrence (Hubbs 1991).

In the USGS (Moring, 2002) biological assessment, eighteen species of fish were collected from the five reaches with the Santa Elena reach having the greatest number of species and Colorado Canyon having the least. The collection at Santa Elena was dominated by minnows. These differences could be explained by geomorphic differences allowing for greater access to all habitat types or increased habitat availability.

Fish inhabiting the Lower Canyons reach of the Rio Grande include a large number of swift-water adapted species such as *R. cataracta*e and *M. aestivalis*. Most of the remaining (not extinct) elements of Chihuahuan Desert ichthyofauna are found within the Lower Canyons reach. Annual collections from 2010–2012 on average have yielded 21 species (Saunders, unpublished data). Mexican stoneroller (*Campostoma ornatum*) a bottom dwelling herbivore that prefers gravel/rock substrates in clear water riffles and pools has declined dramatically likely due to the introduction of plains killifish (*Fundulus zebrinus*)(Edwards et al., 2002). Hubbs reported in the mid 50's that the species was the most abundant fish in Tornillo Creek. In 1977, Hubbs reported this species only from Alamito creek near the confluence with the Rio Grande where it was reported to have a fairly high relative abundance level (48% Alamito Creek, 12% Rio Grande). Hubbs and Echelle (1972) voiced concern for the species and suggested it be considered endangered due to population declines and habitat loss due to siltation, channelization, and low flows. In 1990, Hubbs again listed the species rare and near endangered status.

A 2004 study of fish within the entire reach noted seven species less than found by Hubbs (1977). *N. chihuahua*, *N. jemezanus*, *P. promelas*, *C. elongatus*, *Menidia beryllina*, *Morone chrysops*, and *Micropterus salmoides* were not found during this study.

3.6.3.5 Riparian Biology

To date, no analysis of the historic riparian condition of the Parks or Lower Canyons reach of the Rio Grande has been published. Qualitative assessments of riparian conditions before anthropogenic flow controls can be made based on written historic accounts and photography (e.g. 1848 Emory survey, 1859-60 Camel Corps account). It appears that this reach of the Rio Grande supported fairly narrow, discontinuous riparian vegetation at the edges of a wide, shallow, and dynamic channel. Overstory (gallery) forest patches are known to have occurred in the region, but these patches were neither well-developed nor continuous.

Currently, the banks of the Rio Grande are dominated largely by dense infestations of exotic and invasive vegetation, specifically giant cane (*Arundo donax*), and salt cedar (*Tamarix* spp.), with the general distributional pattern being the dominance of salt cedar at the upper reaches, and increasing density of giant cane downstream (NPS and CONANP – unpublished data). Throughout the reach, dense patches of native river cane (or common reed, *Phragmites australis*) occur and in some places can be as dominant as *Arundo*. Both community and landscape-level plant diversity are low in exotic-dominated riparian areas. However, in some areas where well developed floodplains exist, native dominated mesquite bosques occur, and there are a few remnant patches of overstory cottonwood and willow forest scattered throughout the Big Bend of the Rio Grande.

Dean and Schmidt (2011) have identified a feedback between the establishment of riparian vegetation and sediment accumulation along the channel of the Rio Grande. Other researchers have identified the importance of natural and modified in shaping riparian vegetation communities (Stromberg, 2001). Non-native riparian vegetation, salt cedar and giant cane, is currently being managed along significant lengths (i.e. 30km) of the Rio Grande. Additionally, salt cedar leaf beetles (*Diorhabda* spp.), a biocontrol agent for salt cedar, are successfully established throughout the region. However, little is understood concerning the mechanisms that drive non-native vs. native vegetation establishment and proliferation, and the role that the current flow regime has on the patterns of native vs. non-native vegetation establishment and proliferation. Investigations regarding riparian vegetation dynamics in relation to flow magnitude and duration would be valuable in providing future instream flow recommendations.

3.6.4 Geomorphology Overlay

As described in Section 2.6, the modern Rio Grande is a disequilibrium river where rapid channel narrowing occurs during low flow years, and channel widening occurs during rare, large, long duration floods (Dean and Schmidt, 2011; Dean et al., 2011a). Thus, channel and floodplain morphology is rarely in a static or equilibrium state, but instead, constantly changes. The rate and magnitude of change is determined by the amount of sediment input by ephemeral tributaries and upstream reaches, and the frequency and magnitude of flows that transport and redistribute the supplied sediment. Short duration floods lack the ability to cause significant bank erosion, yet are efficient at suspending fine sediment and depositing that sediment on top of active gravel bars, and in low velocity areas along the channel margin (Dean et al., 2011a, 2011b)(**Figure 3.6-7**). This often results in the infilling of important habitats such as side-channels and backwaters. Additionally, short duration floods that inundate the floodplain cause vertical accretion of the floodplain surface thereby increasing the height of the floodplain above the channel bed and causing vertical disconnection of the floodplain from in-channel habitats.

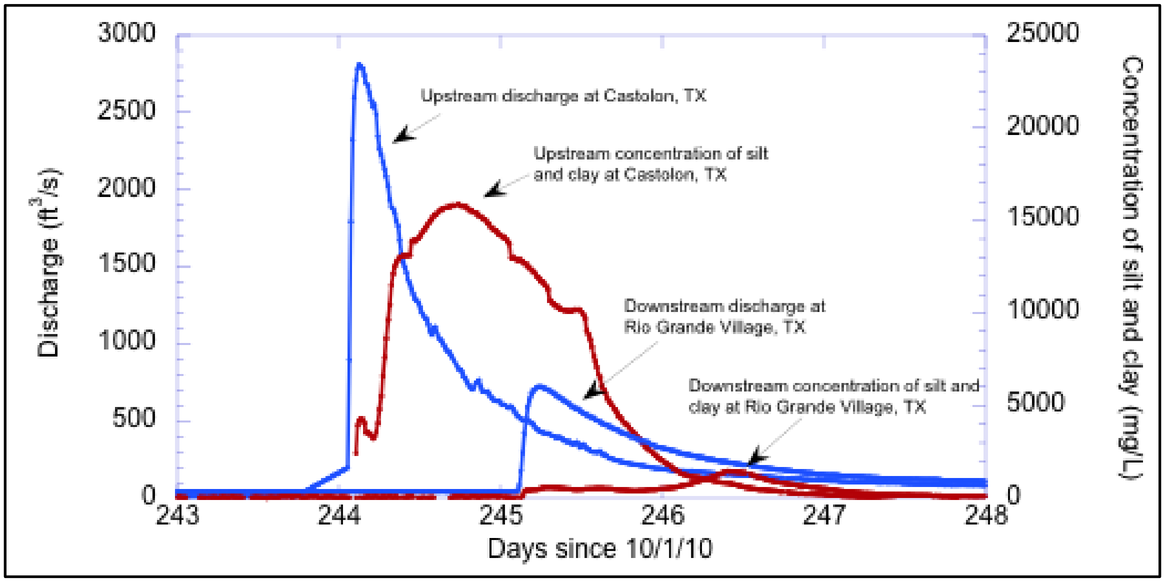


Figure 3.6-7. Preliminary analyses of suspended sediment dynamics at sediment gaging stations near Castolon and Rio Grande Village, TX during a flash flood in June 2010, see additional descriptive text below in italics.

Caption 3.6-7 continued - Suspended sediment gaging stations are operated by the USGS Grand Canyon Monitoring and Research Center (GCMRC) and Utah State University (USU). Between the two gaging stations, the short duration flash flood quickly attenuated downstream. During flood attenuation, greater than 90% of the mud that was transported into the study reach at Castolon was deposited within the channel and was not exported from the study reach at Rio Grande Village, TX. Preliminary data adapted from Dean et al., 2011b, unpublished data.

Channel resetting floods caused by tropical storms in the Rio Conchos watershed are the only means by which channel narrowing has been reversed over the last 60 years, and because of the channel-widening effects and habitat rejuvenation capabilities, are deemed a beneficial ecosystem service. However, these floods are entirely determined by climatic phenomenon that are relatively unpredictable, and are thus unreasonable to incorporate into an environmental flow program. Alternatively, environmental flows should be developed in order to limit channel narrowing and floodplain formation in the years between resetting events. HEFR analyses and environmental flow recommendations should thus be viewed through the lens of the geomorphic processes that are presently understood.

For the purposes of an environmental flow program on the Upper Rio Grande, recommended flows should provide physical ecosystem services such as fine sediment export to prevent channel narrowing, reorganization of the channel bed and habitat rejuvenation through the mobilization of transport of gravel and cobbles, scour of vegetation along the channel margin and from the channel bed, bank erosion, and channel migration. Dean and Schmidt (2011) and Dean et al., (2011a) demonstrated that only the largest floods, in excess of 35,300 ft³/s are able to actively widen the channel, and strip vegetation from the floodplain. During periods when there is a large in-channel supply of sediment, or during episodes of high sediment inputs, even floods exceeding a 5-year recurrence interval of approximately 21,190 ft³/s fail to widen the channel, and instead cause channel narrowing, and vertical floodplain accretion (Dean et al., 2011).

For the reasons mentioned above, environmental flow prescriptions should consist of flows that maximize shear stress on the bed and banks of the river channel (for sediment transport purposes) without overtopping the channel banks and causing vertical floodplain accretion. The mechanisms for achieving this goal would consist of channel filling flows. The duration of these flows should occur for the longest possible duration to maximize sediment export and channel-bed reconfiguration. A short duration flood would most likely only result in the deposition of fine sediment on in-channel bars. Addition benefits would include the scouring of maturing algal communities, local bank erosion, and the maintenance of channel width.

Recent 1-dimensional hydraulic modeling efforts using the US Army Corps of Engineers Hydrologic Engineering Centers River Analysis System (HEC-RAS) have been conducted by Utah State University (USU) in order to quantify the discharge of a "channel-filling flow". Estimating a channel filling flow is difficult because the effects of the 2008 channel-resetting flood were not the same everywhere. There was little channel widening in some areas, and catastrophic widening in others. Thus, channel filling flow estimates vary considerably depending upon reach-scale geomorphic controls. This is evident based on modeling results for three reaches in BBNP: Castolon, Hot Springs, and Solis. As shown in **Figure 3.6-8**, each reach has a range of discharges that fill the channel before overtopping the channel banks.

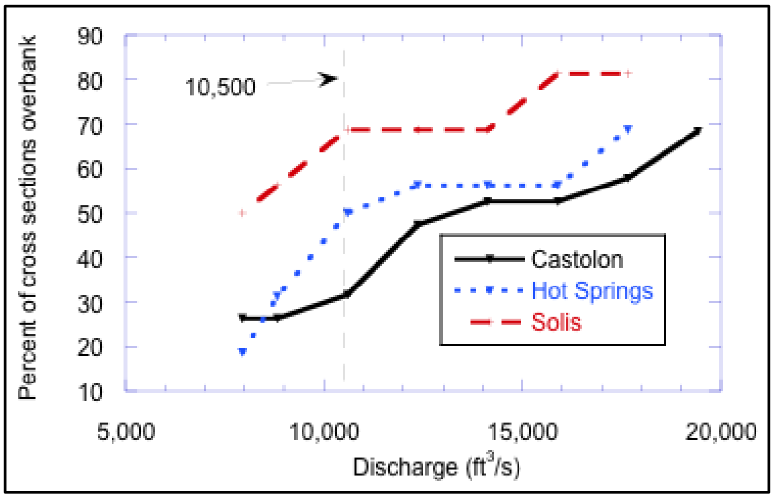


Figure 3.6-8. Results from 1-dimensional hydraulic modeling to characterize the magnitude of a channel filling flow.

Caption 3.6-8 continued - The decrease in slope of each of these lines indicates that the narrow portions of the channel have been filled. We defined the breaks in slope for the Solis and Hot Springs reaches as the channel filling flow. Adapted from Dean and Schmidt (2011b).

Model results indicate that flows less than 8,800 ft^3/s produce overbank flow in all three reaches (**Figure 3.6-8**). For each increasing modeled discharge, the number of overbank cross sections increases, however, there is an approximate threshold discharge at which the rate of increase declines. In the Solis reach, this threshold appears to be at approximately 10,500 ft^3/s, where nearly 70% (11 of 16) of the cross sections are overbank (**Figure 3.6-8**). In the Hot Springs reach, this threshold appears to be at approximately 12,350 ft^3/s, where over 55% (19 of 33) of the cross sections are overbank (**Figure 3.6-8**). In the Castolon reach, the threshold appears to be between 12,350 and 14,125 ft^3/s, where approximately 50% (10 of 19) of the cross sections are overbank (**Figure 3.6-8**).

These thresholds indicate variability in channel width and bank height among the three reaches and within each reach. In all reaches, there are narrow portions of the channel where floodplain inundation occurs at relatively low discharges, and wide portions where the floodplains don't get inundated unless extreme floods occur. For these reasons, defining a threshold discharge for floodplain inundation was difficult. However, based on the change in slope of the curves in **Figure 3.6-8**, we define the threshold discharge as the point at which most of the narrow reaches begin to overtop their banks; this discharge is approximately 10,500 ft^3/s and is roughly equivalent to a 2-year flood at the Johnson's Ranch gage.

3.6.4.1 Sediment Transport

Sediment transport is a highly non-linear process. Small changes in flow, and associated boundary shear-stress, may cause vastly different transport rates (Erwin et al., 2011). This is true for both suspended sediment and bed load. For suspended sediment, there may also be development of a progressive lag between suspended-sediment concentration and the kinematic discharge wave during a flood (Heidel, 1956; Dinehart, 1998). For these reasons, as well as others, correlation between discharge and sediment transport rate is difficult (**Figure 3.6-9** and **Figure 3.6-10**).

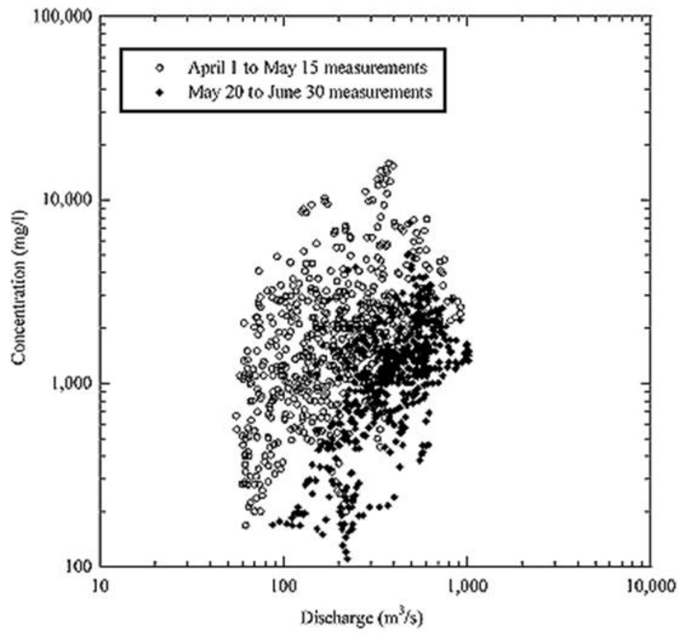


Figure 3.6-9. Plot of suspended sediment concentration vs. discharge on the Green River near Jenson, UT showing the 2 orders of magnitude difference in suspended-sediment concentration in relation to discharge. Figure taken from Grams and Schmidt (2002).

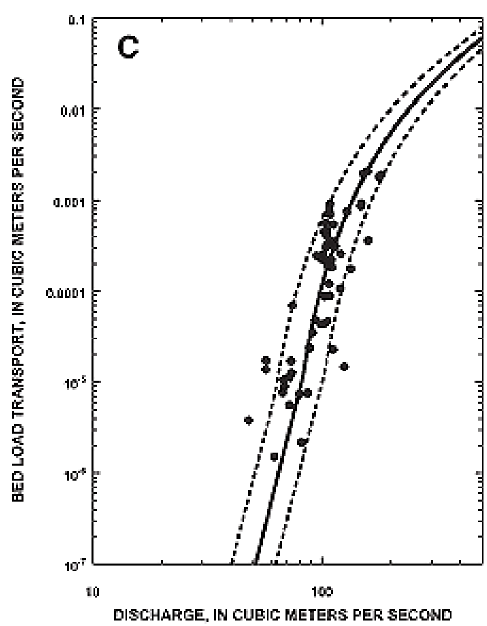


Figure 3.6-10. Plot of bed load transport vs. discharge on the Snake River in Grand Teton National Park, WY, showing highly non-linear bed-load transport and the large uncertainty when correlating bed-load transport to discharge (Erwin et al., 2011).

There are little data concerning sediment transport rates on the Rio Grande. The philosophy of establishing environmental flows based on estimates of a channel-filling flow (Section 3.3) is based upon first principles of sediment transport (i.e. greater shear stress = greater transport), as well as the current understanding of geomorphic changes associated with the different types of flood flows outlined in Section 3.6.1.1. However, the hypothesis that long-duration channel-filling flows will alleviate problems of sediment loading within the channel is only assumed. Below, we talk about some preliminary sediment transport analyses to inform this assumption.

A suspended sediment monitoring campaign was recently initiated by the USGS GCMRC and USU in 2010. Two suspended-sediment monitoring stations were installed near Castolon, TX and Rio Grande Village, TX. These gages are near-continuously monitoring such that real-time transport data can be obtained, thus negating the reliance of imprecise sediment rating curves. This monitoring campaign is still in the initial phase of calibration, and preliminary results of transport in 2011 are limited because of the lack of flood flows that occurred. However, preliminary analyses indicate that 1) dam releases (in this case, long duration high flow pulses) have the potential to export silt and clay from the study reach, and 2) dam releases (long-duration high flow pulses) promote the transport of fine sediment if inputs happen concurrently with high main-stem flows (**Figure 3.6-11**). Findings were different concerning sand, however, sand concentrations were quite low (<100 mg/L) and thus are probably negligible concerning large scale sediment dynamics. We hypothesize that a steady state channel-filling flow will operate in a similar manner to the dam release in **Figure 3.6-11**, however, sediment transport analyses have not been conducted on a flow of that magnitude.

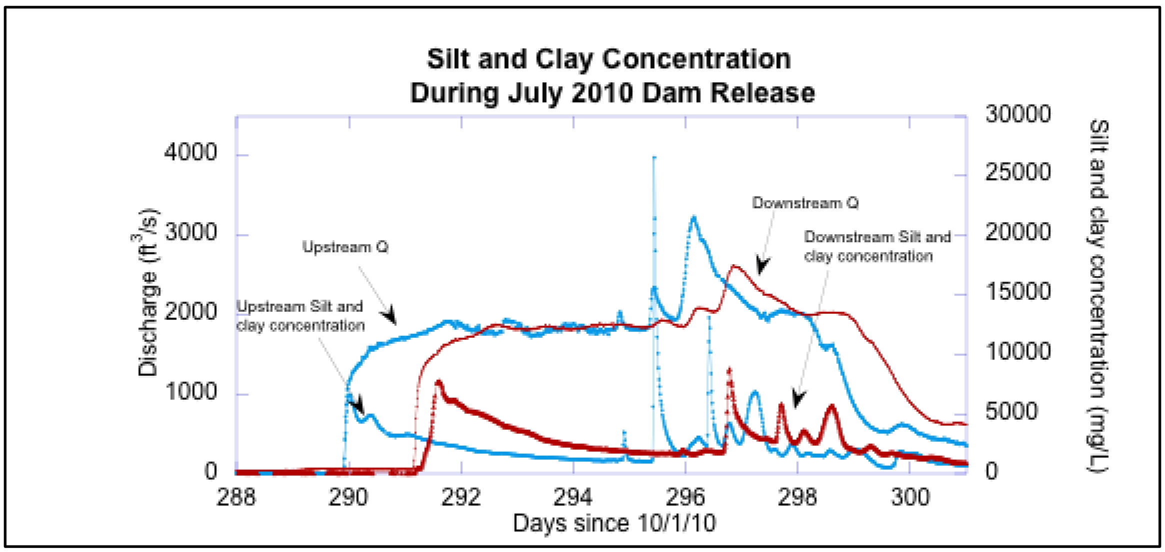


Figure 3.6-11. Preliminary analyses of suspended silt and clay transport during a dam release in July 2010.

Caption 3.6-11 continued - Note that at the downstream gage, silt and clay concentration was always higher during the steady state release indicating that silt and clay was exported. Also, note that silt and clay inputs from flash floods superimposed on the top of the dam release were translated through the reach indicating that sediment attenuation did not occur in contrast to data shown in Figure 3.6-7.

There are even less data concerning bed load transport on the Rio Grande. Dean and Schmidt (2011c) show that tributary flash floods have caused aggradation of coarse sediment (gravel and cobbles) at tributary junctions between 2009 and 2012 (**Figure 3.6-12**). There have been no main-stem flows that have been able to mobilize and/or reorganize these deposits and there have been no main-stem flows that have approached the magnitude of a channel-filling flow.

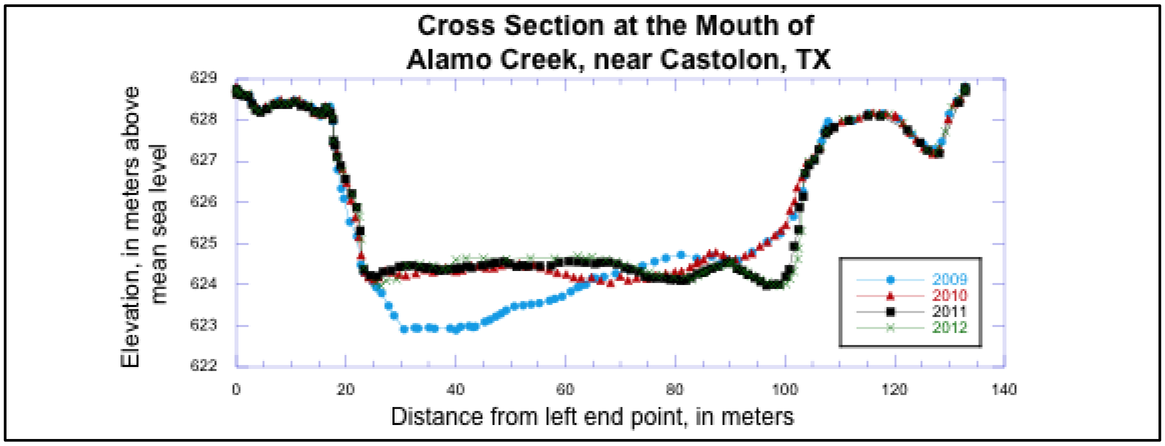


Figure 3.6-12. Channel cross sections measured at the mouth of Alamo Creek near Castolon, TX between 2009 and 2012. Note the aggradation of the channel bed between 2009 and 2010.

We conducted some exploratory bed load transport modeling to investigate the sediment transport potential of the coarse-grained deposits at the mouth of Alamo Creek; one of these reaches where gravel aggradation is occurring. The purpose of this modeling was to examine the threshold of bed load mobility, quantify the uncertainty in these estimates, and to model the sediment transport characteristics for a flow that approaches a channel filling flow of 10,500 ft³/s. We conducted this modeling using the same 1-dimensional hydraulic models mentioned in Section 3.6.4, and used the sediment analysis functions with grain size data obtained from data collection in the field. We designed a simple stepped hydrograph with each step consisting of a 6-hour period. The first step was raised from a base flow of 35 ft³/s to 3,530 ft³/s, and each additional step was in an increment of 1,765 ft³/s (**Figure 3.6-13**).

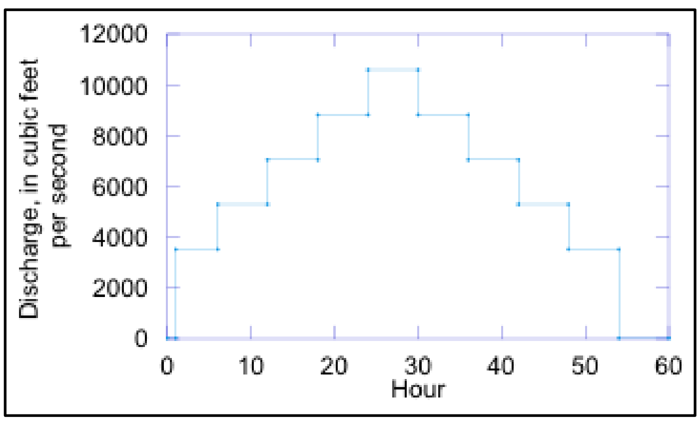


Figure 3.6-13. Stepped hydrograph used in the 1-dimensional sediment analysis completed using HEC-RAS.

Using the surveyed cross-section geometry and grain size data measured in the field, we ran the sediment analysis using the Meyer-Peter-Mueller sediment transport equation (1),

$$(1) \qquad (k_r/k'_r)\ \gamma RS = 0.047(\gamma_s-\gamma)d_m + 0.25(\gamma/g)^{1/3}\ ((\gamma_s-\gamma)/\gamma)^{2/3}\ q_s^{2/3}$$

where qs is the sediment transport rate per unit width, kr is a roughness coefficient, k'r is the roughness attributed to the sediment grains, γ is the unit weight of water, γs is the unit weight of the sediment, g is the acceleration due to gravity, dm is the median particle diameter, R is the hydraulic radius, and S is the energy gradient (USACE, 2010).

Model results show that at this location, gravel becomes mobile at flows less than 3,530 ft³/s. At the peak modeled discharge of approximately 10,500 ft³/s (channel-filling flow), more than 25 tons of sediment is transported per day. Over the length of the hydrograph, a cumulative amount of 1,611 tons of sediment is transported through a cross section (**Figure 3.6-13** and **Figure 3.6-14**). These results show that a channel-filling flow is able to mobilize the gravel deposits in this reach.

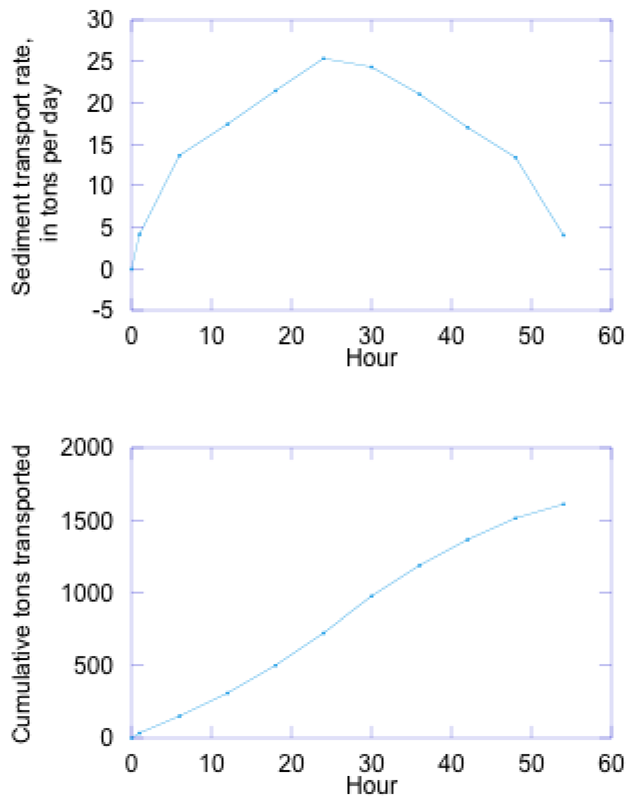


Figure 3.6-14. Sediment transport calculations for a cross section near Alamo Creek obtained from 1-dimensional sediment modeling. (a) Sediment transport rate over the duration of the model run. (b) Cumulative volume of sediment transported over the duration of the model run.

When these numbers are compared to the preliminary analyses of sediment influx from Alamo Creek as measured by detailed topographic surveys, a crude mass balance can be developed. Between 2011 and 2012, USU conducted detailed surveys of the aggrading Alamo Creek gravel deposits. Digital elevation models (DEM) were built of the surveyed section of the channel for each year, and the 2011 DEM was subtracted from the 2012 DEM to calculate the elevation difference between the two years. To limit the degree of uncertainty in the surveys, all differences less than approximately 6 inches were excluded from the analyses. Calculations of the difference between the two surveys indicate that over 3,140 tons of sediment was deposited within the river channel during that year (**Figure 3.6-15**); roughly twice as much as sediment flux calculated for the 60-hour sediment modeling run. Based on the modeling results, a channel filling flow will have to occur for longer than 18 hours in order to move the 2011-2012 accumulated amount of sediment downstream.

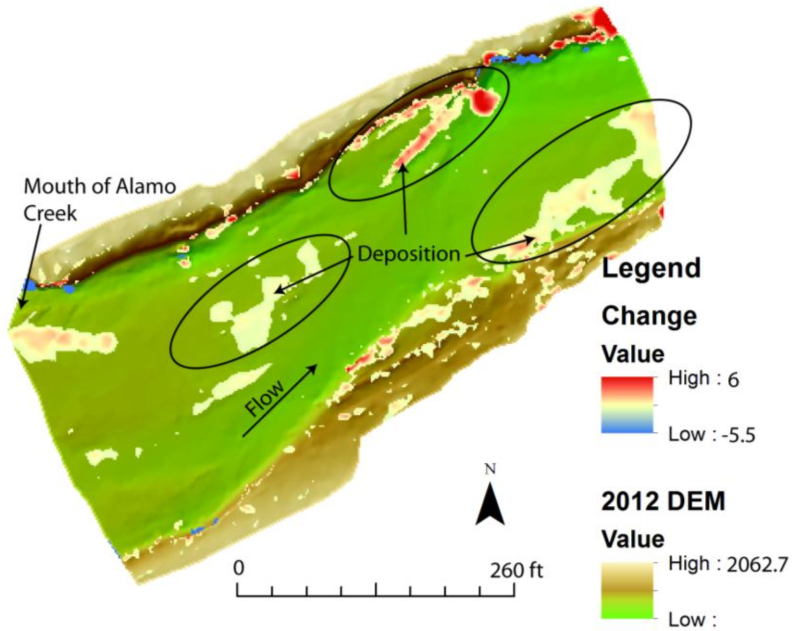


Figure 3.6-15. 2012 DEM of the Rio Grande downstream from the mouth of Alamo Creek. Areas of green are within the channel. Brownish areas are the banks. Areas of deposition and erosion between 2011 and 2012 surveys are shown in gradational red to blue scale. Nearly all channel change consisted of deposition.

Analyses like these can be useful, however, there is large uncertainty around any estimate of sediment transport as shown in **Figure 3.6-9** and **Figure 3.6-10**. We employed a Monte Carlo approach (Wilcock et al., 2009) to investigate the uncertainty in the modeling. This approach takes user-specified ranges of input data concerning the channel roughness, the grain size of the bed, and the threshold for mobility in the form of the Shield's parameter. Once the specified ranges are input, a normal distribution of values is created based on the standard deviation of the ranges of data, centered on the user-specified "best estimate" (**Figure 3.6-16**). Then, the critical discharge (the discharge required for bed mobility) and the cumulative sediment transport (in tons) are calculated 1,000 times using randomly selected values of the three parameters from the normal distributions. The output is a probability distribution of the critical discharge and cumulative transport based on the 1000 runs.

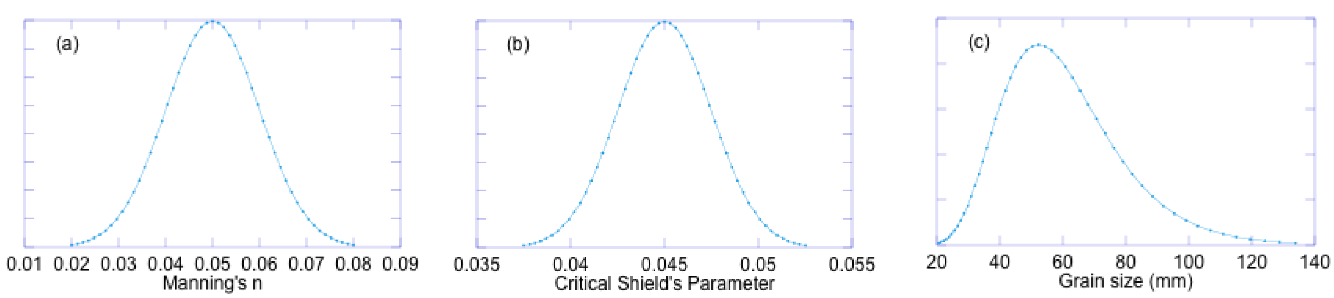


Figure 3.6-16. Probability distribution functions of Manning's n (roughness parameter), the critical Shield's parameter (values used for mobility threshold), and grain size distribution (obtained from field measurements) used in the Monte Carlo analysis. These distributions are based on user inputs for the purpose of understanding the uncertainty involved in sediment transport estimates.

The Monte Carlo results show the relative uncertainty involved with the prediction of sediment transport without field data of actual transport rates for which to calibrate the sediment transport equations. Monte Carlo simulations show that in a simplified channel with the same slope and width as used in the 1-dimensional modeling, and the given range of input values, the threshold for gravel mobility generally does not occur until discharge exceeds 15,000 ft^3/s (**Figure 3.6-17**). Often the threshold is much larger. Additionally, over 980 of the 1,000 simulations calculated the total cumulative transport for the input hydrograph to be less than 220 tons per day. It is likely that the critical discharge is over predicted by the Monte Carlo runs because true channel topography is not used, and instead the cross section is assumed to be quasi-trapezoidal. However, the Monte Carlo simulations show that there is a large degree of uncertainty in predicting when bed-load transport will occur. Thus, there is great caution when applying sediment transport models to problems without a comprehensive understanding of the factors driving transport in any given reach.

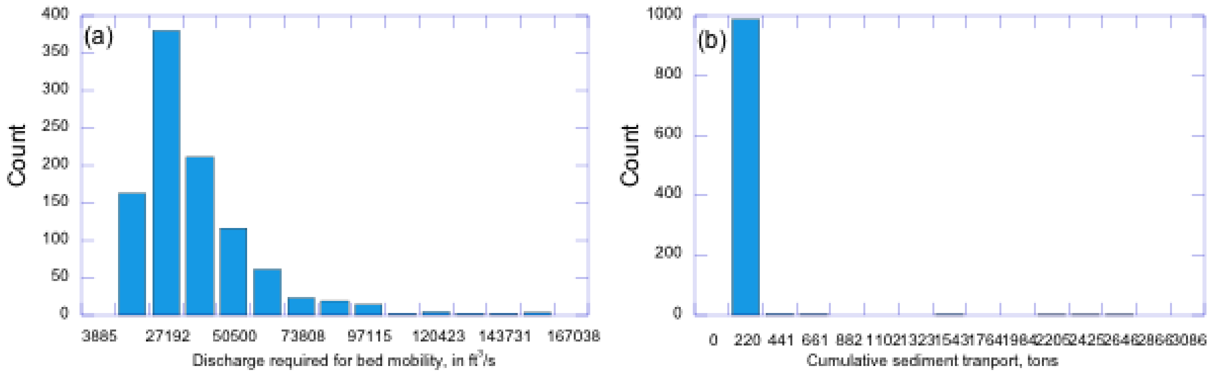


Figure 3.6-17. Results of the Monte Carlo simulation.

*Caption 3.6-17 continued - (a) Distribution of 1000 calculations of the threshold discharge for bed-load transport based on the range of user defined inputs (**Figure 3.6-16**). The threshold for motion in this analysis is much greater than in the 1-dimensional modeling, and the relative uncertainty in predicting the discharge required for bed-load mobility is apparent. (b) Distribution of the cumulative transport calculations over the range of the hydrograph is **Figure 3.6-13**. Note that the cumulative transport is much lower than predicted by the 1-dimensional modeling, which also is an indicator of the uncertainty involved in modeling sediment transport without field data for calibration.*

Continued suspended-sediment monitoring on the Rio Grande is needed to constrain suspended sediment transport dynamics for proposed environmental flow scenarios. Additionally, a comprehensive bed-load transport study needs to be conducted in order to understand which flows are capable of mobilizing the channel bed, and how much transport occurs during given flow events. These types of data are integral when designing environmental flow programs based on physical river processes. Measurements of geomorphic change are alone not enough to inform managers of the mechanisms responsible for the change.

3.7 Pecos River

3.7.1 Hydrology-based Environmental Flow Regimes

Development of initial hydrology-based flow regimes for five of the six Pecos River sub-basin gages (Pecos River at Orla, Pecos, Girvin and Langtry and Independence Creek near Sheffield) followed the methods and parameters described in Section 3.3. There was not sufficient period of record at the sixth gage (Pecos River at Brotherton Ranch near Pandale) for HEFR analysis. For this gage, we are recommending only subsistence and base flows. Our subsistence flow recommendation for all three seasons is the 95^{th} percentile (Q95) of the current period of record which is 39 ft^3/s. Evaluation and refinement of this initial subsistence flow should be a component of the adaptive management phase. Base flows for this gage were developed from instream habitat modeling as described in Section 3.7.3. No episodic events (high flow pulses or overbank flows) are being recommended at this time, but should be developed as a longer period of record becomes available and/or through other methods in the adaptive management phase.

3.7.2 Water Quality overlay

The Pecos River in west Texas is divided into two segments by the TCEQ. The Upper Pecos, Segment 2311, which extends from immediately upstream of the confluence with Independence Creek to Red Bluff Dam in Loving /Reeves County (309 miles). The Lower Rio Grande, Segment 2310, extends from the confluence with Independence Creek to the weir dam near Langtry, Texas (89 miles).

The Pecos River is an important source of surface water in the arid western portion of Texas and is one of the main US tributaries flowing into the Rio Grande. Natural geologic deposits in the Pecos River watershed increase the concentration of chloride, sulfate, and dissolved solids to levels that are as much as ten times higher than typical surface waters.

In addition to these natural deposits, salt cedar (*Tamarisk* sp.) contributes to elevated salinity levels in the Pecos River. Salt cedar is an exotic invasive, salt tolerant species that increases salinity by transpiration of freshwater sources. Other activities such as oil and gas exploration, irrigation demands, and droughts compound the issues facing water quality and water quantity in the Pecos River.

The visible results of increasing salinity are the fish kills caused by the brackish water species of golden alga, *Prymnesium parvum.* Fish kills related to *P. parvum* have been documented in the Pecos River since 1985.

The Upper Pecos River is dominated by low flow and high dissolved solids. Segment 2311 is listed as impaired for DO in the lower portion of the water body. Segment 2311 can be further divided into three sections, one from the TX-NM state line to the Ward II turnout, one from Ward II turnout to Iraan, and one from Iraan to the confluence of Independence Creek. The upper 102 river miles, from the TX-NM state line to the Ward II turnout, (**Figure 2.6-8** and **Figure 2.6-10**) is under complete control of the Red Buff Water Power Control District. If the district has sufficient water for irrigation, ample water is released for this section of the river. Even during normal rainfall years, if the water supply is too low for irrigation, portions of this section of the river will be dry (**Figure 3.7-1**).

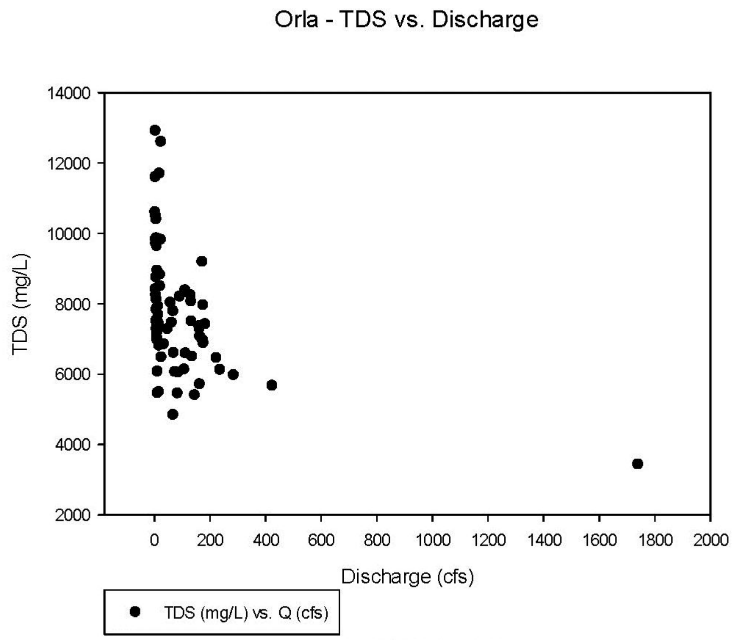
Figure 3.7-1. Dry Pecos River Bed.

Water quality is affected by water from the Rustler formation. Salt Creek originates from Rustler springs which contribute 45,700 tons of salt per year in 2,675 acre feet of water per year. This water is injected into the Pecos River just below Red Bluff Dam.

The vast majority of water in this section and the overpowering influence is the water from Red Bluff Reservoir itself. Shortly after construction of the Red Bluff Dam in 1936, water outflow 1937-1940 was reported to be 4,710 ppm TDS (Howard and Love, 1943). Currently the salinity of the Red Bluff outflow, when measured at Orla, is 6,150 ppm TDS (Miyamoto 2007). Due to evaporation, salt concentrations will increase but only a small amount before the last of the water is removed from the river at the Ward II turnout.

The water quality is checked at the surface water gage near Orla. Data from the Texas Clean Rivers Program of the IBWC and TCEQ is depicted in the two following figures. The data indicates there is a slight decrease in salinity over the past 30 years. However, it is clear the water quality is extremely variable. This gaging station is nine river miles below the Red Bluff Reservoir and is therefore directly related to the water quality in the reservoir. It is also upstream of all irrigation districts. Rustler Aquifer water does enter the Pecos River via Salt Creek which is located between Red Bluff Reservoir and the Orla gage. Discharge data also relates the frequency of the low flows in the river

It must be related that this flow gage is unreliable but we have no knowledge of when the gage became unreliable. TPWD was conducting habitat surveys just below the Orla gage during the summer of 2011. Measured flow was approximately 60 ft^3/s while the gage was reporting 11 ft^3/s. Red Bluff Water Power Control District also knows not to use the gage and omits any flow data associated with it. This is an obvious example of how incorrect data are used in research activities.



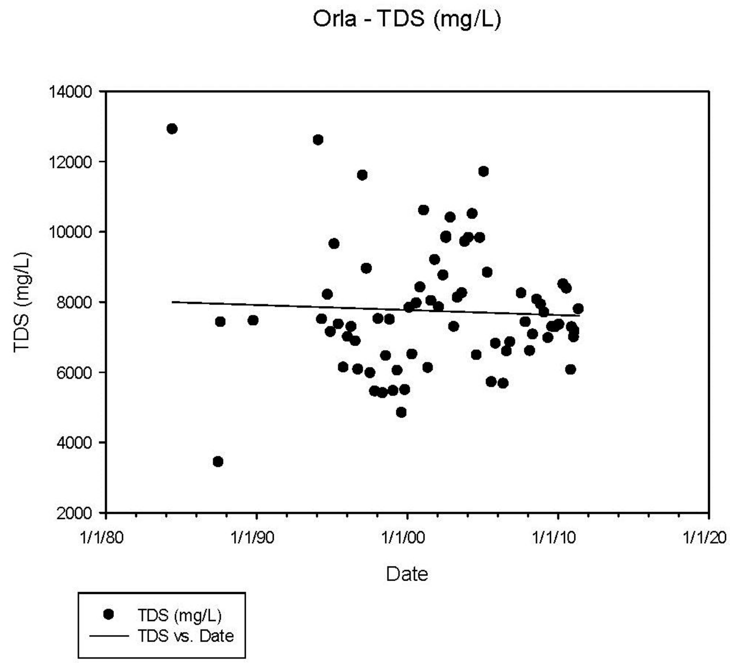


Figure 3.7-2. Water quality data for the Pecos River at Orla.

During rainfall events which are large enough to produce runoff, the effect upon the river is minimal. Standard operating procedure is to allow the first day of river flow through the riverbed and then open the gates to the diversions to capture any “free” water from the river. This dilutes and freshens water in the irrigation canals but does little to help maintain river form or water quality. The Loving, Reeves II, Ward III, and Ward II Irrigation Districts are between the Orla gage and the Pecos gage. The HFER analysis at the Pecos gage show 0.5 ft^3/s low base flow and high base flow is 32 ft^3/s in the winter and 104 ft^3/s during the summer. This difference is the difference between no irrigation in the winter and peak irrigation in the summer. The first days flow is allowed to stay in the river because it is the highest level of TDS and high in debris. The first flush is left in the river as it is undesirable for irrigation purposes.

Although the stretch from the TX-NM state line may be dry due to no releases from Red Bluff Reservoir, the river section from Ward II turnout to Iraan will always have water except during the driest of years. During the drought of 2011, this section of the river had water flowing. The water source is thought to be the Pecos Valley Aquifer. Unfortunately, this source is the worst quality water in the Pecos Valley Aquifer (**Figure 3.7-3**).

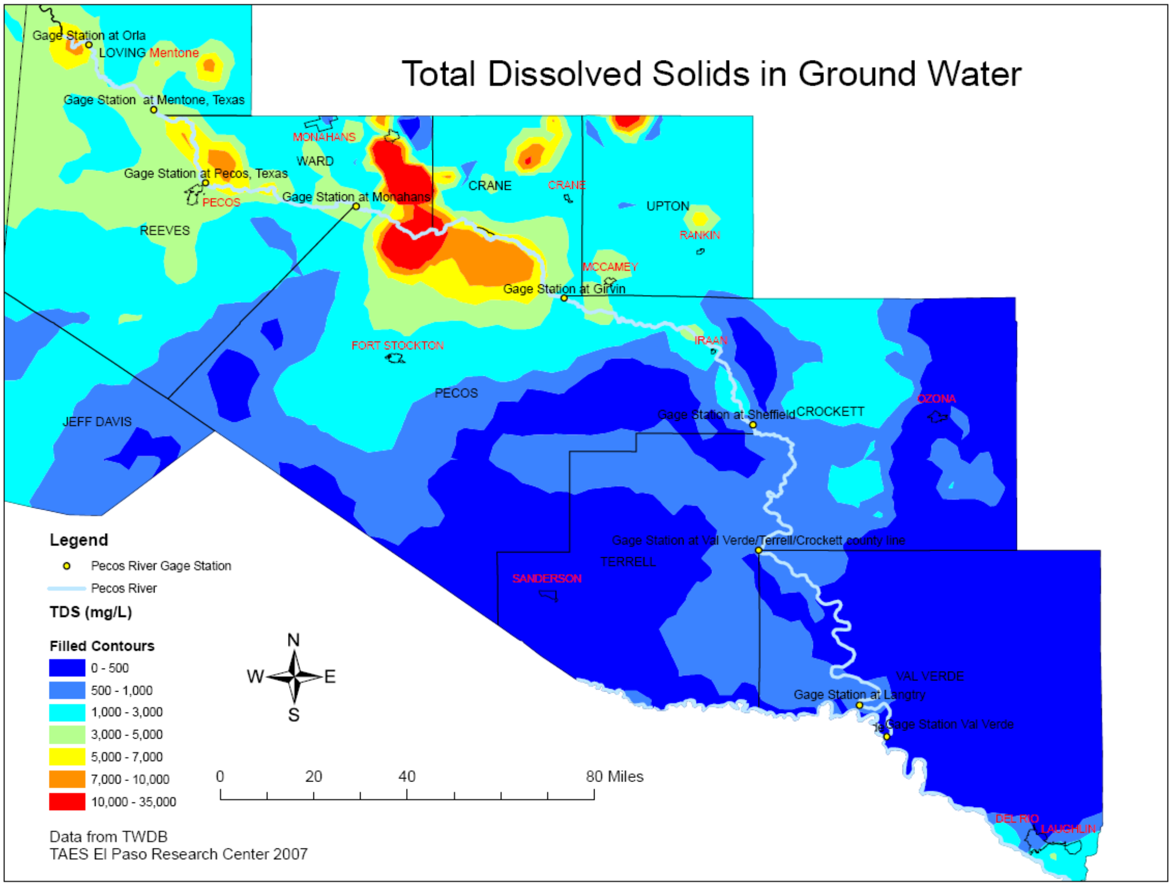
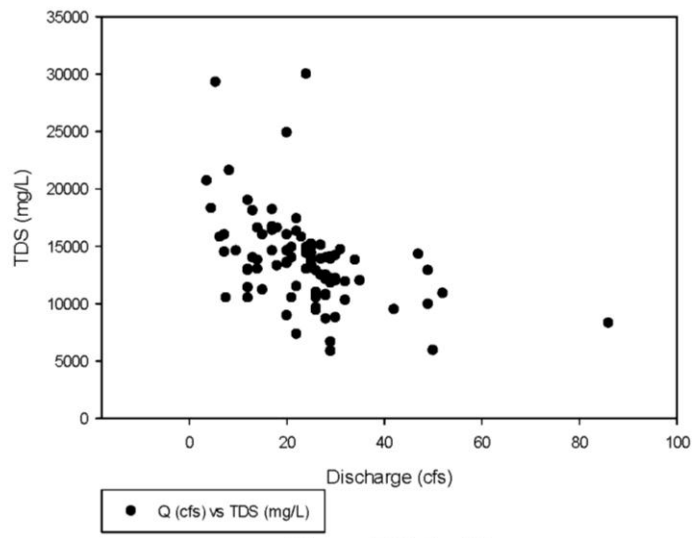


Figure 3.7-3. Distribution of ground water total dissolved solids (TDS) in the Pecos Basin of Texas.

This portion of the river is represented by the Girvin gage by the Texas Clean Rivers Program. TCRP data indicate the average water quality at Girvin is steady at about 15,000 ppm TDS. Generally the water quality decreases as flow decreases and water quality improves as the flow increases. The consistent quality over time further accentuates the proposal that Red Bluff Reservoir water flow and quality influence stop at Ward II irrigation district turnout and the flow through Girvin is the result of springs downstream of the Ward II irrigation district turnout.

Girvin – TDS vs. Discharge



Girvin – TDS (mg/L)

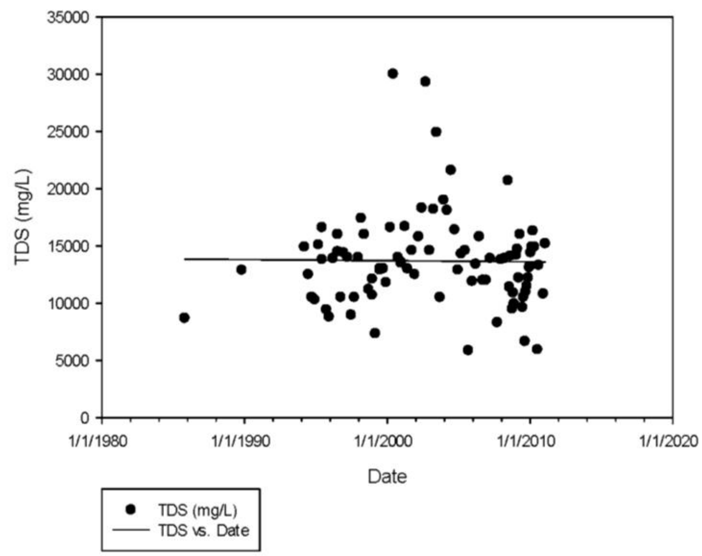


Figure 3.7-4. Water quality data for the Pecos River at Girvin.

During the winter months, the water quality will remain between 12,000 and 15,000 ppm TDS in this section. However, during the summer months, the water quality will remain between 12,000 to 15,000 ppm TDS near Coyanosa but will increase to 28,500 ppm TDS at Iraan. This increase in concentration is presumed to be from evaporation. It is important to realize, the first 80 miles of this 187 mile section of the river is cutoff from overland flow by irrigation canals (**Figure 2.6-10**). The poor quality spring flow is only supplemented by other Pecos Valley springs and irrigation return flow in the area. Area storm water flows never reach the Pecos River in the upper 80 miles of this section.

Just downstream of Iraan, the ground water quality greatly increases as its source is the Edwards Aquifer. However, it takes until the river reaches Independence Creek before the river can be designated a sound ecological environment. Below Iraan, the overland flows typically reach the river although there are no perennial streams other than Independence Creek.

At the confluence of the Pecos River and Independence Creek, the river flow volume increases by 42% and the TDS concentrations decrease by 50%. The TDS concentrations at Langtry are approximately 2,000 ppm (Miyamoto 2008).

The Texas Clean Rivers Program water quality data is extremely consistent for Independence Creek.

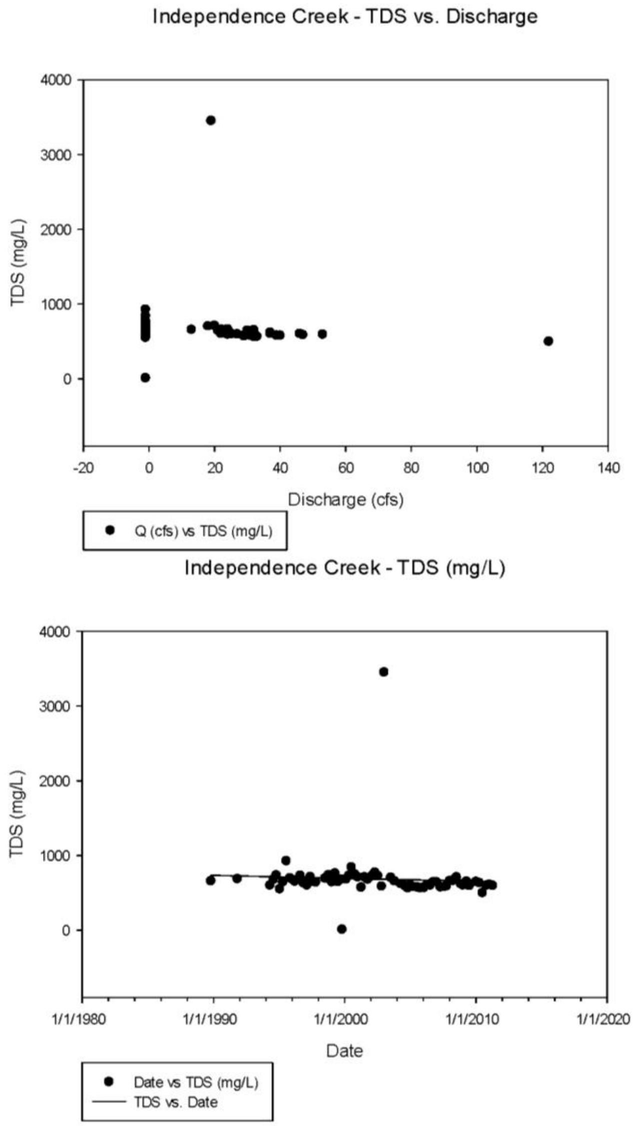


Figure 3.7-5. Water quality data for the Pecos River at Independence Creek near Sheffield.

Stream flow salinity at Girvin has increased since 1941. No salinity data are available at Girvin after 1982 except occasional measurements through the Texas Clean Rivers Program (TCRP). The flow has decreased to a range of 16,000 to 25,000 acre feet / year since the 1950s. Salinity reported at Langtry does not follow the salinity patterns above Red Bluff Reservoir but instead, follows the flow pattern at Girvin. The saline water passing through Girvin is the main source of salts, although it is diluted through tributary inflow below Girvin. Salinity at Langtry is around 2,000 ppm, and exceeds the Texas drinking water standards (Miyamoto 2008). The figures below depict how the flow patterns at Langtry follow the flow patterns at Girvin.

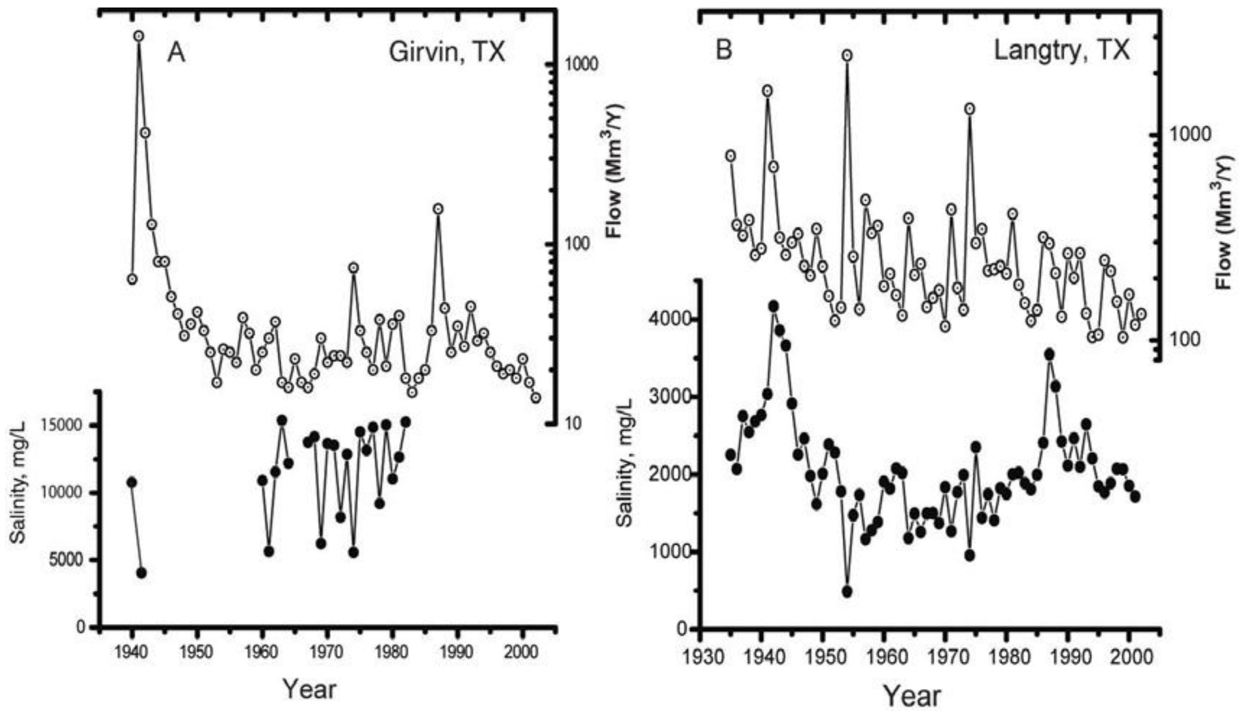


Figure 3.7-6. Historical records of flow and salinity at Girvin and Langtry (original data at Girvin from USGS, those at Langtry from IBWC).

Water quality at Langtry is slowly improving, however, during the same 30 year period, flow has been slowly decreasing. This information supports the hypothesis that there is less inflow above Iraan and therefore less salinity inflow. Water quality is improving due to less influence from brackish waters above Iraan and greater percentages of freshwater from the Edwards Aquifer. Water quality in the Lower Pecos River is greatly improved by flow from Independence Creek and continues to improve with additional ground water input before entering Amistad Reservoir. Currently, the Lower Pecos River is fully supporting all of the designated uses and water quality criteria.

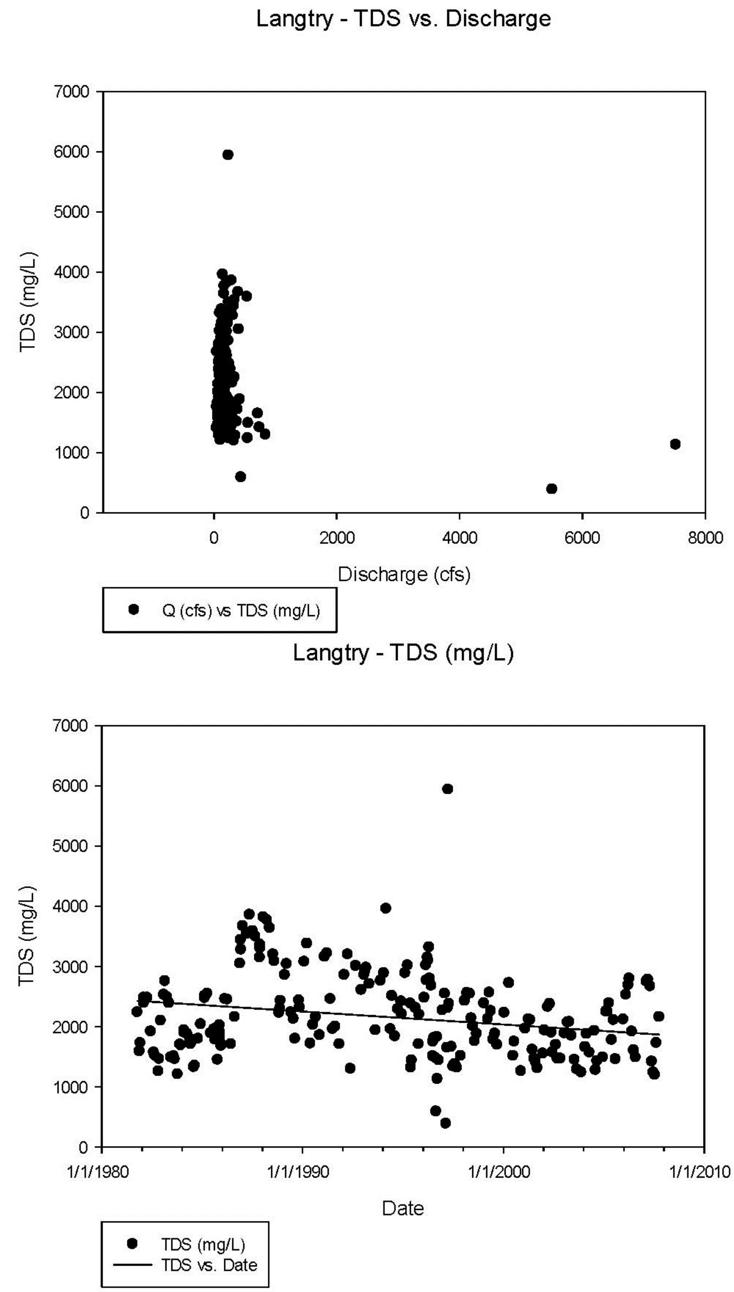


Figure 3.7-7. Water quality data from the Pecos River at Langtry.

3.7.3 Flow-habitat Modeling Results and Overlay (Independence Creek and Pecos River)

Site-specific results of flow-habitat analysis are presented and briefly summarized with conclusions for Independence Creek near Sheffield and the Pecos River at Brotherton Ranch near Sheffield. 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 three seasons) of subsistence flows and the three levels of base flows. The key to focal species abbreviations used in figures and tables throughout this section is: *E. gra*.=Rio Grande darter, *C. Pro*.=Proserpine shiner, *D. arg*.=manantial roundnose minnow, *N. ama*.=Texas shiner, *N. bra*.=Tamaulipas shiner, *N. str*.=sand shiner, *M. con*.=gray redhorse, *I. lup*.=headwater catfish, *A. mex*.=Mexican tetra, *L. meg*.=longear sunfish, *M. sal*.=largemouth bass and *C. cya*.=Rio Grande cichlid.

The flow-habitat modeling for Independence Creek near Sheffield indicates that the hydrology-based flow recommendations for base flows do not maintain suitable aquatic habitats for most of the focal species, but do maintain habitat diversity at this site (**Figure 3.7-9** and **Figure 3.7-10**, **Table 3.7-1** through **Table 3.7-4**, **Appendix 3.4**). The range of our Base Flow recommendations does not overlap the peaks of many of the focal species' flow-WUA curves, but intersect them on the rising portions of the curves. Because of this, the percent of Max WUA numbers for many species do not provide enough suitable habitat (**Table 3.7-1**). Regarding Subsistence flows, the 20% minimum threshold was easily met for all species in all seasons. However, regarding Base flows, there are six species for which one or more minimum thresholds of percent of maximum WUA were not maintained by the hydrology-based numbers, so some modifications to the initial flow regime are necessary to maintain instream habitats.

There is a general trend that habitat areas continue to increase across the entire range of flows modeled and only one or two curves in pool cross sections peak below 500 ft^3/s (**Figure 3.7-9**a, **Table 3.7-1**, **Table 3.7-2**). This is most likely due to the nature of the Independence Creek channel, which is wide and flat. In contrast to the Devils River site, this site has riffles, pools and runs in nearly the same proportion without one being dominant. Another consequence of the base flow range intersecting the flow-WUA curves on the steeply rising portion of the curves is that even small reductions in base flow recommendations results in significant reductions in habitat.

Because species are not evenly distributed among cross-sections at our sites, we decided to emphasize cross-section subsets in biological overlay decision-making. All three riffle species (Rio Grande darter, Proserpine shiner and manantial roundnose minnow) did have the 75% Base-Low threshold met, but the 90% threshold was not met until above the Base-High range (**Figure 3.7-10**b, **Table 3.7-3**). For two of these three species (Rio Grande darter, Proserpine shiner) 40 ft^3/s is needed to meet the 90% threshold in the riffle cross-sections and the other (manantial roundonse minnow) 30 ft^3/s. One of the three primary run species (headwater catfish) also does not have the 90% threshold met until above the Base-High range; 40 ft^3/s is needed to achieve 90% (**Figure 3.7-10**c, **Table 3.7-4**). The other two run species (Texas shiner and gray redhorse) did have their thresholds met in the Base flow ranges. Pool species all had their 75% thresholds met in or below the Base flow range (**Figure 3.7-10**d).

Figure 3.7-11 and **Table 3.7-5** show the results of the habitat time series analysis for the whole period of record of historical flows at Independence Creek near Sheffield. These results are for all cross-sections and do not consider cross-section subsets separately, though this could be done in the future. We recommend that environmental flow standards adopted by the BBASC not reduce these frequencies more than 10%.

3.7.3.1 Effects of flow-habitat analysis on environmental flow recommendations

As a result of this analysis we made significant modifications to the hydrology-based flow regimes in the Base flow range. The three tiers of Base flow resulting from HEFR analysis at Independence Creek are very similar (within 5 ft³/s of one another) and there is no indication from the habitat analysis that three tiers are required to maintain instream habitats. So, we reduced the number of Base Flow tiers thereby simplifying the flow regime somewhat. We recommend two base flow tiers, a Base-Low tier with numbers similar to the HEFR-derived values and a second tier which we call "Base-Normal" that has flow numbers defined by the habitat analysis. We recommend a Base-Low with 25 ft³/s for all three seasons and the Base-Normal with 40 ft³/s for all seasons. The number of 40 ft³/s is recommended to maintain sufficient habitats for four imperiled species; Proserpine shiner, Rio Grande darter, manantial roundnose minnow and headwater catfish.

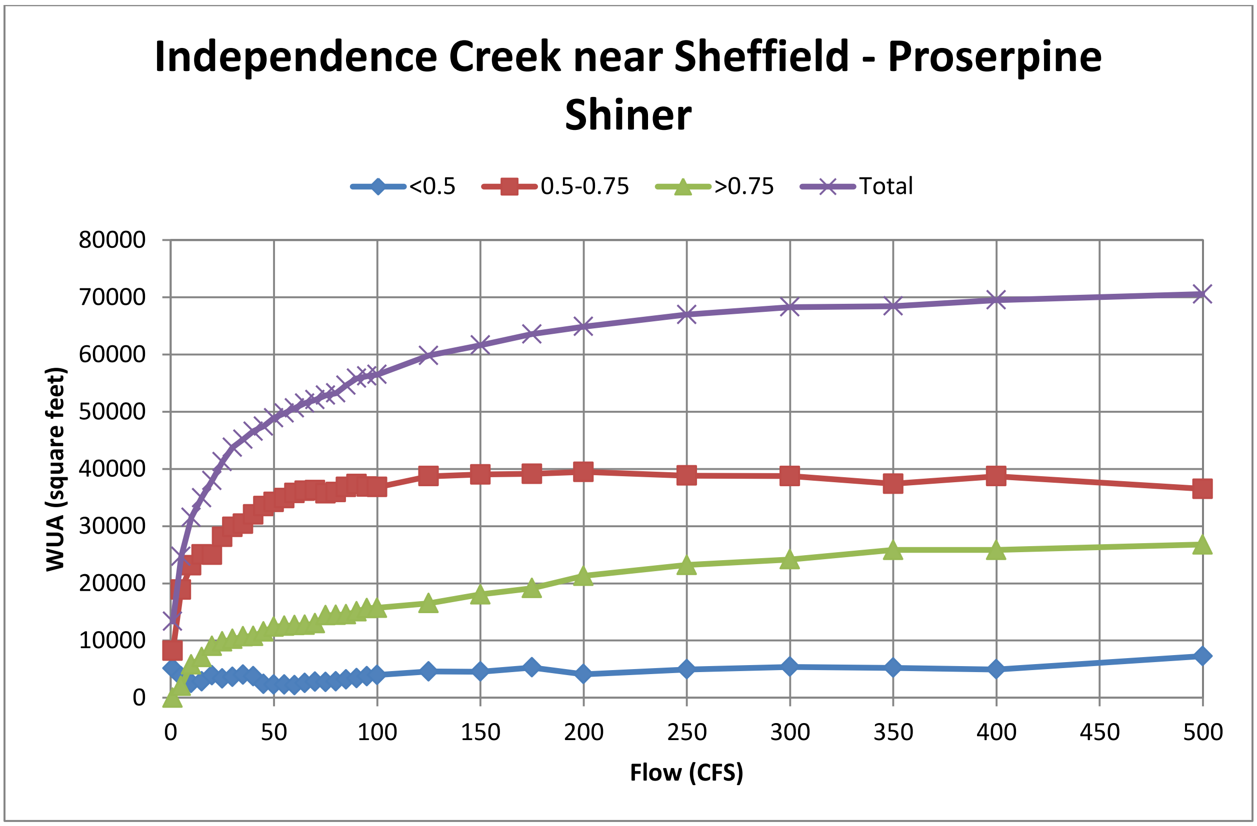


Figure 3.7-8. Four ranges of weighted usable habitat area quality (<0.5, 0.5-0.8, >0.8, and total) versus modeled flow (ft³/s) for proserpine shiner (Cyprinella proserpina) at Independence Creek near Sheffield.

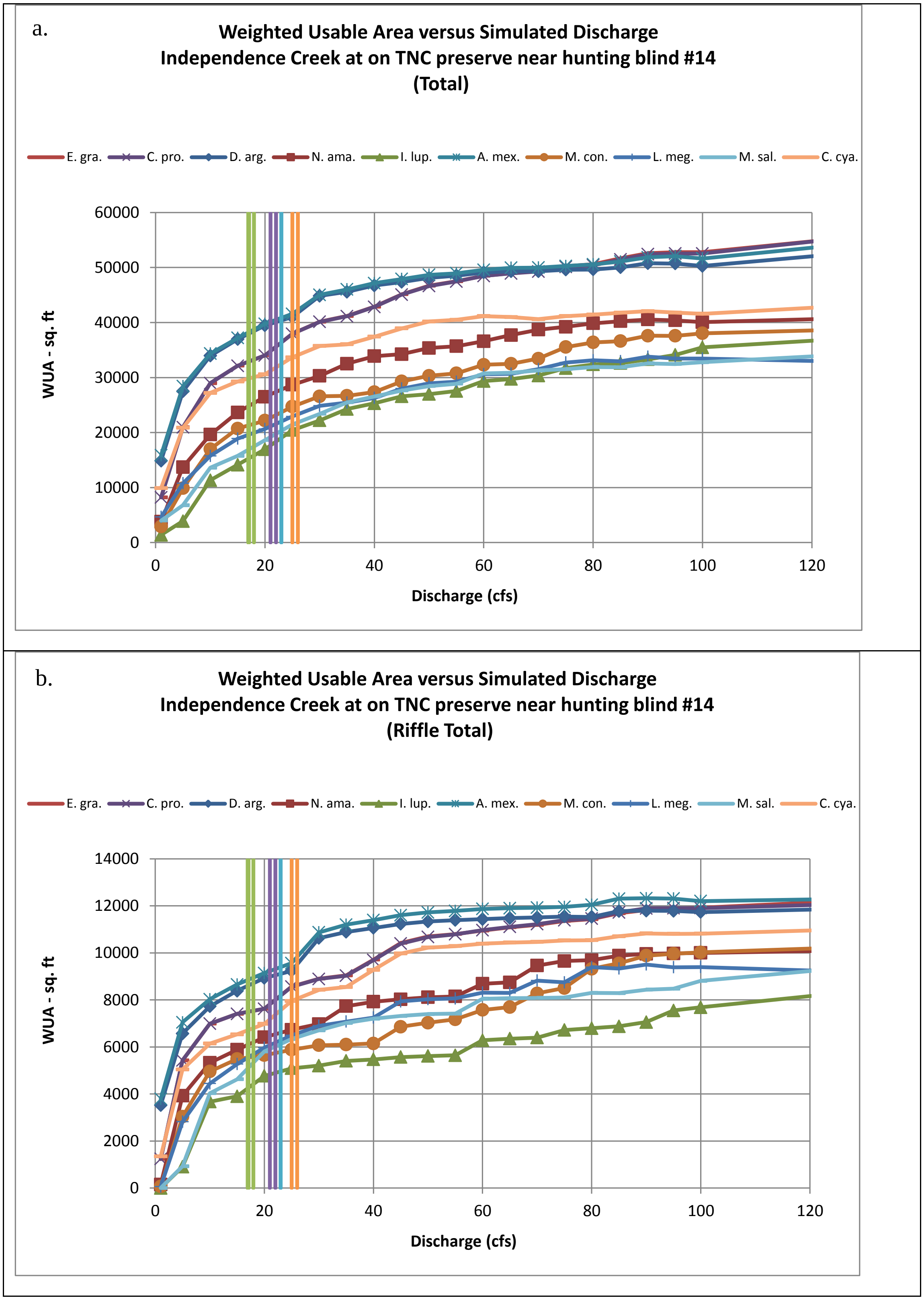
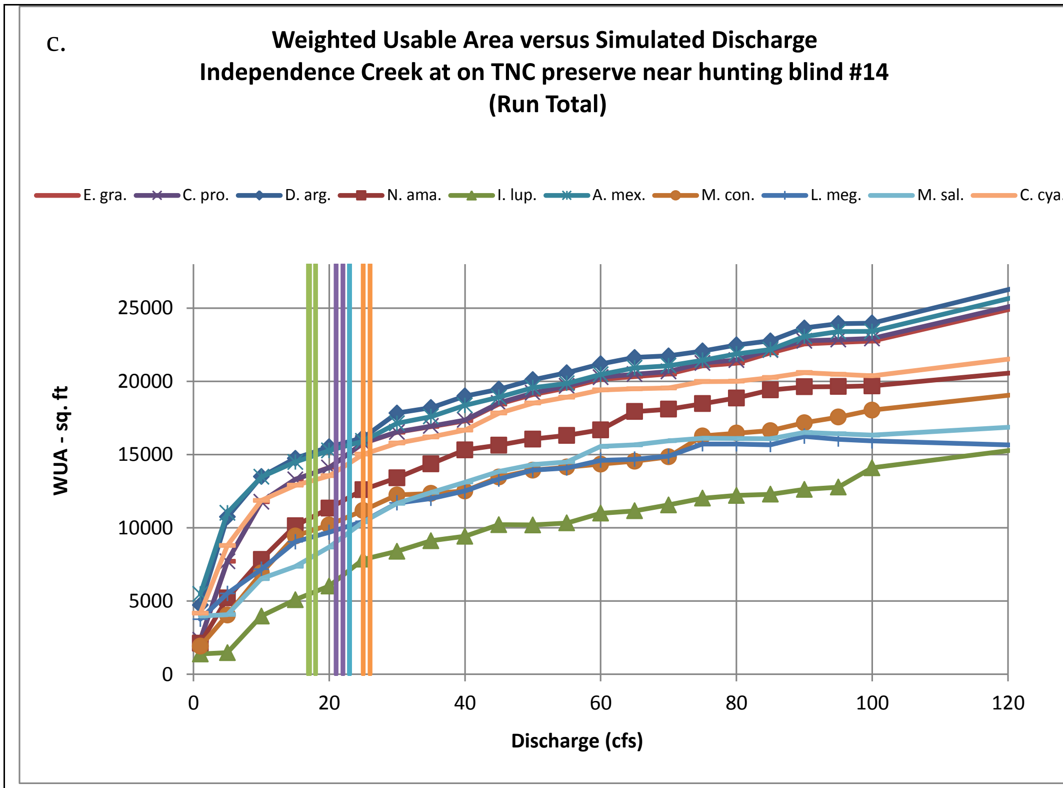


Figure 3.7-9. Weighted usable habitat area with a 0.5 minimum quality threshold versus modeled flow (ft³/s) for 10 focal species at Independence Creek near Sheffield. Shown are WUA versus flow relationships for a) all cross-sections, b) riffle cross-sections, c) run cross-sections and d) pool cross-sections. Vertical bars bracket environmental flow regime components.



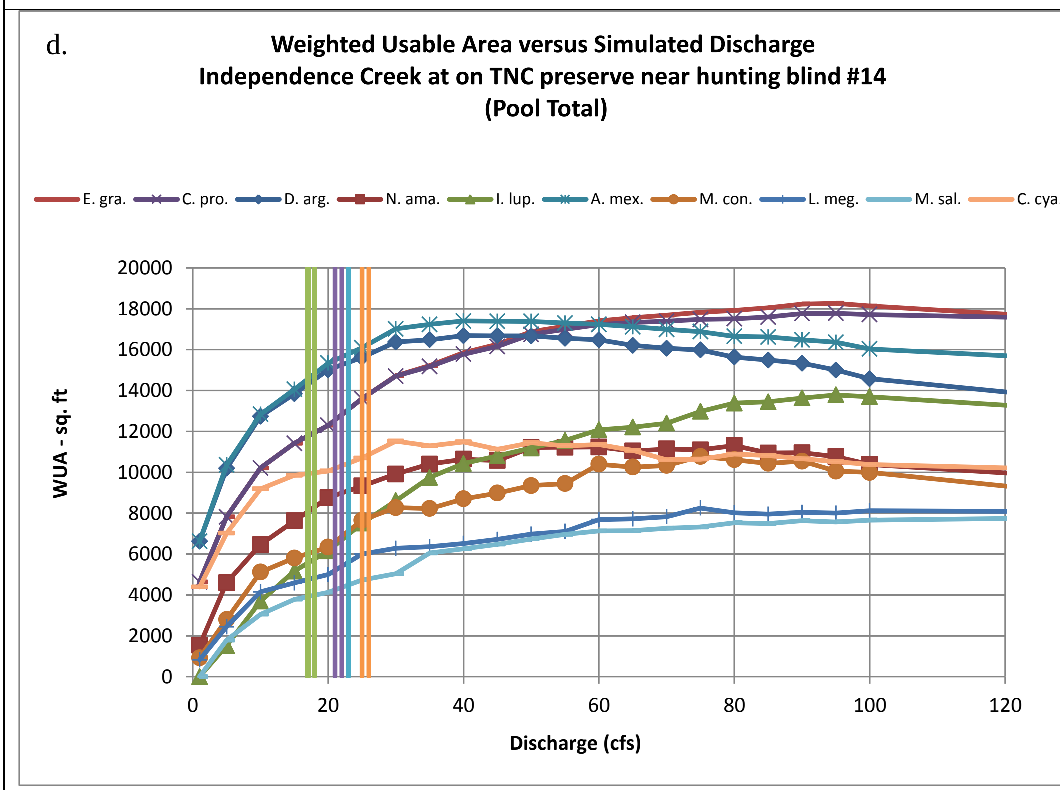
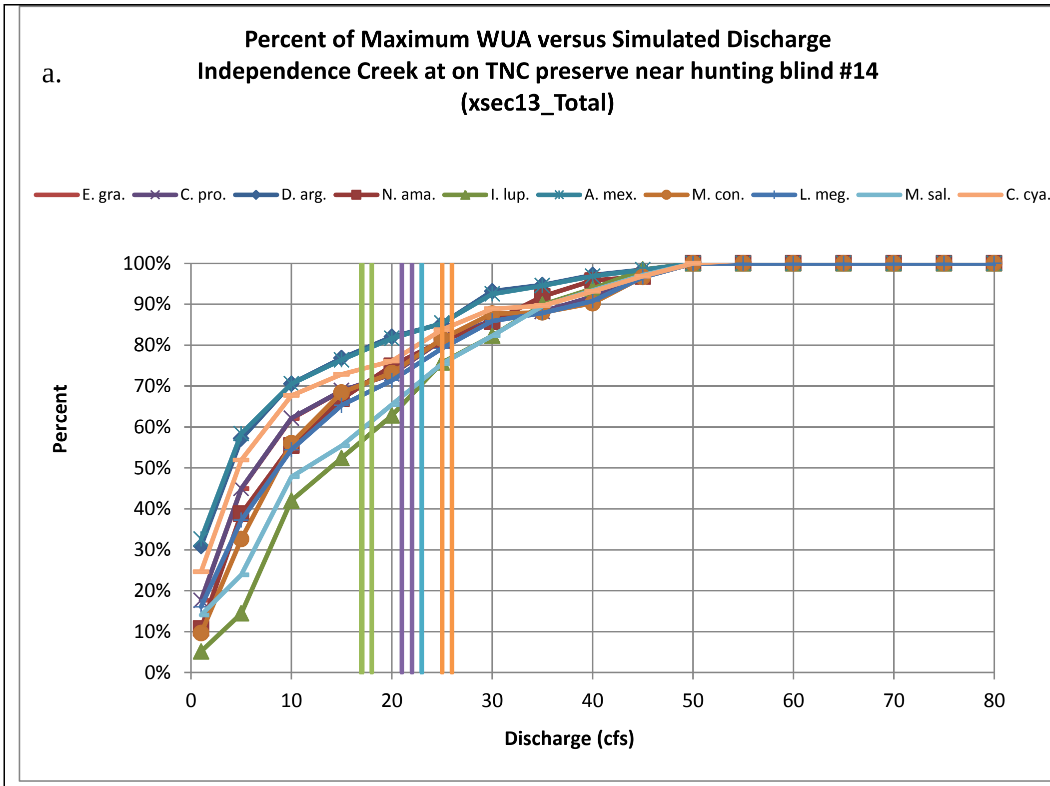


Figure 3.7-9. Continued.



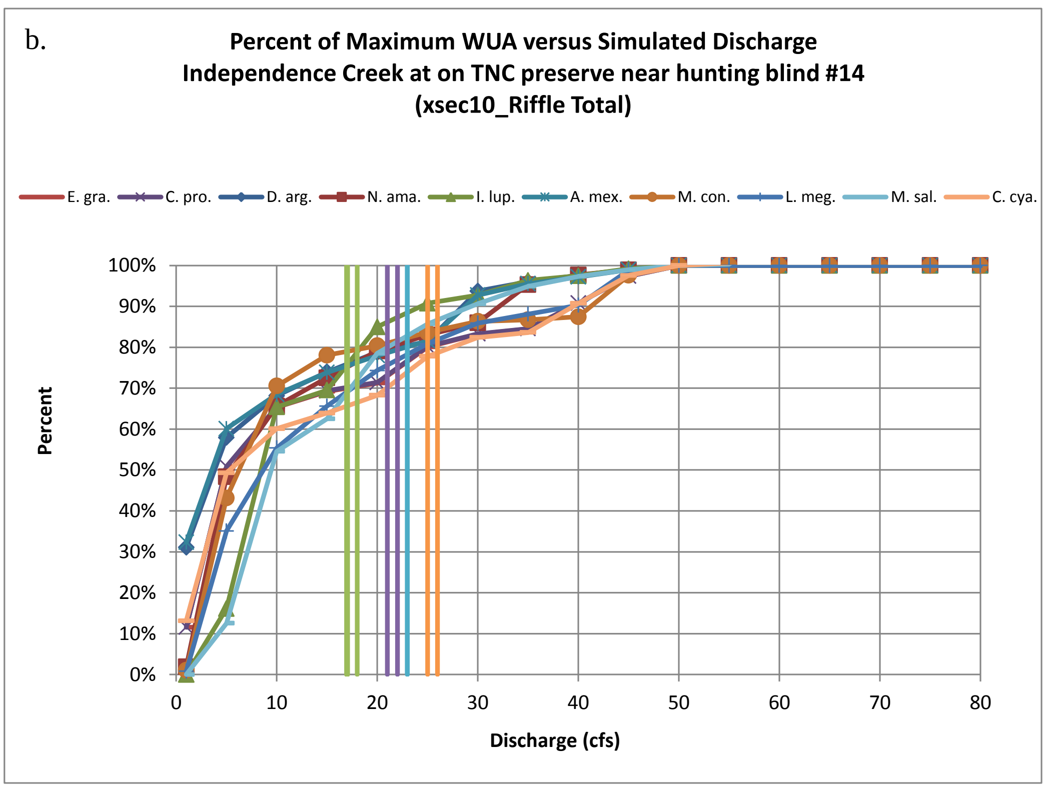
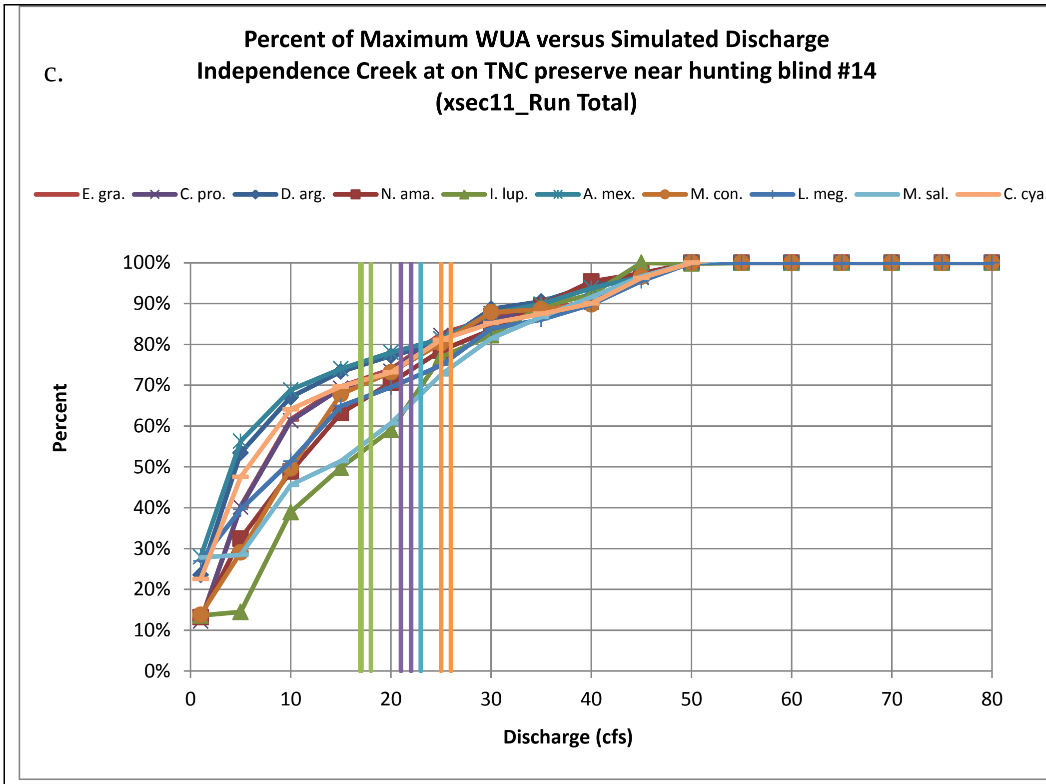


Figure 3.7-10. Graphs a) and b);



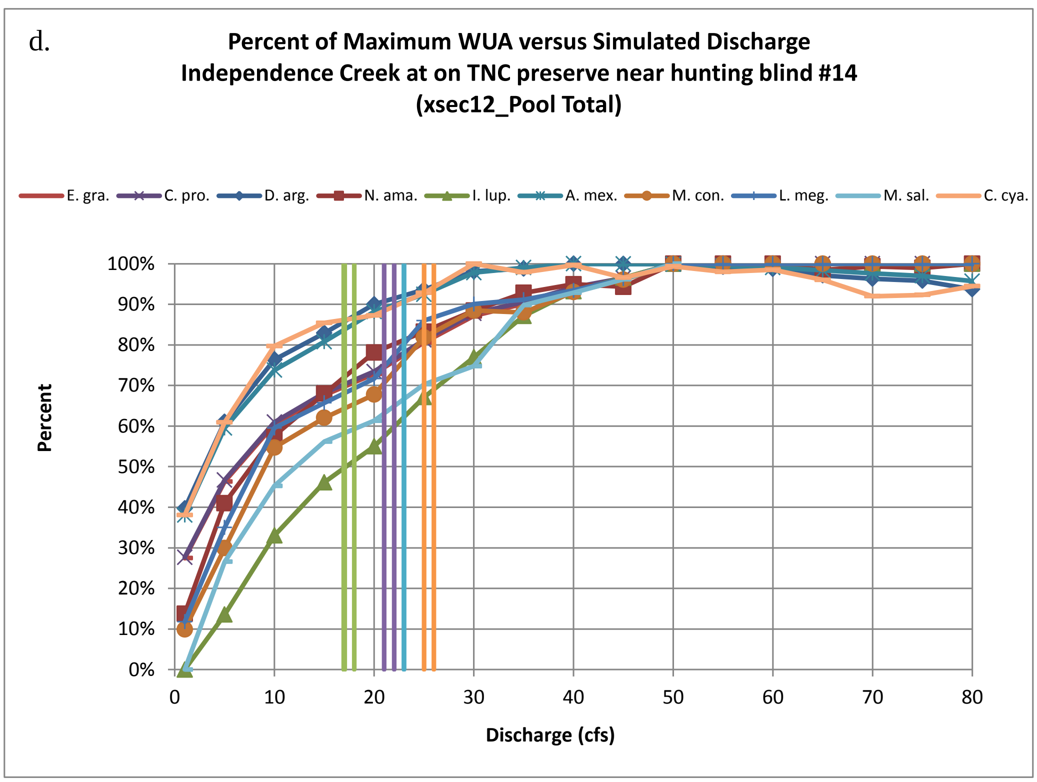


Figure 3.7-10. Percent of maximum weighted usable habitat area with a 0.5 minimum quality threshold versus modeled flow (ft³/s) for 10 focal species at Independence Creek near Sheffield. Shown are percent of maximum WUA versus flow relationships for a) all cross-sections, b) riffle cross-sections, 3) run cross-sections and d) pool cross-sections. Vertical bars bracket environmental flow regime components.

Table 3.7-1. Percent of maximum weighted usable habitat area with a 0.5 minimum quality threshold for 10 focal species resulting from hydrology-based flow regime (HEFR) results at the Independence Creek near Sheffield. Shown are percentages for Subsistence and all three ranges of Base Flows. Shaded cells are those flows meeting "enoughness" thresholds of 20 % for Subsistence flows and 75 or 90 % (per requirements for each species) for all three ranges of Base Flows.

Focal Species	Flow Component	Percent of Maximum Weighted Usable Area		
		Winter	Spring	Monsoon
Cyprinella proserpina	Subsistence	71%	71%	71%
	Base - Low	76%	75%	75%
	Base - Medium	78%	78%	78%
	Base - High	81%	82%	81%
Dionda argentosa	Subsistence	80%	79%	79%
	Base - Low	83%	83%	83%
	Base - Medium	84%	84%	84%
	Base - High	85%	87%	85%
Notropis amabilis	Subsistence	72%	70%	70%
	Base - Low	77%	76%	76%
	Base - Medium	79%	79%	79%
	Base - High	81%	82%	81%
Moxostoma congestum	Subsistence	71%	70%	70%
	Base - Low	77%	75%	75%
	Base - Medium	78%	78%	78%
	Base - High	82%	83%	82%
Ictalurus lupus	Subsistence	59%	57%	57%
	Base - Low	68%	65%	65%
	Base - Medium	71%	71%	71%
	Base - High	76%	77%	76%
Astyanax mexicanus	Subsistence	80%	79%	79%
	Base - Low	83%	82%	82%
	Base - Medium	84%	84%	84%
	Base - High	85%	87%	85%
Micropterus salmoides	Subsistence	51%	50%	50%
	Base - Low	58%	56%	56%
	Base - Medium	60%	60%	60%
	Base - High	63%	64%	63%
Lepomis megalotis	Subsistence	69%	68%	68%
	Base - Low	75%	73%	73%
	Base - Medium	76%	76%	76%
	Base - High	79%	81%	79%
Etheostoma grahami	Subsistence	71%	70%	70%
	Base - Low	76%	75%	75%
	Base - Medium	78%	78%	78%
	Base - High	81%	82%	81%
Cichlasoma cyanoguttatum	Subsistence	64%	63%	63%
	Base - Low	67%	66%	66%
	Base - Medium	69%	69%	69%
	Base - High	71%	72%	71%

Table 3.7-2. Percent of maximum weighted usable area across all cross-sections with a minimum habitat quality of 0.5 for all 10 focal species at all modeled flows for Independence Creek near Sheffield. Shaded cells are those flows meeting "enoughness" thresholds of 75 or 90 % (per requirements for each species).

Modeled Flow (FT^3/S)	***C. pro.***	***D. arg.***	***N. ama.***	***M. con.***	***I. lup.***	***A. mex.***	***M. sal.***	***L. meg.***	***E. gra.***	***C. cya.***
1	18%	31%	11%	10%	5%	33%	12%	16%	18%	21%
5	45%	57%	39%	33%	14%	58%	20%	37%	45%	44%
10	62%	71%	55%	56%	42%	71%	40%	54%	62%	57%
15	69%	77%	67%	68%	52%	76%	46%	65%	69%	62%
20	73%	82%	75%	73%	63%	82%	55%	71%	73%	65%
25	81%	85%	81%	82%	76%	85%	63%	79%	81%	71%
30	86%	93%	86%	88%	82%	92%	69%	86%	86%	75%
35	88%	95%	92%	88%	90%	95%	75%	88%	88%	76%
40	92%	97%	96%	90%	94%	97%	78%	91%	92%	79%
45	97%	98%	97%	97%	98%	98%	81%	97%	97%	82%
50	100%	100%	100%	100%	100%	100%	83%	100%	100%	85%
55	100%	100%	100%	100%	100%	100%	85%	100%	100%	86%
60	100%	100%	100%	100%	100%	100%	90%	100%	100%	87%
65	100%	100%	100%	100%	100%	100%	91%	100%	100%	87%
70	100%	100%	100%	100%	100%	100%	92%	100%	100%	86%
75	100%	100%	100%	100%	100%	100%	93%	100%	100%	87%
80	100%	100%	100%	100%	100%	100%	94%	100%	100%	88%
85	100%	100%	100%	100%	100%	100%	93%	100%	100%	88%
90	100%	100%	100%	100%	100%	100%	96%	100%	100%	89%
95	100%	100%	100%	100%	100%	100%	95%	100%	100%	88%
100	100%	100%	100%	100%	100%	100%	96%	100%	100%	88%
125	100%	100%	100%	100%	100%	100%	100%	100%	100%	91%
150	100%	100%	100%	100%	100%	100%	99%	100%	100%	93%
175	100%	100%	100%	100%	100%	100%	97%	100%	100%	95%
200	100%	100%	100%	100%	100%	100%	98%	100%	100%	100%
250	100%	100%	100%	100%	100%	100%	93%	100%	100%	100%
300	100%	100%	100%	100%	100%	100%	97%	100%	100%	100%
350	100%	100%	100%	100%	100%	100%	95%	100%	100%	99%
400	100%	100%	100%	100%	100%	100%	93%	100%	100%	98%
500	100%	100%	100%	100%	100%	100%	87%	81%	100%	94%

Table 3.7-3. Percent of maximum weighted usable area across riffle cross-sections with a minimum habitat quality of 0.5 for all 10 focal species at all modeled flows for Independence Creek near Sheffield. Shaded cells are those flows meeting "enoughness" thresholds of 75 or 90 % (per requirements for each species).

Modeled Flow (FT^3/S)	***C. pro.***	***D. arg.***	***N. ama.***	***M. con.***	***I. lup.***	***A. mex.***	***M. sal.***	***L. meg.***	***E. gra.***	***C. cya.***
1	12%	31%	2%	1%	0%	32%	0%	1%	12%	13%
5	51%	58%	48%	43%	16%	60%	13%	35%	51%	49%
10	65%	68%	66%	71%	65%	68%	55%	55%	65%	60%
15	69%	74%	73%	78%	70%	74%	63%	66%	69%	64%
20	71%	79%	79%	80%	85%	78%	79%	74%	71%	68%
25	80%	81%	83%	84%	91%	82%	86%	81%	80%	78%
30	83%	94%	86%	86%	93%	93%	91%	86%	83%	82%
35	85%	96%	95%	87%	96%	96%	95%	88%	85%	84%
40	91%	98%	98%	87%	97%	97%	97%	90%	91%	91%
45	97%	99%	99%	98%	99%	99%	99%	99%	97%	98%
50	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
55	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
60	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
65	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
70	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
75	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
80	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
85	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
90	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
95	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
100	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
125	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
150	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
175	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
200	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
250	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
300	100%	100%	100%	100%	100%	89%	100%	100%	100%	100%
350	100%	100%	100%	100%	100%	87%	100%	100%	100%	100%
400	100%	100%	100%	100%	100%	83%	100%	100%	100%	100%
500	100%	92%	100%	100%	100%	81%	100%	96%	100%	100%

Table 3.7-4. Percent of maximum weighted usable area across run cross-sections with a minimum habitat quality of 0.5 for all 10 focal species at all modeled flows for Independence Creek near Sheffield. Shaded cells are those flows meeting "enoughness" thresholds of 75 or 90 % (per requirements for each species).

Modeled Flow (FT^3/S)	*C. pro.*	*D. arg.*	*N. ama.*	*M. con.*	*I. lup.*	*A. mex.*	*M. sal.*	*L. meg.*	*E. gra.*	*C. cya.*
1	12%	24%	13%	14%	14%	28%	28%	27%	12%	22%
5	40%	53%	32%	29%	14%	56%	28%	40%	40%	48%
10	61%	67%	49%	50%	39%	69%	46%	51%	62%	64%
15	69%	73%	63%	68%	50%	74%	51%	65%	70%	70%
20	73%	77%	71%	73%	59%	78%	61%	69%	74%	73%
25	82%	80%	79%	80%	77%	81%	73%	75%	83%	81%
30	86%	89%	84%	88%	82%	88%	81%	84%	86%	85%
35	88%	91%	90%	89%	89%	90%	87%	86%	89%	88%
40	90%	94%	95%	90%	92%	94%	92%	90%	91%	90%
45	96%	97%	97%	97%	100%	97%	97%	96%	97%	96%
50	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
55	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
60	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
65	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
70	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
75	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
80	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
85	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
90	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
95	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
100	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
125	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
150	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
175	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
200	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
250	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
300	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
350	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
400	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
500	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

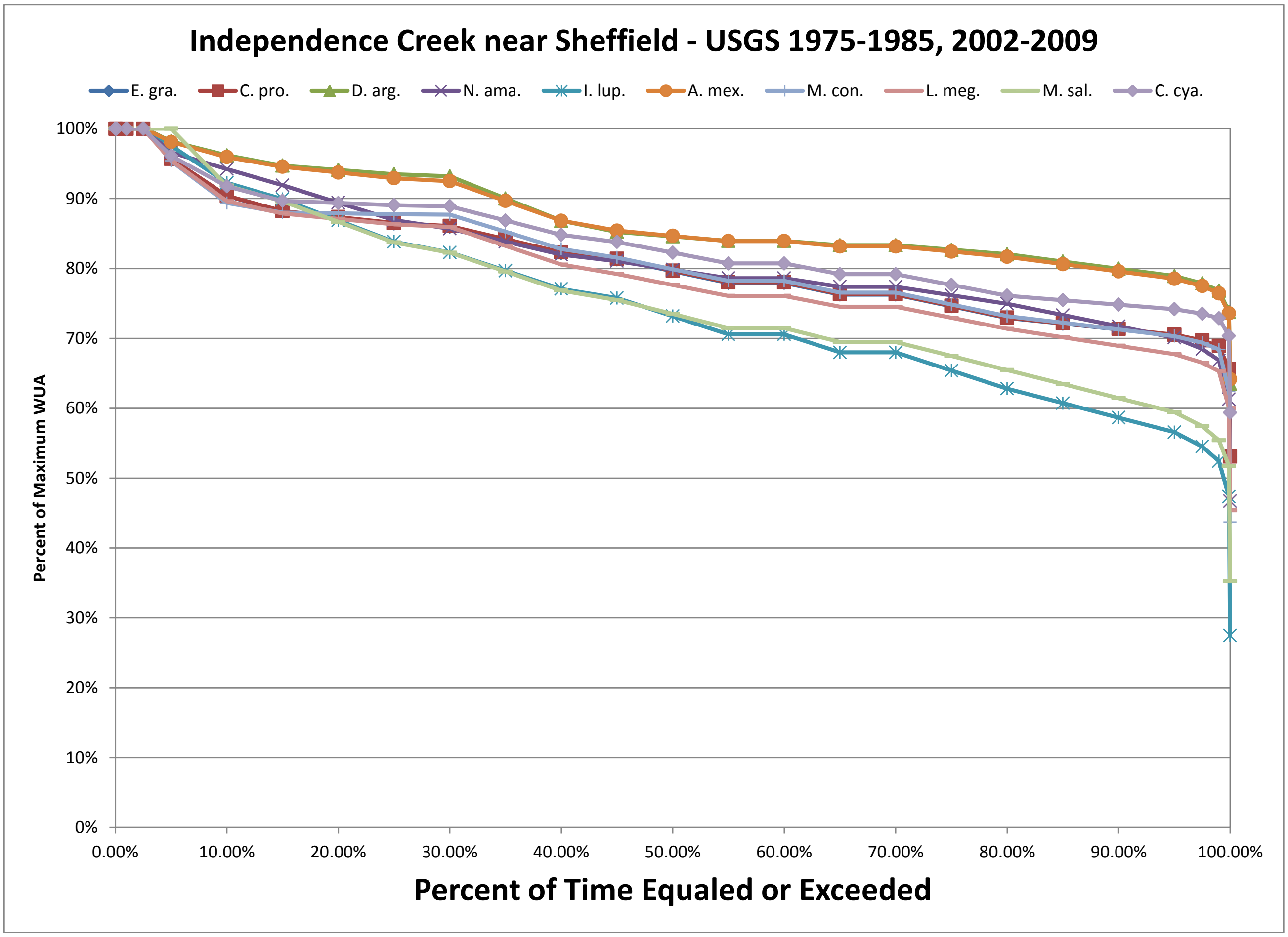


Figure 3.7-11. Habitat frequency curves for 10 focal species for the full period of record of historical flows (1975-1985, 2002-2009) at the USGS gage at Independence Creek near Sheffield.

Table 3.7-5. Percent of maximum habitat maintained by the range of percent exceedance examined for the full period of record of historical flows at Independence Creek near Sheffield. Shaded cells are those exceedance levels that meet the 75 or 90 % (per requirements for each species) enoughness thresholds. Data presented are for all cross-sections.

Percent Exceedance Level	***C. pro.***	***D. arg.***	***N. ama.***	***M. con.***	***I. lup.***	***A. mex.***	***M. sal.***	***L. meg.***	***E. gra.***	***C. cya.***
99.99%	53%	64%	47%	44%	27%	64%	35%	45%	53%	59%
99.9%	66%	74%	61%	62%	47%	74%	52%	60%	66%	70%
99%	69%	77%	67%	68%	52%	76%	55%	65%	69%	73%
98%	70%	78%	68%	69%	55%	77%	57%	67%	70%	74%
95%	71%	79%	70%	70%	57%	79%	59%	68%	70%	74%
90%	71%	80%	72%	71%	59%	80%	61%	69%	71%	75%
85%	72%	81%	73%	72%	61%	81%	63%	70%	72%	75%
80%	73%	82%	75%	73%	63%	82%	65%	71%	73%	76%
75%	75%	83%	76%	75%	65%	82%	67%	73%	75%	78%
70%	76%	83%	77%	77%	68%	83%	69%	75%	76%	79%
65%	76%	83%	77%	77%	68%	83%	69%	75%	76%	79%
60%	78%	84%	79%	78%	71%	84%	71%	76%	78%	81%
55%	78%	84%	79%	78%	71%	84%	71%	76%	78%	81%
50%	80%	85%	80%	80%	73%	85%	73%	78%	80%	82%
45%	81%	85%	81%	82%	76%	85%	75%	79%	81%	84%
40%	82%	87%	82%	83%	77%	87%	77%	81%	82%	85%
35%	84%	90%	84%	85%	80%	90%	80%	83%	84%	87%
30%	86%	93%	86%	88%	82%	92%	82%	86%	86%	89%
25%	86%	93%	87%	88%	84%	93%	84%	86%	86%	89%
20%	87%	94%	89%	88%	87%	94%	87%	87%	87%	89%
15%	88%	95%	92%	88%	90%	95%	90%	88%	88%	90%
10%	90%	96%	94%	89%	92%	96%	92%	90%	90%	92%
5%	96%	98%	97%	95%	98%	98%	100%	95%	96%	96%
3%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
1%	100%	102%	100%	100%	100%	100%	100%	100%	100%	100%
0.1%	100%	113%	100%	100%	100%	100%	100%	100%	100%	100%
0.01%	100%	115%	100%	100%	100%	100%	100%	100%	100%	100%

3.7.3.2 Pecos River at Brotherton Ranch near Pandale

There is not a sufficient period of record of daily flows for the Pecos River at Brotherton Ranch near Pandale for a full HEFR run. But, to determine the general magnitude of base flows at this gage we did an abbreviated hydrographic separation in IHA using default percentages. From this we derived the 25th, 50th and 75th percentiles for low flows for each month as a Base-Low, Base-Medium and Base-High (respectively) value. We then averaged these flows across the months for the seasons to calculate a single number for each of the 3 base flow tiers for each season (**Table 3.7-6**).

Table 3.7-6. Initial base flow numbers derived from an abbreviated hydrographic separation using IHA for the Pecos River at Brotherton near Pandale.

Base Flow Tier	Winter	Spring	Monsoon
High	111	89	107
Medium	101	76	85
Low	80	60	62

The flow-habitat modeling for the Pecos River at Brotherton Ranch near Pandale indicates that the flow recommendations for base flows resulting from our abbreviated hydrology analysis do maintain suitable aquatic habitats for most of the focal species and maintain habitat diversity at this site (**Figure 3.7-13** and **Figure 3.7-14, Table 3.7-7** through **Table 3.7-10**, **Appendix 3.4**). The range of our Base Flow recommendations does overlap the peaks of several of the focal species' flow-WUA curves and the percent of Max WUA numbers for most species provides enough suitable habitat (**Table 3.7-7**). Regarding Subsistence flows, the 20% minimum threshold was easily met for all species in all seasons. However, regarding Base flows, there is one species for which one or more minimum thresholds of percent of maximum WUA were not maintained by the hydrology-based numbers, so some modifications to the initial flow regime are necessary to maintain instream habitats.

There is a general trend that nearly all species' habitat area curves do peak in the range of flows modeled and our range of Base flows does overlap the peaks for most species (**Figure 3.7-13**a, **Table 3.7-7**, **Table 3.7-8**), with the exception of two species of conservation concern, proserpine shiner and Tamaulipas shiner. In contrast to the Devils River site, this site has riffles, pools and runs in nearly the same proportion without one being dominant.

Because species are not evenly distributed among cross-sections at our sites, we decided to emphasize cross-section subsets in biological overlay decision-making. All four riffle species (Rio Grande darter, proserpine shiner, manantial roundnose minnow and Tamaulipas shiner) did have both the 75% Base-Low threshold and their 90% thresholds met in the Base flow range (**Figure 3.7-14**b, **Table 3.7-9**), though the minimum flow needed to maintain 90% of Tamaulipas shiner WUA in riffle cross-sections (90 ft^3/s) was just above the Spring Base-High number. All three of the primary run species (Texas shiner, Tamaulipas shiner and gray redhorse) have their 75% or 90% thresholds met in or below the Base flow range (**Figure 3.7-14**c, **Table 3.7-10**). Pool species all had their 75% thresholds met in or below the Base flow range (**Figure 3.7-14**d).

Figure 3.7-15 and **Table 3.7-11** show the results of the habitat time series analysis for the whole period of record of historical flows at the Pecos River at Brotherton Ranch near Pandale. These results are for all cross-sections and do not consider cross-section subsets separately, though this could be done in the future. We recommend that environmental flow standards adopted by the BBASC not reduce these frequencies more than 10%. However, these numbers are derived from a very short period of record and need to be strengthened by reexamination after a longer period of daily flow record.

3.7.3.3 Effects of flow-habitat analysis on environmental flow recommendations

As a result of this analysis we made significant modifications to the hydrology-based flow regimes resulting from the abbreviated analysis in the Base flow range. Two tiers of base flow are created. A Base-Low tier is created with the numbers from our abbreviated hydrographic separation and analysis. These flows need to remain at least 60 ft³/s because the minimum thresholds for Rio Grande darter, Proserpine shiner and Tamaulipas shiner are not met for any flows below this magnitude. A second tier, called Base-Normal, is created using the Base-Medium numbers from our abbreviated hydrology analysis but with the Spring and Monsoon numbers increased to 90 ft³/s to meet the minimum threshold for Tamaulipas shiner in riffle cross-sections. Because the Base-High numbers are not significantly higher than the Base-Medium numbers and because of uncertainty due to the short period of record, we are not recommending a third Base-High tier of flows. We also make this recommendation for the sake of simplicity of the flow regime recommendations. However, it should be recognized that we view these numbers, including the Base-Normal, as minimum numbers. These should not be diluted further.

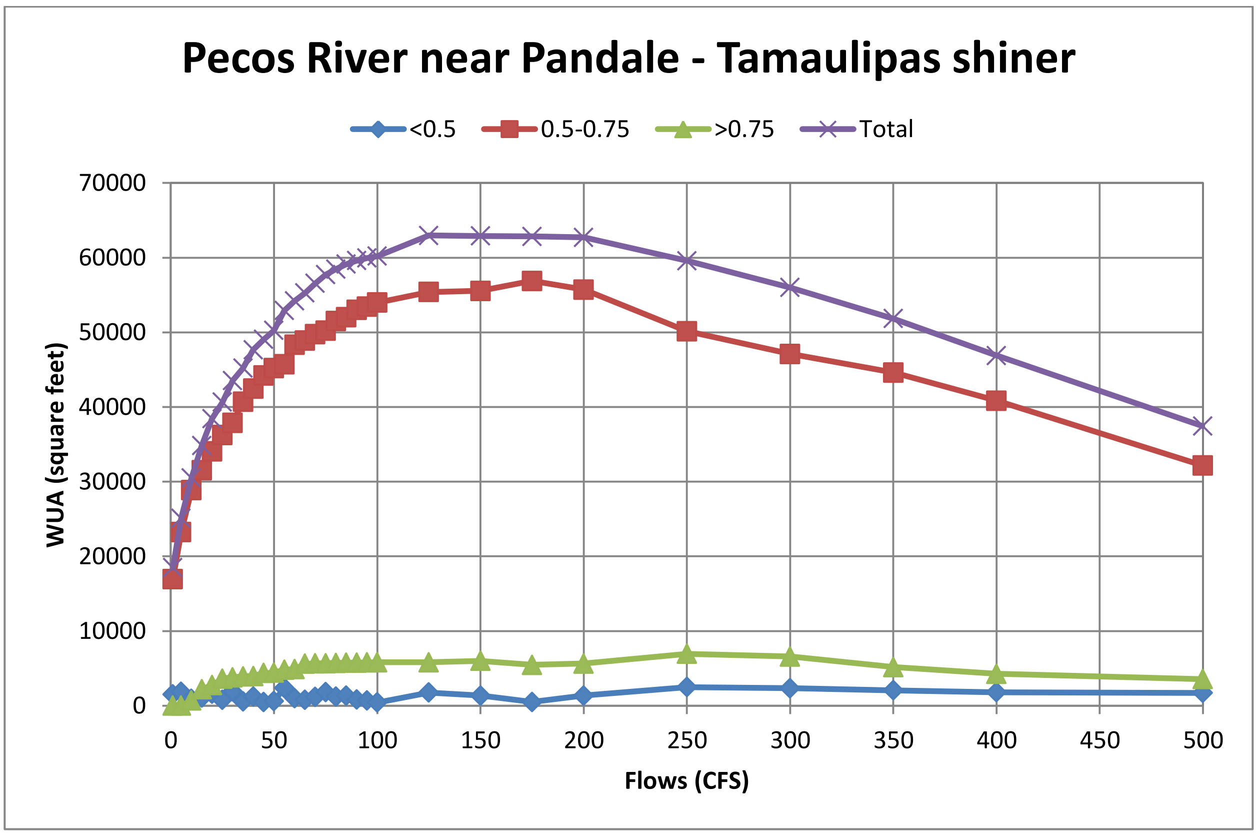
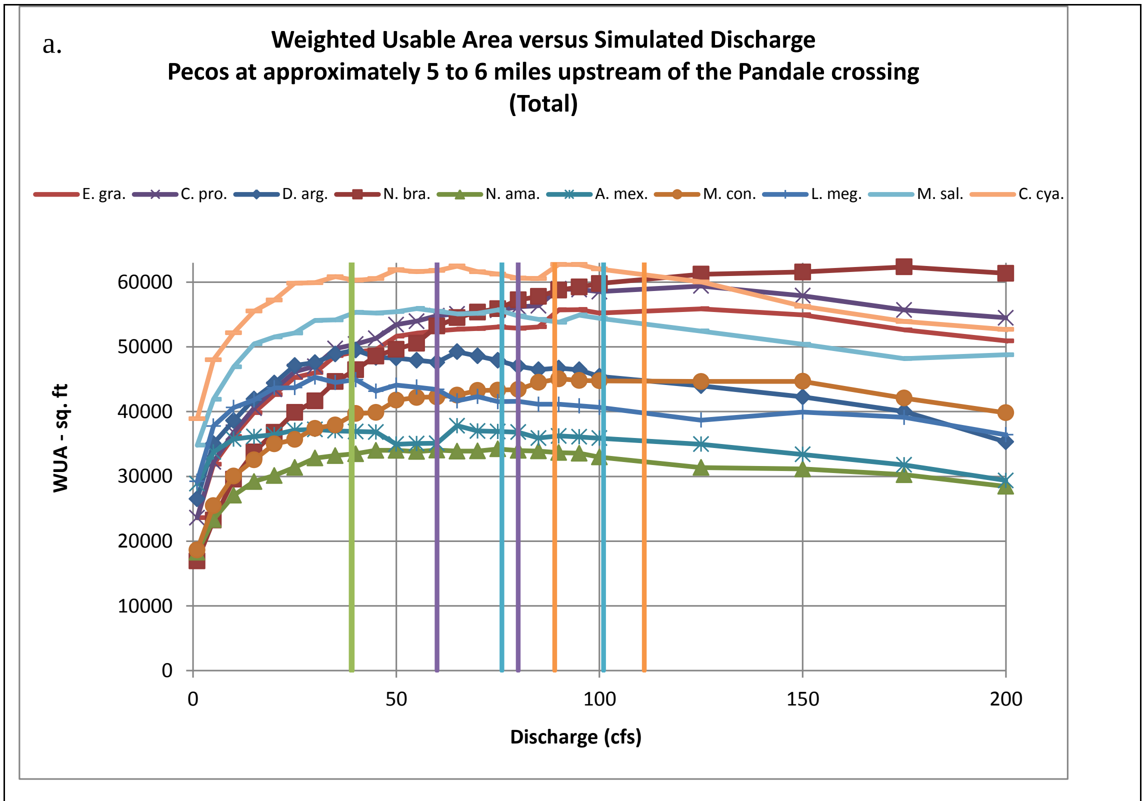


Figure 3.7-12. Four ranges of weighted usable habitat area quality (<0.5, 0.5-0.8, >0.8, and total) versus modeled flow (ft³/s) for Tamaulipas shiner (Notropis braytoni) at the Pecos River at Brotherton Ranch near Pandale.



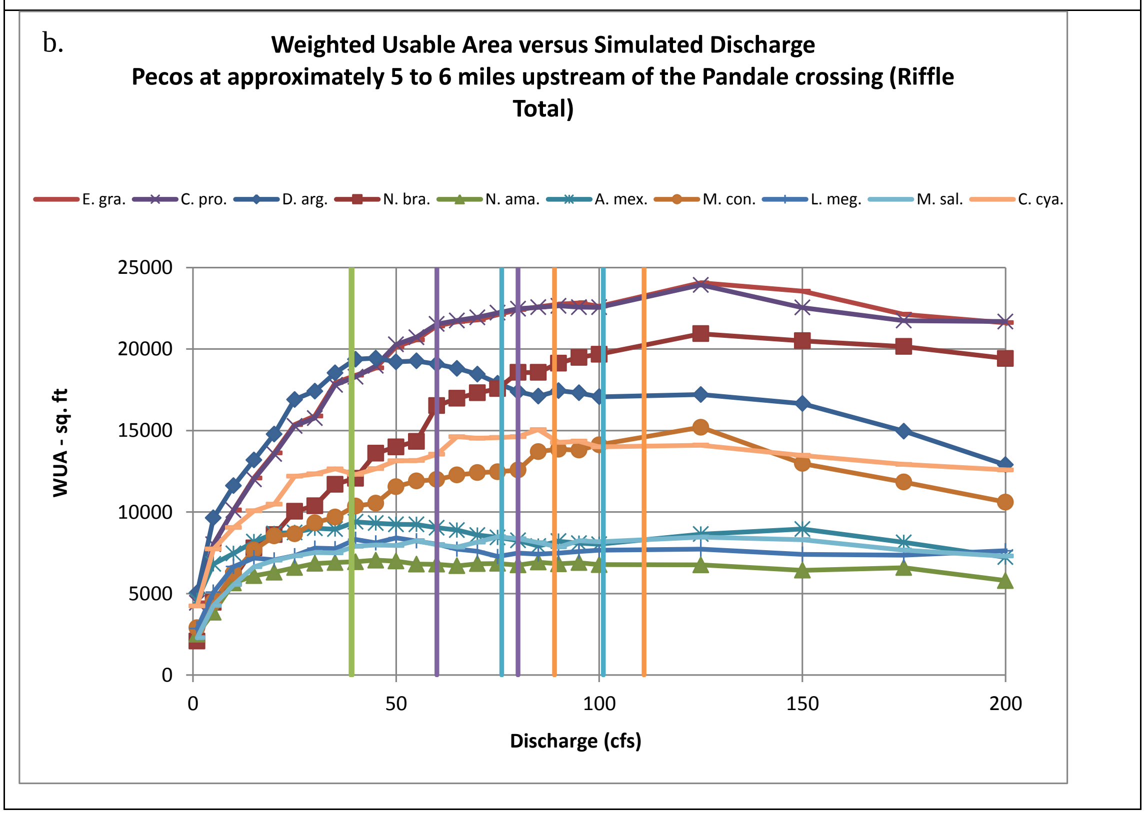
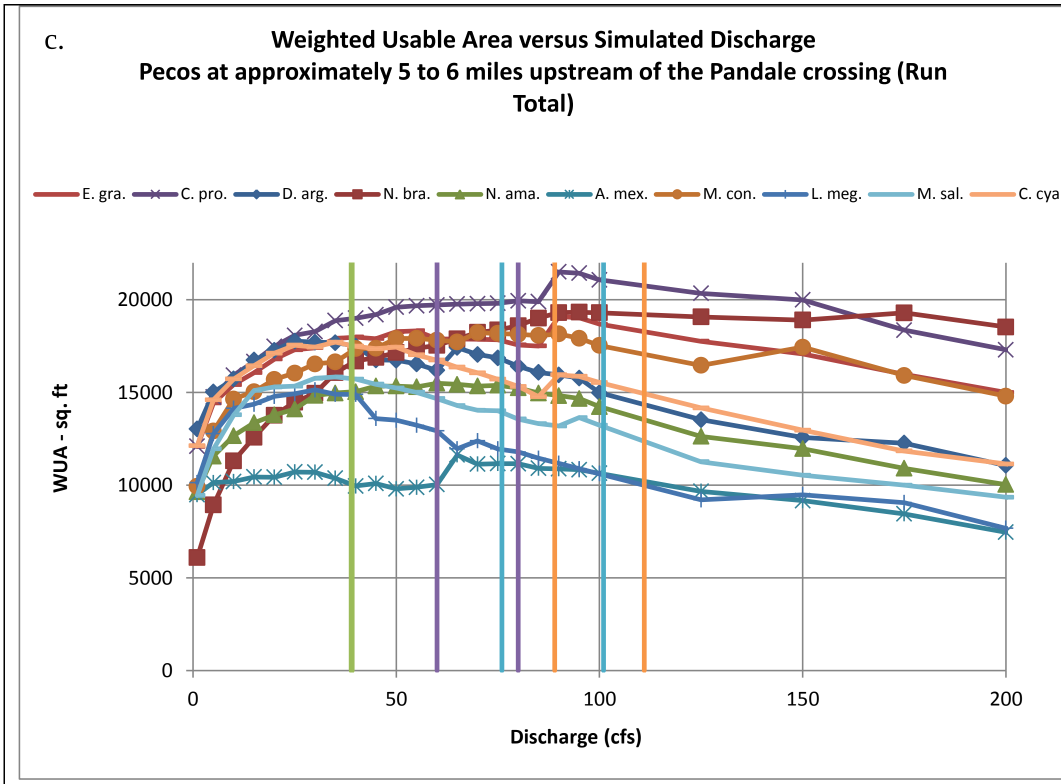


Figure 3.7-13. Weighted usable habitat area with a 0.5 minimum quality threshold versus modeled flow (ft³/s) for 10 focal species at the Pecos River at Brotherton Ranch near Pandale. Shown are WUA versus flow relationships for a) all cross-sections, b) riffle cross-sections, 3) run cross-sections and d) pool cross-sections. Vertical bars bracket environmental flow regime components.



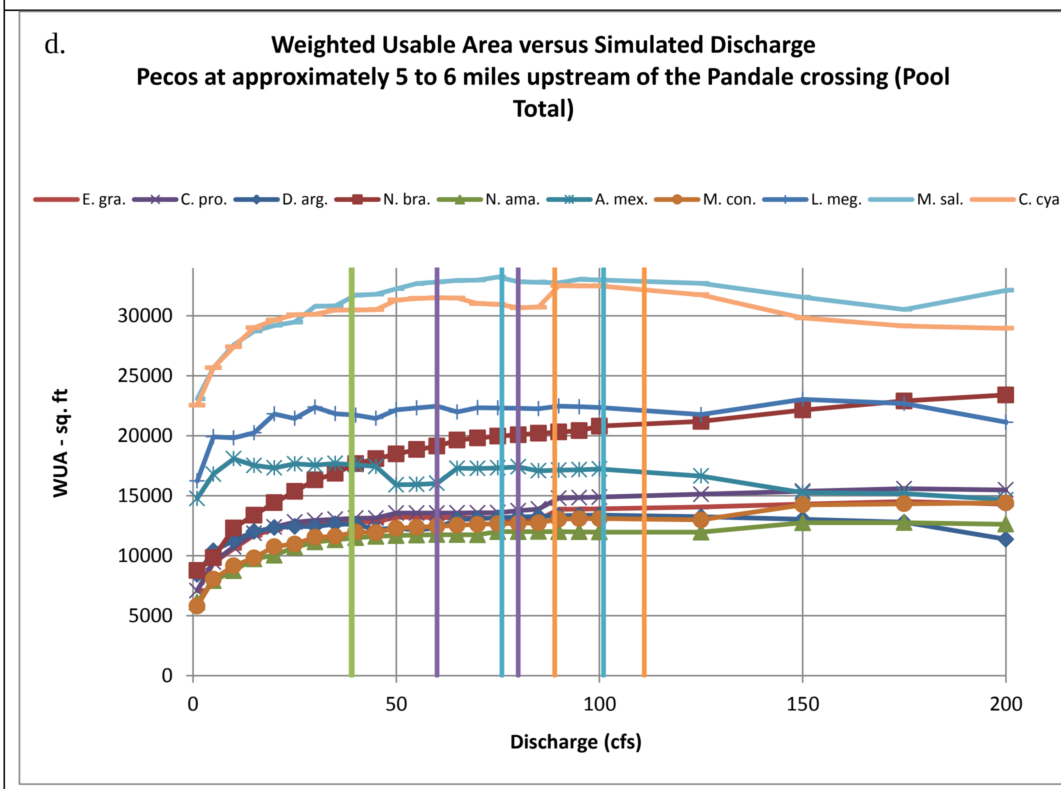


Figure 3.7-13. Continued.

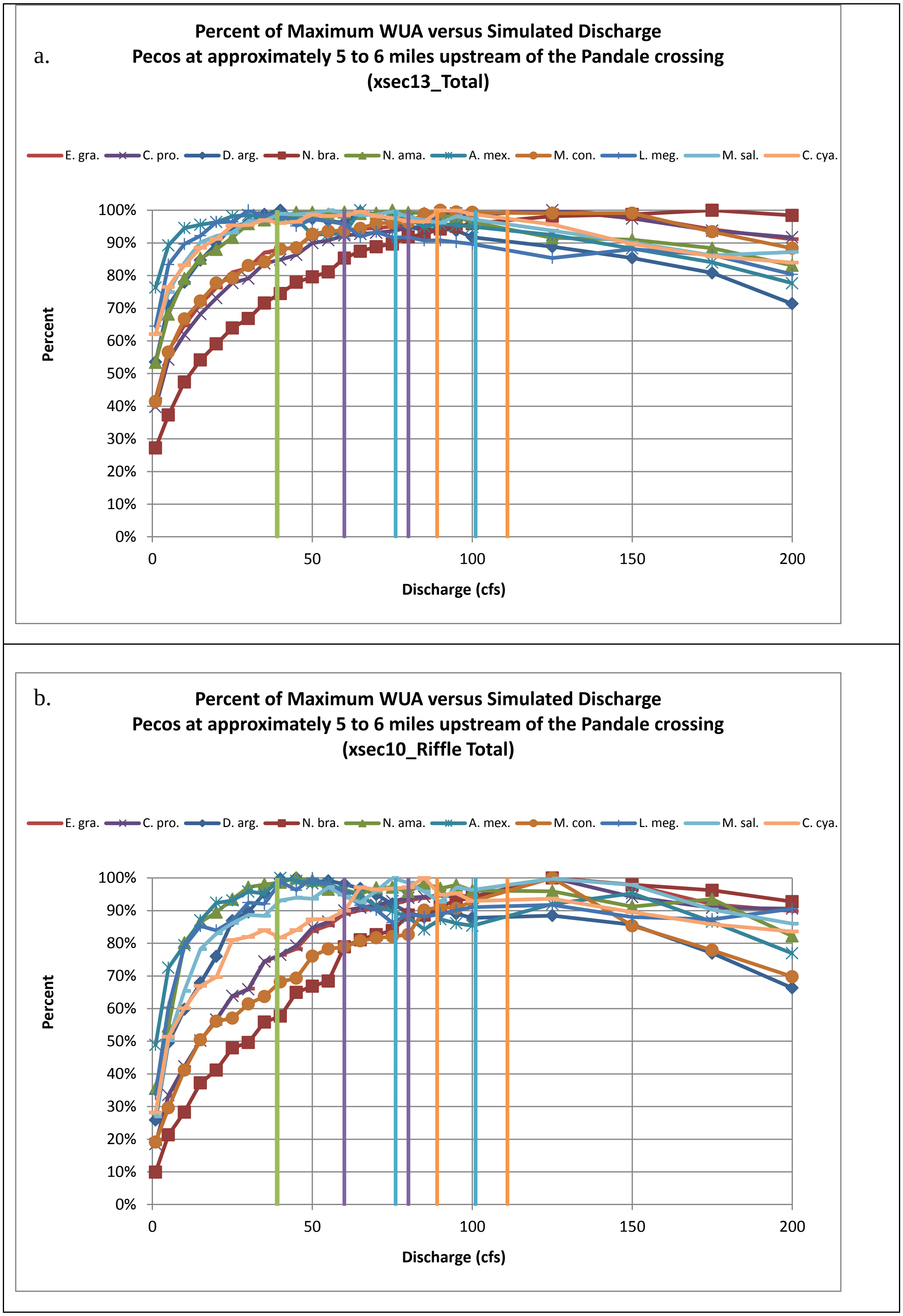
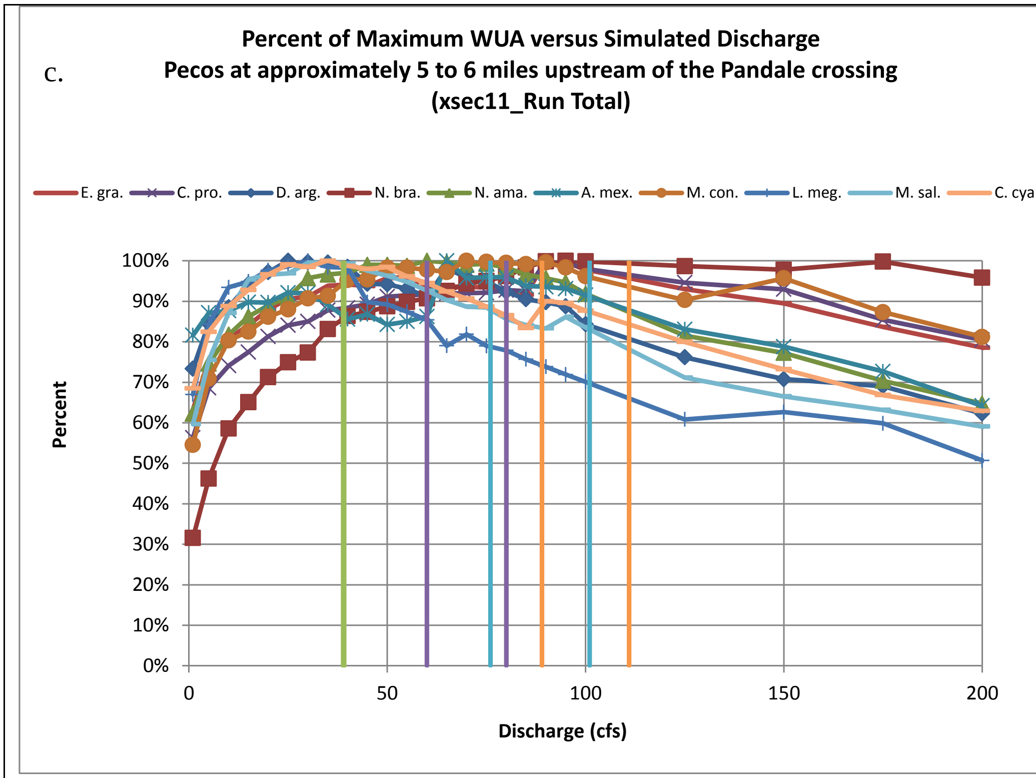


Figure 3.7-14. Graphs a) and b)



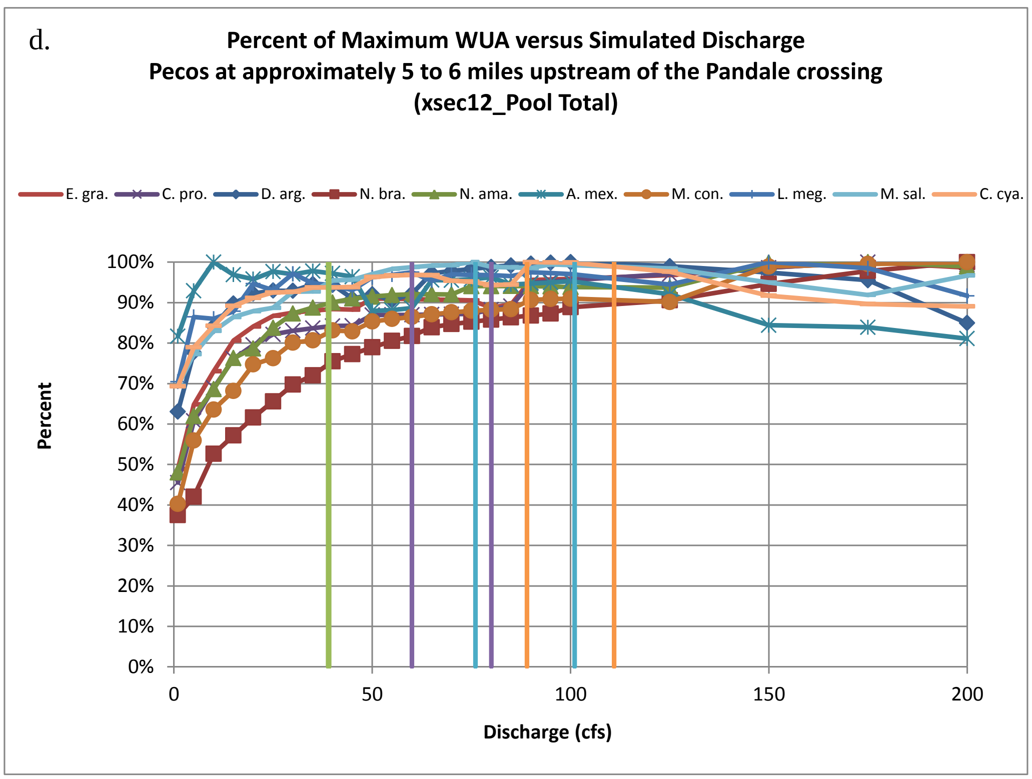


Figure 3.7-14. Percent of maximum weighted usable habitat area with a 0.5 minimum quality threshold versus modeled flow (ft³/s) for 10 focal species at the Pecos River at Brotherton Ranch near Pandale. Shown are percent of maximum WUA versus flow relationships for a) all cross-sections, b) riffle cross-sections, 3) run cross-sections and d) pool cross-sections. Vertical bars bracket environmental flow regime components.

Table 3.7-7. Percent of maximum weighted usable habitat area with a 0.5 minimum quality threshold for 10 focal species resulting from abbreviated hydrology analysis results at the Pecos River at Brotherton Ranch near Pandale. Shown are percentages for Subsistence and all three ranges of Base Flows. Shaded cells are those flows meeting "enoughness" thresholds of 20 % for Subsistence flows and 75 or 90 % (per requirements for each species) for all three ranges of Base Flows.

Focal Species	Flow Component	Percent of Maximum Weighted Usable Area		
		Winter	Spring	Monsoon
Cyprinella proserpina	Subsistence	88%	88%	88%
	Base - Low	93%	92%	92%
	Base - Medium	98%	92%	93%
	Base - High	97%	99%	97%
Dionda argentosa	Subsistence	99%	99%	99%
	Base - Low	92%	91%	94%
	Base - Medium	84%	94%	91%
	Base - High	81%	90%	82%
Notropis amabilis	Subsistence	97%	97%	97%
	Base - Low	98%	100%	100%
	Base - Medium	91%	99%	97%
	Base - High	87%	96%	89%
Notropis braytoni	Subsistence	86%	86%	86%
	Base - Low	96%	91%	91%
	Base - Medium	100%	95%	98%
	Base - High	99%	100%	100%
Moxostoma congestum	Subsistence	94%	94%	94%
	Base - Low	99%	98%	98%
	Base - Medium	96%	100%	99%
	Base - High	94%	99%	95%
Astyanax mexicanus	Subsistence	86%	86%	86%
	Base - Low	96%	86%	92%
	Base - Medium	91%	96%	94%
	Base - High	88%	94%	89%
Micropterus salmoides	Subsistence	99%	99%	99%
	Base - Low	86%	93%	92%
	Base - Medium	83%	88%	84%
	Base - High	78%	83%	80%
Lepomis megalotis	Subsistence	98%	98%	98%
	Base - Low	78%	85%	83%
	Base - Medium	70%	79%	76%
	Base - High	66%	74%	68%
Etheostoma grahami	Subsistence	94%	94%	94%
	Base - Low	92%	94%	94%
	Base - Medium	98%	93%	92%
	Base - High	96%	98%	96%
Cichlasoma cyanoguttatum	Subsistence	99%	99%	99%
	Base - Low	87%	95%	94%
	Base - Medium	87%	88%	83%
	Base - High	84%	89%	86%

Table 3.7-8. Percent of maximum weighted usable area across all cross-sections with a minimum habitat quality of 0.5 for all 10 focal species at all modeled flows for the Pecos River at Brotherton Ranch near Pandale. Shaded cells are those flows meeting "enoughness" thresholds of 75 or 90 % (per requirements for each species).

Modeled Flow (FT^3/S)	*C. pro.*	*D. arg.*	*N. ama.*	*N. bra.*	*M. con.*	*A. mex.*	*L. meg.*	*M. sal.*	*E. gra.*	*C. cya.*
1	40%	54%	53%	28%	41%	76%	64%	62%	42%	62%
5	54%	71%	68%	38%	57%	89%	83%	75%	57%	77%
10	62%	78%	79%	48%	67%	95%	90%	84%	65%	83%
15	68%	85%	85%	55%	72%	96%	92%	90%	71%	88%
20	73%	90%	88%	60%	78%	96%	96%	92%	76%	91%
25	78%	95%	92%	65%	79%	98%	96%	93%	81%	95%
30	79%	96%	96%	68%	83%	99%	100%	97%	82%	95%
35	84%	99%	97%	73%	84%	98%	98%	97%	87%	97%
40	85%	100%	98%	75%	88%	98%	99%	99%	88%	96%
45	86%	98%	99%	79%	88%	97%	95%	99%	89%	96%
50	90%	97%	99%	81%	93%	92%	97%	99%	92%	99%
55	91%	97%	99%	82%	94%	93%	97%	100%	93%	98%
60	92%	96%	99%	86%	94%	93%	96%	99%	94%	98%
65	93%	99%	99%	89%	94%	100%	92%	98%	94%	100%
70	93%	98%	99%	90%	96%	98%	93%	99%	95%	98%
75	94%	97%	100%	91%	96%	98%	92%	100%	95%	98%
80	95%	95%	99%	93%	96%	97%	92%	98%	95%	97%
85	95%	94%	99%	94%	99%	95%	91%	97%	95%	97%
90	99%	94%	98%	95%	100%	96%	91%	96%	100%	100%
95	99%	94%	98%	96%	99%	95%	90%	98%	100%	100%
100	99%	92%	96%	97%	99%	95%	90%	97%	99%	99%
125	100%	89%	92%	99%	99%	92%	85%	94%	100%	96%
150	97%	85%	91%	100%	99%	88%	88%	90%	98%	90%
175	94%	81%	88%	100%	93%	84%	86%	86%	94%	86%
200	92%	71%	83%	100%	88%	78%	80%	87%	91%	84%
250	85%	61%	76%	93%	77%	71%	73%	78%	81%	75%
300	76%	51%	71%	87%	69%	65%	63%	75%	70%	66%
350	69%	46%	65%	81%	67%	60%	54%	67%	64%	60%
400	62%	40%	58%	73%	60%	59%	43%	58%	59%	55%
500	47%	32%	41%	58%	42%	50%	35%	41%	46%	37%

Table 3.7-9. Percent of maximum weighted usable area across riffle cross-sections with a minimum habitat quality of 0.5 for all 10 focal species at all modeled flows for the Pecos River at Brotherton Ranch near Pandale. Shaded cells are those flows meeting "enoughness" thresholds of 75 or 90 % (per requirements for each species).

Modeled Flow (FT^3/S)	*C. pro.*	*D. arg.*	*N. ama.*	*N. bra.*	*M. con.*	*A. mex.*	*L. meg.*	*M. sal.*	*E. gra.*	*C. cya.*
1	19%	26%	36%	10%	19%	49%	34%	27%	18%	28%
5	34%	50%	55%	21%	30%	73%	60%	50%	33%	51%
10	42%	60%	80%	28%	41%	79%	79%	65%	42%	60%
15	50%	68%	86%	37%	50%	87%	85%	78%	50%	67%
20	57%	76%	89%	41%	56%	92%	84%	83%	57%	70%
25	64%	87%	94%	48%	57%	93%	87%	86%	64%	81%
30	66%	90%	97%	50%	61%	96%	92%	89%	66%	82%
35	74%	95%	98%	56%	64%	95%	92%	88%	75%	84%
40	76%	100%	99%	58%	68%	100%	99%	93%	76%	82%
45	79%	100%	100%	65%	69%	99%	96%	94%	78%	84%
50	85%	99%	99%	67%	76%	98%	100%	94%	84%	87%
55	87%	99%	97%	68%	78%	98%	98%	97%	85%	87%
60	90%	98%	96%	79%	79%	96%	95%	94%	89%	90%
65	91%	97%	95%	81%	81%	95%	92%	93%	90%	97%
70	92%	95%	97%	83%	82%	91%	90%	96%	91%	96%
75	93%	92%	97%	84%	82%	90%	86%	100%	92%	97%
80	94%	89%	96%	89%	83%	88%	89%	99%	93%	97%
85	94%	88%	98%	89%	90%	84%	88%	96%	94%	100%
90	95%	90%	97%	91%	91%	87%	89%	93%	95%	95%
95	94%	89%	98%	93%	91%	86%	90%	97%	95%	95%
100	94%	88%	96%	94%	93%	85%	91%	96%	94%	93%
125	100%	88%	96%	100%	100%	92%	92%	100%	100%	94%
150	94%	86%	91%	98%	85%	95%	88%	98%	98%	90%
175	91%	77%	94%	96%	78%	87%	87%	90%	92%	86%
200	91%	66%	82%	93%	70%	77%	91%	86%	90%	84%
250	82%	52%	82%	85%	53%	71%	81%	77%	71%	68%
300	69%	44%	93%	81%	48%	71%	65%	77%	56%	54%
350	60%	37%	90%	72%	53%	66%	59%	68%	47%	48%
400	49%	32%	83%	65%	49%	64%	30%	43%	42%	40%
500	34%	27%	64%	51%	34%	57%	21%	28%	30%	29%

Table 3.7-10. Percent of maximum weighted usable area across run cross-sections with a minimum habitat quality of 0.5 for all 10 focal species at all modeled flows for the Pecos River at Brotherton Ranch near Pandale. Shaded cells are those flows meeting "enoughness" thresholds of 75 or 90 % (per requirements for each species).

Modeled Flow (FT^3/S)	***C. pro.***	***D. arg.***	***N. ama.***	***N. bra.***	***M. con.***	***A. mex.***	***L. meg.***	***M. sal.***	***E. gra.***	***C. cya.***
1	56%	73%	62%	32%	55%	82%	67%	60%	63%	68%
5	69%	85%	75%	46%	71%	87%	84%	75%	76%	82%
10	74%	89%	82%	59%	80%	88%	93%	87%	81%	89%
15	77%	94%	86%	65%	83%	90%	95%	95%	84%	93%
20	81%	97%	89%	71%	86%	90%	98%	97%	88%	97%
25	84%	100%	91%	75%	88%	92%	99%	97%	91%	99%
30	85%	100%	96%	77%	91%	92%	100%	100%	91%	98%
35	88%	100%	97%	83%	91%	89%	98%	100%	94%	100%
40	88%	98%	97%	86%	95%	86%	98%	99%	94%	99%
45	89%	94%	99%	87%	95%	87%	90%	98%	94%	98%
50	91%	94%	99%	89%	98%	84%	89%	96%	96%	98%
55	92%	93%	99%	90%	98%	85%	87%	95%	96%	96%
60	92%	91%	100%	91%	98%	86%	85%	93%	94%	95%
65	92%	98%	100%	93%	97%	100%	79%	90%	94%	92%
70	92%	96%	99%	94%	100%	96%	82%	89%	94%	91%
75	92%	95%	99%	95%	100%	96%	79%	88%	93%	89%
80	93%	92%	98%	96%	99%	96%	78%	86%	92%	87%
85	93%	91%	97%	98%	99%	94%	76%	84%	92%	83%
90	100%	90%	96%	100%	100%	94%	74%	83%	100%	90%
95	100%	89%	95%	100%	98%	93%	72%	86%	100%	90%
100	98%	84%	92%	100%	96%	92%	70%	84%	98%	88%
125	95%	76%	82%	99%	90%	83%	61%	71%	93%	80%
150	93%	71%	77%	98%	96%	79%	63%	67%	89%	73%
175	85%	69%	70%	100%	87%	73%	60%	63%	84%	67%
200	80%	62%	65%	96%	81%	64%	51%	59%	79%	63%
250	69%	53%	52%	84%	69%	57%	41%	50%	72%	53%
300	61%	42%	42%	74%	56%	51%	36%	42%	59%	42%
350	56%	41%	36%	68%	49%	39%	30%	33%	56%	39%
400	49%	41%	31%	62%	42%	42%	23%	27%	49%	33%
500	39%	28%	19%	45%	25%	32%	11%	14%	41%	21%

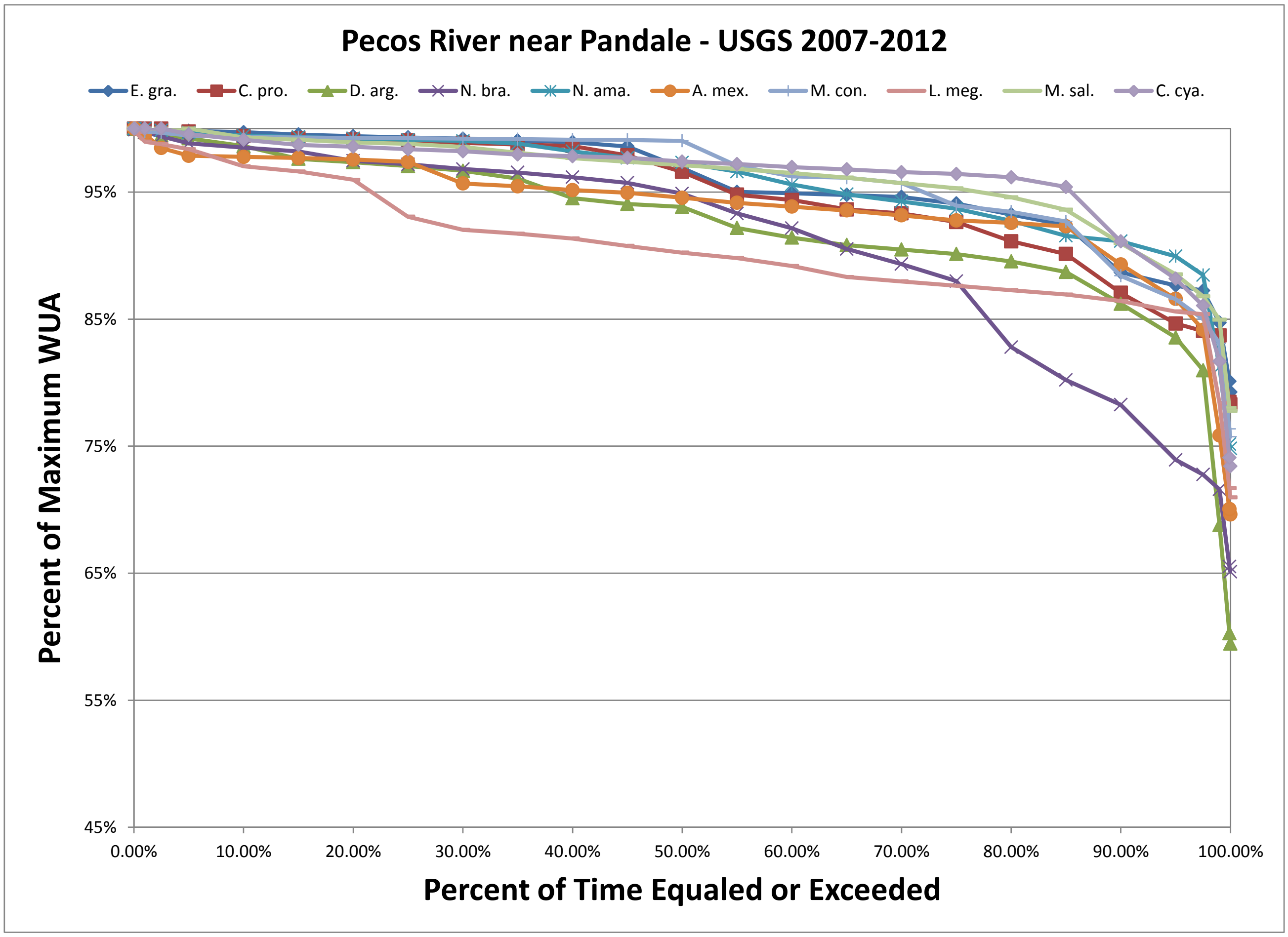


Figure 3.7-15. Habitat frequency curves for 10 focal species for the full period of record of historical flows (2007-2012) at the USGS gage at the Pecos River at Brotherton Ranch near Pandale.

Table 3.7-11. Percent of maximum habitat maintained by the range of percent exceedance examined for the full period of record (2007-2012) of historical flows at the Pecos River at Brotherton Ranch near Pandale. Shaded cells are those exceedance levels that meet the 75 or 90 % (per requirements for each species) enoughness thresholds. Data presented are for all cross-sections.

Percent Exceedance Level	*E. gra.*	*C. pro.*	*D. arg.*	*N. bra.*	*N. ama.*	*A. mex.*	*M. con.*	*L. meg.*	*M. sal.*	*C. cya.*
99.99%	79%	78%	59%	65%	75%	70%	76%	71%	78%	73%
99.9%	80%	78%	60%	66%	75%	70%	76%	72%	78%	74%
99%	85%	84%	69%	72%	81%	76%	83%	78%	85%	82%
98%	87%	84%	81%	73%	88%	84%	85%	85%	87%	86%
95%	88%	85%	84%	74%	90%	87%	87%	86%	89%	88%
90%	89%	87%	86%	78%	91%	89%	88%	86%	91%	91%
85%	92%	90%	89%	80%	92%	92%	93%	87%	94%	95%
80%	93%	91%	90%	83%	93%	93%	93%	87%	95%	96%
75%	94%	93%	90%	88%	94%	93%	94%	88%	95%	96%
70%	95%	93%	90%	89%	94%	93%	96%	88%	96%	97%
65%	95%	94%	91%	91%	95%	94%	96%	88%	96%	97%
60%	95%	94%	91%	92%	96%	94%	96%	89%	97%	97%
55%	95%	95%	92%	93%	97%	94%	97%	90%	97%	97%
50%	97%	97%	94%	95%	97%	95%	99%	90%	97%	97%
45%	99%	98%	94%	96%	98%	95%	99%	91%	97%	98%
40%	99%	99%	95%	96%	98%	95%	99%	91%	98%	98%
35%	99%	99%	96%	97%	99%	95%	99%	92%	98%	98%
30%	99%	99%	97%	97%	99%	96%	99%	92%	99%	98%
25%	99%	99%	97%	97%	99%	97%	99%	93%	99%	98%
20%	99%	99%	97%	97%	99%	98%	99%	96%	99%	99%
15%	100%	99%	98%	98%	99%	98%	99%	97%	99%	99%
10%	100%	99%	99%	98%	99%	98%	99%	97%	99%	99%
5%	100%	100%	99%	99%	100%	98%	99%	98%	100%	100%
3%	100%	100%	99%	99%	100%	98%	100%	99%	100%	100%
1%	100%	100%	100%	100%	100%	100%	100%	99%	100%	100%
0.1%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
0.01%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

3.7.4 Geomorphology overlay

Little work has been done on sediment transport and geomorphic processes on the Pecos River. The Upper Pecos traverses the sediments of the Pecos Alluvium, and thus, has a large sediment supply in this alluvial reach. The lower Pecos is generally confined within bedrock, and the remaining alluvial portions of the bottomland are generally overfit due to reductions in flow over the last 100 years. The invasion of non-native salt cedar is believed to have stabilized sediments in some of the alluvial reaches in the upper Pecos, however, removal of this vegetation in other reaches is believed to have resulted in increased erosion. Areas of sediment storage and evacuation have not been explicitly identified, and the direct role of salt cedar in driving the storage and evacuation of sediment is not well understood. A comprehensive geomorphic history over the last century should be constructed to better understand the geomorphic evolution of the Pecos River. Studies of sediment transport processes in association with other geomorphic factors such as valley and channel width, gradient, grain size of channel sediments, and relative density of vegetation will help shed light on the geomorphic behavior of the Pecos River. We consider this an important item for the BBASC to consider in adaptive management.

The fish community within the Pecos River is known to respond to such flow events and the channel changes that high flow pulses and overbank flows produce (Harrell 1978). However, the role that geomorphic processes have in determining the available aquatic habitat, and the flows that drive these geomorphic processes are not understood. A stronger understanding of geomorphic processes and their dependence on flows, particularly high flow pulses and overbank flows, is needed for the Pecos River. We consider this an important item for the BBASC to consider in adaptive management.

3.8 Devils

3.8.1 Hydrology-based Environmental Flow Regimes

Development of initial hydrology-based flow regimes for the two Devils River sub-basin gages followed the methods and parameters described in Section 3.3. No modifications were made to the hydrology-based flow regimes based on the water quality overlay (see Section 3.8.2), but some modifications were made at the Devils River near Juno according to flow-habitat modeling results as a main component of the biological overlay (see Section 3.8.3).

Table 3.8-1. Environmental flow components and their functions in the Devils River sub-basin.

Flow Component	Hydrology	Geomorphology	Biology	Water Quality
No-Flow Periods	Flow ceases between perennial pools		Generally stressful for fish communities -Isolated pool habitats increase predation on prey species -Poor water quality, predator stress, and high biomass in isolated pool habitats increases chances for disease and parasite outbreaks -Pool habitats are avoided by *D. argentosa* (Cantu and Winemiller 1997)	Temperatures rise and oxygen levels decrease. - Temperatures held at thermal extremes stress fish community (i.e. shallow isolated pools)
Subsistence Flows	Infrequent low flows	Increased deposition of fine and organic particles	Provide restricted aquatic habitat limit connectivity - Loss of spring flow and instream habitats, reductions in water quality are a threat to *D. argentosa* (Edwards 1999) - Reduced water quality and quantity one of reasons for extirpation of D. diaboli in Sycamore Creek - *C. proserpina* is intolerant of lentic conditions resulting from reservoir construction (Williams et al. 1985; Bonner et al. 2008) and is threatened by decreased spring flows, habitat loss and fragmentation, and alteration of flow regimes (Bonner et al. 2008)	Elevate temperature and constituent concentrations Maintain adequate levels of dissolved oxygen
Base Flows	Average flow condition, including variability	Maintain soil moisture and ground water table Maintain a diversity of habitats	Provide suitable aquatic habitat, Provide connectivity along channel corridor - *Dionda diaboli*, *D. argentosa*, and *C. proserpina* rely on spring fed systems and habitats (Harrell 1978, Hubbs 1995, Bonner et al. 2005) -*D. argentosa* reproduction from fall – spring with peak in Fall in Devils River (Cantu and Winemiller 1997) -*D. diaboli* are likely broadcast spawners (Gibson et al. 2004) with reproduction occurring in the spring (Edwards 1999, Garrett 2002). Spawning activity and breeding colors were noted in Pinto Creek in December (Edwards 2003) -*C. proserpina* spawning season from late spring to early fall in Devils River (Valdes and Winemiller 1997; Bonner et al. 2008). - *E. grahami* spawns late March to early June (Harrell 1980) - *C. cyanoguttatum* in NE Mexico spawn during late spring (Darnell 1962; Birkhead 1980)	Provide suitable in-channel water quality

High Flow Pulses	In channel short duration, high flows	Maintain channel and substrate characteristics; Prevent encroachment of riparian vegetation	Serve as recruitment events for organisms; Provide connectivity to near-channel water bodies -*D. argentosa* and *N. amabilis* are adapted to flood prone environments (Harrell 1978) - *M. congestum* spawns during Feb/Mar and then again in April/May (Bean 2006, Bean and Bonner 2008) in central Tx stream -*D. diaboli* needs maintenance of gravel-cobble substrates and aquatic vegetation (Edwards 1999, Garrett et al. 2004)	Restore in-channel water quality after prolonged low flow periods.
Overbank flows	Infrequent high flows that exceed the channel	Provide lateral channel movement and floodplain maintenance; Recharge floodplain water table; form new habitats; flush organic material into channel; Deposit nutrients in floodplain	Provide new life phase cues for organisms; Maintain diversity of riparian vegetation; Provide conditions for seedling development; Provide connectivity to floodplain -Post-flooding proserpine shiners gain bio-mass riverwide, shifting toward intermediate-type habitats between channels and pools (Harrell 1978) -*N. amabilis* were collected in intermediate habitats between channels and pools and post-flood were collected from riffles and similar habitats (Harrell 1978). Spawning occurs in central Tx stream from Feb – Sept. (Littrell 2006, Miller et al. 2005)	Restore water quality in floodplain water bodies
Channel Maintenance	For most streams, channel maintenance occurs mostly during pulse and overbank flows	Long-term maintenance of existing channel morphology	Maintains foundation for physical habitat features instream -Diversity of instream habitat important to maintain feeding, spawning, and nursery habitats for fish -*D. argentosa* utilize many instream habitats (not found in isolated pools or pools with no flowing water; Cantu and Winemiller 1997)	Water quality condition like those during pulse overbank flows

3.8.2 Water Quality overlay

The Devils River is a single segment that extends from the confluence of Little Satan Creek in Val Verde County to the confluence of Dry Devils River in Sutton County. Water quality is monitored at several locations throughout this reach from Baker's Crossing (at the location of the near Juno gage) near the headwaters to Pafford's Crossing where the Devils flows into Lake Amistad.

As previously noted, the Devils River is one of the most pristine water bodies in Texas and a great deal has been done to protect the quality of the river by protecting the watershed. Currently, the Devils River is fully supporting all of the designated uses and water quality criteria. However, increasing oil and gas production in the watershed poses a threat to water quality. Of the water quality parameters most likely to be flow-related, there have been no violations of dissolved oxygen and temperature standards though TDS concentrations are increasing so that the average is very near the water quality criterion for Segment 2309.

Figure 3.8-1 shows the general dilute characteristics of the Devils River as measured just below Dolan Falls downstream from the near Juno gage and Pafford's Crossing. The TDS is slightly higher upstream at the Dolan Falls site. A general trend of increasing TDS is observed in the Pafford's crossing data, with a slope of 0.0017 indicating an increase of 0.62 mg/L per year. **Figure 3.8-2** shows the TDS for the Devils River at Pafford's crossing plotted against discharge. There is little trend in these data, with a similar amount of TDS measurements above the standard throughout the range of subsistence flows (84-91 ft³/s), base flows (160 to 253 ft³/s) and lower high flow pulses. This does not suggest concern that the HEFR-derived subsistence flows of 84-91 ft³/s would result in an increased risk of violation of TDS standards. This also suggests that there is likely another explanation for the increasing TDS trend (i.e., not decreasing flows or increased occurrence of flows near subsistence) at Pafford's Crossing.

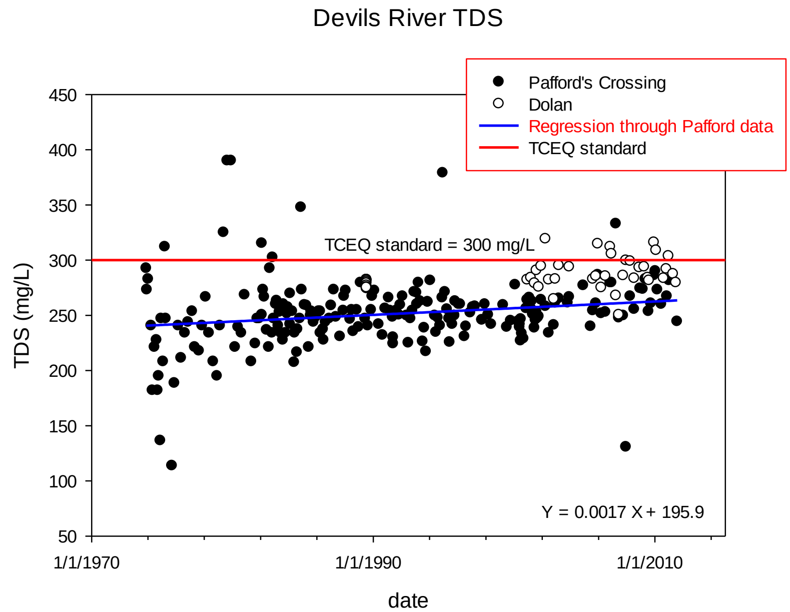


Figure 3.8-1. Total dissolved solids measurements for the Devils River above Dolan Falls and at Pafford's Crossing. Also shown is the TCEQ standard of 300 mg/L and a regression line for the Pafford's Crossing data indicating an increasing trend.

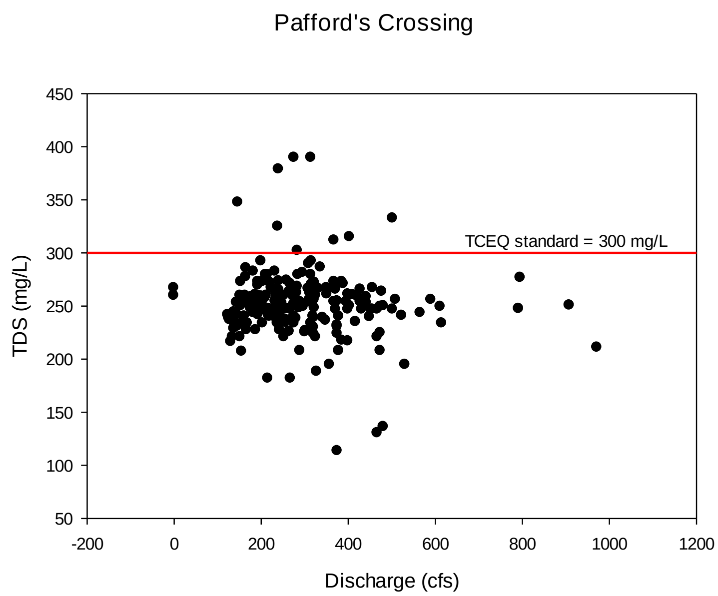


Figure 3.8-2. Total dissolved solids versus flow for the Devils River at Pafford's Crossing.

3.8.3 Flow-habitat Modeling Results and Overlay (Devils River at Juno)

Site-specific results of flow-habitat analysis are presented and briefly summarized with site-specific conclusions for the Devils River near Juno. 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 three seasons) of subsistence flows and the three levels of base flows. The key to focal species abbreviations used in figures and tables throughout this section is: *E. gra*.=Rio Grande darter, *C. Pro*.=Proserpine shiner, *D. arg*.=manantial roundnose minnow, *D. dia*.=Devils River minnow, *N. ama*.=Texas shiner, *N. str*.=sand shiner, *A. mex*.=Mexican tetra, *L. meg*.=longear sunfish, *M. sal*.=largemouth bass and *C. cya*.=Rio Grande cichlid.

The flow-habitat modeling for the Devils River near Juno indicates that the hydrology-based flow recommendations for base flows maintain suitable aquatic habitats for most of the focal species and maintain habitat diversity at this site (**Figure 3.8-2** and **Figure 3.8-3**, **Table 3.8-1** through **Table 3.8-4**, **Appendix 3.4**). 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 area (**Table 3.7-1**). Regarding Subsistence flows, the 20% minimum threshold was easily met for all species in all seasons. However, regarding Base flows, there are three species for which one or more minimum thresholds of percent of maximum WUA were not maintained by the hydrology-based numbers, so some modifications to the initial flow regime are necessary to maintain instream habitats.

There is a general trend that habitats across all cross-sections are well maintained by even very low flows (**Figure 3.8-2**a, **Table 3.8-1**, **Table 3.8-2**). However, this is most likely due to the fact that pool cross-sections dominate the site (i.e., total habitat area in pool cross-sections is three to four times higher than riffle and run cross-sections; **Figure 3.8-2**) and WUA for most species is highest in pool cross-sections at very low flows (**Figure 3.8-2**d).

Largely because of the heavy influence of pool cross-sections on habitat totals and because species are not evenly distributed among cross-sections at our sites, we decided to emphasize cross-section subsets in biological overlay decision-making. Two of the three riffle species (Rio Grande darter and Proserpine shiner) did have the 75% Base-Low met, but the 90% threshold was not met until above the Base-High range (**Figure 3.8-3**b, **Table 3.8-3**). For these two species 125 ft³/s is needed to meet the 90% threshold in the riffle cross-sections. Proserpine shiner does have higher percentages in run cross-sections. The third riffle species, manantial roundnose minnow, had the 75% Base-Low threshold met and the 90% threshold is met in the Base-Medium range. Both of the primary run species, Devils River minnow and Texas shiner, had their thresholds met in the Base flow ranges (**Figure 3.8-3**c, **Table 3.8-4**). For Devils River minnow, the 75% Base-Low threshold was met (actually below the Base-Low range) and the 90% threshold is also met in the Base-Dry range. Pool species meet 75% at very low flows, which suggests that they are not flow-sensitive at the Devils River (**Figure 3.8-3**d).

Figure 3.8-4 and **Table 3.8-5** show the results of the habitat time series analysis for the whole period of record of historical flows at the Devils River near Juno. These results are for all cross-sections and do not consider cross-section subsets separately, though this could be done in the future. Because these percentages are for all cross-sections, many species see their minimum thresholds met at a very high frequency. We recommend that environmental flow standards adopted by the BBASC not reduce these frequencies more than 10%.

3.8.3.1 Effects of flow-habitat analysis on environmental flow recommendations

As a result of this analysis we made two modifications to the hydrology-based flow regimes in the Base flow range. We felt that we needed to have 125 ft³/s in at least some portion of the flow regime because it is the minimum flow needed to maintain two of our riffle species. Because the spring spawning season is the most important time for habitat maintenance, we chose to increase the base flows for only this season. We increased the Spring base flow to 125 ft³/s for both the Base-Medium and Base-High tiers. We considered simplification of the flow regime (i.e., reducing the number of tiers of base flow), but did not see a strong reason for this at the Devils River.

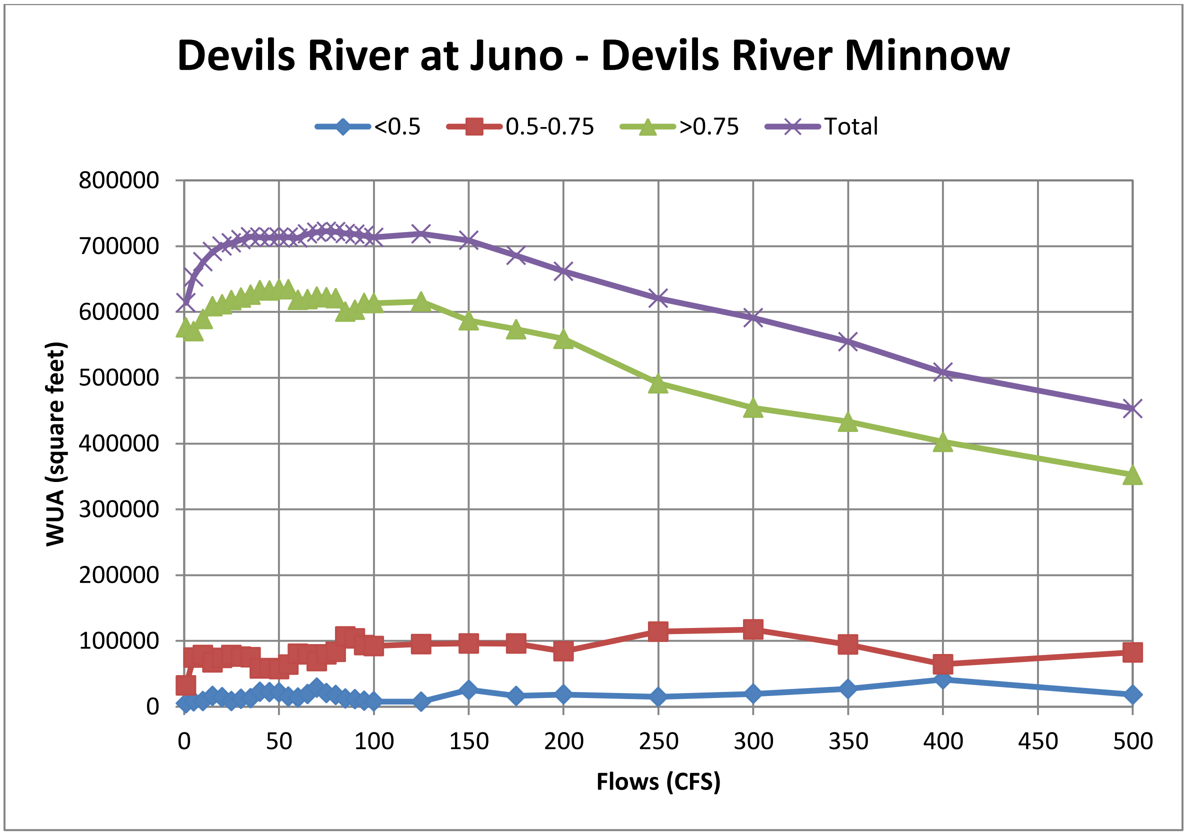
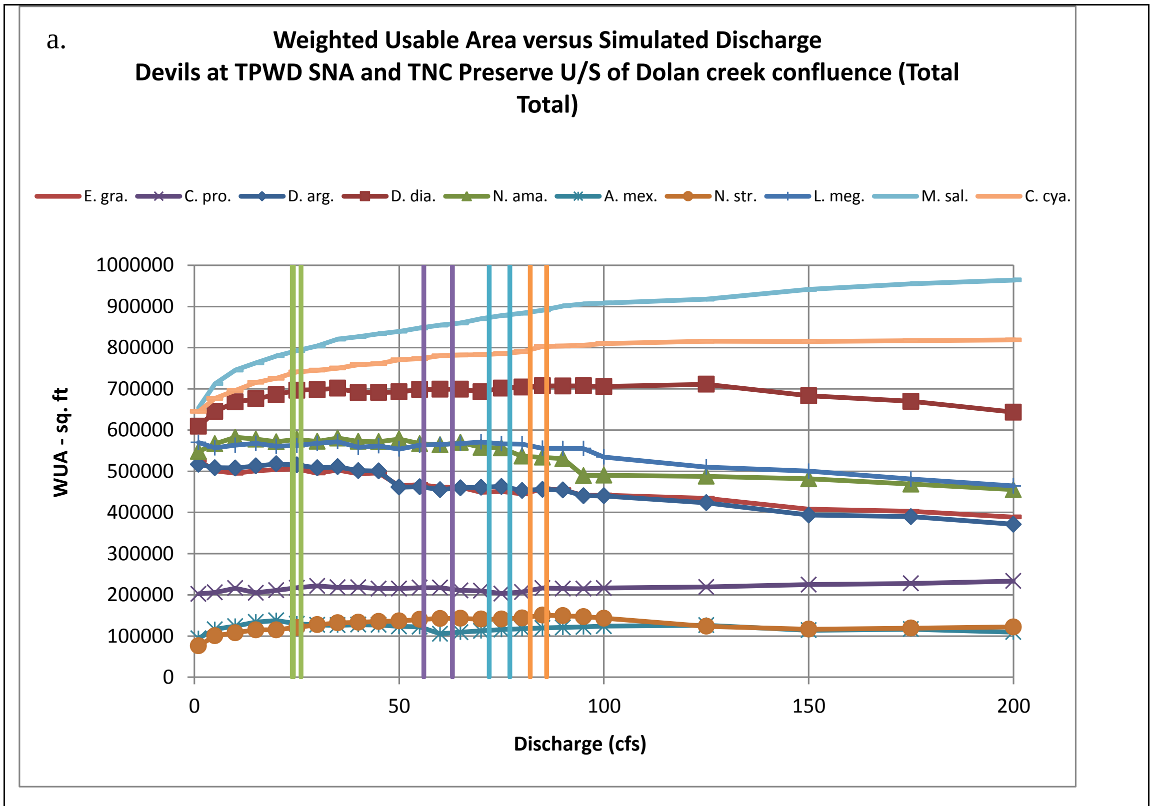


Figure 3.8-1. Four ranges of weighted usable habitat area quality (<0.5, 0.5-0.75, >0.75, and total) versus modeled flow (ft³/s) for Devils River minnow (*Dionda diaboli*) at the Devils River near Juno.



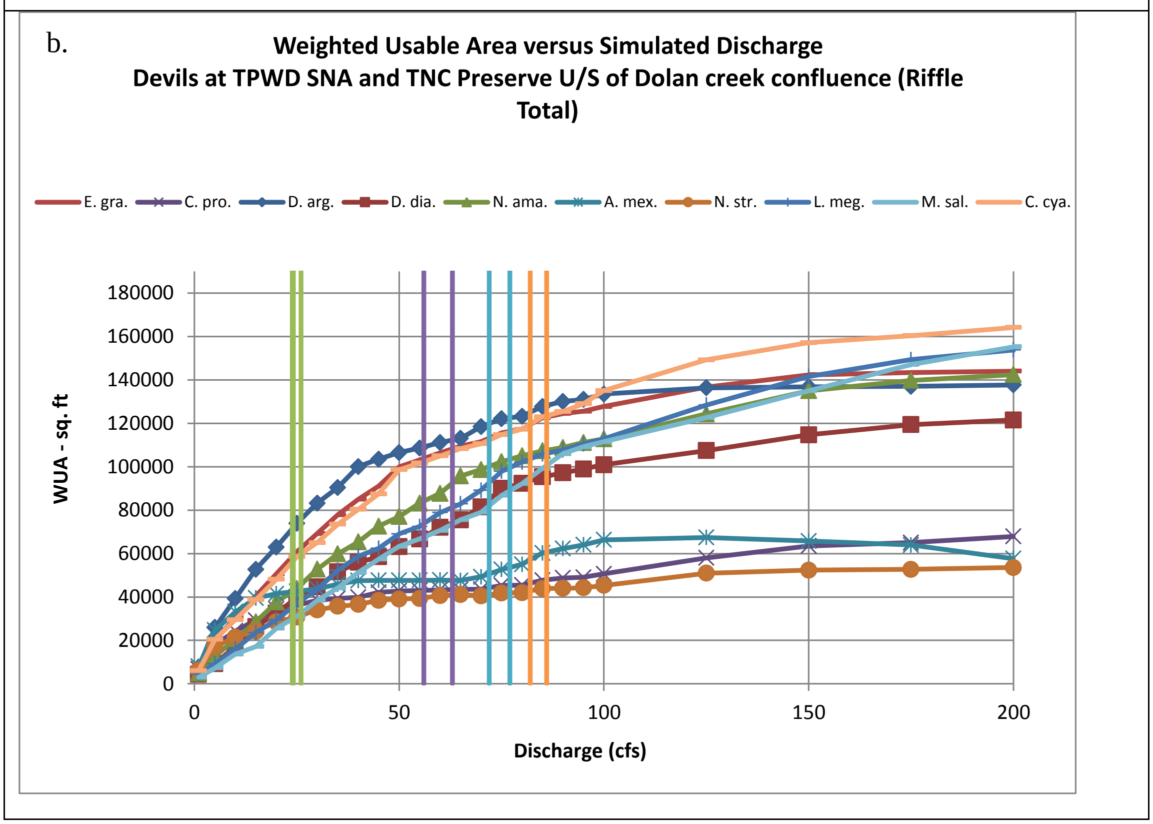
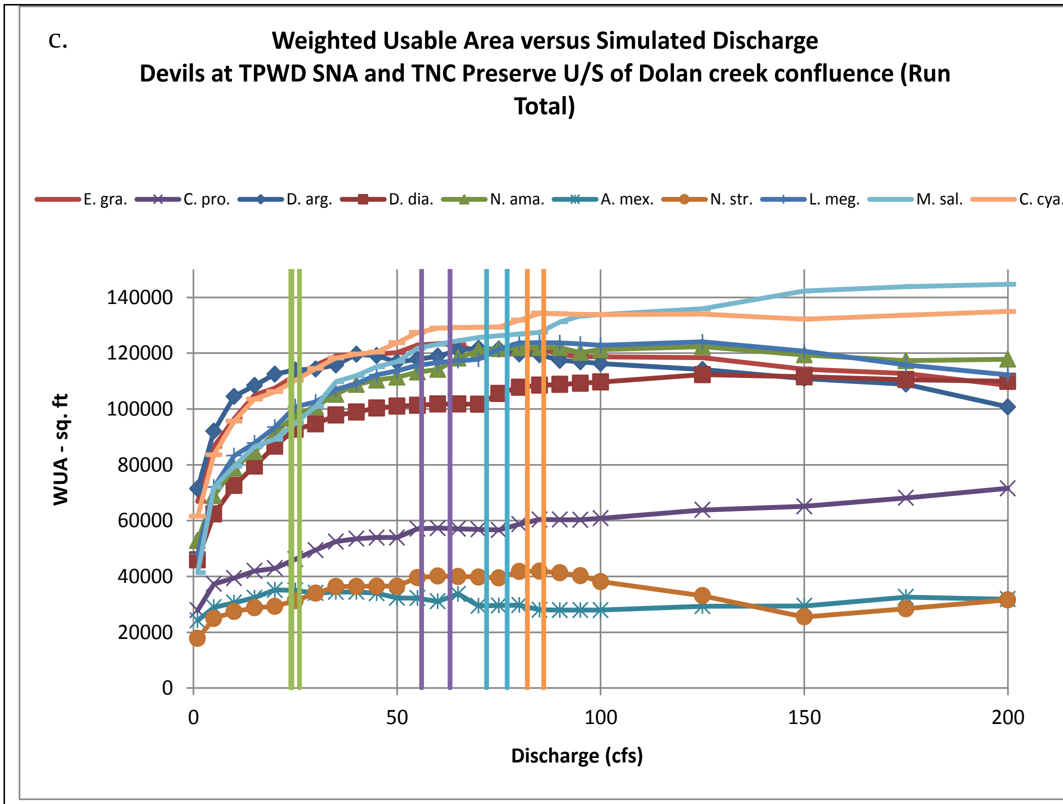


Figure 3.8-2. Weighted usable habitat area with a 0.5 minimum quality threshold versus modeled flow (ft³/s) for 10 focal species at the Devils River near Juno. Shown are WUA versus flow relationships for a) all cross-sections, b) riffle cross-sections, c) run cross-sections and d) pool cross-sections. Vertical bars bracket environmental flow regime components.

c.



d.

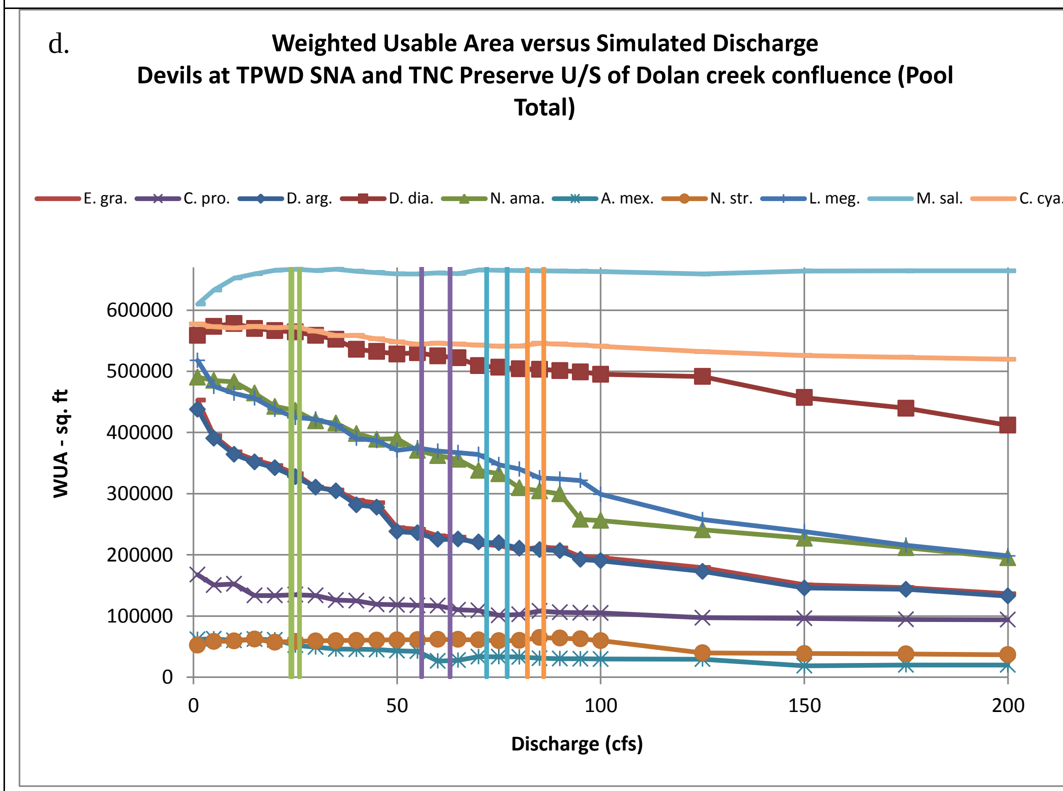


Figure 3.8-4. Continued.

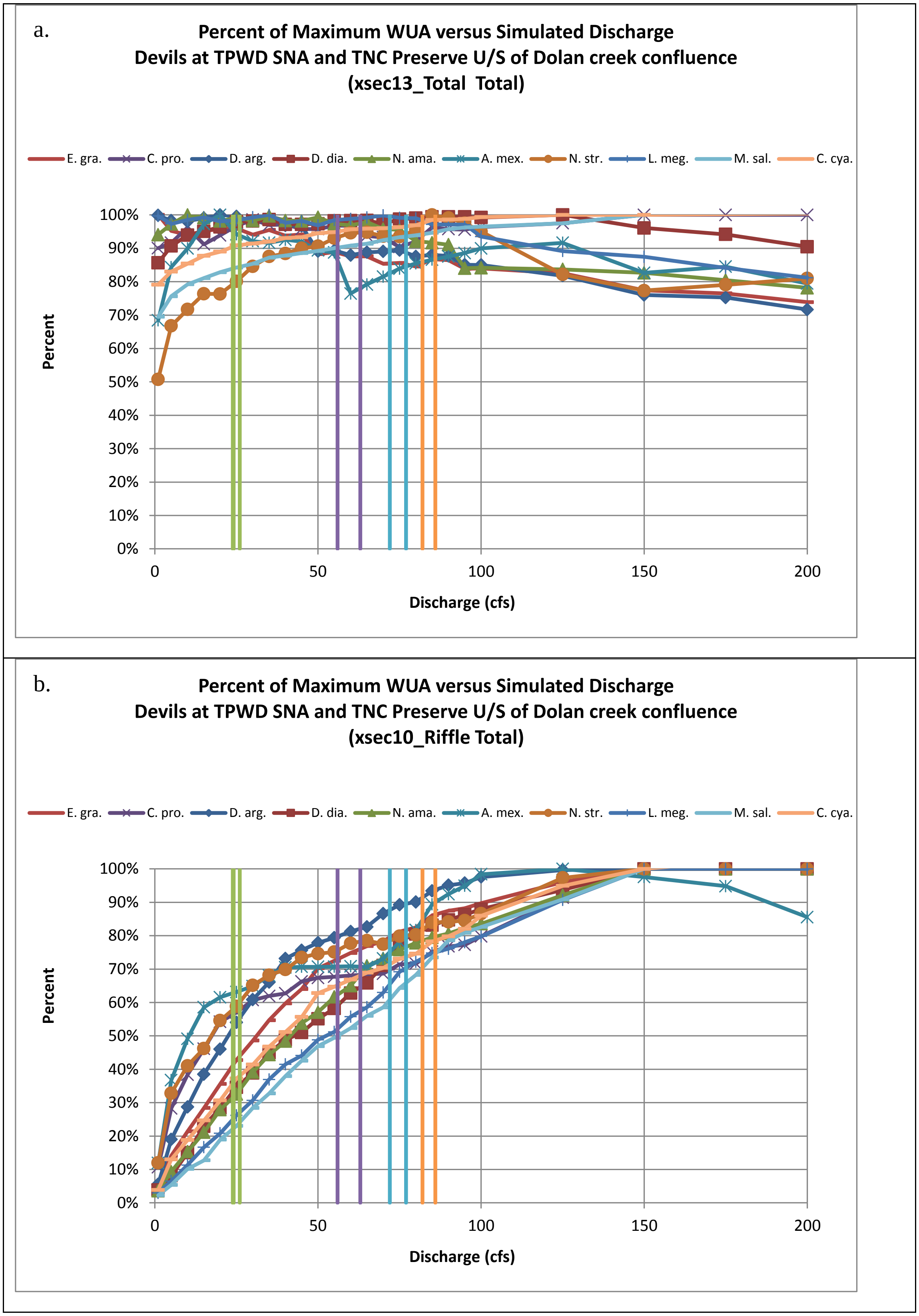


Figure 3.8-5. Graphs a) and b).

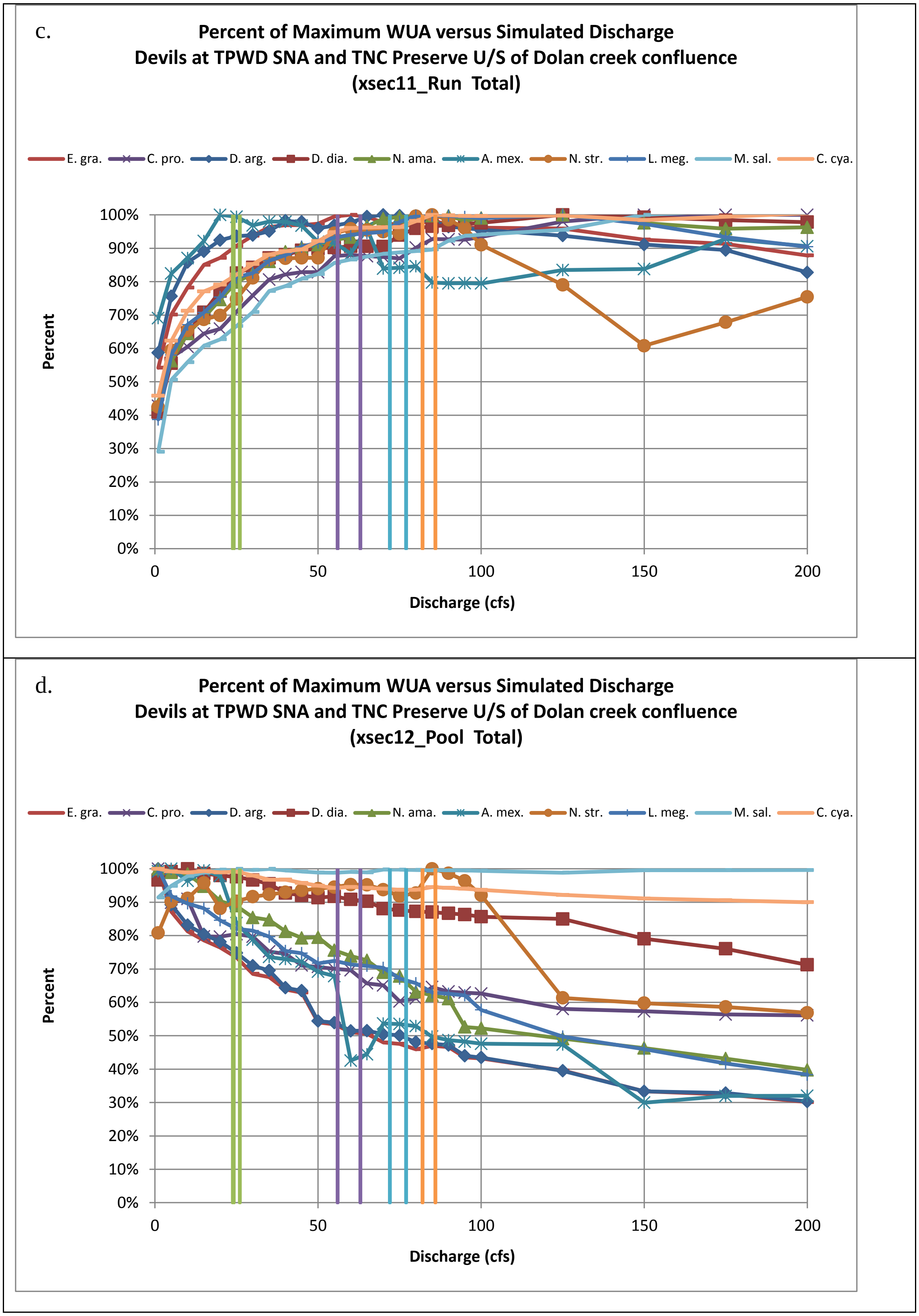


Figure 3.8-3. Percent of maximum weighted usable habitat area with a 0.5 minimum quality threshold versus modeled flow (ft³/s) for 10 focal species at the Devils River near Juno. Shown are percent of maximum WUA versus flow relationships for a) all cross-sections, b) riffle cross-sections, 3) run cross-sections and d) pool cross-sections

Table 3.8-2. Percent of maximum weighted usable habitat area with a 0.5 minimum quality threshold for 10 focal species resulting from hydrology-based flow regime (HEFR) results at the Devils River near Juno. Shown are percentages for Subsistence and all three ranges of Base Flows. Shaded cells are those flows meeting "enoughness" thresholds of 20 % for Subsistence flows and 75 or 90 % (per requirements for each species) for all three ranges of Base Flows.

Focal Species	Flow Component	Percent of Maximum Weighted Usable Area		
		Winter	Spring	Monsoon
Cyprinella proserpina	Subsistence	97%	96%	97%
	Base - Low	97%	97%	95%
	Base - Medium	91%	92%	91%
	Base - High	94%	95%	96%
Dionda argentosa	Subsistence	99%	100%	99%
	Base - Low	89%	88%	88%
	Base - Medium	89%	89%	89%
	Base - High	88%	88%	88%
Dionda diaboli	Subsistence	98%	98%	98%
	Base - Low	98%	98%	98%
	Base - Medium	98%	98%	99%
	Base - High	99%	99%	99%
Notropis amabilis	Subsistence	99%	99%	99%
	Base - Low	97%	97%	97%
	Base - Medium	96%	96%	94%
	Base - High	92%	92%	92%
Notropis stramineus	Subsistence	81%	79%	81%
	Base - Low	93%	94%	95%
	Base - Medium	94%	94%	94%
	Base - High	97%	99%	100%
Astyanax mexicanus	Subsistence	94%	95%	94%
	Base - Low	86%	79%	78%
	Base - Medium	83%	82%	85%
	Base - High	86%	86%	87%
Micropterus salmoides	Subsistence	84%	84%	84%
	Base - Low	90%	91%	91%
	Base - Medium	93%	93%	94%
	Base - High	94%	94%	95%
Lepomis megalotis	Subsistence	99%	98%	99%
	Base - Low	99%	99%	99%
	Base - Medium	99%	100%	99%
	Base - High	98%	98%	97%
Etheostoma grahami	Subsistence	96%	96%	96%
	Base - Low	89%	88%	88%
	Base - Medium	86%	85%	85%
	Base - High	85%	86%	87%
Cichlasoma cyanoguttatum	Subsistence	91%	91%	91%
	Base - Low	95%	96%	96%
	Base - Medium	96%	96%	97%
	Base - High	98%	98%	99%

Table 3.8-3. Percent of maximum weighted usable area across <u>all</u> cross-sections with a minimum habitat quality of 0.5 for all 10 focal species at all modeled flows for the Devils River near Juno. Shaded cells are those flows meeting "enoughness" thresholds of 75 or 90 % (per requirements for each species).

Modeled Flow (FT^3/S)	*C. pro.*	*D. arg.*	*D. dia.*	*N. ama.*	*N. str.*	*A. mex.*	*M. sal.*	*L. meg.*	*E. gra.*	*C. cya.*
1	100%	90%	100%	86%	94%	68%	51%	100%	69%	79%
5	95%	92%	98%	91%	97%	84%	67%	97%	76%	83%
10	94%	96%	98%	94%	100%	90%	72%	98%	79%	85%
15	95%	91%	99%	95%	99%	97%	76%	99%	81%	88%
20	96%	94%	100%	96%	98%	100%	76%	98%	83%	89%
25	96%	97%	100%	98%	99%	94%	80%	98%	84%	91%
30	94%	99%	98%	98%	98%	92%	85%	99%	85%	91%
35	95%	97%	99%	99%	100%	92%	88%	100%	87%	92%
40	94%	97%	97%	97%	98%	93%	88%	98%	88%	93%
45	94%	96%	97%	97%	98%	92%	90%	98%	89%	93%
50	88%	96%	89%	97%	99%	89%	91%	97%	89%	95%
55	89%	97%	89%	98%	97%	89%	93%	98%	90%	95%
60	88%	97%	88%	98%	97%	76%	95%	99%	91%	96%
65	88%	94%	89%	98%	98%	79%	95%	99%	91%	96%
70	85%	93%	89%	97%	96%	82%	94%	100%	92%	96%
75	86%	90%	89%	99%	96%	84%	93%	99%	93%	96%
80	85%	92%	88%	99%	92%	85%	95%	99%	94%	97%
85	87%	96%	88%	99%	92%	87%	100%	97%	95%	98%
90	86%	96%	88%	99%	91%	88%	99%	97%	96%	99%
95	84%	96%	85%	99%	84%	89%	98%	97%	96%	99%
100	84%	96%	85%	99%	84%	90%	95%	93%	96%	99%
125	83%	98%	82%	100%	84%	92%	82%	89%	97%	100%
150	77%	100%	76%	96%	83%	83%	77%	87%	100%	100%
175	76%	100%	75%	94%	80%	85%	79%	84%	100%	100%
200	74%	100%	72%	90%	78%	79%	81%	81%	100%	100%
250	68%	100%	65%	85%	74%	79%	78%	78%	100%	100%
300	60%	99%	59%	80%	70%	81%	80%	73%	100%	99%
350	58%	100%	58%	74%	67%	81%	84%	68%	100%	98%
400	57%	100%	55%	66%	61%	86%	94%	66%	100%	99%
500	54%	100%	52%	61%	59%	98%	100%	57%	100%	99%

Table 3.8-4. Percent of maximum weighted usable area across riffle cross-sections with a minimum habitat quality of 0.5 for all 10 focal species at all modeled flows for the Devils River near Juno. Shaded cells are those flows meeting "enoughness" thresholds of 75 or 90 % (per requirements for each species).

Modeled Flow (FT^3/S)	*C. pro.*	*D. arg.*	*D. dia.*	*N. ama.*	*N. str.*	*A. mex.*	*M. sal.*	*L. meg.*	*E. gra.*	*C. cya.*
1	11%	6%	4%	4%	12%	12%	2%	3%	5%	4%
5	28%	19%	8%	9%	33%	37%	5%	7%	14%	13%
10	38%	29%	15%	15%	41%	49%	10%	11%	21%	19%
15	46%	39%	23%	21%	46%	59%	13%	17%	28%	25%
20	54%	46%	28%	28%	55%	62%	19%	21%	36%	31%
25	57%	54%	35%	33%	59%	63%	23%	26%	43%	37%
30	61%	61%	39%	39%	65%	65%	28%	31%	49%	41%
35	62%	66%	45%	44%	68%	68%	33%	37%	55%	47%
40	63%	73%	49%	48%	70%	71%	38%	41%	60%	51%
45	66%	76%	51%	54%	73%	71%	43%	44%	64%	56%
50	67%	78%	55%	57%	75%	71%	47%	49%	70%	63%
55	68%	79%	58%	62%	75%	71%	49%	51%	72%	65%
60	68%	81%	63%	65%	78%	71%	52%	56%	75%	67%
65	68%	83%	66%	71%	79%	71%	56%	59%	77%	69%
70	69%	87%	71%	73%	77%	73%	59%	63%	78%	70%
75	71%	89%	78%	76%	80%	78%	64%	69%	81%	73%
80	72%	90%	80%	78%	80%	82%	68%	72%	82%	75%
85	75%	93%	83%	79%	84%	89%	73%	75%	86%	78%
90	77%	95%	85%	81%	84%	92%	79%	76%	87%	80%
95	77%	96%	86%	82%	85%	95%	81%	78%	88%	82%
100	80%	98%	88%	84%	87%	98%	83%	80%	90%	86%
125	91%	100%	94%	92%	97%	100%	91%	91%	96%	95%
150	100%	100%	100%	100%	100%	98%	100%	100%	100%	100%
175	100%	100%	100%	100%	100%	95%	100%	100%	100%	100%
200	100%	100%	100%	100%	100%	86%	100%	100%	100%	100%
250	100%	100%	100%	100%	100%	86%	100%	100%	100%	100%
300	100%	100%	100%	100%	100%	87%	100%	100%	100%	100%
350	100%	98%	100%	100%	100%	86%	100%	100%	100%	100%
400	100%	92%	100%	100%	100%	85%	100%	100%	97%	100%
500	100%	79%	100%	100%	100%	69%	100%	100%	87%	100%

Table 3.8-5. Percent of maximum weighted usable area across run cross-sections with a minimum habitat quality of 0.5 for all 10 focal species at all modeled flows for the Devils River near Juno. Shaded cells are those flows meeting "enoughness" thresholds of 75 or 90 % (per requirements for each species).

Modeled Flow (FT³/S)	*C. pro.*	*D. arg.*	*D. dia.*	*N. ama.*	*N. str.*	*A. mex.*	*M. sal.*	*L. meg.*	*E. gra.*	*C. cya.*
1	43%	59%	41%	43%	42%	69%	29%	39%	54%	46%
5	57%	76%	56%	56%	59%	82%	51%	58%	70%	62%
10	60%	86%	65%	64%	65%	87%	56%	67%	78%	71%
15	64%	89%	71%	69%	69%	92%	61%	71%	85%	77%
20	66%	92%	77%	75%	70%	100%	63%	75%	87%	79%
25	71%	94%	83%	80%	75%	99%	67%	81%	91%	82%
30	76%	94%	84%	82%	81%	97%	71%	83%	94%	85%
35	81%	95%	87%	86%	87%	98%	77%	86%	96%	88%
40	82%	98%	88%	89%	87%	98%	79%	88%	97%	89%
45	83%	98%	89%	90%	87%	97%	81%	90%	97%	90%
50	83%	96%	90%	91%	87%	92%	82%	92%	97%	92%
55	88%	97%	90%	93%	94%	92%	86%	93%	100%	95%
60	88%	98%	91%	93%	96%	88%	87%	94%	100%	96%
65	88%	99%	91%	97%	95%	96%	88%	95%	100%	96%
70	87%	100%	91%	99%	95%	84%	88%	95%	98%	96%
75	87%	100%	94%	99%	94%	84%	89%	98%	97%	96%
80	90%	98%	96%	100%	100%	85%	89%	100%	97%	98%
85	93%	98%	97%	100%	100%	80%	90%	100%	99%	100%
90	93%	96%	97%	100%	99%	79%	92%	100%	97%	100%
95	93%	96%	97%	98%	96%	80%	94%	99%	96%	100%
100	93%	96%	98%	99%	91%	79%	94%	99%	96%	100%
125	98%	94%	100%	100%	79%	83%	96%	100%	96%	100%
150	100%	91%	99%	98%	61%	84%	100%	97%	93%	98%
175	100%	89%	98%	96%	68%	93%	100%	93%	91%	99%
200	100%	83%	98%	96%	75%	91%	100%	90%	88%	100%
250	100%	75%	96%	95%	78%	89%	100%	89%	82%	99%
300	100%	63%	93%	87%	84%	91%	100%	86%	68%	95%
350	100%	59%	92%	81%	91%	82%	100%	79%	64%	92%
400	100%	57%	89%	73%	99%	92%	100%	76%	60%	93%
500	100%	64%	78%	67%	100%	100%	100%	64%	62%	99%

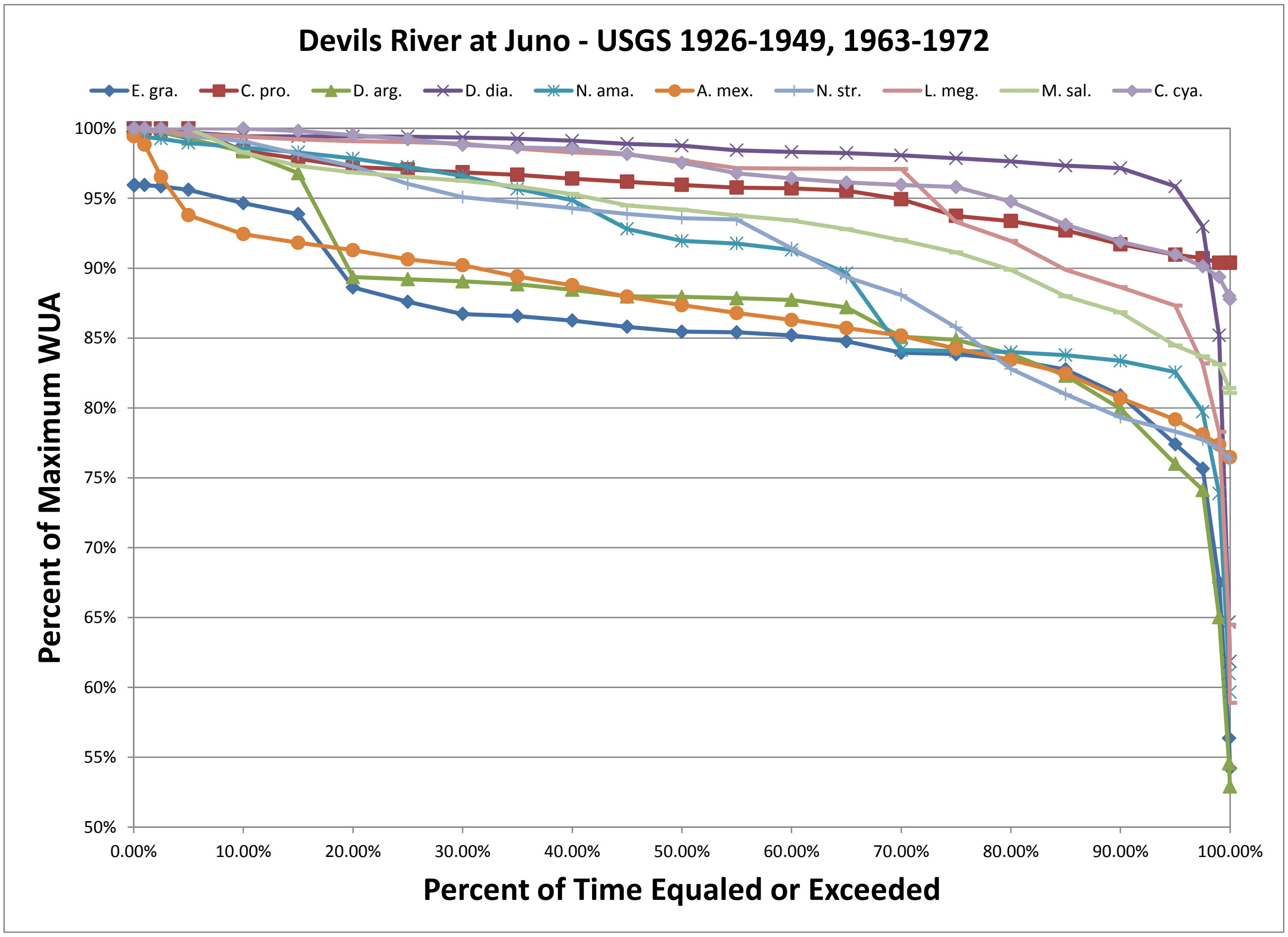


Figure 3.8-4. Habitat frequency curves for 10 focal species for the full period of record of historical flows (1926-1949, 1963-1972) at the USGS gage at the Devils River near Juno.

Table 3.8-6. Percent of maximum habitat maintained by the range of percent exceedance examined for the full period of record of historical flows at the Devils River near Juno. Shaded cells are those exceedance levels that meet the 75 or 90 % (per requirements for each species) enoughness thresholds. Data presented are for all cross-sections.

Percent Exceedance Level	***C. pro.***	***D. arg.***	***D. dia.***	***N. ama.***	***N. str.***	***A. mex.***	***M. sal.***	***L. meg.***	***E. gra.***	***C. cya.***
99.99%	90%	53%	62%	60%	76%	76%	81%	59%	54%	88%
99.9%	90%	55%	65%	61%	76%	76%	81%	64%	56%	88%
99%	90%	65%	85%	74%	77%	77%	83%	78%	68%	89%
98%	91%	74%	93%	80%	78%	78%	84%	83%	76%	90%
95%	91%	76%	96%	83%	78%	79%	84%	87%	77%	91%
90%	92%	80%	97%	83%	79%	81%	87%	89%	81%	92%
85%	93%	82%	97%	84%	81%	82%	88%	90%	83%	93%
80%	93%	84%	98%	84%	83%	83%	90%	92%	83%	95%
75%	94%	85%	98%	84%	86%	84%	91%	93%	84%	96%
70%	95%	85%	98%	84%	88%	85%	92%	97%	84%	96%
65%	96%	87%	98%	90%	89%	86%	93%	97%	85%	96%
60%	96%	88%	98%	91%	91%	86%	93%	97%	85%	96%
55%	96%	88%	98%	92%	93%	87%	94%	97%	85%	97%
50%	96%	88%	99%	92%	94%	87%	94%	98%	85%	98%
45%	96%	88%	99%	93%	94%	88%	94%	98%	86%	98%
40%	96%	88%	99%	95%	94%	89%	95%	98%	86%	99%
35%	97%	89%	99%	96%	95%	89%	96%	99%	87%	99%
30%	97%	89%	99%	97%	95%	90%	96%	99%	87%	99%
25%	97%	89%	99%	97%	96%	91%	97%	99%	88%	99%
20%	97%	89%	99%	98%	97%	91%	97%	99%	89%	100%
15%	98%	97%	99%	98%	98%	92%	97%	99%	94%	100%
10%	98%	98%	99%	99%	99%	92%	98%	99%	95%	100%
5%	100%	99%	100%	99%	99%	94%	100%	100%	96%	100%
3%	100%	100%	100%	99%	100%	97%	100%	100%	96%	100%
1%	100%	100%	100%	99%	100%	99%	100%	100%	96%	100%
0.1%	100%	100%	100%	100%	100%	99%	100%	100%	96%	100%
0.01%	100%	100%	100%	100%	100%	99%	100%	100%	96%	100%

3.8.4 Geomorphology overlay

Little work has been done on sediment transport and geomorphic processes on the Devils River. 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 Devils River channel shape, sediment dynamics and flow. The Devils River has primarily a bedrock channel that is likely rather constant in its configuration. However, there is extensive transport of coarse sediments in floods that likely plays an important role in maintaining instream habitat features. The fish community is known to respond to such flow events and the channel changes they produce (Harrell 1978). It is also possible that historical land uses such as grazing may have impacted these sediment dynamics. A stronger understanding of these processes and their dependence on flows, particularly high flow pulses and overbank flows, is needed for the Devils River. We consider this an important item for the BBASC to consider in adaptive management.

Section 4. Environmental Flow Recommendations

4.1 Environmental Flow Regime Summaries

Table 4.1-1. Environmental Flow Regime Recommendation, Alamito Creek.

<table>
<tr><td>Overbank Flows</td><td colspan="12">Qp: 2,469 ft³/s with Average Frequency 1 per 5 years
Regressed Volume is 9,996
Regressed Duration is 6</td></tr>
<tr><td rowspan="4">High Flow Pulses</td><td colspan="12">Qp: 1,459 ft³/s with Average Frequency 1 per 2 years
Regressed Volume is 5,763
Regressed Duration is 6</td></tr>
<tr><td colspan="12">Qp: 915 ft³/s with Average Frequency 1 per year
Regressed Volume is 3,535
Regressed Duration is 5</td></tr>
<tr><td colspan="4">Qp: 2 ft³/s with Average Frequency 1 per 2 seasons

Volume is 1,448
Duration is 4</td><td colspan="4">Qp: 484 ft³/s with Average Frequency 1 per 2 seasons
Volume is 1,448
Duration is 4</td><td colspan="4">Qp: 1,250 ft³/s with Average Frequency 1 per 2 seasons
Volume is 5,175

Duration is 6</td></tr>
<tr><td colspan="4"></td><td colspan="4">Qp: 226 ft³/s with Average Frequency 1 per season
Volume is 648

Duration is 4</td><td colspan="4">Qp: 675 ft³/s with Average Frequency 1 per season
Volume is 2,700
Duration is 6</td></tr>
<tr><td rowspan="3">Base Flows (ft³/s)</td><td colspan="4">1.8(49.5%)</td><td colspan="4">1.8(36.9%)</td><td colspan="4">1.8(49.4%)</td></tr>
<tr><td colspan="4">1.4(67.5%)</td><td colspan="4">1.4(47.4%)</td><td colspan="4">1.4(58.5%)</td></tr>
<tr><td colspan="4">1.1(85.1%)</td><td colspan="4">1.1(69.5%)</td><td colspan="4">1.1(74.9%)</td></tr>
<tr><td>Subsistence Flows (ft³/s)</td><td colspan="4">0.71(97.8%)</td><td colspan="4">0.71(87.0%)</td><td colspan="4">0.71(87.8%)</td></tr>
<tr><td></td><td>Nov</td><td>Dec</td><td>Jan</td><td>Feb</td><td>Mar</td><td>Apr</td><td>May</td><td>Jun</td><td>Jul</td><td>Aug</td><td>Sep</td><td>Oct</td></tr>
<tr><td></td><td colspan="4">Winter</td><td colspan="4">Spring</td><td colspan="4">Monsoon</td></tr>
</table>

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

Notes:

1. Period of record: 1/1/1932 to 12/31/2009

2. Subsistence and base flows calculated using non-zero flows only.

Table 4.1-2. Environmental Flow Regime Recommendation, Rio Grande below Rio Conchos near Presidio.

Channel Resetting Flows	Qp: Greater than 35,000 ft³/s with Average Frequency of 1 per 10 years											
Overbank Flows	No flow recommendations											
High Flow Pulses	Qp: 10,500 ft³/s with Average Frequency 1 per year Volume is 273,397 Duration is 5											
Base Flows (ft³/s)	901(38.2%)				675(32.4%)				816(60.6%)			
	590(58.8%)				348(50.5%)				537(72.8%)			
	367(78.0%)				227(65.3%)				310(84.5%)			
Subsistence Flows (ft³/s)	95(98.6%)				52(89.6%)				80(96.8%)			
	Nov	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**
	Winter				**Spring**				**Monsoon**			

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

Notes:

1. Period of record: 1/1/1901 to 2/28/1914 and 3/1/1931 to 12/31/1967

2. Subsistence and base flows calculated using non-zero flows only.

Table 4.1-3. Environmental Flow Regime Recommendation, Terlingua Creek.

	Winter	Spring	Monsoon
Overbank Flows	Qp: 5,933 ft³/s with Average Frequency 1 per 5 years Volume is 18,999 Duration is 7		
High Flow Pulses	Qp: 3,673 ft³/s with Average Frequency 1 per 2 years Volume is 11,913 Duration is 7		
	Qp: 2,370 ft³/s with Average Frequency 1 per year Regressed Volume is 7,760 Regressed Duration is 6		
	Qp: 49 ft³/s with Average Frequency 1 per 2 seasons Volume is 241 Duration is 5	Qp: 1,621 ft³/s with Average Frequency 1 per 2 seasons Volume is 5,261 Duration is 5	Qp: 3,002 ft³/s with Average Frequency 1 per 2 seasons Volume is 9,961 Duration is 7
	Qp: 6 ft³/s with Average Frequency 1 per season Volume is 111 Duration is 4	Qp: 950 ft³/s with Average Frequency 1 per season Volume is 3,079 Duration is 5	Qp: 2,041 ft³/s with Average Frequency 1 per season Volume is 6,890 Duration is 7
		Qp: 389 ft³/s with Average Frequency 1 per season Volume is 1,261 Duration is 4	Qp: 1,130 ft³/s with Average Frequency 1 per season Volume is 3,899 Duration is 6
Base Flows (ft³/s)	2.8(47.0%)	2.8(42.3%)	2.8(66.1%)
	2.5(58.6%)	2.5(53.3%)	2.5(73.8%)
	2.1(75.4%)	2.1(67.3%)	2.1(82.7%)
Subsistence Flows (ft³/s)	1.4(96.2%)	1.1(96.7%)	1.1(97.7%)
	Nov, Dec, Jan, Feb	Mar, Apr, May, Jun	Jul, Aug, Sep, Oct

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

Notes:

1. Period of record: 1/1/1932 to 12/31/2009

2. Subsistence and base flows calculated using non-zero flows only.

Table 4.1-4. Environmental Flow Regime Recommendation, Rio Grande at Johnson's Ranch.

	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Channel Resetting Flows	Qp: Greater than 35,000 ft^3/s with Average Frequency of 1 per 10 years											
Overbank Flows	No flow recommendations											
High Flow Pulses	Qp: 10,500 ft^3/s with Average Frequency 1 per year Volume is 273,397 Duration is 5											
Base Flows (ft^3/s)	788(43.4%)				469(33.8%)				643(61.8%)			
	509(62.8%)				258(54.7%)				406(74.6%)			
	339(81.3%)				168(71.1%)				228(85.8%)			
Subsistence Flows (ft^3/s)	N/A				40(91.3%)				40(97.5%)			
	Winter				Spring				Monsoon			

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

Notes:

1. Period of record: 1/1/1936 to 12/31/1967

2. Subsistence and base flows calculated using non-zero flows only.

Table 4.1-5. Environmental Flow Regime Recommendation, Rio Grande at Foster's Weir.

<table>
<tr><td>Overbank Flows</td><td colspan="12">Qp: 24,190 ft^3/s with Average Frequency 1 per 5 years
Volume is 514,209
Duration is 28</td></tr>
<tr><td rowspan="4">High Flow Pulses</td><td colspan="12">Qp: 12,710 ft^3/s with Average Frequency 1 per 2 years
Volume is 255,443
Duration is 17</td></tr>
<tr><td colspan="12">Qp: 9,394 ft^3/s with Average Frequency 1 per year
Volume is 3180,801
Duration is 14</td></tr>
<tr><td colspan="4" rowspan="2"></td><td colspan="4">Qp: 6,145 ft^3/s with Average Frequency 1 per 2 seasons
Volume is 100,385
Duration is 9</td><td colspan="4">Qp: 11,650 ft^3/s with Average Frequency 1 per 2 seasons
Volume is 258,289
Duration is 16</td></tr>
<tr><td colspan="4">Qp: 4,344 ft^3/s with Average Frequency 1 per season
Volume is 69,770
Duration is 7</td><td colspan="4">Qp: 7,451 ft^3/s with Average Frequency 1 per season
Volume is 146,598
Duration is 11</td></tr>
<tr><td rowspan="3">Base Flows (ft^3/s)</td><td colspan="4">883(34.1%)</td><td colspan="4">823(39.9%)</td><td colspan="4">975(58.7%)</td></tr>
<tr><td colspan="4">682(55.6%)</td><td colspan="4">599(54.5%)</td><td colspan="4">735(71.3%)</td></tr>
<tr><td colspan="4">540(76.3%)</td><td colspan="4">449(68.4%)</td><td colspan="4">530(82.8%)</td></tr>
<tr><td>Subsistence Flows (ft^3/s)</td><td colspan="4">331(98.3%)</td><td colspan="4">301(90.1%)</td><td colspan="4">290(96.4%)</td></tr>
<tr><td></td><td>Nov</td><td>Dec</td><td>Jan</td><td>Feb</td><td>Mar</td><td>Apr</td><td>May</td><td>Jun</td><td>Jul</td><td>Aug</td><td>Sep</td><td>Oct</td></tr>
<tr><td></td><td colspan="4">Winter</td><td colspan="4">Spring</td><td colspan="4">Monsoon</td></tr>
</table>

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

Notes:

1. Period of record: 1/1/1962 to 12/31/2009

2. Subsistence and base flows calculated using non-zero flows only.

Table 4.1-6. Environmental Flow Regime Recommendation, Pecos River near Orla.

Overbank Flows	Qp: 1,770 ft³/s with Average Frequency 1 per 5 years Volume is 8,979 Duration is 23		
High Flow Pulses	Qp: 1,090 ft³/s with Average Frequency 1 per 2 years Volume is 5,617 Duration is 18		
	Qp: 619 ft³/s with Average Frequency 1 per year Volume is 4,687 Duration is 13		
	Qp: 109 ft³/s with Average Frequency 1 per 2 seasons Volume is 4,460 Duration is 6	Qp: 577 ft³/s with Average Frequency 1 per 2 seasons Volume is 19,077 Duration is 15	Qp: 772 ft³/s with Average Frequency 1 per 2 seasons Volume is #N/A Duration is 12
	Qp: 53 ft³/s with Average Frequency 1 per 2 seasons Volume is #N/A Duration is 4	Qp: 417 ft³/s with Average Frequency 1 per season Volume is 13,530 Duration is 13	Qp: 429 ft³/s with Average Frequency 1 per season Volume is 1,412 Duration is 9
Base Flows (ft³/s)	17(31.9%)	44(58.5%)	69(52.4%)
	12(50.1%)	15(72.0%)	33(68.3%)
	8.8(67.1%)	9.1(82.6%)	12(82.7%)
Subsistence Flows (ft³/s)	3.3(92.1%)	3.3(96.5%)	3.3(96.6%)
	Nov Dec Jan Feb	**Mar Apr May Jun**	**Jul Aug Sep Oct**
	Winter	**Spring**	**Monsoon**

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

Notes:

1. Period of record: 1/1/1938 to 12/31/2009

2. Subsistence and base flows calculated using non-zero flows only.

Table 4.1-7. Environmental Flow Regime Recommendation, Pecos River near Pecos .

	Nov, Dec, Jan, Feb (Winter)	Mar, Apr, May, Jun (Spring)	Jul, Aug, Sep, Oct (Monsoon)
Overbank Flows	Qp: 3,620 ft^3/s with Average Frequency 1 per 5 years Volume is 131,386 Duration is 23		
High Flow Pulses	Qp: 2,180 ft^3/s with Average Frequency 1 per 2 years Volume is 77,538 Duration is 19		
	Qp: 1,380 ft^3/s with Average Frequency 1 per year Volume is 46,974 Duration is 16		
	Qp: 231 ft^3/s with Average Frequency 1 per 2 seasons Volume is 8,297 Duration is 12	Qp: 1,190 ft^3/s with Average Frequency 1 per 2 seasons Volume is #N/A Duration is 13	Qp: 1,270 ft^3/s with Average Frequency 1 per 2 seasons Volume is 40,068 Duration is 14
	Qp: 231 ft^3/s with Average Frequency 1 per season Volume is 1,581 Duration is 6	Qp: 488 ft^3/s with Average Frequency 1 per season Volume is #N/A Duration is 9	Qp: 470 ft^3/s with Average Frequency 1 per season Volume is 8,422 Duration is 10
	Qp: 21 ft^3/s with Average Frequency 1 per season Volume is #N/A Duration is 3	Qp: 255 ft^3/s with Average Frequency 1 per season Volume is 361 Duration is 7	Qp: 224 ft^3/s with Average Frequency 1 per season Volume is #N/A Duration is 8
Base Flows (ft^3/s)	32 (45.1%)	78 (50.7%)	104 (45.0%)
	9.9 (65.5%)	16 (66.6%)	30 (65.5%)
	5.7 (82.3%)	4.6 (82.1%)	5.2 (82.3%)
Subsistence Flows (ft^3/s)	0.5 (98.8%)	0.4 (98.3%)	0.4 (98.1%)
	Winter	**Spring**	**Monsoon**

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

Notes:

1. Period of record: 1/1/1902 to 12/31/1935

2. Subsistence and base flows calculated using non-zero flows only.

Table 4.1-8. Environmental Flow Regime Recommendation, Pecos River near Girvin.

	Winter (Nov, Dec, Jan, Feb)	Spring (Mar, Apr, May, Jun)	Monsoon (Jul, Aug, Sep, Oct)
Overbank Flows	Qp: 923 ft³/s with Average Frequency 1 per 5 years Volume is 34,421 Duration is 35		
High Flow Pulses	Qp: 299 ft³/s with Average Frequency 1 per 2 years Volume is 9,895 Duration is 16		
	Qp: 161 ft³/s with Average Frequency 1 per year Volume is 4,511 Duration is 11		
	Qp: 47 ft³/s with Average Frequency 1 per 2 seasons Volume is 1,903 Duration is 11	Qp: 152 ft³/s with Average Frequency 1 per 2 seasons Volume is 1,756 Duration is 9	Qp: 164 ft³/s with Average Frequency 1 per 2 seasons Volume is 2,043 Duration is 10
	Qp: 231 ft³/s with Average Frequency 1 per season Volume is 1,581 Duration is 6	Qp: 72 ft³/s with Average Frequency 1 per season Volume is 1,199 Duration is 6	Qp: 100 ft³/s with Average Frequency 1 per season Volume is 1,419 Duration is 7
	Qp: 21 ft³/s with Average Frequency 1 per season Volume is #N/A Duration is 3	Qp: 44 ft³/s with Average Frequency 1 per season Volume is 1,027 Duration is 4	Qp: 57 ft³/s with Average Frequency 1 per season Volume is 1,008 Duration is 4
Base Flows (ft³/s)	32(53.1%)	25(45.8%)	27(42.4%)
	27(70.3%)	19(63.3%)	18(60.1%)
	22(85.4%)	14(78.7%)	13(73.9%)
Subsistence Flows (ft³/s)	8.7(100.0%)	6.8(95.8%)	6.3(93.8%)
	Nov, Dec, Jan, Feb	Mar, Apr, May, Jun	Jul, Aug, Sep, Oct
	Winter	Spring	Monsoon

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

Notes:

1. Period of record: 1/1/1939 to 12/31/2011

2. Subsistence and base flows calculated using non-zero flows only.

Table 4.1-9. Environmental Flow Regime Recommendation, Independence Creek near Sheffield.

Overbank Flows	Qp: 1,100 ft³/s with Average Frequency 1 per 5 years Volume is 5,800 Duration is 22		
High Flow Pulses	Qp: 612 ft³/s with Average Frequency 1 per 2 years Volume is 3,863 Duration is 18		
	Qp: 182 ft³/s with Average Frequency 1 per year Volume is 2,114 Duration is 11		
	Qp: 33 ft³/s with Average Frequency 1 per 2 seasons Volume is 2,666 Duration is 15	Qp: 100 ft³/s with Average Frequency 1 per 2 seasons Volume is 1,637 Duration is 8	Qp: 231 ft³/s with Average Frequency 1 per 2 seasons Volume is 1,777 Duration is 9
		Qp: 42 ft³/s with Average Frequency 1 per season Volume is 1,115 Duration is 7	Qp: 44 ft³/s with Average Frequency 1 per season Volume is 1,013 Duration is 5
Base Flows (ft³/s)	40	40	40
	25	25	25
Subsistence Flows (ft³/s)	18(99.2%)	17(96.1%)	17(92.5%)
	Nov **Dec** **Jan** **Feb**	**Mar** **Apr** **May** **Jun**	**Jul** **Aug** **Sep** **Oct**
	Winter	**Spring**	**Monsoon**

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

Notes:

1. Period of record: 1/1/1975 to 2/28/1985 and 3/1/2000 to 12/31/2009

2. Subsistence and base flows calculated using non-zero flows only.

Table 4.1-10. Environmental flow regime recommendation, Pecos River near Brotherton Ranch.

	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Overbank Flows	No flow recommendations											
High Flow Pulses	No flow recommendations											
Base Flows (cfs)	101				90				90			
	80				60				62			
Subsistence Flows (cfs)	39				39				39			
	Winter				**Spring**				**Monsoon**			

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

Notes:

1. Period of record: 1/1/2008 to 12/31/2010

2. Subsistence and base flows calculated using non-zero flows only.

Table 4.1-11. Environmental Flow Regime Recommendation, Pecos River at Langtry.

	Winter (Nov, Dec, Jan, Feb)	Spring (Mar, Apr, May, Jun)	Monsoon (Jul, Aug, Sep, Oct)
Overbank Flows	Qp: 15,540 ft³/s with Average Frequency 1 per 5 years Volume is 63,337 Duration is 22		
High Flow Pulses	Qp: 7,593 ft³/s with Average Frequency 1 per 2 years Volume 35,590 Duration is 17		
High Flow Pulses	Qp: 3,991 ft³/s with Average Frequency 1 per year Volume is 23,372 Duration is 14		
High Flow Pulses		Qp: 2,670 ft³/s with Average Frequency 1 per 2 seasons Volume is 15,836 Duration is 9	Qp: 6,357 ft³/s with Average Frequency 1 per 2 seasons Volume is 33,460 Duration is 17
High Flow Pulses		Qp: 569 ft³/s with Average Frequency 1 per season Volume is 6,871 Duration is 6	Qp: 1,441 ft³/s with Average Frequency 1 per season Volume is 14,961 Duration is 9
High Flow Pulses		Qp: 252 ft³/s with Average Frequency 1 per season Volume is 5,468 Duration is 4	Qp: 459 ft³/s with Average Frequency 1 per season Volume is 11,300 Duration is 5
Base Flows (ft³/s) High	182 (51.8%)	158 (47.4%)	163 (47.2%)
Base Flows (ft³/s) Medium	154 (69.1%)	131 (65.3%)	135 (60.9%)
Base Flows (ft³/s) Low	133 (85.0%)	109 (80.5%)	108 (73.7%)
Subsistence Flows (ft³/s)	70 (99.9%)	76 (97.6%)	76 (93.3%)

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

Notes:

1. Period of record: 1/1/1967 to 12/31/2010

2. Subsistence and base flows calculated using non-zero flows only.

Table 4.1-12. Environmental Flow Regime Recommendation, Devils River near Juno

	Winter (Nov, Dec, Jan, Feb)	Spring (Mar, Apr, May, Jun)	Monsoon (Jul, Aug, Sep, Oct)
Overbank Flows	Qp: 39,200 ft³/s with Average Frequency 1 per 5 years Volume is 147,711 Duration is 17		
High Flow Pulses	Qp: 15,900 ft³/s with Average Frequency 1 per 2 years Volume is 72,060 Duration is 15		
High Flow Pulses	Qp: 3,570 ft³/s with Average Frequency 1 per year Volume is 21,870 Duration is 13		
High Flow Pulses	Qp: 2 ft³/s with Average Frequency 1 per 2 seasons Volume is 2,666 Duration is 15	Qp: 2,340 ft³/s with Average Frequency 1 per 2 seasons Volume is 11,472 Duration is 8	Qp: 10,500 ft³/s with Average Frequency 1 per 2 seasons Volume is 54,533 Duration is 21
High Flow Pulses		Qp: 387 ft³/s with Average Frequency 1 per season Volume is 6,313 Duration is 8	Qp: 990 ft³/s with Average Frequency 1 per season Volume is 13,068 Duration is 13
Base Flows (ft³/s) – High	125	125	125
Base Flows (ft³/s) – Medium	125	125	125
Base Flows (ft³/s) – Low	56(81.6%)	59(76.0%)	63(76.9%)
Subsistence Flows (ft³/s)	26(97.1%)	24(95.8%)	26(95.3%)

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

Notes:

1. Period of record: 1/1/1926 to 2/28/1949 and 3/1/1963 to 12/31/1972

2. Subsistence and base flows calculated using non-zero flows only.

Table 4.1-13. Environmental Flow Regime Recommendation, Devils River at Pafford's Crossing.

<table>
<tr><td>Overbank Flows</td><td colspan="12">Qp: 34,110 ft³/s with Average Frequency 1 per 5 years
Volume is 148,364
Duration is 22</td></tr>
<tr><td rowspan="5">High Flow Pulses</td><td colspan="12">Qp: 10,100 ft³/s with Average Frequency 1 per 2 years
Volume 59,961
Duration is 16</td></tr>
<tr><td colspan="12">Qp: 3,673 ft³/s with Average Frequency 1 per year
Volume is 34,752
Duration is 13</td></tr>
<tr><td colspan="4"></td><td colspan="4">Qp: 1,462 ft³/s with Average Frequency 1 per 2 seasons
Volume is 21,327
Duration is 9</td><td colspan="4">Qp: 6,816 ft³/s with Average Frequency 1 per 2 seasons
Volume is 46,548
Duration is 14</td></tr>
<tr><td colspan="4"></td><td colspan="4">Qp: 558 ft³/s with Average Frequency 1 per season
Volume is 17,374
Duration is 7</td><td colspan="4">Qp: 1,872 ft³/s with Average Frequency 1 per season
Volume is 27,781
Duration is 9</td></tr>
<tr><td colspan="4"></td><td colspan="4"></td><td colspan="4">Qp: 318 ft³/s with Average Frequency 1 per season
Volume is 27,781
Duration is 9</td></tr>
<tr><td rowspan="3">Base Flows (ft³/s)</td><td colspan="4">243(56.5%)</td><td colspan="4">253(41.5%)</td><td colspan="4">238(49.7%)</td></tr>
<tr><td colspan="4">200(69.0%)</td><td colspan="4">207(59.3%)</td><td colspan="4">206(62.9%)</td></tr>
<tr><td colspan="4">175(81.3%)</td><td colspan="4">160(74.5%)</td><td colspan="4">166(76.5%)</td></tr>
<tr><td>Subsistence Flows (ft³/s)</td><td colspan="4">84(96.3%)</td><td colspan="4">91(94.1%)</td><td colspan="4">87(94.7%)</td></tr>
<tr><td></td><td>Nov</td><td>Dec</td><td>Jan</td><td>Feb</td><td>Mar</td><td>Apr</td><td>May</td><td>Jun</td><td>Jul</td><td>Aug</td><td>Sep</td><td>Oct</td></tr>
<tr><td></td><td colspan="4">Winter</td><td colspan="4">Spring</td><td colspan="4">Monsoon</td></tr>
</table>

<table>
<tr><td rowspan="4">Flow Levels</td><td>High (75th %ile)</td></tr>
<tr><td>Medium (50th %ile)</td></tr>
<tr><td>Low (25th %ile)</td></tr>
<tr><td>Subsistence</td></tr>
</table>

Notes:

1. Period of record: 1/1/1960 to 12/31/2009

2. Subsistence and base flows calculated using non-zero flows only.

4.1.1 Hydrologic Conditions

The Upper Rio Grande BBEST recommends that seasonal hydrologic conditions at our environmental flow recommendation locations 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 %, 50 %, and 25 % 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 % of the time. These proportions would be achieved by selecting percentile triggers (i.e., 10th percentile and below as subsistence conditions, 10th to 25th as dry, 25th to 75th as average and 75th and higher as wet) from a flow record incorporating current permit conditions, generally using a TCEQ Water Availability Model. For the Rio Grande basin we recommend that these triggers be developed using the Rio Grande basin WAM or other applicable tools. 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. Compliance with high flow pulse and overbank flow recommendations is not intended to be subject to hydrologic conditions.

4.1.2 Subsistence Flows

The primary functions of our subsistence flow recommendations are to maintain water quality (primarily dissolved oxygen, temperature and total dissolved solids), some amount of instream habitat area and habitat connectivity to ensure that native aquatic organisms can re-colonize a stream segment once normal flows return and to provide life cycle cues related to periods of low flow (**Table 3.1-1**). It is the assumption of the URG BBEST that subsistence flows will not threaten an SEE or prevent the rehabilitation of an unsound ecological environment.

For eleven of our thirteen flow recommendation locations, we recommend the seasonal subsistence flows derived from HEFR (see Section 3.3 for description of HEFR methodology). For one location in the Pecos sub-basin we derived the subsistence flow using another method (see below) and for one location in the Rio Grande sub-basin the HEFR-derived subsistence flow was modified for one season to maintain minimal habitat connectivity (see below).

The Upper Rio Grande BBEST recommends that translation of seasonal subsistence flows into environmental flow standards and permit conditions 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 Upper Rio Grande BBEST further recommends that all inflow be passed when inflows are between the specified seasonal base and subsistence values under dry hydrologic conditions. Only under subsistence hydrologic conditions (which, as defined above, apply up to 10 percent of the time), may inflow passage be reduced to seasonal subsistence values.

4.1.2.1 Rio Grande Sub-basin

No violations of stream standards for dissolved oxygen or temperature have been noted in or near the Rio Grande sub-basin gages for which flow recommendations are provided. However, increasing salinity has been noted in the Parks Reach and may become an issue for the Lower Canyons reach (Bennett et al., 2012). No water quality information is available for the gages on Terlingua or Alamito Creeks. For that reason it is the recommendation of the URG BBEST that HEFR outputs be accepted as adequate for maintain water quality at two of the three Rio

Grande gages(RG below RC and Fosters Ranch) and for the two creek gages. We find that there is not supportable reason to lower HEFR outputs.

Continuous water quality monitoring on the Rio Grande only began in 2005. In the spring of 2003, a 58-day period of low flow of less than one cubic meter per second occurred at the Gage near Johnson Ranch. This discharge is equal to HEFR subsistence flow out puts for the Spring season for this gage. This low flow event prompted the National Park Service and the U.S. Geological Survey to re-evaluate the status of fish communities in Big Bend National Park, comparing results of a 1999 evaluation with the post low-flow study. Results of the study indicate that fish communities diminished in both numbers of individuals and species diversity during the intervening period (Moring, 2005). It is not known if the decline is attributable to water quality issues associated with the low flow period or some other environmental factor. A more recent study by the USGS to quantify habitat availability at Rio Grande Silvery Minnow release and professional judgment of fish biologists suggest that flows of 35 ft^3/s may not provide adequate habitat connectivity. Therefore it is the consensus of the URG BBEST that HEFR outputs for the Winter season subsistence flows (28 ft^3/s) for the Rio Grande at Johnson's Ranch be adjusted upward to equal the HEFR output for Monsoon of 40 ft^3/s. There have not been similar studies conducted in the vicinity of the gage below the Rio Conchos, thus, subsistence flows were not able to be adjusted based on professional judgment as was done at Johnson's Ranch.

4.1.2.2 Pecos River Sub-basin

There have been no violations of water quality standards for dissolved oxygen or temperature in the Lower Pecos River (i.e., Pecos at Brotherton Ranch near Pandale and Pecos at Langtry). There has been a gradual decrease in flow in the last 30 years at the Pecos River near Langtry. It is imperative we protect ground water flows into the river to maintain adequate flow. However, we do feel confident that the subsistence flow recommendations derived from historical hydrology using HEFR will continue to maintain water quality.

In the Upper Pecos River between Red Bluff Reservoir and Independence Creek, TCEQ has declared the river impaired due to low dissolved oxygen and there are extremely high total dissolved solids in this stretch of the river. Therefore, the current hydrology of the Upper Pecos River does not maintain a sound ecological environment and because our HEFR numbers were derived from the current impacted hydrology we do not have confidence that our subsistence recommendations will enhance current condition to maintain a sound ecological environment. Instead we make the current subsistence flow recommendations with the objective of maintaining current conditions and mitigating against further deterioration of water quality conditions. The subsistence flows needed to restore this reach to a sound ecological environment would then be developed in the adaptive management phase. The best method to determine the appropriate subsistence flow for the Upper Pecos is to vary the release from Red Bluff Reservoir and measure the dissolved oxygen and total dissolved solids at Iraan. Once the dissolved oxygen and TDS requirements are met and maintained, this would be the flow required at Iraan to meet the subsistence requirements for a sound ecological environment for the Upper Pecos River. This would need to be repeated during each of the winter, spring, and monsoon seasons.

4.1.2.3 Devils River Sub-basin

There have been no violations of water quality standards for dissolved oxygen or temperature in the Devils River. And, while there have been some measurements above standards for total dissolved solids, these have occurred just as frequently at flows well above subsistence and do not seem to be flow-related. So, we feel confident that the subsistence flow recommendations derived from historical hydrology will continue to maintain water quality.

4.1.3 Base Flows

The functions of our base flow recommendations are to maintain instream habitat quantity, quality and diversity, variable flow conditions, longitudinal connectivity and water quality (**Table 3.1-1**). Variability is essential in order to balance the unique habitat requirements of aquatic species and communities. For this reason, our base flow recommendations began with three tiers of base flows (low, medium and high) across the three seasons derived from HEFR analysis. The HEFR-derived base flows were reviewed and modified for two locations, one each in the Pecos and Devils River sub-basins (see below). Also, one location in the Pecos River sub-basin had its base flow numbers derived primarily from the flow-habitat analysis (see below).

The Upper Rio Grande BBEST recognizes that translation of seasonal base flows into environmental flow standards and permit conditions may result in reduction of our recommended seasonal base values as a result of the issuance of new surface water appropriations or amendments. For reaches that have been found to have sound ecological environments, the Upper Rio Grande BBEST finds some degree of reduction in frequency of high and medium base flow recommendations below historical levels to be an acceptable ecological risk. However we do not find that a reduction in frequency of low base flows is acceptable. We state in Section 3.4 that up to a 10% reduction in historical attainment frequency of our habitat thresholds may be acceptable in some cases. However, tables and figures showing percentages of maximum habitat versus discharge for selected species (in Section 3.6.3 and Section 3.7.3) show that any substantial reduction in flows below our base flow recommendations may quickly reduce available instream habitat. Also, we have taken steps to both simplify the base flow portion of our flow regime recommendations and to determine the minimum flows needed to maintain habitats for our focal species. Thus, any reduction beyond the current base flow recommendations would likely put at risk key ecological components that maintain a sound ecological environment. The URG BBEST recommends that the issuance of new surface water appropriations be accompanied by adequate monitoring programs to support adaptive management principles.

4.1.3.1 <u>Rio Grande Sub-basin</u>

Instream habitat modeling has not occurred or is not available anywhere along the Rio Grande or its tributaries. A USGS study of habitat flow relationships is near completion and will be available for the next instream flow analysis (Moring, personal communication). Violations of water quality standards have not occurred and would not be expected to occur at the base flow level. Given this, the unsound ecology of the Parks Reach, the lack of knowledge of the bio-physical relationships in the Lower Canyons reach or the two creeks, it is the consensus of the URG BBEST that HEFR derived base flow recommendations not be adjusted until there is a scientifically supportable reason to do so.

4.1.3.2 <u>Pecos River Sub-basin</u>

The flow-habitat analysis at Independence Creek near Sheffield and the Pecos River at Brotherton near Pandale indicates that base flows derived from historical hydrology are likely to maintain sufficient habitat for the species considered, with a few exceptions. We did modify the HEFR-based flow regime for Independence Creek near Sheffield reducing to two tiers of base flows and increasing flows in the upper tier to 40 ft^3/s to maintain habitats for some of our focal species. Because the flow-habitat analysis at Independence Creek and the Pecos River at Brotherton indicated that historical hydrology-derived base flows are likely to be at least sufficient, we do have confidence that instream habitats would also be maintained by the HEFR-derived flows at the Pecos River at Langtry because it is a similar channel in the Edwards Plateau influenced reach of the Pecos.

We did not have flow-habitat analysis available for the Upper Pecos and the hydrology-based flow regimes are based on altered hydrologic record. Thus, we make the current base flow recommendations resulting from HEFR analysis with the objective of maintaining current conditions and mitigating against further deterioration of instream habitats, biological communities and other factors. he base flows needed to restore this reach to a sound ecological environment would then be developed in the adaptive management phase. To determine the appropriate base flows for the Upper Pecos River, we would have to determine the subsistence flow as described above in Section 4.1.2.2 and Section 2.6.2. The low base flow and the high base flow can then be determined mathematically at the 25%tile and 75%tile levels respectively.

4.1.3.3 Devils River Sub-basin

The flow-habitat analysis at the Devils River near Juno indicated that HEFR-derived base flows are likely to maintain sufficient habitat for the species considered, with a few exceptions. We did slightly modify the HEFR-based flow regime for the Devils River near Juno by increasing the HEFR-derived Base-Medium and Base-High numbers for the Spring season to 125 ft^3/s to maintain habitats for some of our focal species. We did not have flow-habitat analysis available for the Devils River at Pafford’s Crossing so our flow recommendations for that location are the HEFR-derived base flows. Because the flow-habitat analysis at the Devils River near Juno indicated that HEFR-derived base flows are likely to be at least sufficient, we do have confidence that instream habitats would also be maintained by the HEFR-derived flows at Pafford’s.

4.1.4 High pulse flows

The functions of our high flow pulse recommendations are to maintain river channels and floodplain form and prevent encroachment of riparian vegetation (higher pulses 1 per 2 year pulse, somewhat 1 per year pulse), flush organic materials and enhance water quality after prolonged low flows (1 per year, 1 per season pulses), provide connectivity to near-channel water bodies and in channel habitat features and provide life history cues and recruitment events for organisms (seasonal pulses, maybe 1 per year pulse) (**Table 3.1-1**). We used HEFR to develop initial characterizations of high flow pulses from the historical hydrology and utilized geomorphological and other information to refine pulse recommendations at a subset of our gages. These HEFR-derived flows serve as our recommended high flow pulses for all locations except for two of the three mainstem Rio Grande sites where extensive additional hydrologic and geomorphological information was available and from which pulse recommendations were developed (see below).

Our recommended high flow pulses generally include peak daily average flow rates and cumulative volumes and durations for high flow pulses with frequencies (and increasing magnitudes) of two per season, one per season, one per 2 seasons, one per year, one per two years, and one per five years. Our recommendations include central tendency pulse volumes and durations for all high flow pulse events. The framework for high flow pulses for two of the Rio Grande mainstem sites is defined by additional parameters from previous research (see below).

The Upper Rio Grande BBEST recognizes 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 BBEST finds some degree of reduction in pulse magnitude or frequency to be an acceptable ecological risk. However, more information is needed to determine an acceptable modification to high flow pulses for our sites other than the Rio Grande mainstem sites and steps to develop this information are included in Section 5 as adaptive management tasks.

Because the high pulse flows are episodic events, the Upper Rio Grande BBEST recommends that the following criteria 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. 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).

4.1.4.1 Rio Grande Sub-basin

For the Rio Grande mainstem sites high flow pulse recommendations seek to limit the rate and magnitude of channel narrowing. High flow pulses must be of a sufficient frequency and magnitude to mobilize and reorganize coarse gravel and cobble deposits on the channel bed, and must be of sufficient duration to export fine sediment that has accumulated within the river channel.

To achieve these geomorphic goals, we recommend that annual channel filling flows of 10,500 ft^3/s with a minimum of a 5–day duration be excluded from permit consideration. Ideally, high-flow pulses for channel maintenance purposes would happen during, near the end of, or soon after monsoon season for the purposes of exporting the sediment inputs that occur during the monsoon. Alternatively, if an annual high flow pulse is not available during the monsoon season; geomorphic goals could be met with a high pulse flow during the Spring season and would have the benefit of providing biological cues to species such as the Rio Grande Silvery Minnow. Therefore, The URG BBEST recommends that the first high flow pulse of the above stated magnitude and duration following the monsoon season be excluded from permit consideration.

4.1.4.2 Pecos River Sub-basin

For the Lower Pecos River sub-basin we used HEFR to describe high flow pulses from the historical hydrology.

No attempt was made to determine suitable high pulse flows to restore a sound ecological environment in the Upper Pecos since the only available data is from gages established after the Red Bluff Reservoir was constructed. This is managed water data and does not represent a natural flow pattern. The first 182 river miles of the Pecos River are paralleled by irrigation canals which intercept overland flows and prevent them from entering the river (Section 2.6.2). Also, it is standard operating procedures for the irrigation districts to divert any acceptable pulse flow waters from the river at their respective diversion points. Despite this, we make the current base flow recommendations resulting from HEFR analysis with the objective of maintaining current conditions and mitigating against further deterioration of river channel and other factors depending on high the flow pulses that do occur in the current hydrology. The high flow pulses needed to restore this reach to a sound ecological environment would then be developed in the adaptive management phase. This may be accomplished by mathematically determining the high pulse flows from the size of the sub-basins intercepted by the irrigation canals and calculating the flow inputs from historical storm events. These inputs would also consider the runoff coefficients from soil type, slope and vegetation coverage. Probabilities would be determined to simulate pulse flows from multiple storm events in multiple basins. These values would then be cross referenced with habitat requirements for desired fish species and the sediment transport models creating the appropriate habitat. Only then could we make a defendable position as to the required high flow pulses necessary for maintaining a sound ecological environment in the Upper Pecos River.

4.1.4.3 Devils River Sub-basin

For the Devils River sub-basin we used HEFR to describe high flow pulses from the historical hydrology. This analysis resulted in 3 tiers of pulses for Juno (1 per 2 year, 1 per year and one per season for two of the three seasons) and 4 tiers of pulses for Pafford's Crossing (1 per 2 year, 1 per year, one per season for two of the three seasons and 2 per season for one of the three seasons).

4.1.5 Overbank flows

The functions of our overbank flow recommendations are to provide lateral channel movement and floodplain maintenance, recharge the floodplain water table, form new instream habitats, flush organic material into channel, deposit nutrients in the floodplain, provide other life history cues for organisms, maintain diversity of riparian vegetation, provide connectivity to floodplain and to restore water quality in floodplain water bodies (**Table 3.1-1**). We used HEFR to describe overbank flows from the historical hydrology at our sites and defined these recommended overbank flows for most gages at a frequency of one per 5 years using magnitude, duration and volume. Overbank flows for two of the three Rio Grande mainstem sites were defined differently (see below).

4.1.5.1 Rio Grande Sub-basin

Recommendations related to overbank flows in a system in sediment surplus such as the Rio Grande seek to avoid undesirable geomorphic effects. For the purposes of this report we define overbank flows for the Rio Grande below Rio Conchos and at Johnson's Ranch as flow events between 10,500 ft^3/s and 35,300 ft^3/s. We recognize that naturally derived overbank flows may occur infrequently. However, previous research suggests that overbank flows result in overbank sedimentation and vertical floodplain accretion, which is one of the primary processes contributing to channel narrowing.

We recognize that overbank flows may serve many beneficial services, such encouraging native riparian vegetation recruitment and lateral floodplain connectivity. However, little is currently understood regarding riparian vegetation dynamics during overbank floods. Also, the riparian corridor of the Rio Grande is heavily vegetated by non-native vegetation, and thus potential benefits of overbank flows to the riparian vegetation community may be outweighed by benefits to non-native vegetation. Additionally, as described in Section 3.6.4 and **Figure 3.6-11**, a high-flow pulse of 10,500 ft^3/s would help prevent vegetation establishment within the active river channel, which is one of the initial mechanisms by which the channel begins to narrow following a channel-resetting flood.

4.1.5.2 Pecos River Sub-basin

For the Lower Pecos River sub-basin we used HEFR to describe overbank flows from the historical hydrology.

No attempt was made to determine suitable overbank flows to restore a sound ecological environment in the Upper Pecos since the only available data is from gages established after the Red Bluff Reservoir was constructed. Despite this, we make the current base flow recommendations resulting from HEFR analysis with the objective of maintaining current conditions and mitigating against further deterioration of the river channel, floodplain and other factors depending on any overbank flows that do occur in the current hydrology. Any overbank flows needed to restore this reach to a sound ecological environment would then be developed in the adaptive management phase. This may be accomplished by mathematically determining the overbank flows from the size of the sub-basins intercepted by the irrigation canals and calculate the flow inputs from historical storm events. These inputs would also consider the runoff coefficients from soil type, slope and vegetation coverage. Probabilities would be determined to simulate overbank flows from multiple storm events in multiple basins. These values would then be cross referenced with habitat requirements for desired fish species and the sediment transport models creating the appropriate habitat. Only then could we make a defendable position as to the required overbank flow pulses necessary for the Upper Pecos River.

4.1.5.3 Devils River Sub-basin

For the Devils River sub-basin we used HEFR to describe overbank flows from the historical hydrology. This analysis resulted in one tiers of overbank flows for both Juno and Pafford's Crossing.

4.1.6 Reset Flows for the Upper Rio Grande Sub-basin

The URG recognizes that large floods greater than 35,300 ft³/s (channel resetting floods) are instrumental in reversing negative geomorphic changes by evacuating accumulated sediment, stripping non-native vegetation, maintaining channel conveyance capacity, and restoring aspects of the historic geomorphic form of the channel and floodplain. Our current understanding of physical processes indicates that channel resetting floods are the most important portion of the present flow regime with respect to maintaining channel form. Thus, we recommend that the occurrence of large floods greater than 35,300 ft³/s continue to occur at the Rio Grande below the Rio Conchos and Johnson's Ranch gages every 10 years, which is the approximate recurrence interval of these flows at these locations. We recommend that floods greater than 35,300 ft³/s be excluded from permit consideration once per decade.

The URG BBEST recognizes that the last reset flow of 2008 caused great harm to many of the communities along the Rio Conchos and Rio Grande and it is not our position that the beneficial geomorphic effects outweigh the harmful outcomes. Rather it is our position that the negative consequences of the 2008 flow were the result of channel narrowing processes that occurred in the 1990s and 2000s, and the associated loss of channel capacity. The maximum instantaneous discharge of 50,000 ft³/s was well with in the design parameters of the leveed reach at Presidio. The problems associated with the 2008 flood were not unavoidable. Maintenance of channel capacity by limiting the magnitude of sediment accumulation within the channel will help limit flooding impacts during future channel resetting floods.

Section 5. Adaptive Management

5.1 Introduction

Adaptive management is a flexible and iterative decision making process that addresses uncertainties and knowledge gaps through monitoring and focused research. As with all other SB3 stakeholder groups, the Rio Grande BBASC is charged with identifying research and monitoring priorities to address uncertainty, guide and improve subsequent instream flows analysis, define instream flow standards, and to develop strategies to meet instream flow recommendations. Senate Bill 3 specifies the goals of the work plan as follows:

> *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).*

The environmental flow regime recommendations made in this report are based upon the best scientific knowledge available yet there is considerable opportunity for improved understanding. Several other BBEST's have developed detailed suggestions for adaptive management approaches and the URG BBEST recommends that the Rio Grande BBASC consult those plans as well as work plans developed by previous BBASC's for details. What follows in Section 5.2 is our recommendations for future research and monitoring priorities to be addressed in the BBASC's work plan. The Rio Grande BBEST may also be asked by the BBASC to provide refinement to these recommendations and assistance in development of the work plan. In Section 5.3 below we also provide a suggested approach for the adaptive management based in part on the process used in other basins and laid out by the Nueces BBEST.

5.2 Future Research and Monitoring Needs

5.2.1 Describe relationships between flow and physical, chemical, and biological structure and function of the streams and how these relationships support ecological health.

There have been very few studies of the interrelationships between environmental flow regime components and stream health in the Rio Grande basin. It would be valuable to prioritize and focus future monitoring and research programs so that these interrelationships can be hypothesized and tested. This is an overarching goal for all three sub-basins: the Rio Grande, the Pecos River, and the Devils River.

Biologic and ecologic research should focus on the effects of different portions of the flow regime as it applies to ecologic health, such as the rejuvenation of benthic macroinvertebrate communities, reorganization of channel deposits, scouring of benthic algae, and biologic cues for migration or spawning of native fish species. Significant work needs to be conducted to constrain these processes, and refine the current flow recommendations. Some of the analysis in this task may be suited to the biennial state-wide water quality assessment based primarily on TCEQ's Surface Water Quality Monitoring (SWQM) and Texas 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, however these datasets are likely to be lacking in information. Another potential source for information is the National Park Service Chihuahuan Desert Inventory and Monitoring Network. By analyzing information such as biological monitoring data from streams with a range of hydrologic alteration, it may be possible to develop relationships between flow alteration metrics and ecological metrics.

The focus of the report would be on relationships between flows and ecological health in a minimum of two representative stream segments within the sub–basins and reaches identified in this report. This includes the Parks and the Lower Canyons reaches for the Rio Grande, the two major tributaries to the Rio Grande, Alamito and Terlingua creeks, three reaches on the Pecos River, and two reaches on the Devils River. Each of these representative stream segments should be associated with either a permanent gage or a monumented cross section. One potential site within the Lower Canyons is the gage at Foster's Weir. This site will need to be evaluated for impacts caused by the weir, the appropriateness of using that site for long term monitoring, and a determination made as to the ongoing effectiveness and usefulness of the weir.

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 Rio Grande Basin should be assessed and flow-ecology relationships developed using stream gage or other hydrology data.

Given the highly variable geomorphic conditions that exist on the Rio Grande, it is likely that some of these relationships vary in importance and function from year to year. Implementation will therefore require considerable planning and a long term perspective.

5.2.2 Describe relationships between flow and geomorphic processes such as sediment transport

Stream segments within the URG exhibit a wide variety of geomorphic settings including segments for the Rio Grande that are in sediment surplus, bedrock channel segments on the Pecos and Devils, and highly manipulated and regulated segments on the upper Pecos. Apart from a small section of the Rio Grande, there have been no investigations of sediment transport processes within stream segments of the Rio Grande Basin. Analyses of suspended and bed load transport will help in determining the threshold for the reorganization and rejuvenation of stream segments. These processes are important for maintaining the habitat heterogeneity that is important for aquatic species survival during base and subsistence flows. Determination of bed load transport thresholds and associated geomorphic change during high flow pulses will provide the opportunity to re-evaluate the environmental flow prescriptions for high-flow pulses and overbank flows.

Rapidly occurring geomorphic change on the Rio Grande associated with sediment surplus creates great inter-annual uncertainty with respect to habitat availability, channel conveyance capacity and flooding frequency. Sediment inputs from tributaries within the Parks reach can rapidly constrict channel conveyance capacity and smother aquatic habitat. Therefore, it is the recommendation of the URG BBEST that flow recommendations on the Rio Grande be re-evaluated with respect to channel shape every 5 years. As channel narrowing occurs, the capacity of the channel to convey flood water will be reduced, with lower discharge values rising to higher stage elevations. Geomorphic conditions of the channel and floodplain must be monitored annually, and channel filling flow magnitudes should be recalculated in order to predict how the channel filling discharge changes as the channel loses conveyance capacity. Recently initiated and ongoing sediment monitoring studies should be incorporated into future instream flow analysis.

The highly manipulated upper Pecos presents a challenge in that several generations of resource utilization have left a highly disconnected and fragmented channel in need of some serious and thoughtful attention. With the complete diversion of surface flow and highly saline ground water contributions by the Ward II turnout, the upper Pecos is in such degraded shape that potential management solutions like increasing instream flows might threaten the sound ecological environment of the lower Pecos River. It is the consensus of the URG BBEST that a more robust flow history for the Pecos River be developed with available gage data. Additionally, analysis of slack water deposits in tributary mouths could provide information on both flow history and sediment transport history.

Little work has been done on sediment transport and the geomorphic processes on the Devils River. 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 Devils River channel shape, sediment dynamics and flow. The Devils River has primarily a bedrock channel that is likely rather constant in its configuration. However, there is extensive transport of coarse sediments in floods that likely plays an important role in maintaining instream habitat features. The fish community is known to respond to such flow events and the channel changes they produce (Harrell 1978). It is also possible that historical land uses such as grazing may have impacted these sediment dynamics. A stronger understanding of these processes and their dependence on flows, particularly high flow pulses and overbank flows, is needed for the Devils River.

Significant work needs to be conducted to constrain bio-physical process with respect to flow recommendations. Processes such as hyporheic exchange and nutrient and oxygen mediation by biological communities respond to different flow components. Revision of future flow recommendations may improve conditions such as low dissolved oxygen, and provide ecologic benefit, however, these processes are not understood,

5.2.3 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 utilized a simple modeling approach, was only conducted at three sites, and was only conducted under one flow condition at two of the sites. Specific tasks to improve and expand the habitat analysis 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., River 2D) 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.

- Collect additional information about the instream habitats utilized by different species of fish and their different life stages and pair this with information on fish abundance in habitat patches to better understand the role of flow-dependent habitat in structuring fish communities.
- 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.

5.2.4 Identify stream locations 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 and data gaps for individual stream segments. This review would help identify water bodies that may have future water rights applications for diversions or vulnerable water bodies that are not gaged and for which there is not information to base decisions on. Review and identification of additional locations for environmental flow analysis could be summarized in 2013 and 2018.

5.2.5 Describe the relationship between flow and water quality.

Within the Rio Grande basin, there are well established relationships between flow and water quality, particularly between flow and salinity or total dissolved solids (Miyamoto et al., 1995, Raines et al., 2012). Miyamoto et al. (1995) found that salts are accumulating in the URG and that metals, especially Hg and Pb, can be found in concentrations above EPA chronic criteria for aquatic species protection. It would be valuable to initiate investigations related to channel, floodplain and instream processes that mediate water quality in the context of channel narrowing and sediment accumulation. yet there are no studies that have established linkages between water quality and channel process such as hyporheic exchange and sediment transport. Additionally, there are no comprehensive studies aimed at understanding the relationships between flow and nutrient dynamics.

Some of the analysis within this task may be suited to the TCEQ Continuous Water Quality Monitoring Network. For instance, there are currently over 4 years of 15-continuous monitoring data for two stations on the Rio Grande. Continuous water quality stations also exist on the Pecos and Devils Rivers. These data could provide useful information regarding real-time relationships among different flow components and water quality trends because monitoring measurements include water quality parameters as well as a flow measurements. These data may shed light on many phenomenon that are not well understood such as the Rio Grande fish-kills that have been reported during high flow pulses. Additionally, by analyzing these water quality data in concert with discharge data from surrounding gages, potential source areas of contaminants, and the effects of high flow pulses on water quality may be discerned. The complete analyses of these real-time data should be a priority of scientific research, and should be heavily considered for any future environmental flow recommendations.

The Devils River is highly pristine and maintains excellent water quality. However, the development of the lower tract of the Devils River State Natural Area may lead to increased recreational pressure on the river and additional stresses on the river. There is concern that this could manifest itself in water quality problems and a strong baseline knowledge of water quality relations to flow is needed to detect any impacts. In particular, there should be investigation into if there is any anthropogenic influence on the increasing trend in dissolved solids and any relationship to changes in flow. There should also be more work done to see if there are areas where other water quality parameters are potentially vulnerable to effects of reduced flow.

5.2.6 Evaluate reliability and comparability between gages.

Given that the instream flow recommendations are based upon stream flow and water quality gages maintained by several different agencies, the URG recommends a review of gage performance, Quality Assurance/Quality Control (QA/QC) programs and comparability between gages. Upon close examination of data from gages operated by different agencies it is apparent that some discrepancies exist.

5.2.7 Conduct a complete water balance analysis for all stream segments within the upper Rio Grande.

River Segments within the URG are extremely dynamic with flashy hydrographs impacted by extreme runoff events, complete diversions such as at the Ward II turnout on the Pecos, and in some cases stable base flows provided by ground water inputs.

For the Pecos River, we know practically all water is removed from the river at the Ward II turnout, yet extreme runoff events can over top the dam. Poorly quantified or regulated gains and losses are present throughout all stream segments within the URG, especially on the Pecos River. Good management recommendations are disadvantaged by inadequate knowledge of hydrologic attributes.

5.2.8 Evaluate status of benthic macroinvertebrates within the URG.

Benthic macroinvertebrates are sensitive to siltation, poor water quality and disturbance. Invasive species such as European clam Corbicula are known to be indicators of degraded conditions. In many ways benthic macroinvertebrates can be an early indicator of changing conditions. This study could be based on TCEQ methods for determining stream health.

Studies need to be completed on the benthic and mussel health of the Devils River and their relationship to flow. There have been recent collections of the Texas hornshell (*Popenaias popeii*) in the Devils River indicating that the current flow regime may be suitable for maintaining healthy mussel populations. However, there has not been a systematic survey of mussels throughout the perennial reach of the Devils. There is also relatively little known about benthic macroinvertebrate communities and their relationships to flow regime components and response of these communities to flow alteration. Expanding this knowledge in the Devils River sub-basin will likely involve a need to expand benthic macroinvertebrate monitoring.

5.2.9 Investigate the relationship between flow dynamics and riparian vegetation establishment and persistence.

Dean and Schmidt (2011) have identified a feedback between the establishment of riparian vegetation and sediment accumulation along the channel of the Rio Grande. Other researchers have identified the importance of natural and modified hydrologic regimes in shaping riparian vegetation communities (Stromberg, 2001). Non-native riparian vegetation, salt cedar and giant cane, is currently being managed along significant lengths (i.e. 30km) of the Rio Grande. However, little is understood concerning the mechanisms that drive and the role that the current flow regime has on patterns of non-native vs. native vegetation establishment and proliferation. Investigations regarding riparian vegetation dynamics in relation to flow magnitude and duration would be valuable in providing future instream flow recommendations.

5.2.10 Describe relationship of the URG stream segments, its tributaries, and major springs to ground water and how it is likely to be affected by changes in water use.

Many of the stream segments of the URG are highly dependent on ground water input from the Edwards-Trinity Plateau Aquifer. Many of the major springs feeding the segments are known and there have been some gain-loss studies to understand the nature of ground water-surface water connections. However, there is not enough information to predict response of surface waters to potential increases in ground water pumping within the basin.

The Lower Canyons Reach of the Rio Grande, the lower Pecos River, and the entire Devils River are pristine systems that support diverse populations of native species and deliver a great amount of high quality water to Amistad Reservoir. Protecting these resources may require creation of long-term ground water monitoring locations combined with special studies analyzing relationships between ground water levels, stream flows, ground water withdrawals, land cover/use patterns, and meteorological conditions throughout the basin.

5.2.11 Identify water development activities planned for the future, and how they might influence ground water, river flows, and physical and hydrologic connections between the two

With the exception of urban centers like Midland, the human population of the URG is not expected to grow much. However, the urban areas within and adjacent to the URG are looking to develop aquifers within this study area to obtain new sources of water. In addition, oil and gas exploration will require large amounts of fresh water as well as disposal facilities. Many of the stream segments of the URG are in good shape due to ground water inputs and these inputs will be decreased by ground water pumping, these activities (Donnelly, 2007).

Possible water development activities may occur distant from the sites for which environmental flow regimes have been identified, however much of the study area lies above one aquifer, the Edwards Trinity Plateau Aquifer. The linkages between ground water pumping and decreases to stream flow are at least partly understood and described in the Ground water Availability Model (Anaya, 2004).

Water development possibilities identified in the regional water plans and from other sources should be evaluated for their potential to affect stream segments within the URG basin. These studies would start as desk-top studies involving the prioritization of possible water development activities to evaluate. Each development should be evaluated with the appropriate TWDB Ground Water Availability Model. Secondly, these development activities should be evaluated in concert with oil and gas projections to establish cumulative effects.

5.2.12 Creating an Sound Ecological Environment for the Upper Pecos River

If it is a desire to know the flows necessary to establish a sound ecological environment for the Upper Pecos River between Red Bluff Reservoir and Independence Creek, it is necessary to conduct an extremely extensive study outside the scope of this project. An estimated base flow for the river would have to be established. This would be key to the flows required between Ward II irrigation turnout and Iraan. Currently, the flows of the region do not meet subsistence flows as determined by the DO impairment and the high TDS in this stretch of the river.

Reservoir releases would have to provide sufficient flow to alleviate the DO and TDS problems in this section of the river. It would be critical to conduct a study to determine a total water balance form Red bluff Reservoir to Iraan to determine these flows. Once this is established, and through trial and error test a base flow of this portion of the river can be established. Pulse flows and overbank flows must be established from calculations of the drainage basins, soil and vegetation runoff coefficient determinations, and rainfall histories of the various sub-basins which are separated from the river by irrigation canals. Once these flow volumes and durations are calculated for each sub-basin, the flow would be calculated and statistically weighted as to the probabilities of more than one sub-basin producing pulse flow events at the same time.

Pulse flows are as critical to channel maintenance and fish habit as subsistence flows are to keeping them alive.

This entire study would be necessary to determine the level of effort to create a sound ecological environment for the Upper Pecos River from Red Bluff to the confluence with Independence Creek.

5.3 Adaptive Management/Work Plan Process and Products

A process is needed to implement the work plan which will carry out the research and monitoring recommendations described above. This process is well underway in several previous basins and the Rio Grande BBASC may choose to determine its own approach based on how the process has progressed in these other basins. We offer the following suggestion for a process which stakeholders may consider:

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.

1. BBASC and the BBEST, perhaps supported by agencies such as Texas Parks and Wildlife Department, would continue to identify potential sources for funding, monitoring, special studies, and research. Individuals and organizations may be invited to describe local, state, and federal grant opportunities. Opportunities would be sought to adjust existing and upcoming monitoring efforts, particularly Clean Rivers Program work, to address multiple needs including those of the BBASC.
2. The BBASC would convene a work group that would:
   a. Identify baseline sound environment conditions,
   b. Compile information collected for the work plan, and
   c. Analyze information and prepare the initial work plan for BBASC approval and submittal according to the specified schedule.
3. The BBASC would finalize a process and schedule for describing work plan results according to the specified schedule.
4. 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.

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 Rio Grande 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 2012 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 2022. 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.

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