Environmental Flows Recommendations Report

**Final Submission to the
Environmental Flows Advisory 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**

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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

David Buzan, Vice Chair

Robert Edwards, Ph. D.

Carlos Marin, Ph. D.

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

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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.

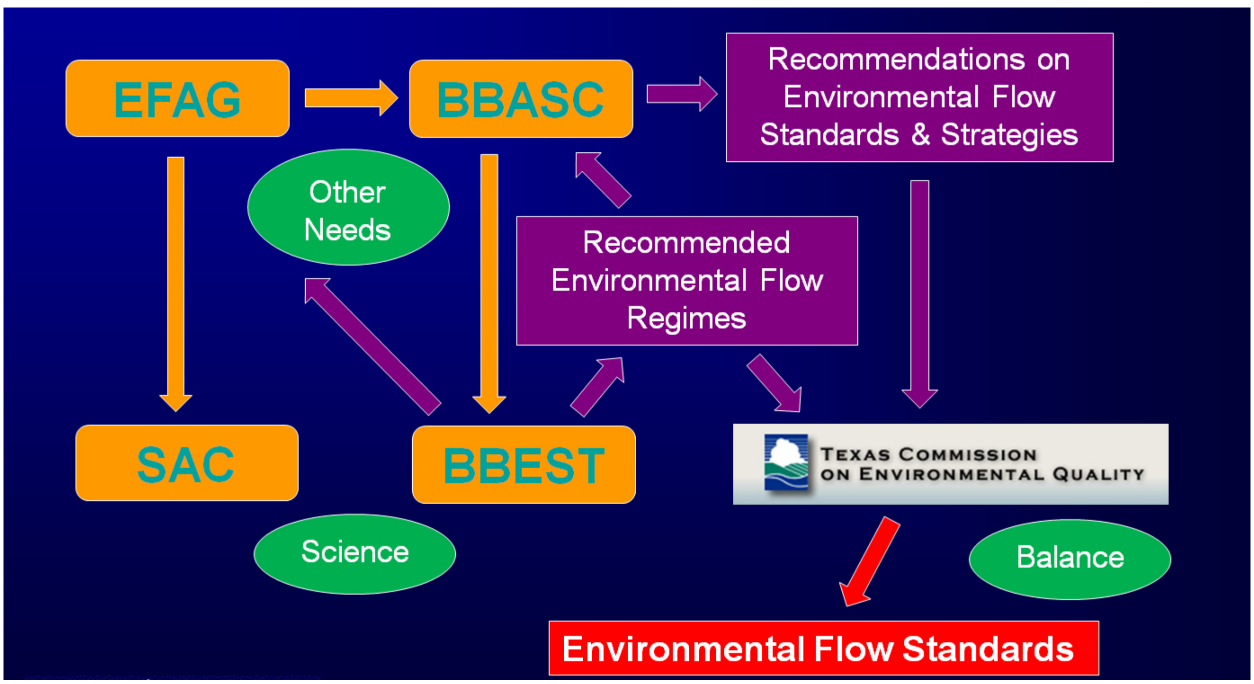

Figure 1.1.1. SB3 Environmental Flow Process (chart developed by Sam Vaugh, Nueces BBEST).

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.

Justification for Upper and Lower Basin BBESTs

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).

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 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

<u>Rio Grande Above Tidal</u>

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

Lower Laguna Madre

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.

Rio Grande Tidal

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.

Bahia Grande and San Martin Lake Complex

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.

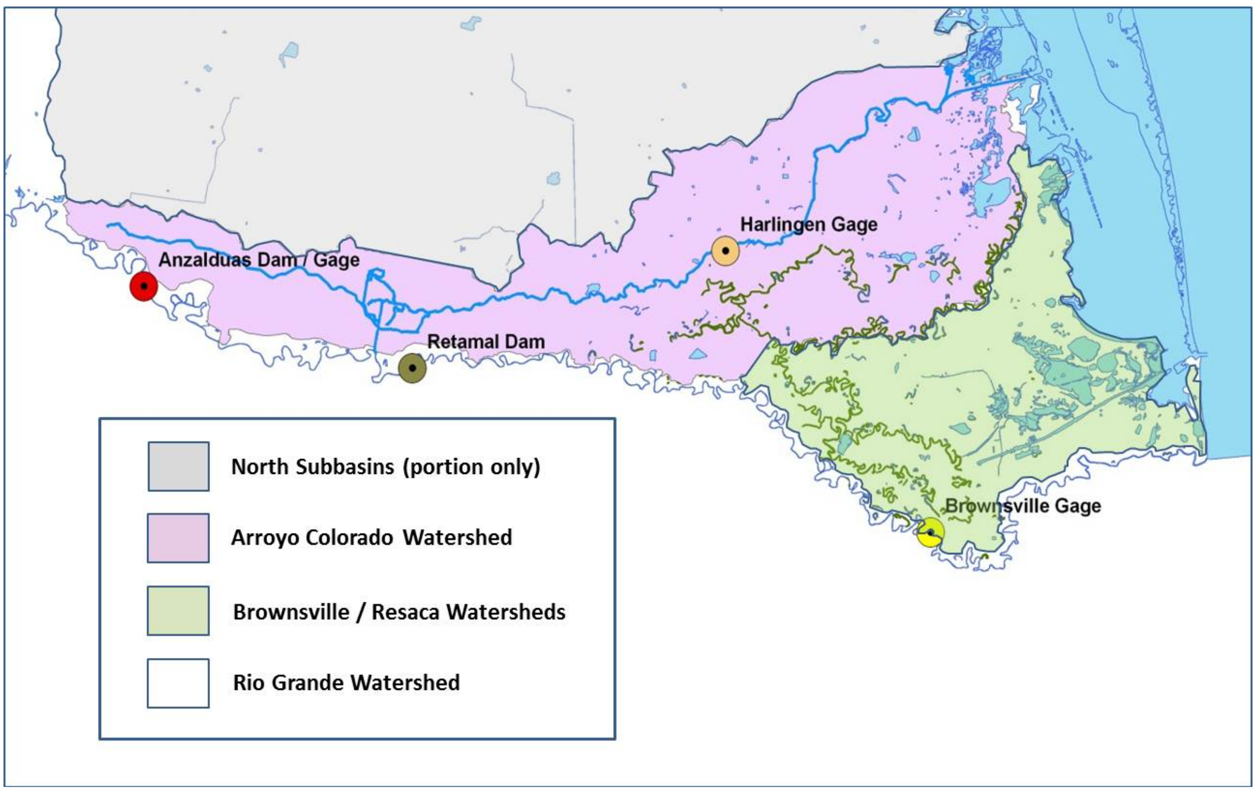


Figure 2.1.1 Study area map showing the three watersheds included in the water balance / flow analysis discussed in this chapter. The Rio Grande watershed is the narrow, white boundary along the Rio Grande River from Anzalduas Dam to the mouth of the river at its confluence with the Gulf of Mexico. (Note: 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 20^{th} 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 20^{th} 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.

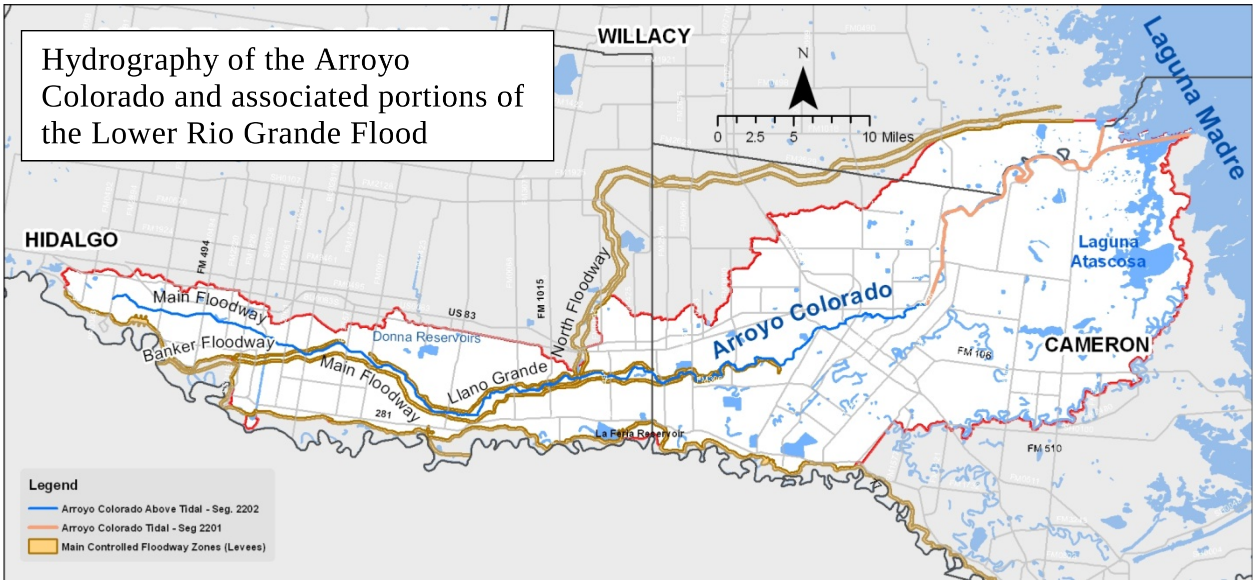


Figure 2.1.2. Detail of the Arroyo Colorado watershed with major stream segments that correspond to the Federal Flood Control Project of the Lower Rio Grande Valley. The tidally influenced segment is shown in light red. Levees that are part of the flood control project are shown in bolded gold lines.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

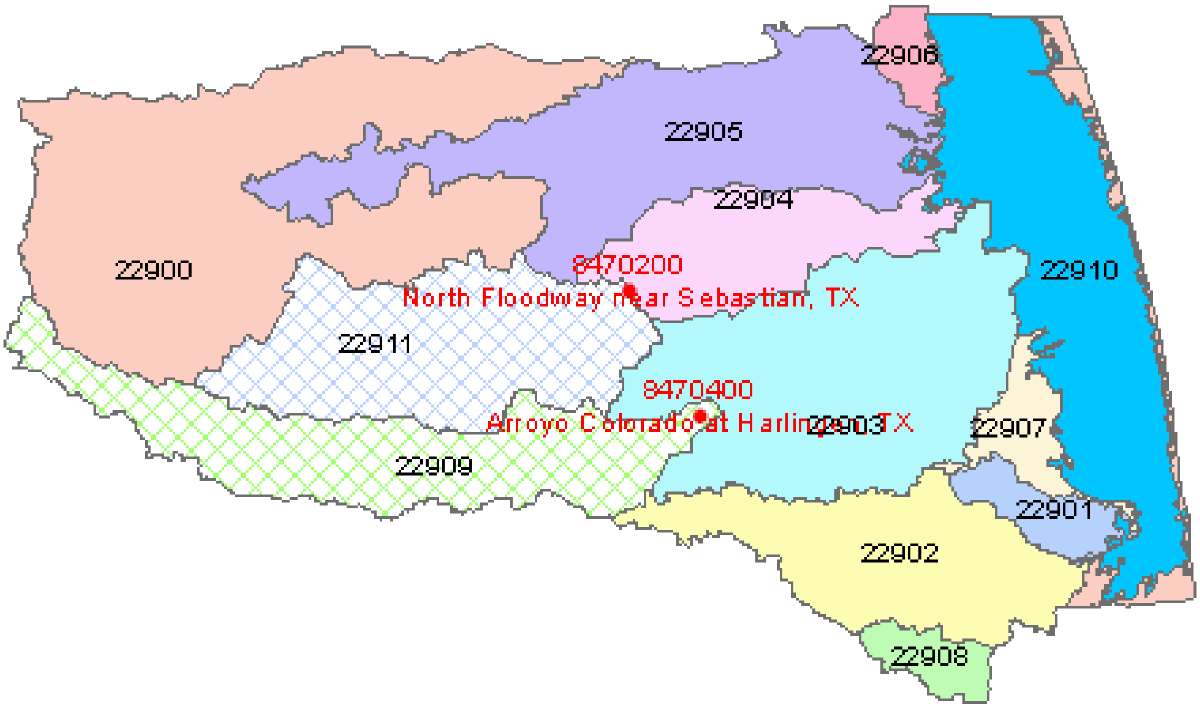


Figure 2.1.3 Study area delineated in subbasins used by the Texas Water Development Board Coastal Hydrology Program (Schoenbaechler et al., 2011)

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.

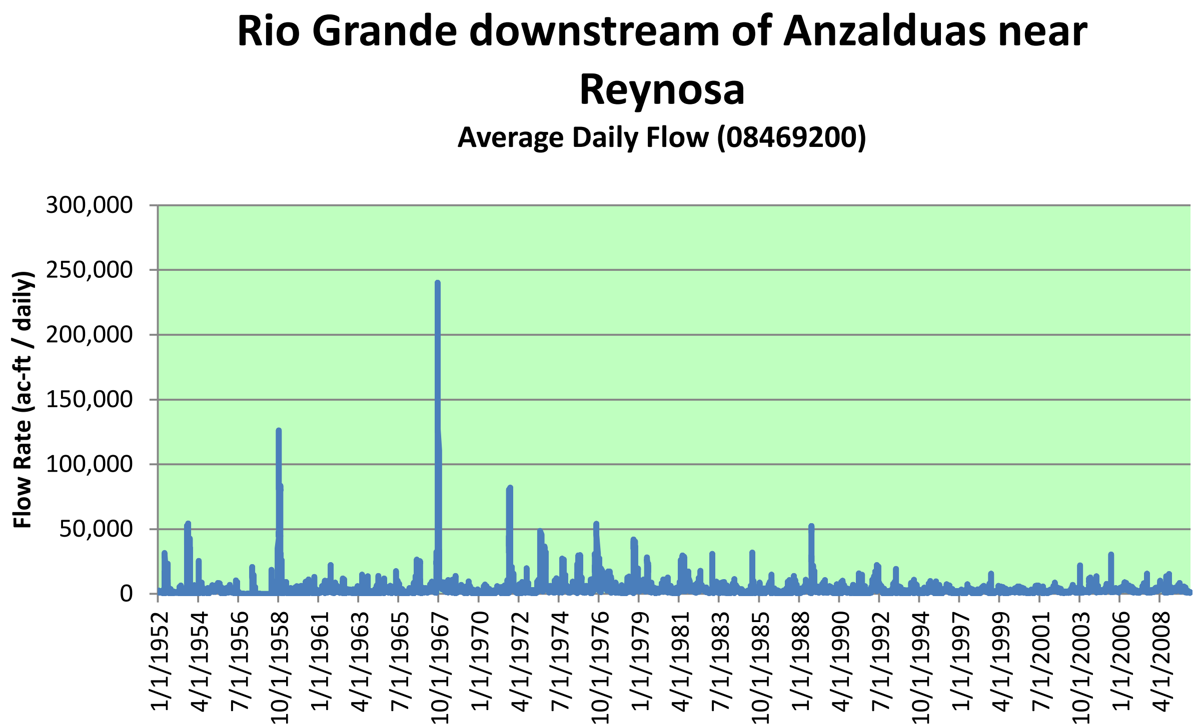


Figure 2.2.2. Average daily flows as recorded by the IBWC gage #08469200 near Mission, TX and Reynosa, Mexico.

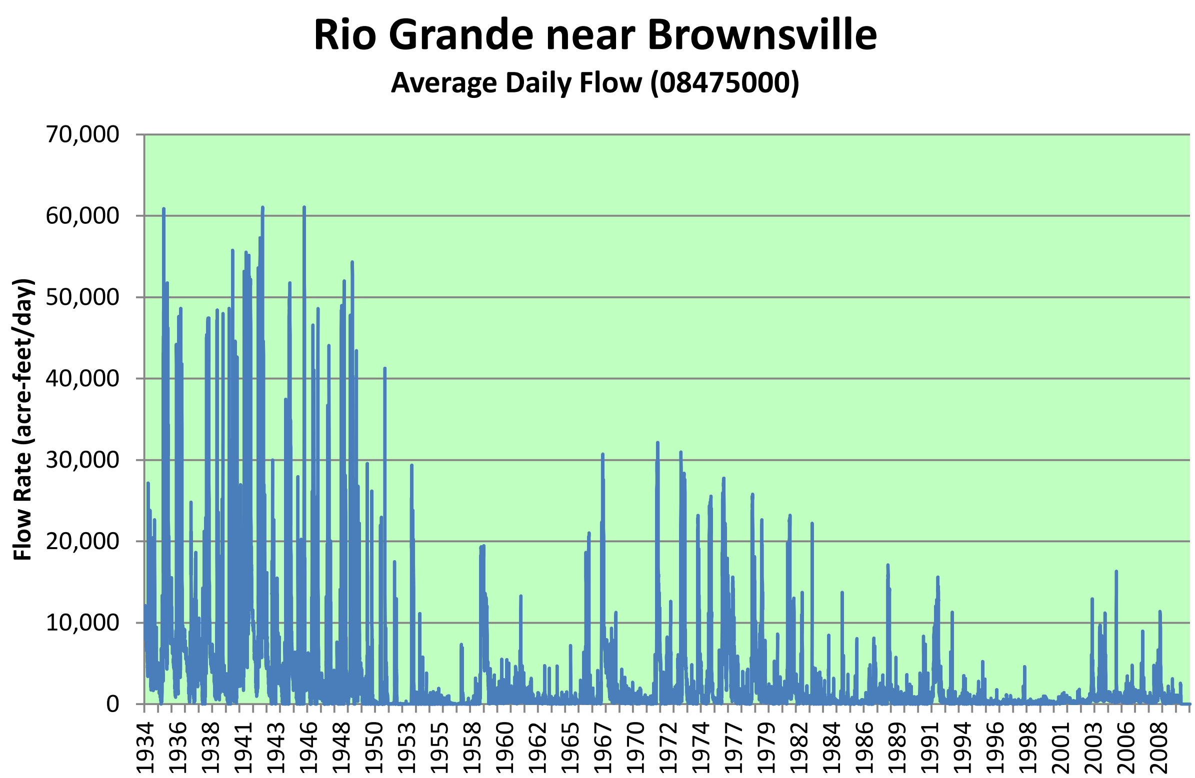


Figure 2.2.3. Average daily flows as recorded by the IBWC gage #08475000 near Brownsville, TX.

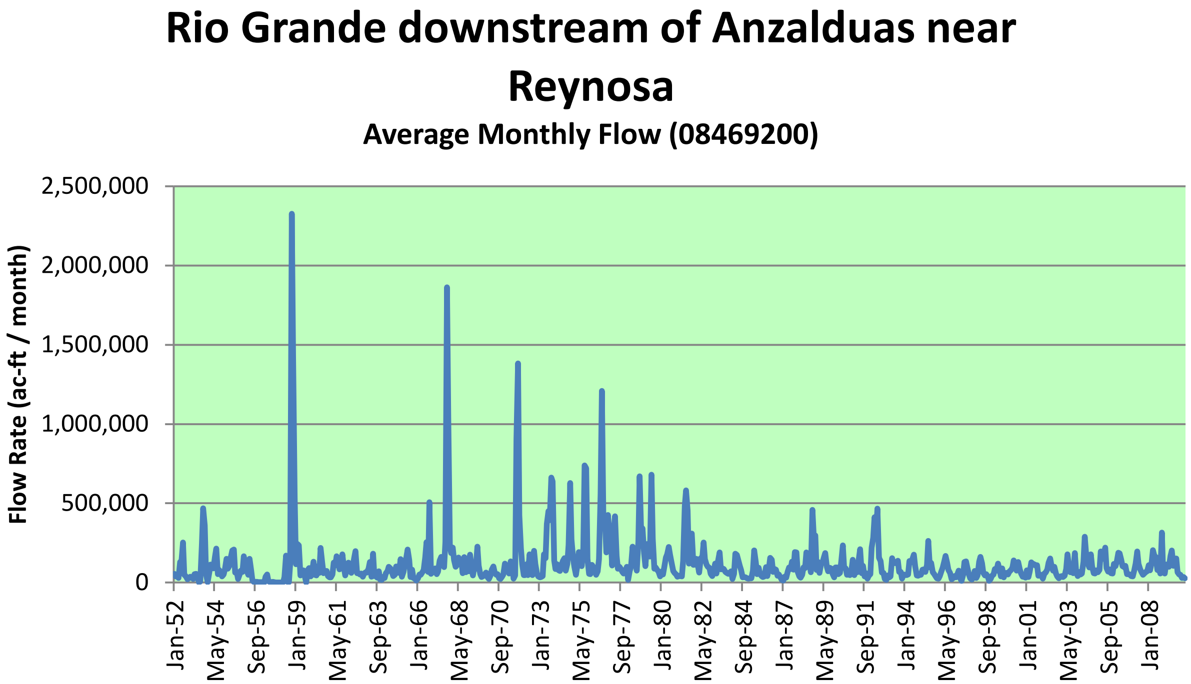


Figure 2.2.4. Average monthly flows as recorded by the IBWC gage #08469200 near Mission, TX and Reynosa, Mexico.

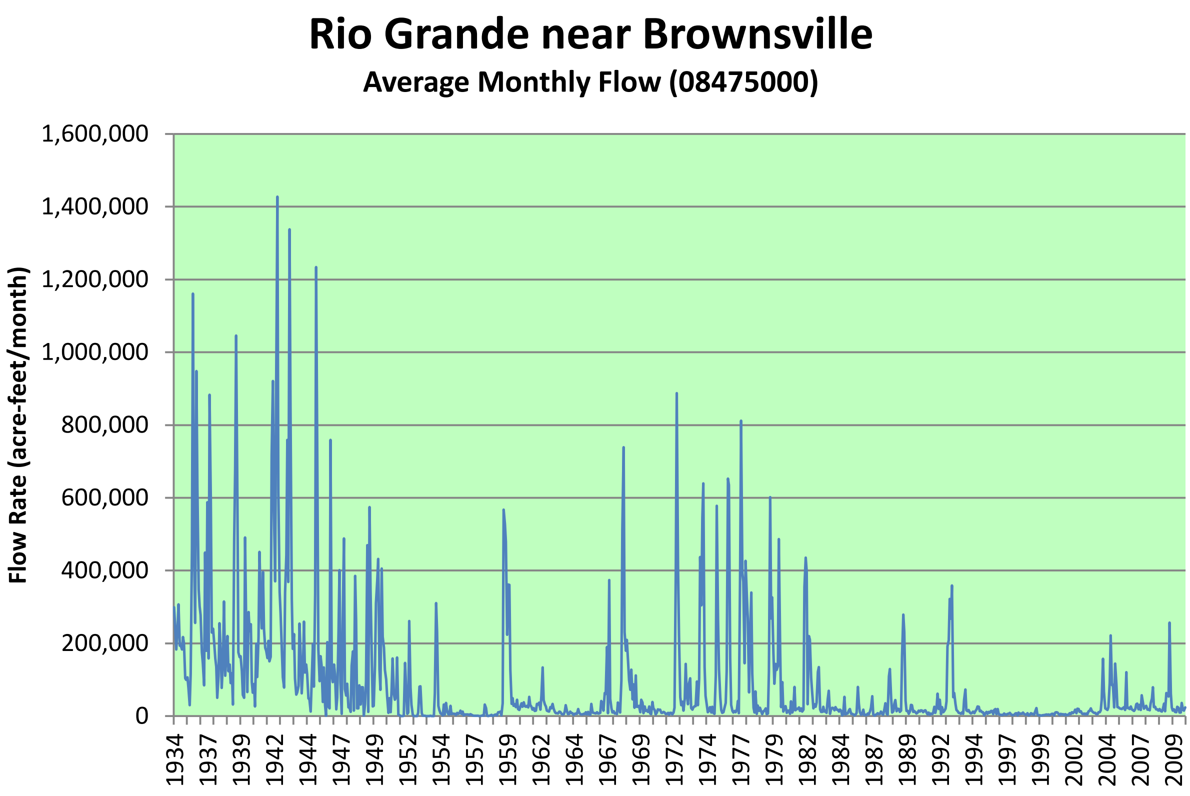


Figure 2.2.5. Average monthly flows as recorded by the IBWC gage #08475000 near Brownsville, TX.

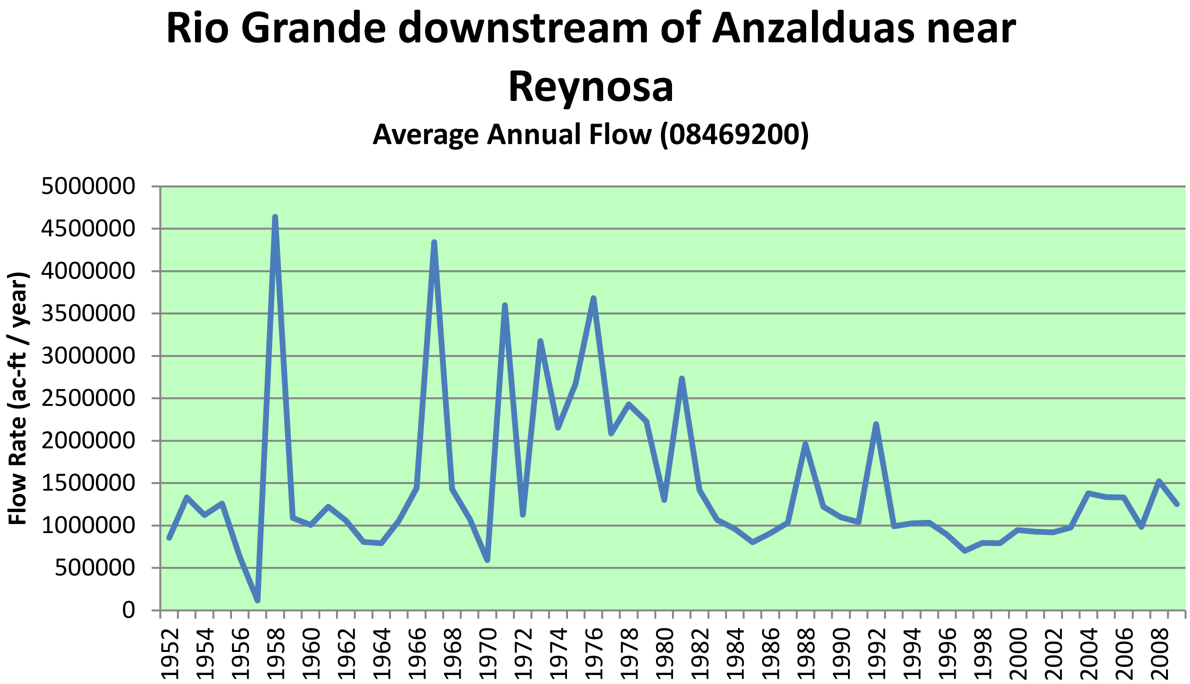


Figure 2.2.6. Average yearly flows as recorded by the IBWC gage #08469200 near Mission, TX and Reynosa, Mexico.

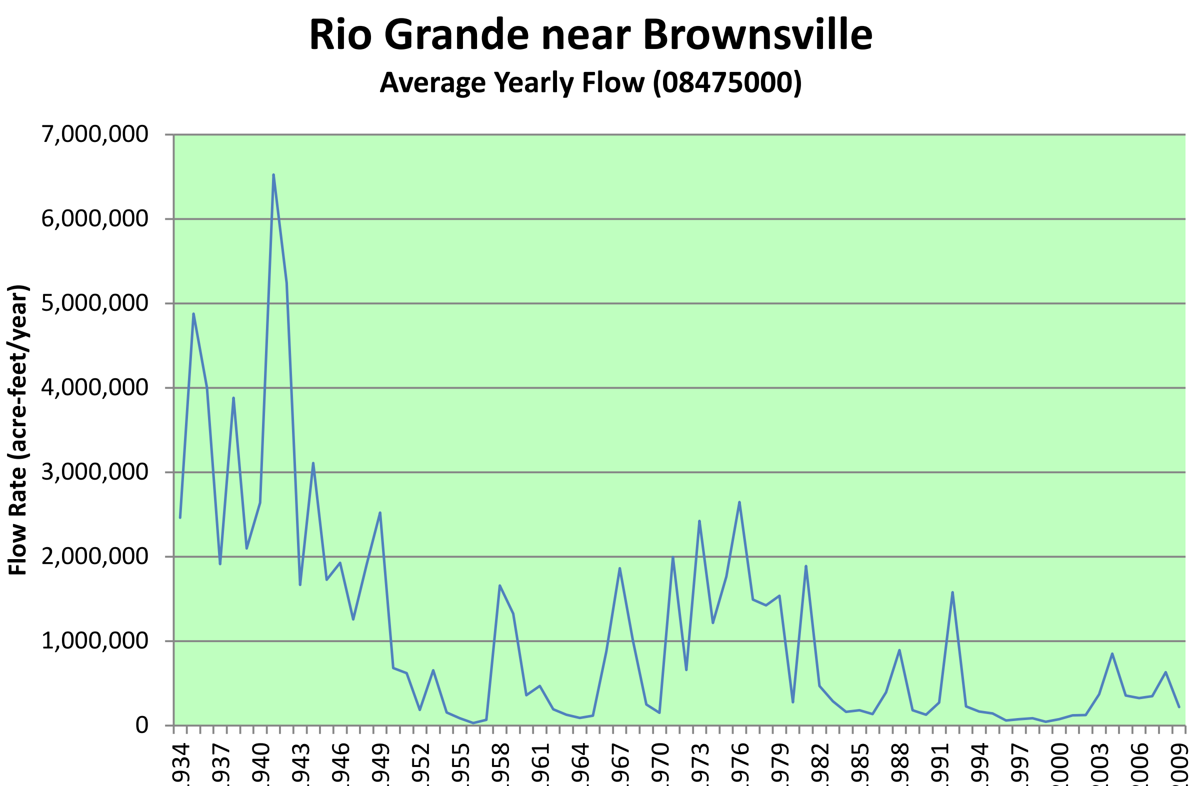


Figure 2.2.7. Average yearly flows as recorded by the IBWC gage #08475000 near Brownsville, TX.

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)
5^{th}	19,306	2,184
10^{th}	30,162	4,148
25^{th}	49,301	8,535
50^{th}	79,199	21,276
75^{th}	132,436	95,612
90^{th}	215,383	267,417
95^{th}	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.

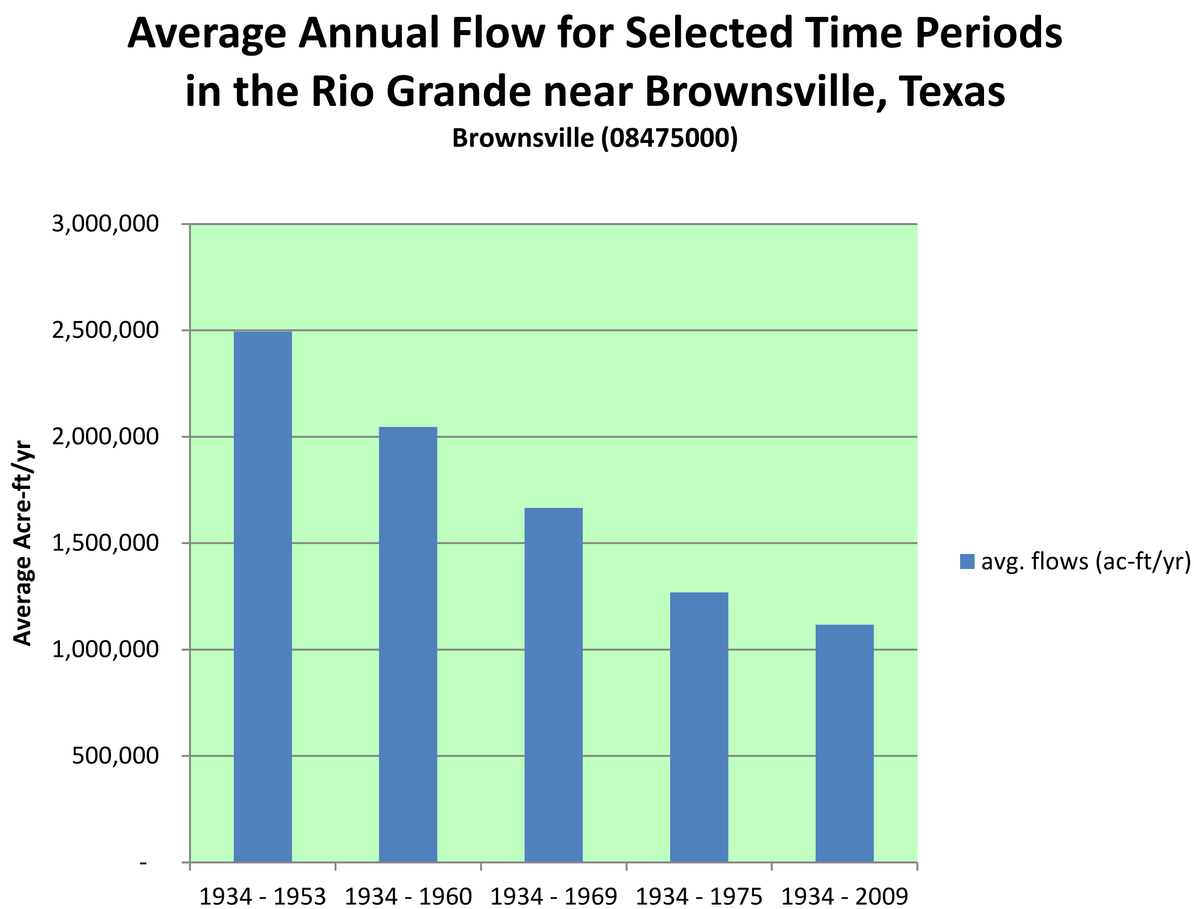


Figure 2.2.8. Average yearly flows grouped cumulatively by time periods coinciding with the construction of the four dams described in Table II.2-4.

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.

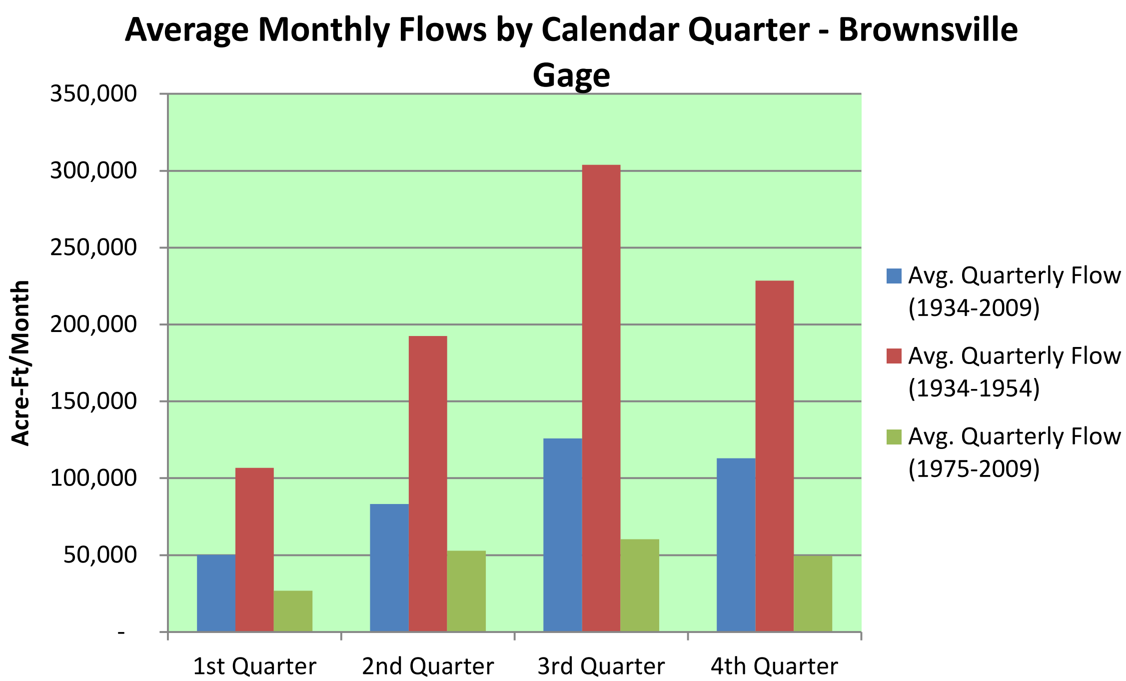


Figure 2.2.9. Average monthly flows at the Brownsville gage grouped quarterly from 1934 to 2009, 1934-1954, and 1975-2009.Arroyo Colorado Historic Flows

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.

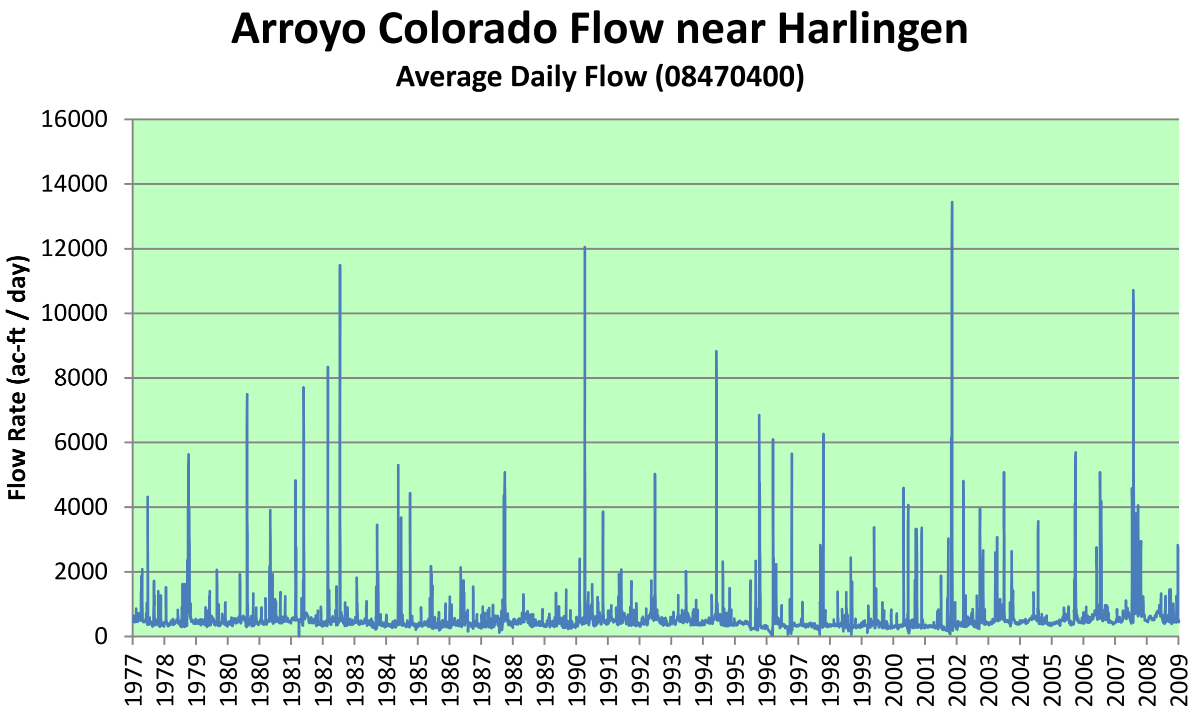


Figure 2.2.10. Average daily flows as recorded by the Harlingen gage in the Arroyo Colorado from 1977 to 2009.

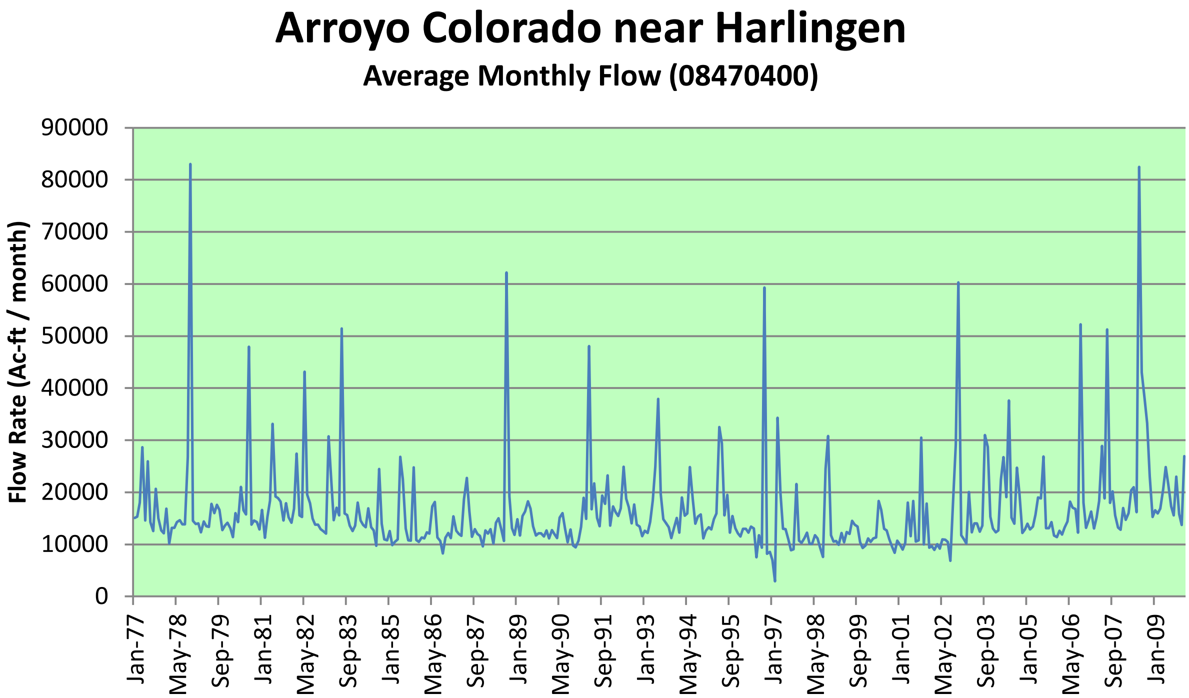


Figure 2.211. Average monthly flows as recorded by the Harlingen Gage in the Arroyo Colorado from 1977 to 2009.

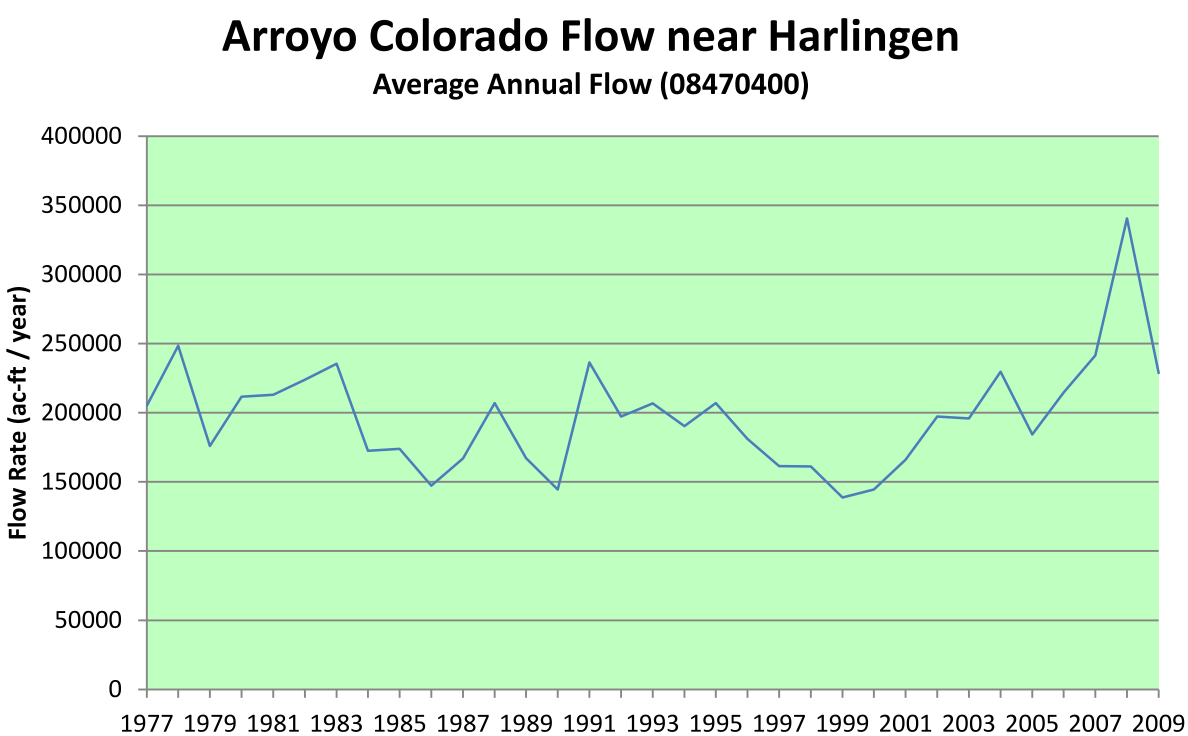


Figure 2.2.12. Average daily flows grouped in the Arroyo Colorado at the Harlingen gage from 1977 to 2009.

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.

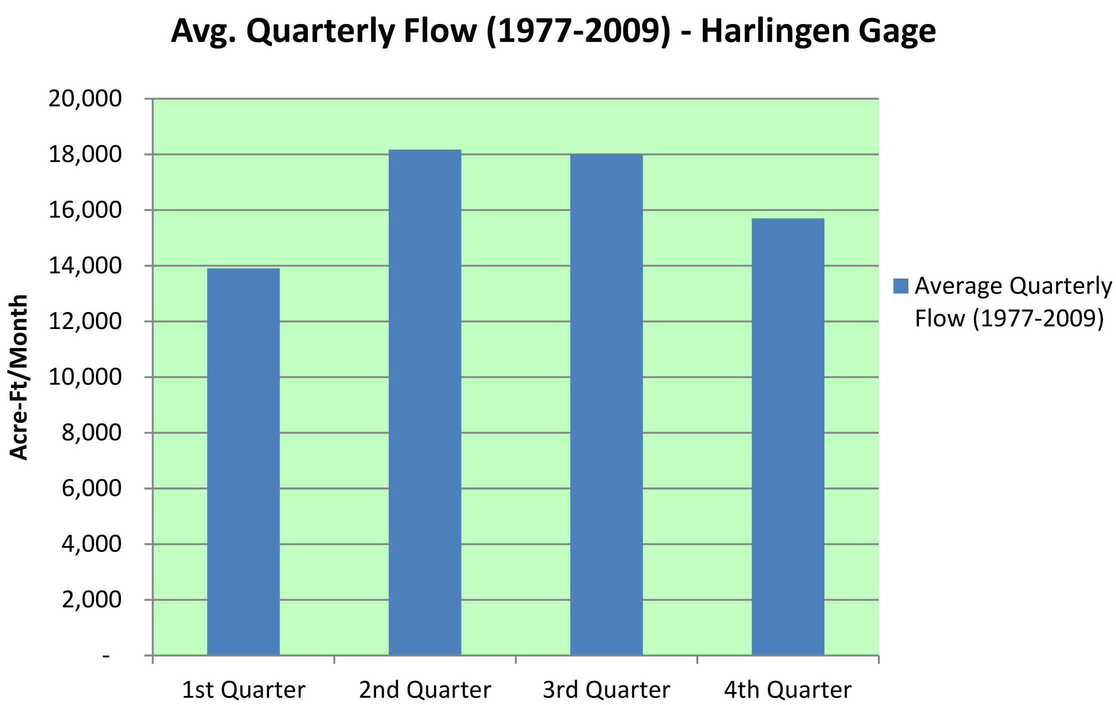


Figure 2.2.13. Average monthly flows grouped quarterly from 1977 to 2009 at the Harlingen Gage

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.

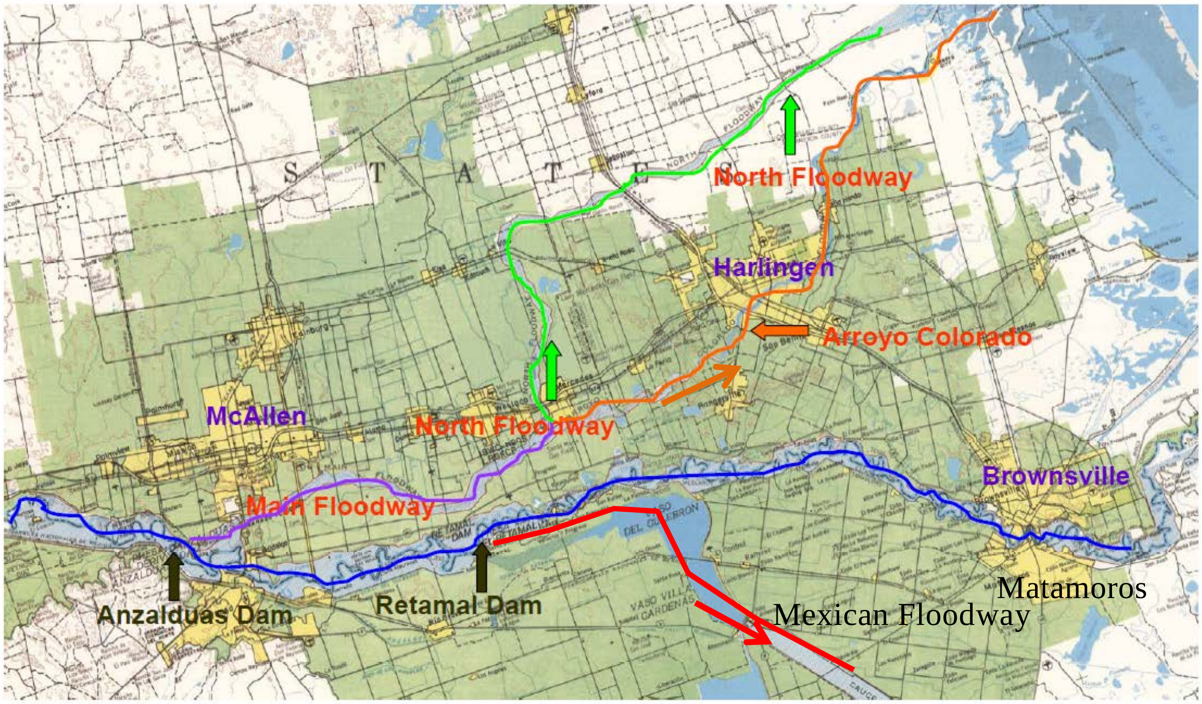


Figure 2.2.14. Generalized schematic of the Lower Rio Grande Flood Control Project showing diversion dams, diversion floodways, and larger cities in the LRGV. (IBWC, 2012 with modifications)

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

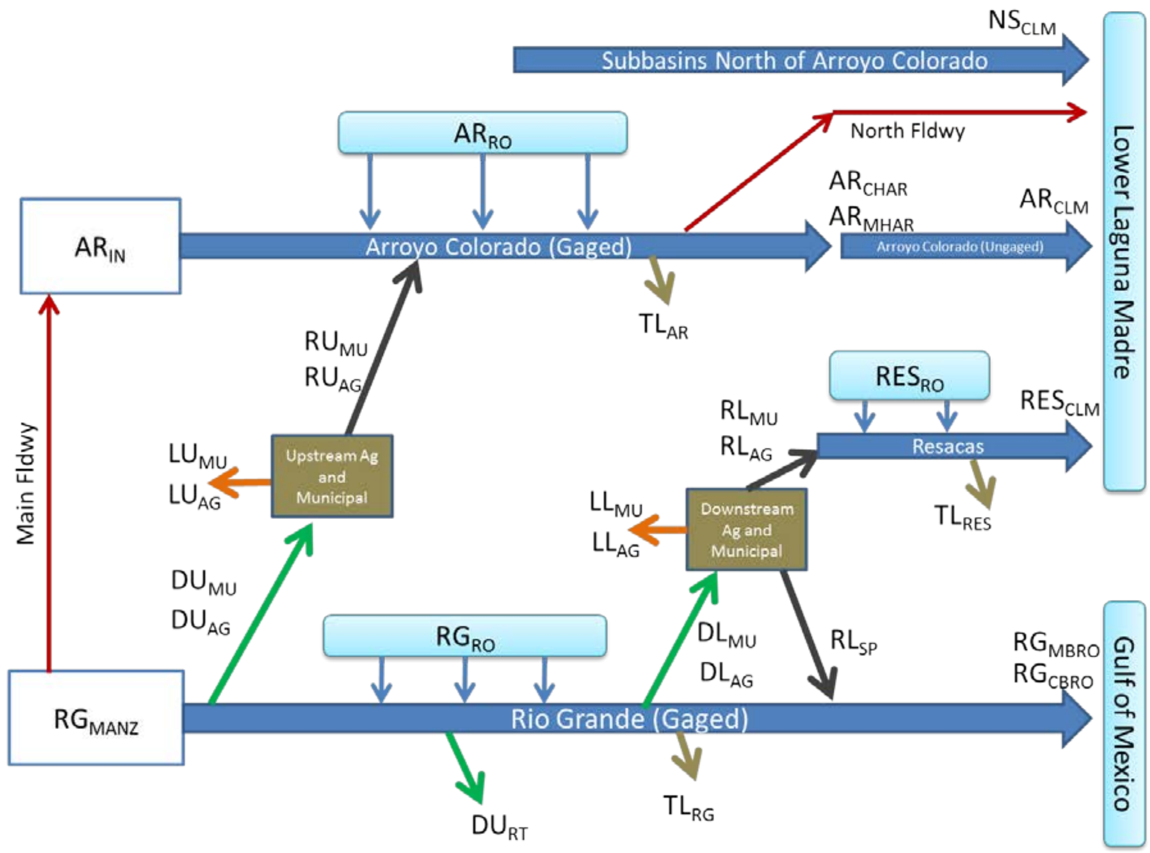


Figure 2.6.1. Flow schematic for the Arroyo Colorado, Rio Grande, and Resaca subbasins showing variables used in water balance calculations. (For a list of variables and descriptions see **Table 2.6.1**)

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

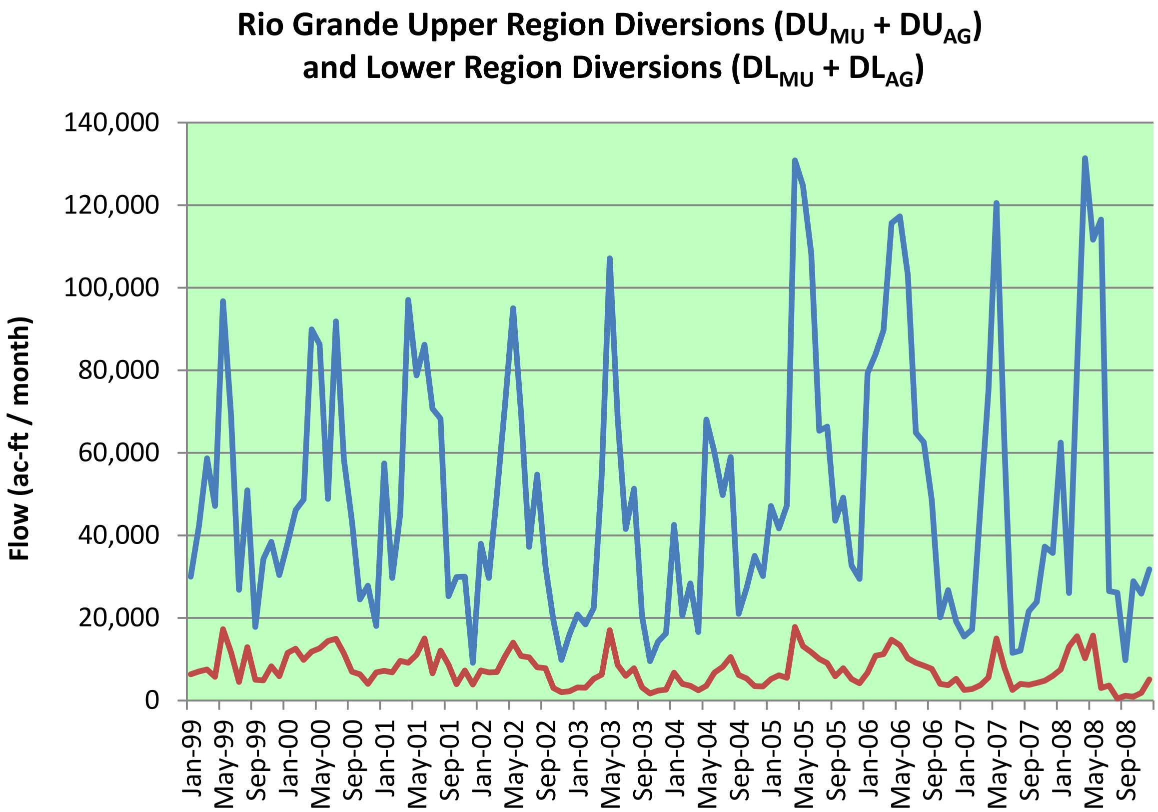


Figure 2.6.2. Monthly average flows for Upper Region and Lower Region Diversions / Withdrawals from the Rio Grande River for combined municipal and agricultural uses.

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.

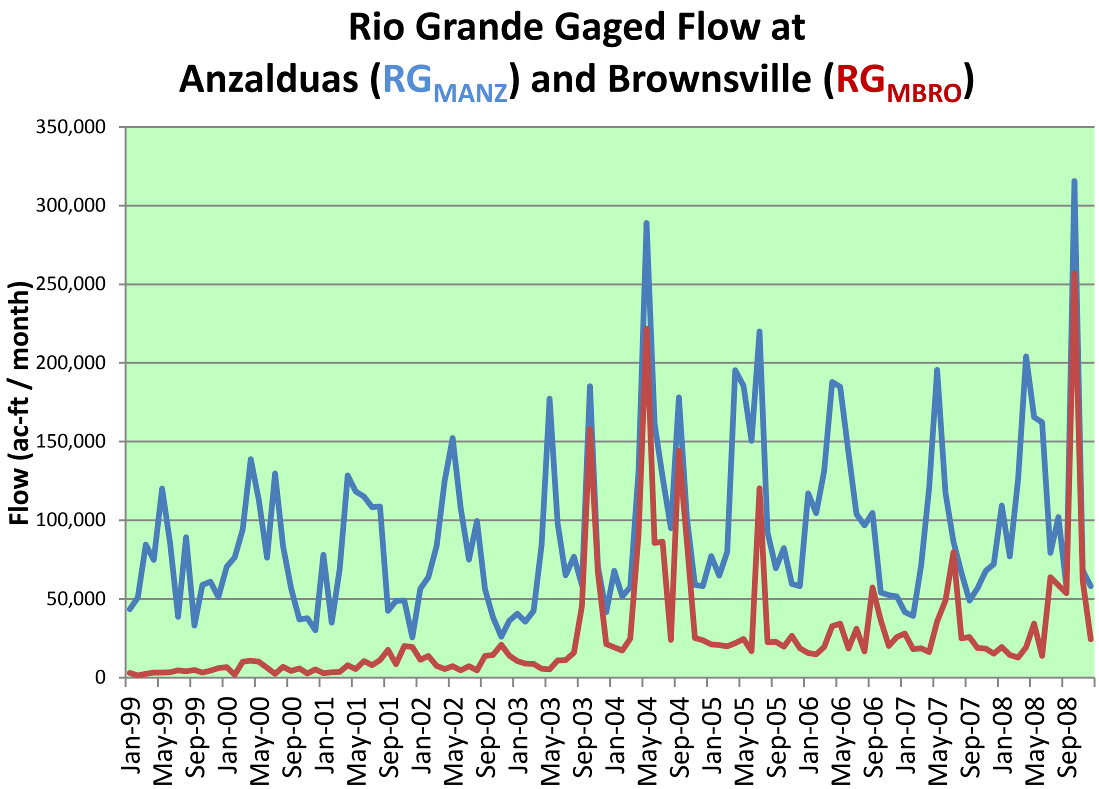


Figure 2.6.3a Monthly average flows for Rio Grande gages just downstream of Anzalduas (blue) and at Brownsville (red).

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.

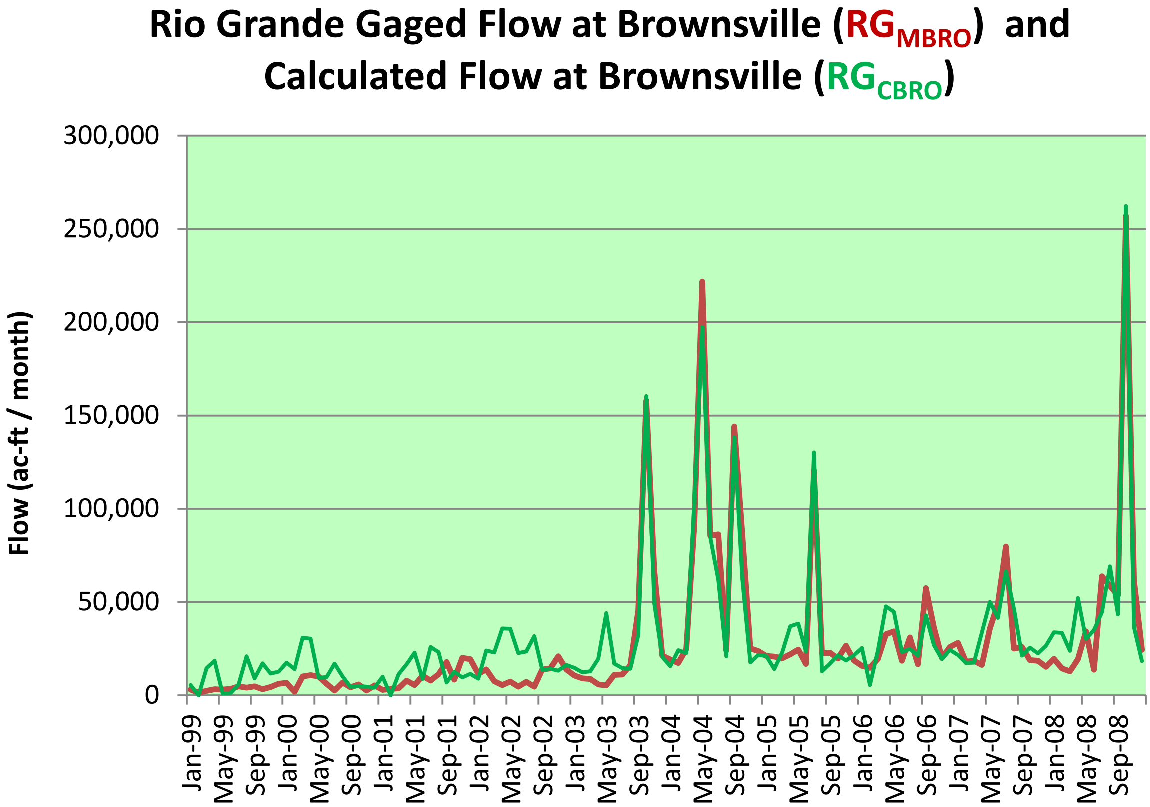


Figure 2.6.3b. Comparison of measured (gaged) flow and calculated flows in the Rio Grande at Brownsville.

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.

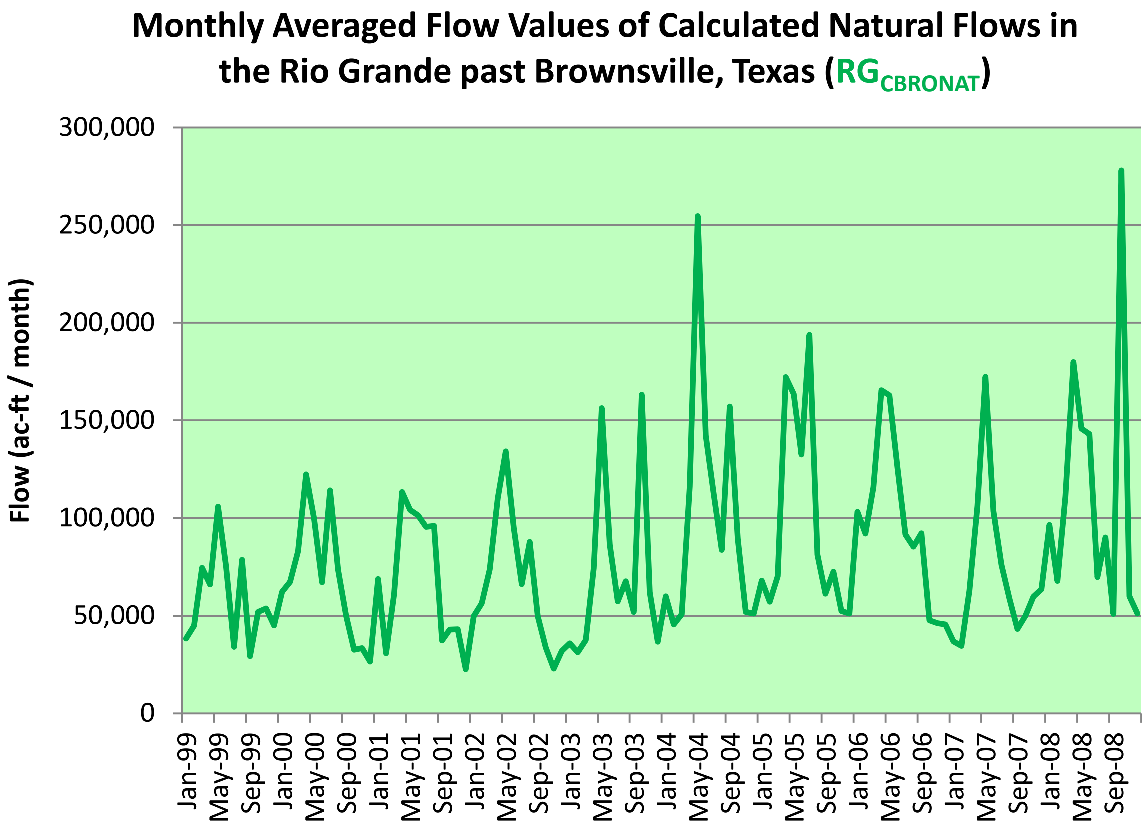


Figure 2.6.4. Monthly average flows for estimated natural flows in the Rio Grande past Brownsville, Texas. (Note: "Natural Flows" were estimated by assuming no agricultural or municipal withdrawals from the Rio Grande within the study area.)

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

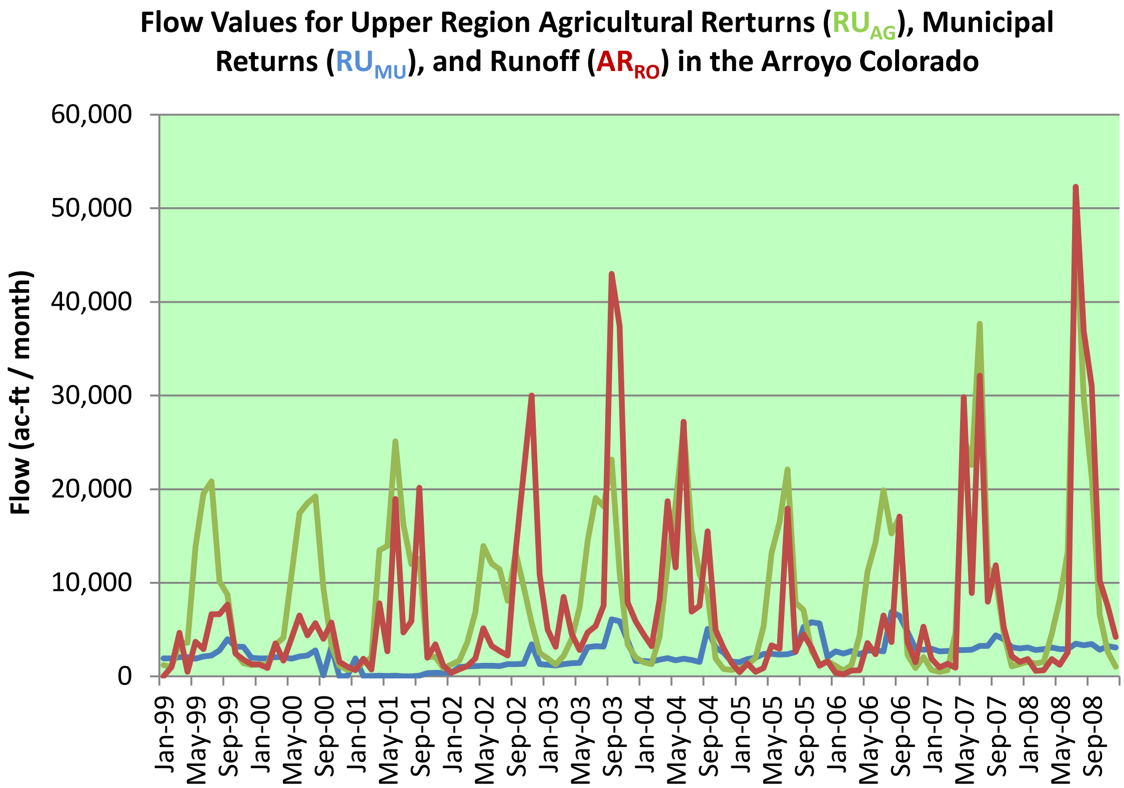


Figure 2.6.5. Monthly average flows for agricultural and municipal returns as well as rainfall runoff for the Arroyo Colorado.

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

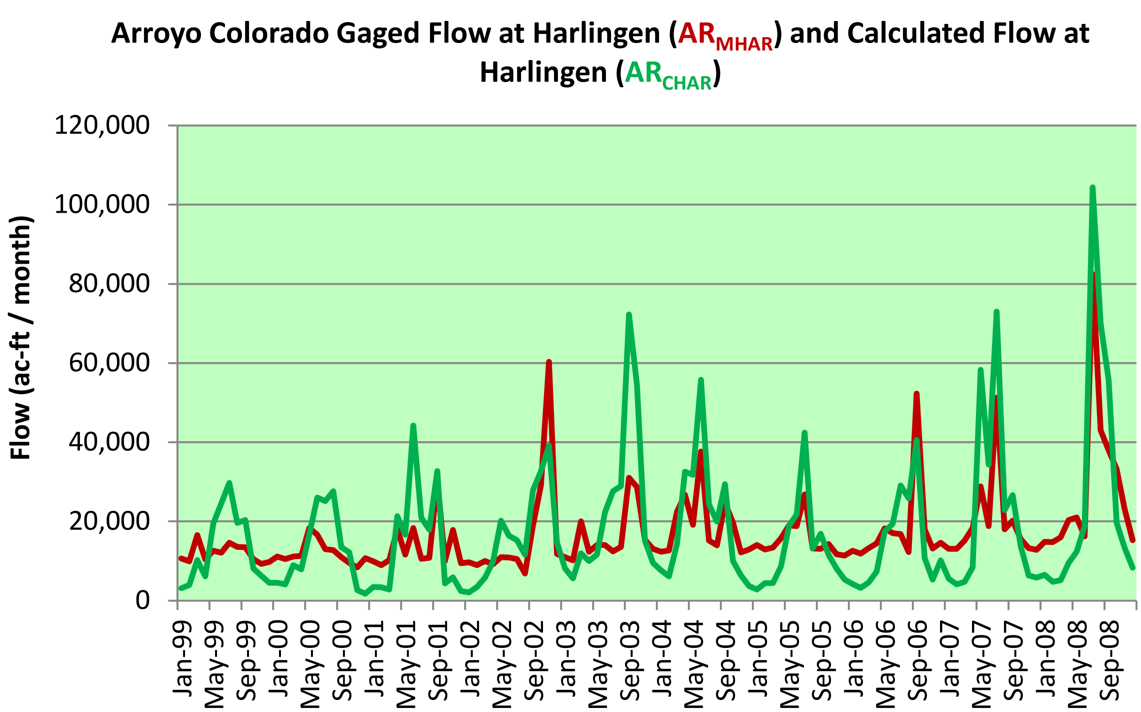


Figure 2.6.6. Comparison of measured (gaged) flow and calculated flows in the Arroyo Colorado at Harlingen.

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

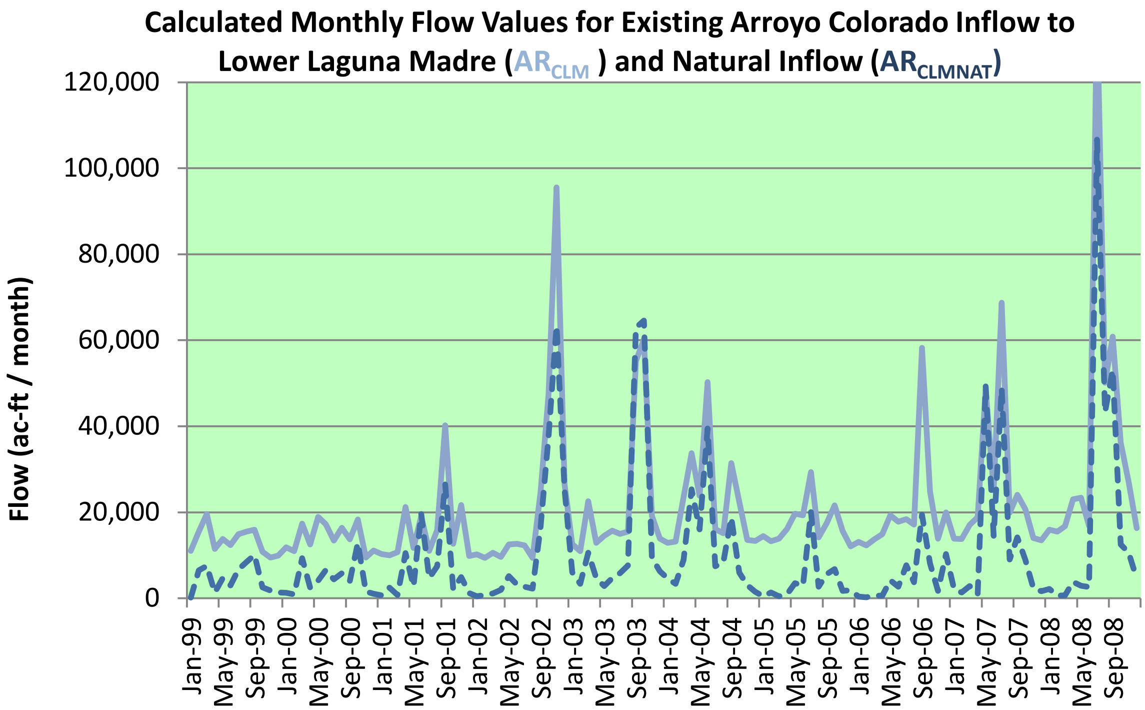


Figure 2.6.7. Graph of existing (AR_{CLM}) and natural inflows (AR_{CLMNAT}) to the Lower Laguna Madre from the Arroyo Colorado. (Both gaged and ungaged basins)

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.

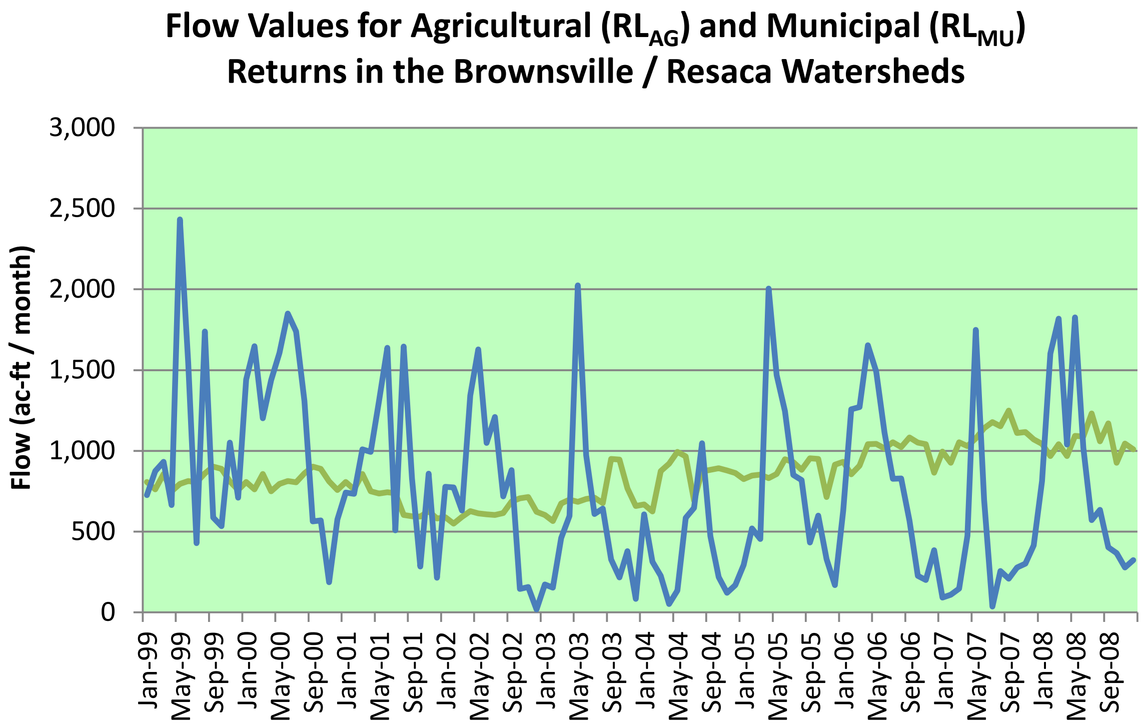


Figure 2.6.8a. Monthly average flows for agricultural and municipal returns in the Brownsville / Resaca watersheds.

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.

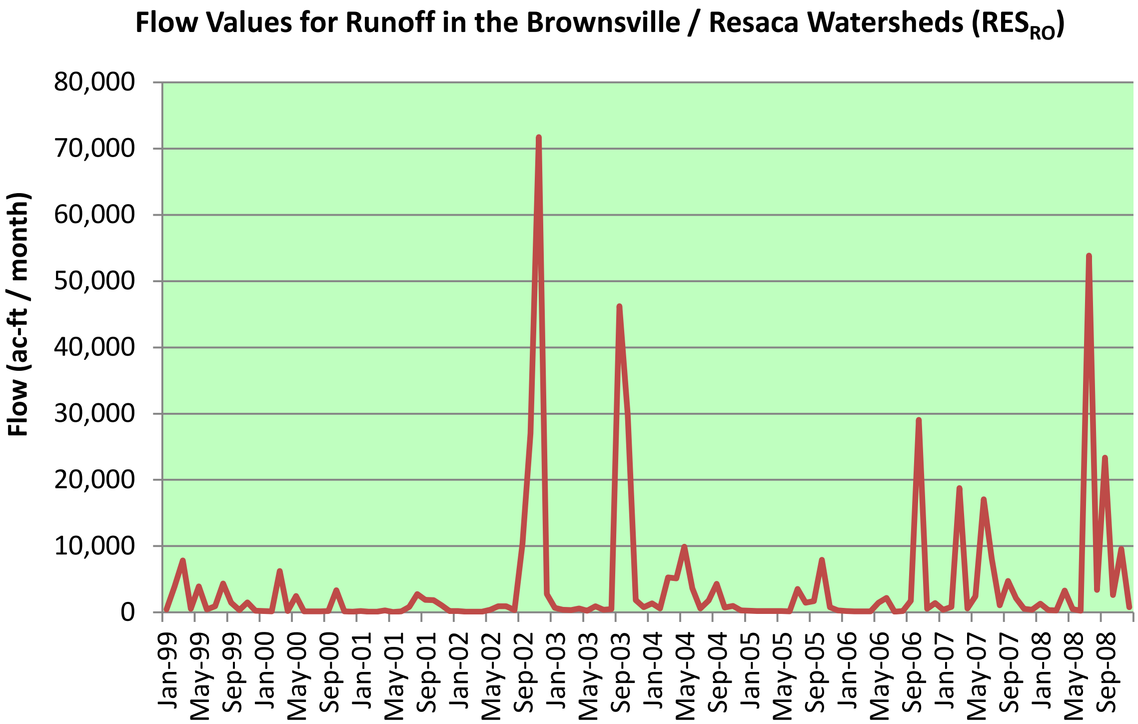


Figure 2.6.8b. Monthly average flows estimated rainfall runoff in the Brownsville / Resaca watersheds.

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}.

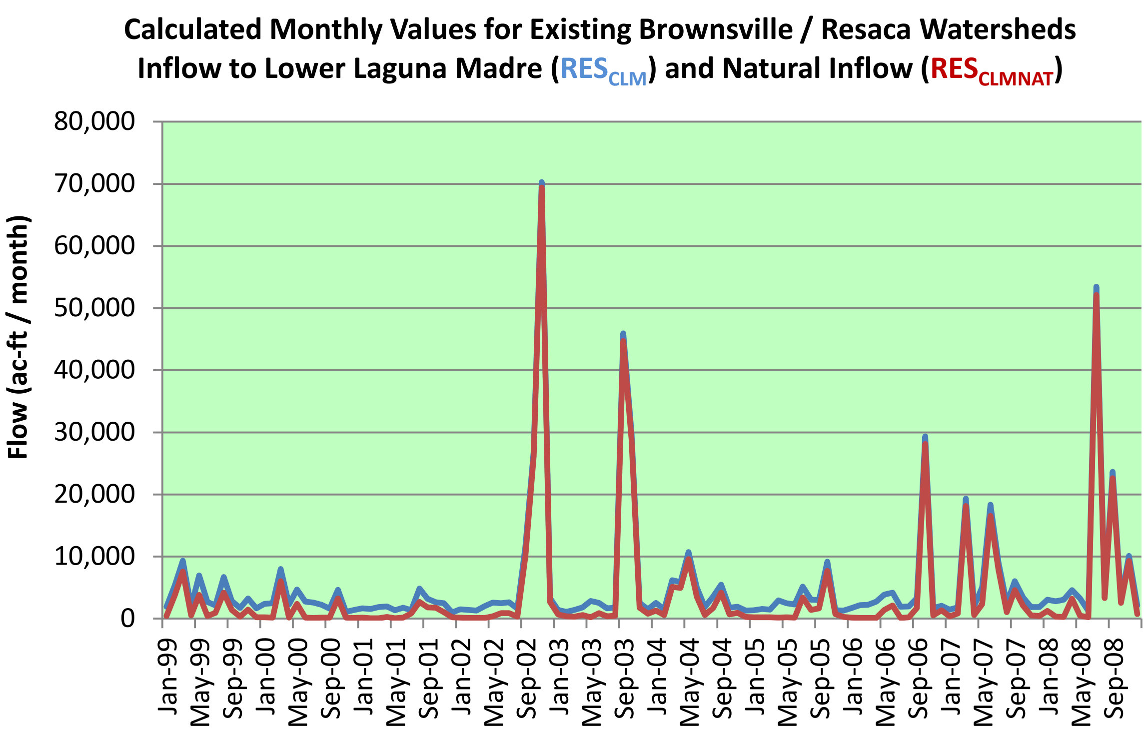


Figure 2.6.9. Graph of existing (RES_{CLM}) and natural inflows (RES_{CLMNAT}) to the Lower Laguna Madre from the Brownsville / Resaca subwatersheds. (All basins ungaged).

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.

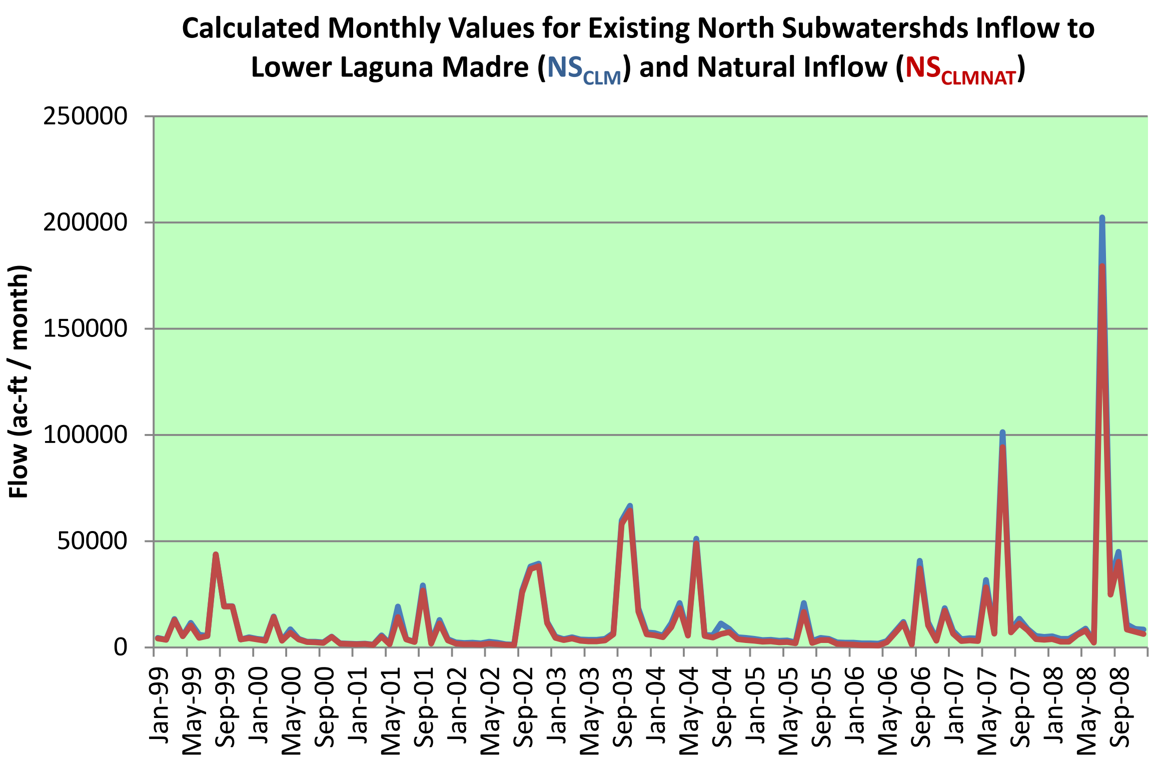


Figure 2.6.10. Graph of existing (NS_{CLM}) and natural inflows (NS_{CLMNAT}) to the Lower Laguna Madre from the basins north of the Arroyo Colorado. (Both gaged and ungaged basins)

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.

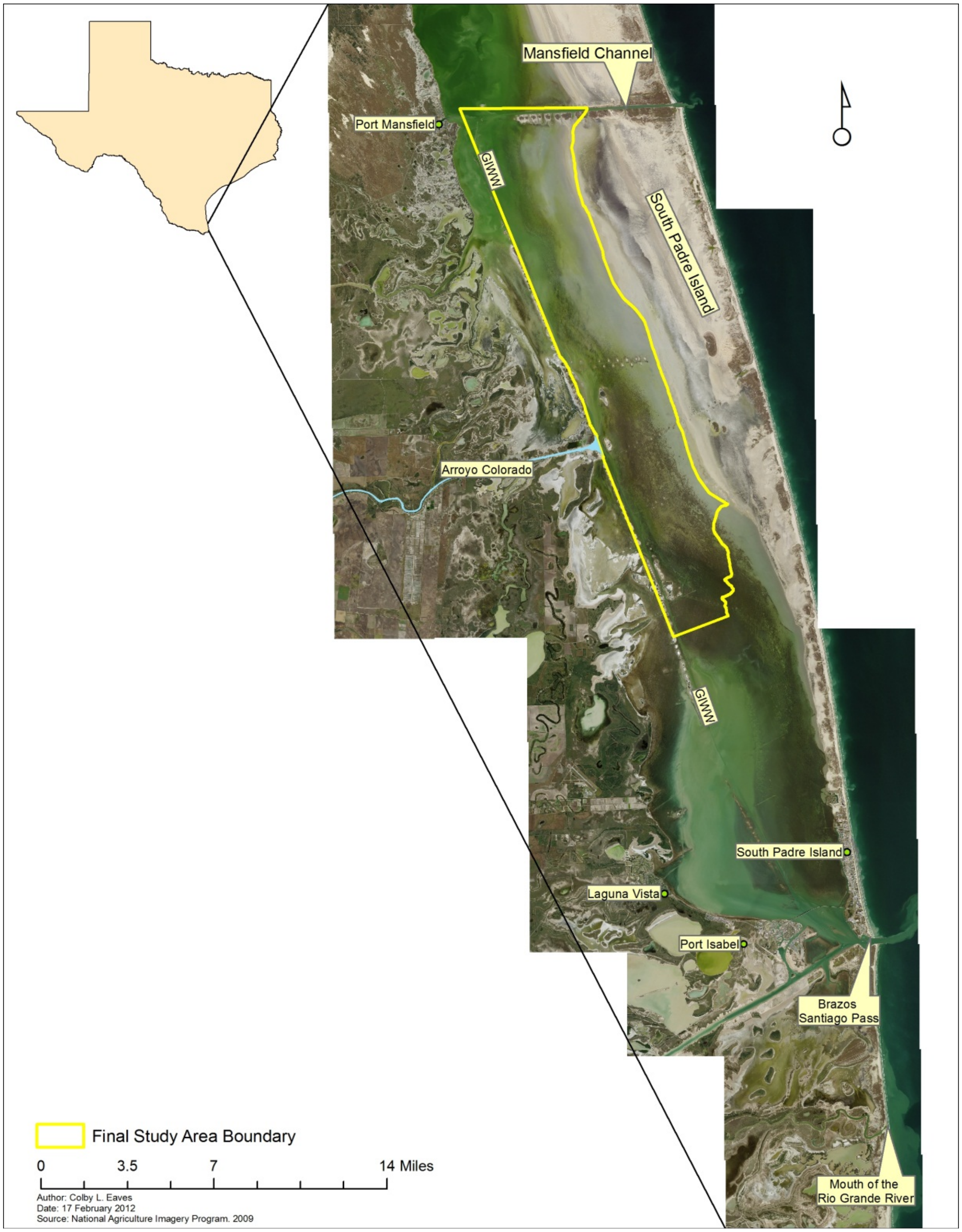


Figure 3.1.1. Color aerial photography mosaic of Lower Laguna Madre taken in January 2009 by National Agricultural Imagery Program (NAIP).

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.

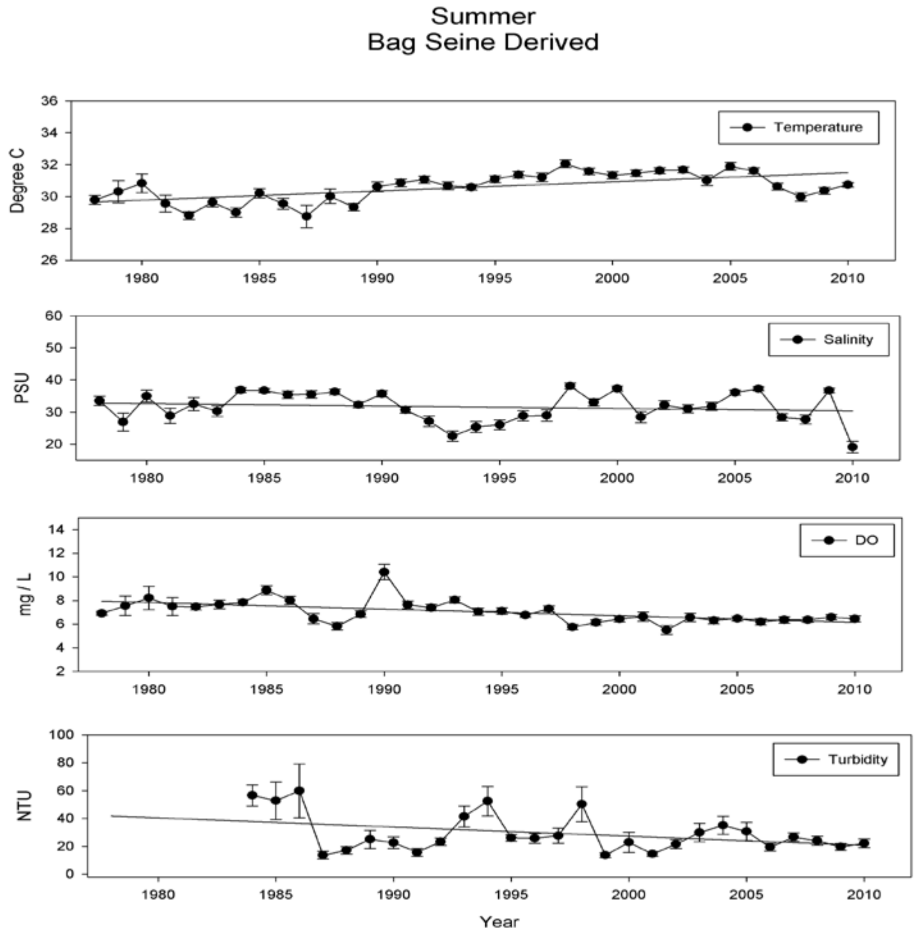


Figure 3.2.1. Mean values of four hydrographic parameters for summer months (Jun-Aug) over entire LLM. Data from TPWD Coastal Fisheries Resource Monitoring database, courtesy of Jim Tolan, TPWD.

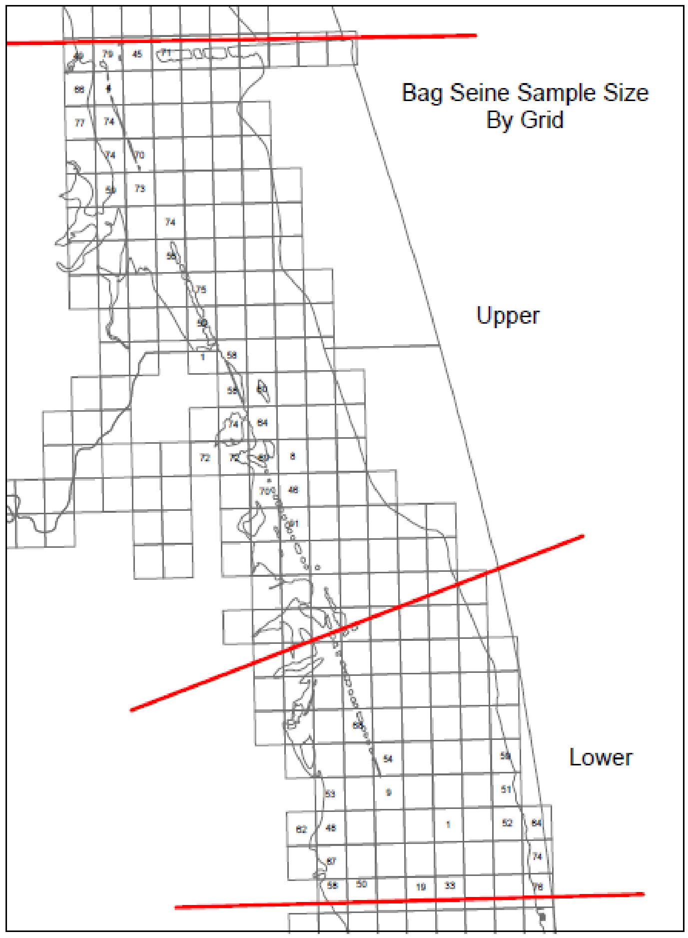


Figure 3.2.2. TPWD sampling stations grid for bag seine collections in LLM study area. Red lines divide study area into northern and southern parts. Data from TPWD Coastal Fisheries Resource Monitoring database, courtesy of Jim Tolan, TPWD.

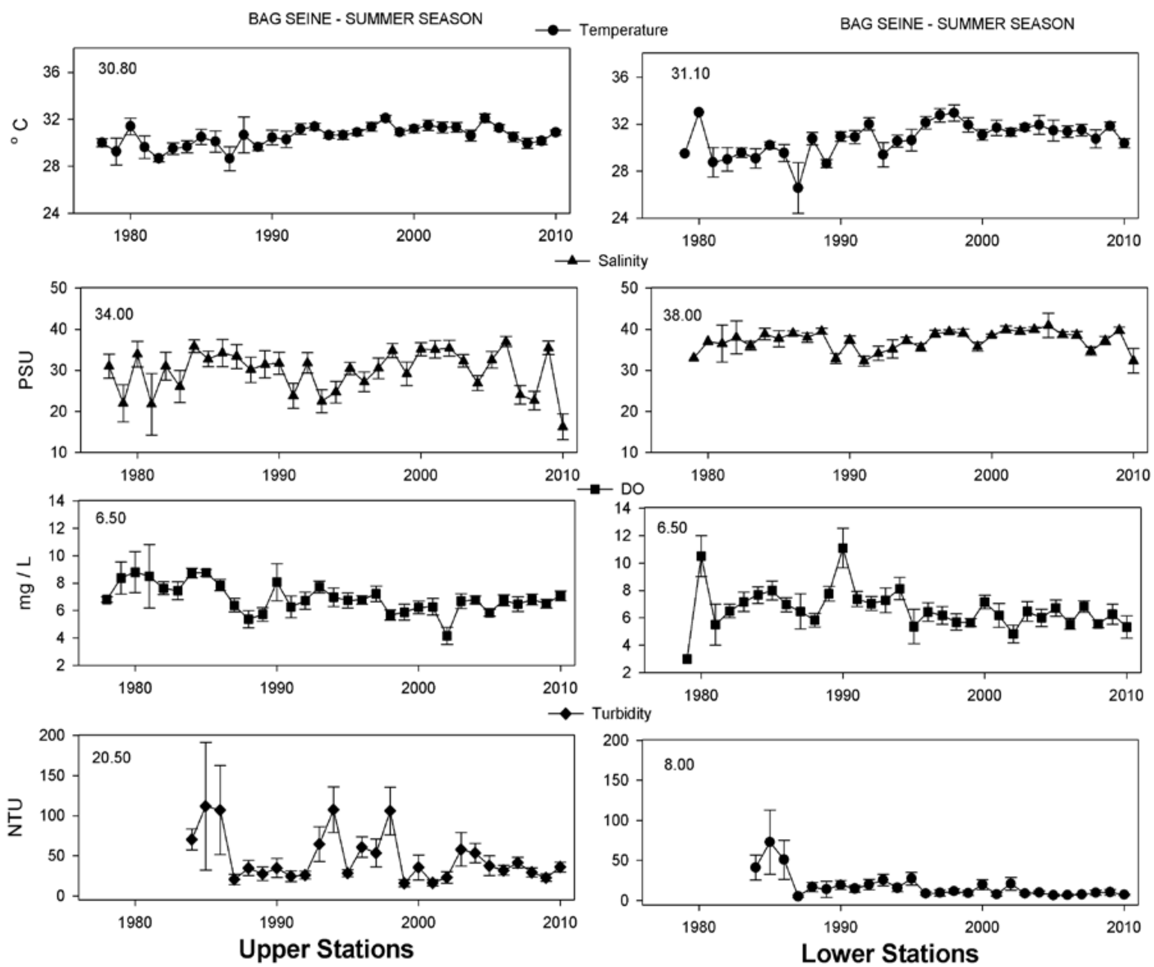


Figure 3.2.3. Mean values of four hydrographic parameters for summer months (Jun-Aug) calculated separately for northern (Upper) and southern (Lower) parts of LLM study area. Mean values listed in upper left corner of graphs. Data from TPWD Resource Monitoring database, courtesy of Jim Tolan, TPWD.

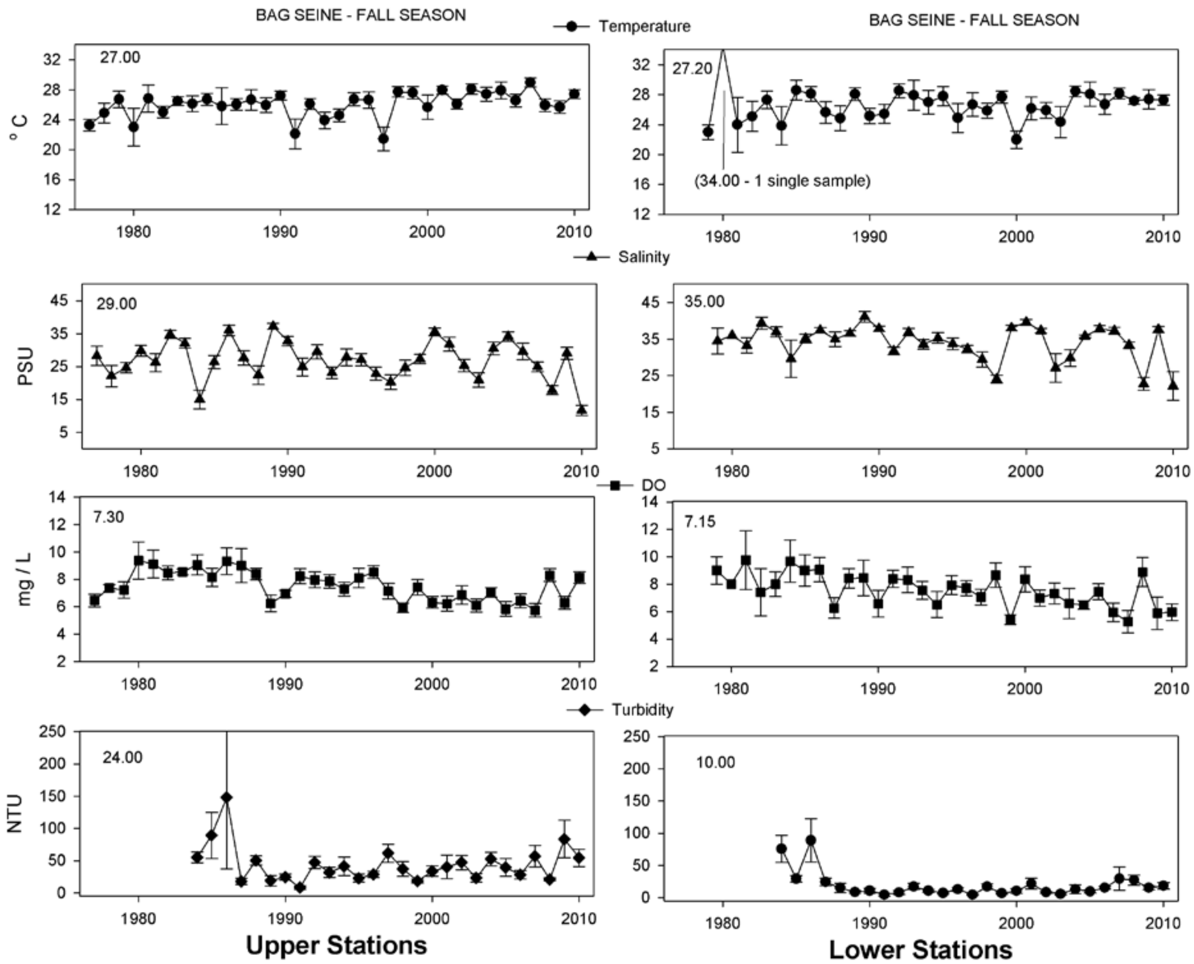


Figure 3.2.4. Mean values of four hydrographic parameters for fall months (Sep-Nov) calculated separately for northern and southern parts of LLM study area. Data from TPWD Resource Monitoring database, courtesy of Jim Tolan, TPWD.

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 (TPWD) since the 1990s. For this report, the BBEST contacted TPWD Coastal Fisheries Division 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 TPWD 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.” TPWD 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.

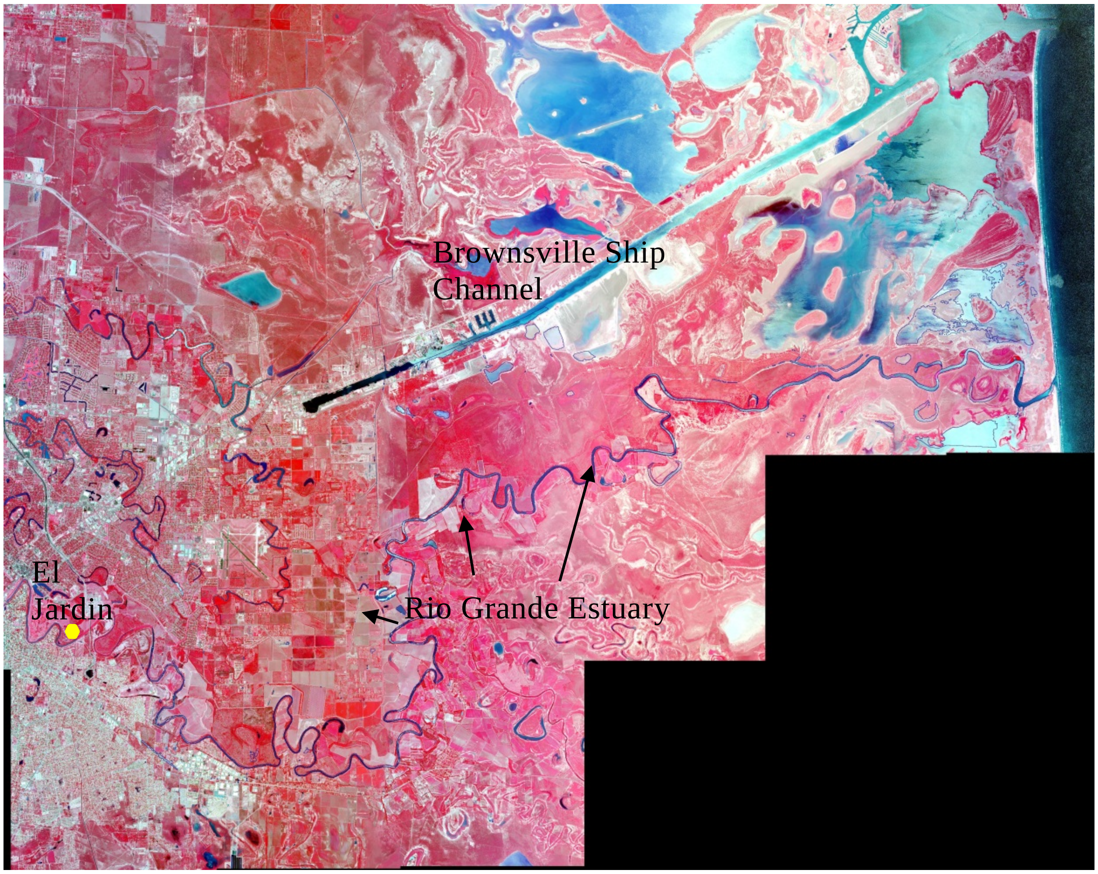


Figure 4.1.1. NAIP 2008 color infrared photography showing the Rio Grande estuary below Brownsville (48 mile reach from El Jardin weir to Gulf of Mexico).

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.

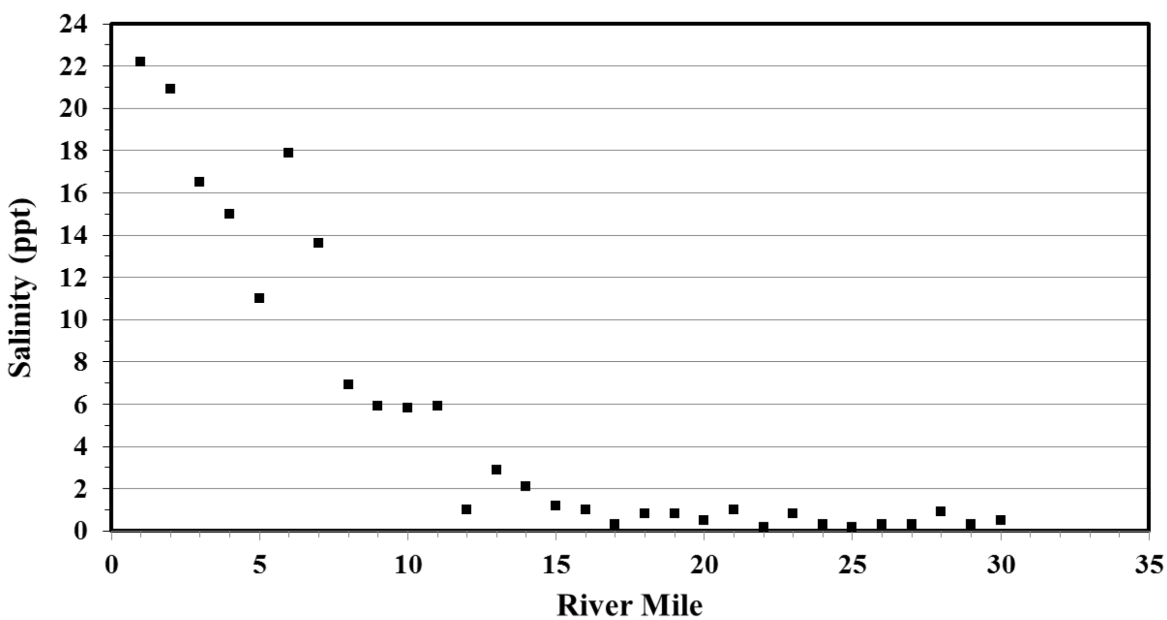


Fig. 4.1.2. Bottom salinity along Rio Grande tidal segment, 1992 to1997 (from TPWD, Brownsville, Coastal Fisheries Lab.).

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**.

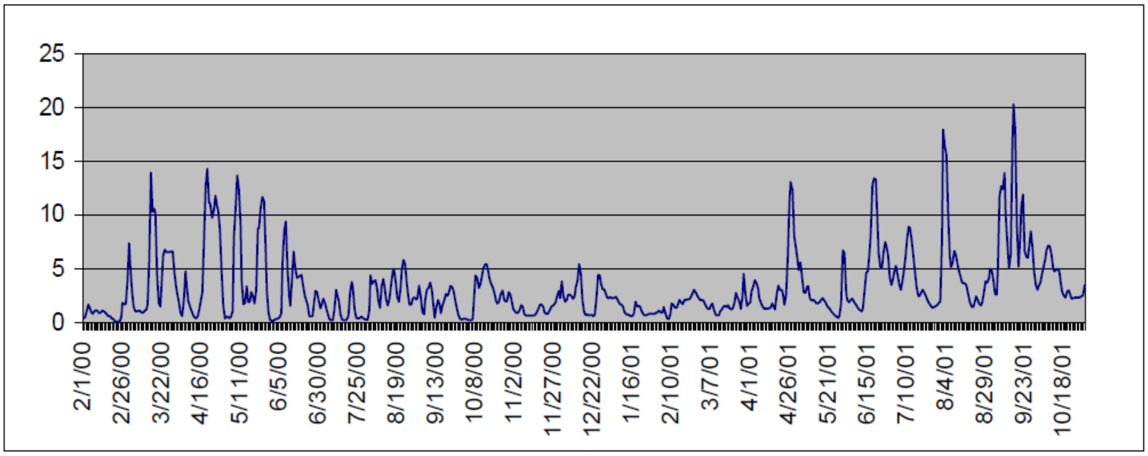


Figure 4.1.4. Summary of flow data in daily average cubic feet per second from IBWC monitored river gage south of Brownsville, Texas, February 2000 to October 2001.

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.

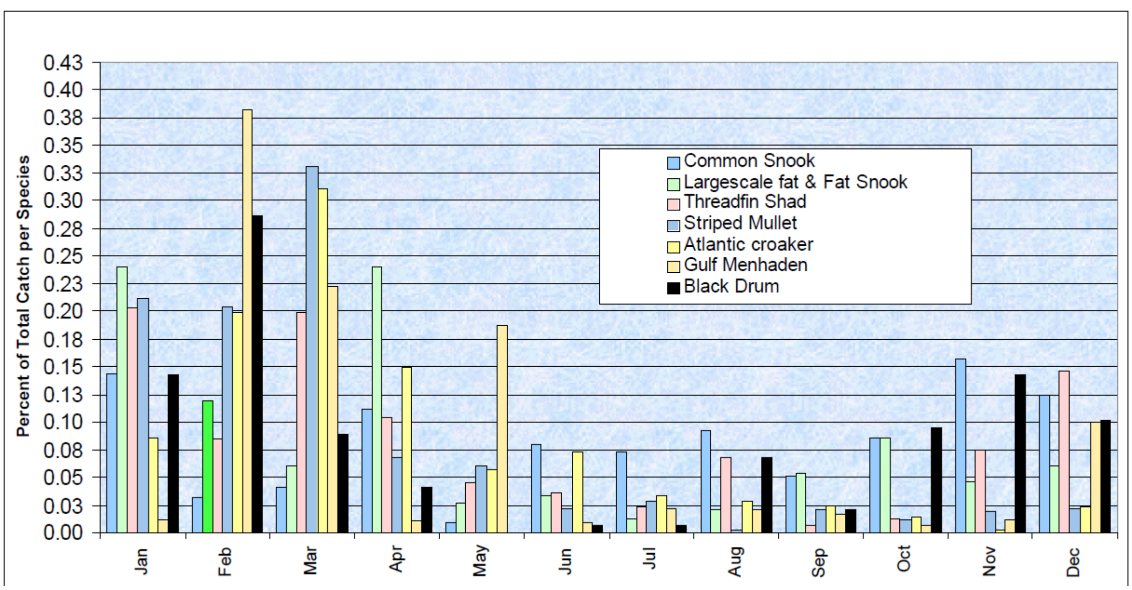


Figure 4.4.2. Percent distribution of selected fish species from the mouth of the Rio Grande to approximately 25 miles upriver. Original data were collected by TPWD from the fall of 1992 to the fall of 1997.

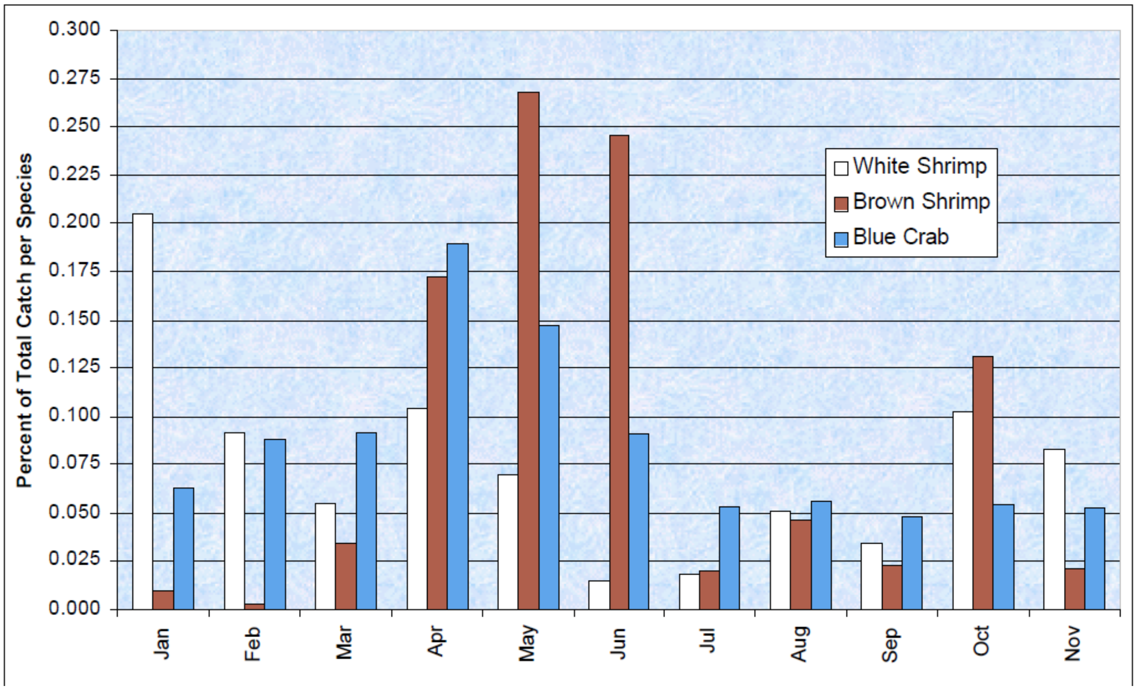


Figure 4.4.3. Percent distribution of white and brown shrimp and blue crab from the mouth of the Rio Grande to approximately 8 miles upriver. Original data were collected by TPWD from the fall of 1992 to the fall of 1997.

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.

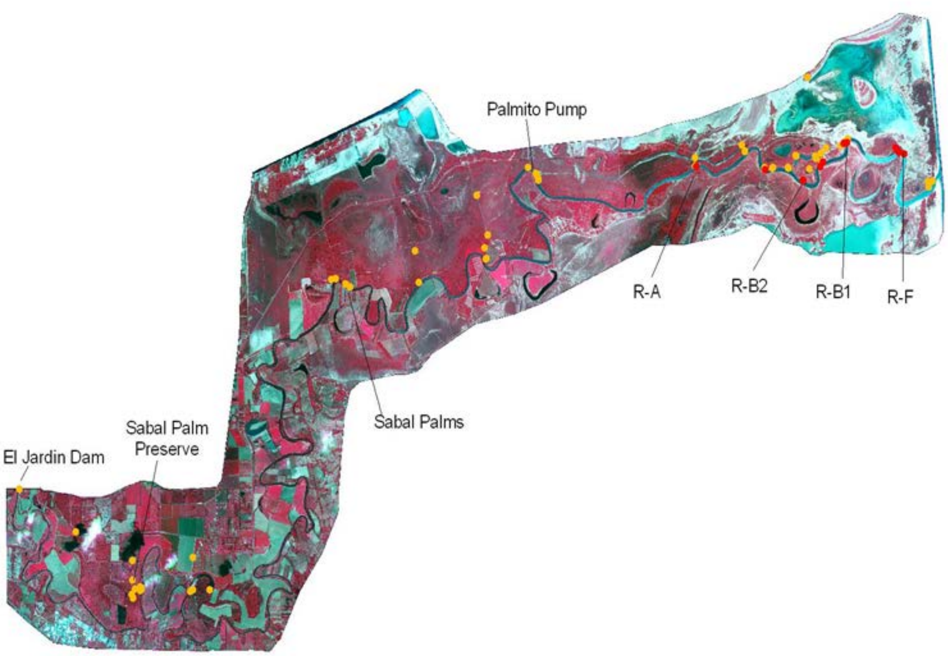


Figure 4.5.1. NAIP 2004 color infrared photography of 1-2 mile corridor along RG estuary, with locations of field study sites. Yellow and red points indicate sampling stations for field surveys since 2007 (yellow) and from 2008-2011 (red).

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).

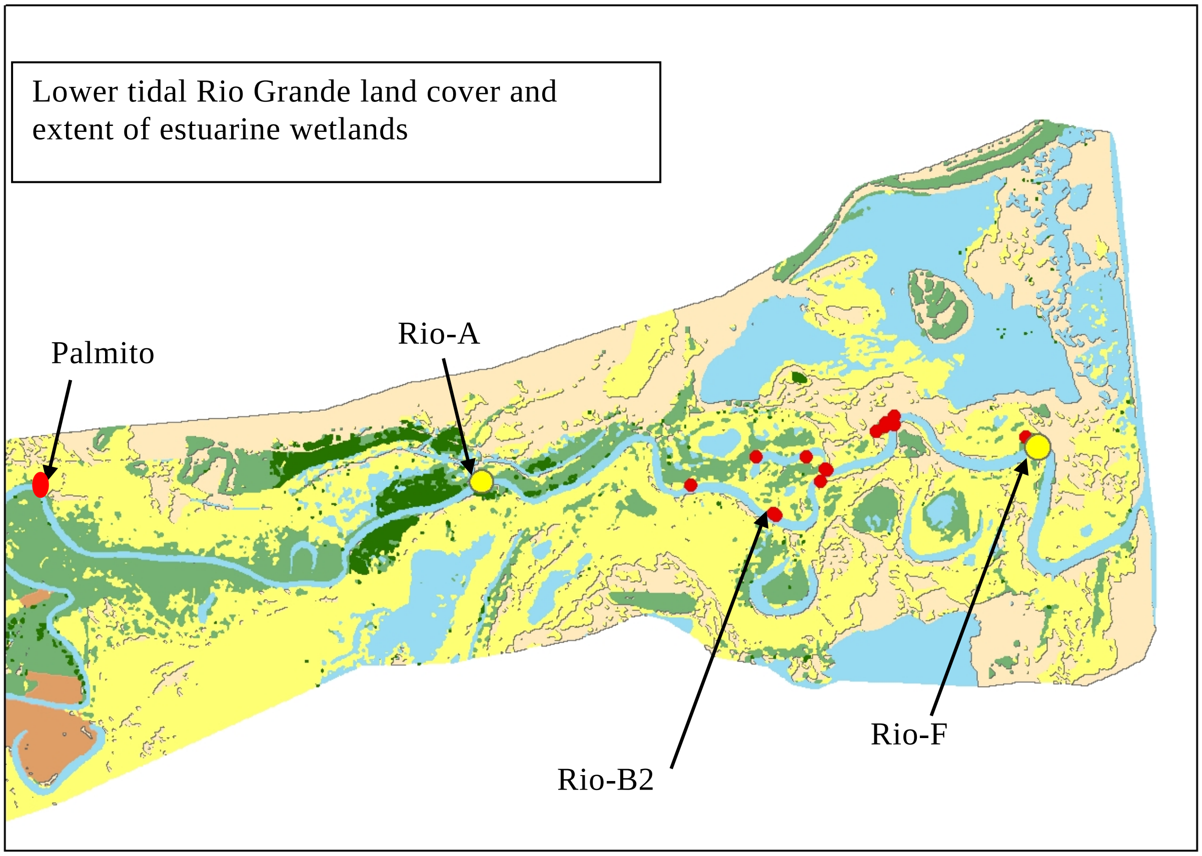


Figure 4.5.2. Enlargement of lower part of Rio Grande estuary below Brownsville (17 mile region from Palmito to Gulf of Mexico), showing classified land cover/land use. Classified areas are: grasslands (yellow), sand/salt flats (beige), shrublands (light green), woodlands (dark green), agriculture (brown),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

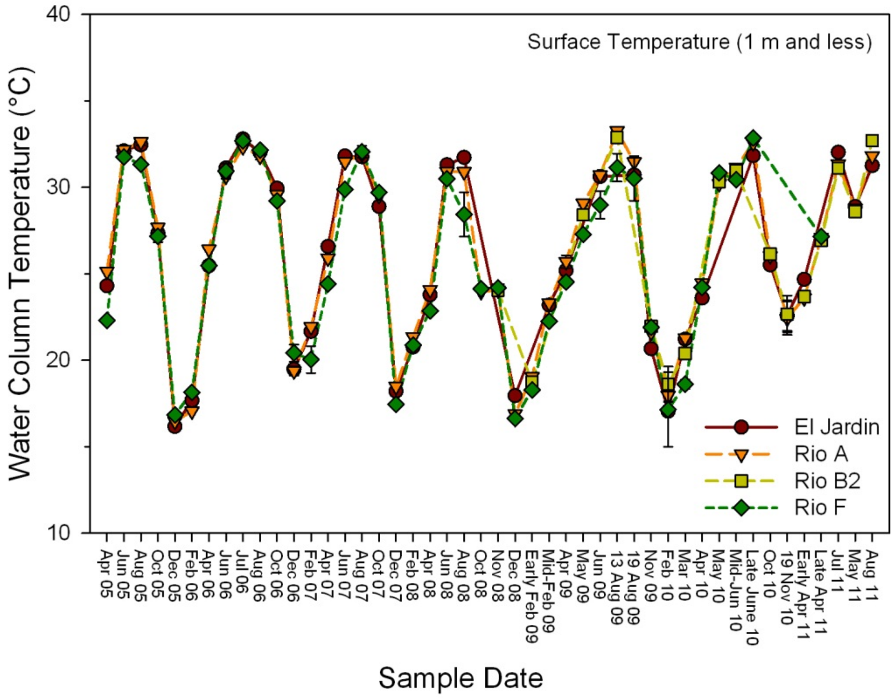


Figure 4.5.3. Tidal segment of Rio Grande surface temperature from April 2005 to August 2011.

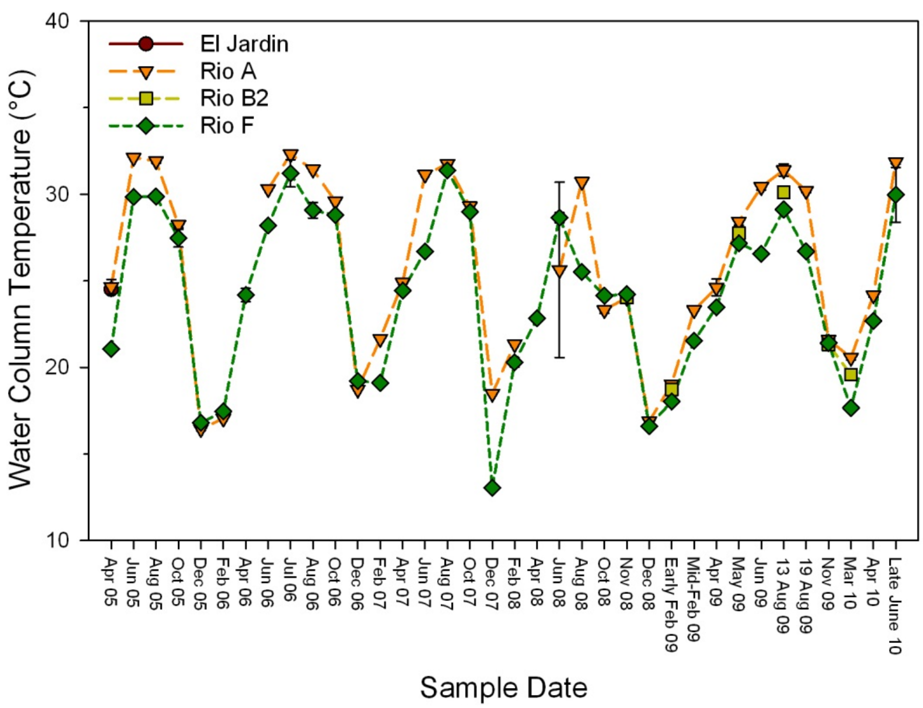


Figure 4.5.4. Tidal segment of Rio Grande bottom temperature (>1m) from April 2005 to June 2010.

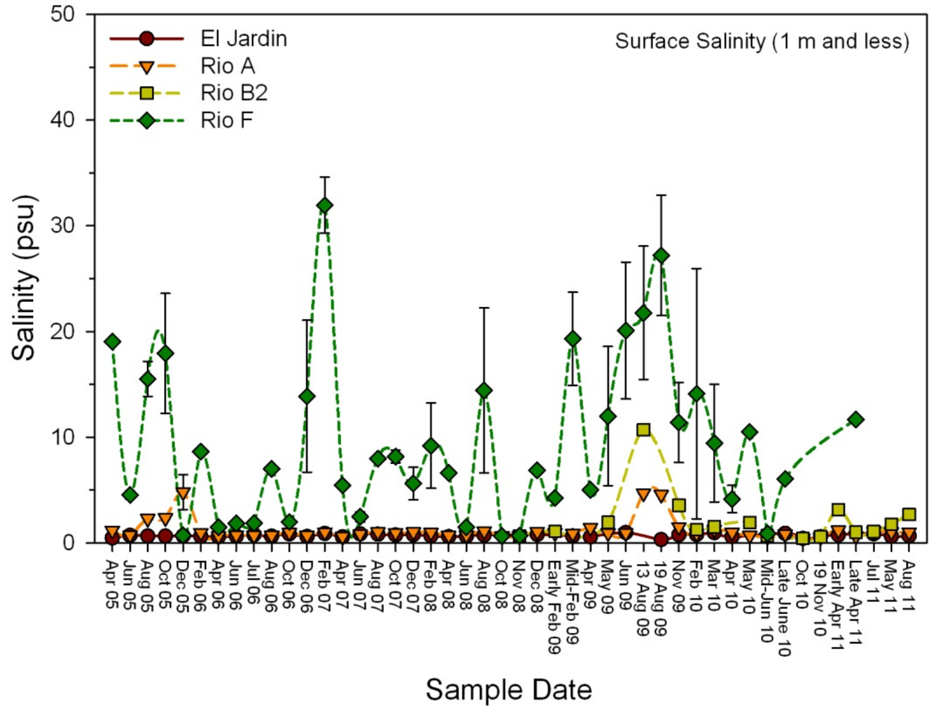


Figure 4.5.5. Tidal segment of Rio Grande surface salinity from April 2005 to August 2011.

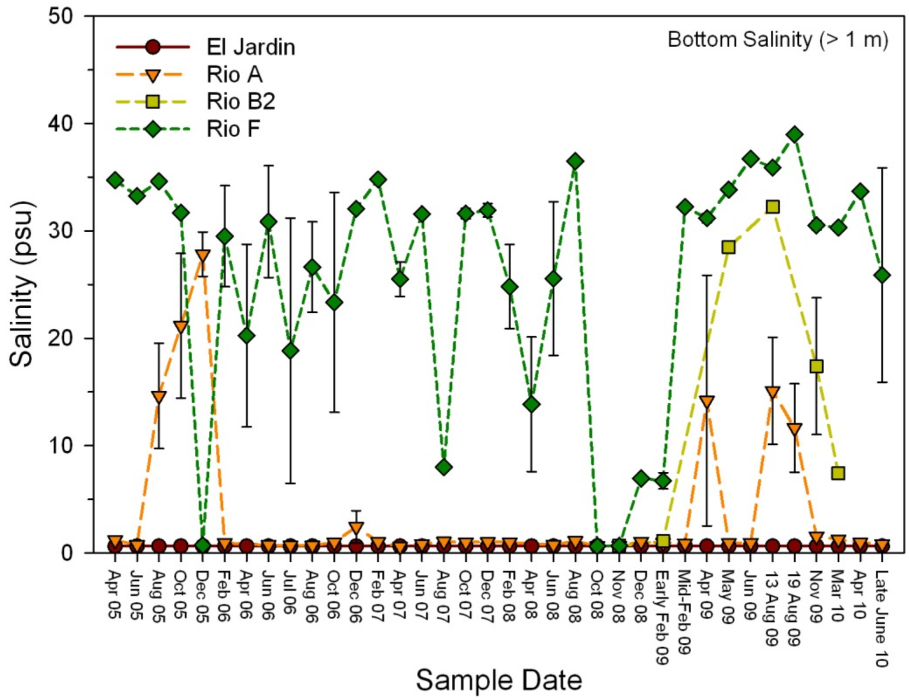


Figure 4.5.6. Tidal segment of Rio Grande bottom salinity from April 2005 to June 2010.

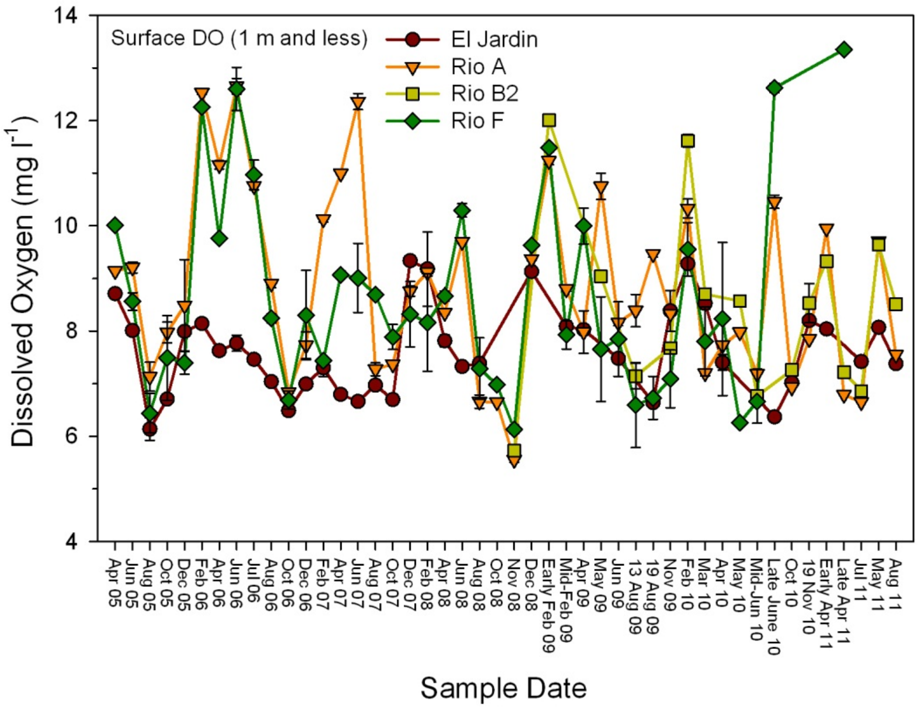


Figure 4.5.7. Tidal segment of Rio Grande, surface dissolved oxygen from April 2005 to August 2011.

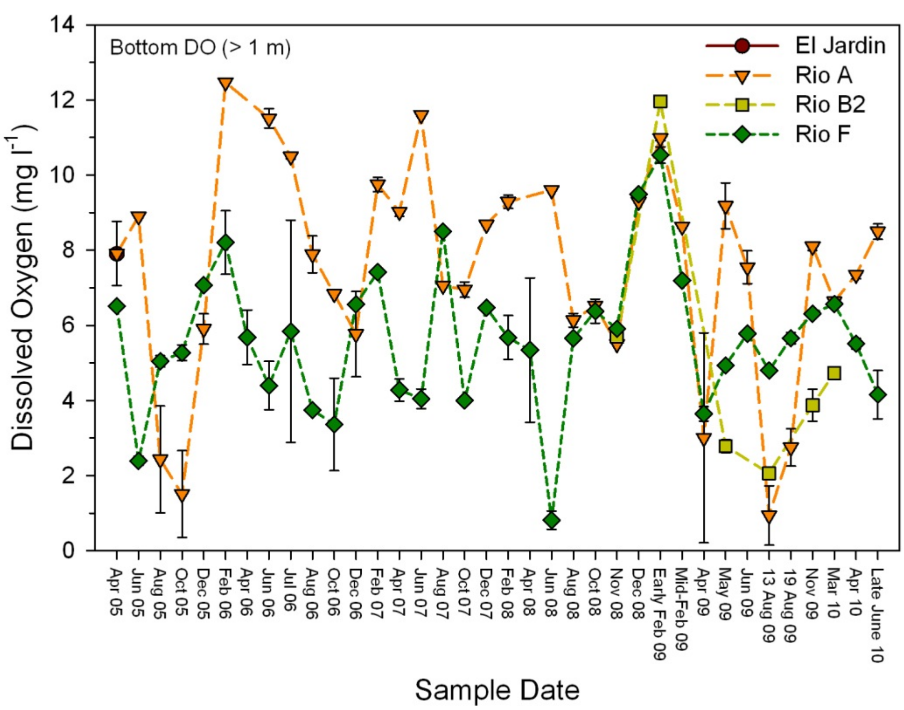


Figure 4.5.8. Tidal segment of Rio Grande, bottom dissolved oxygen from April 2005 to June 2010.

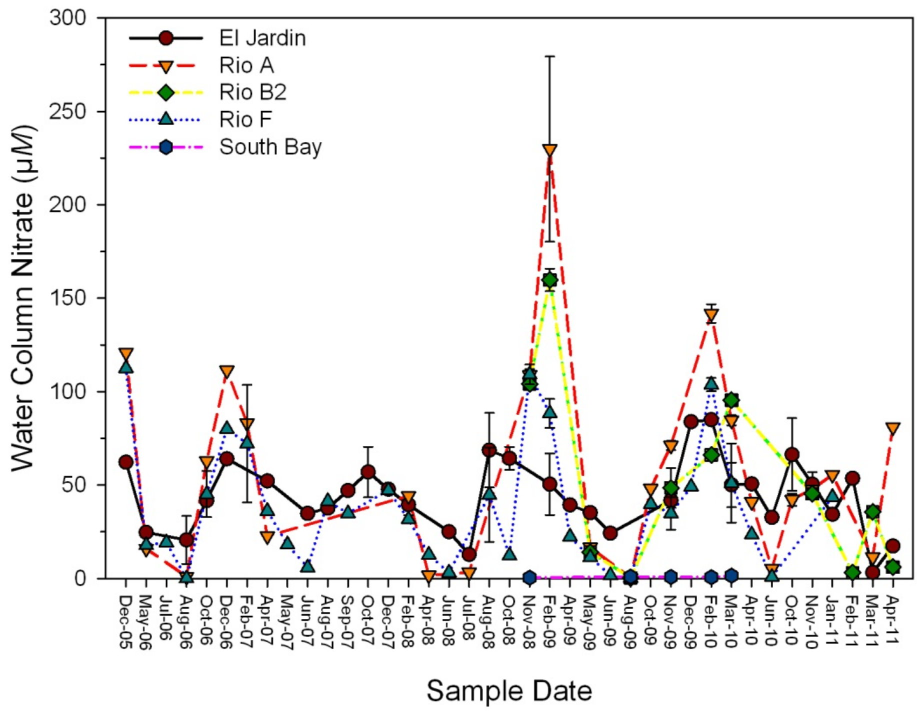


Figure 4.5.9. Tidal segment of Rio Grande surface nitrate-nitrite from December 2005 to April 2011.

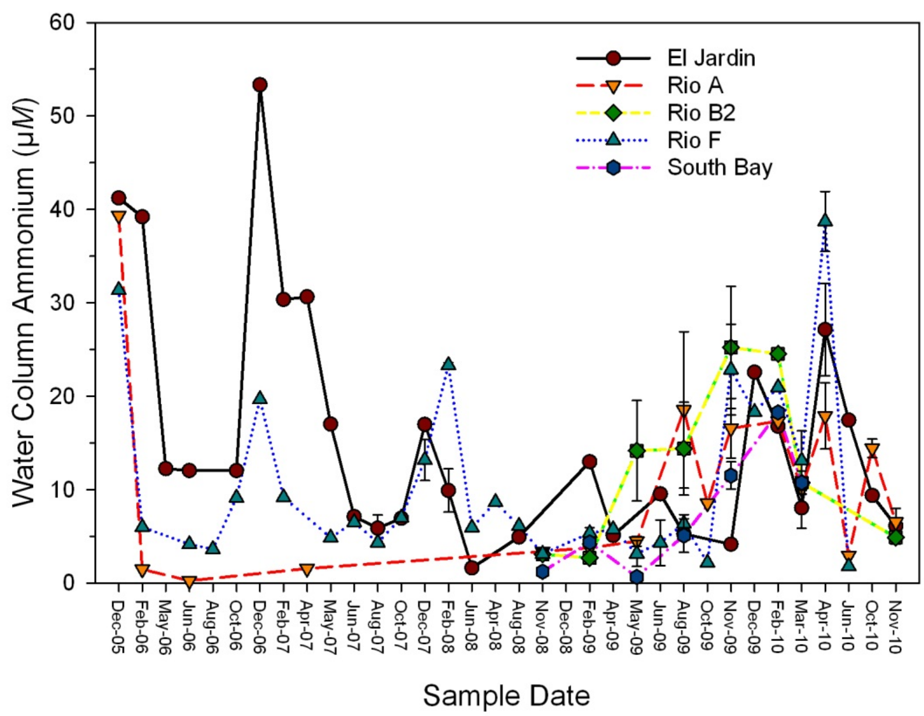


Figure 4.5.10. Tidal segment of Rio Grande surface ammonia from December 2005 to November 2010.

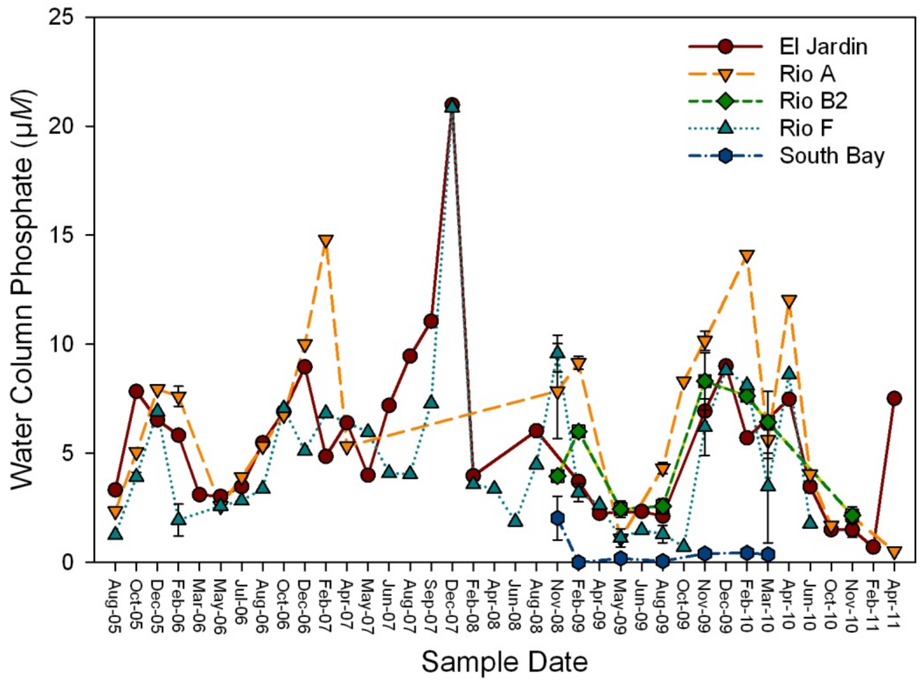


Figure 4.5.11. Tidal segment of Rio Grande, surface dissolved phosphate from August 2005 to April 2011.

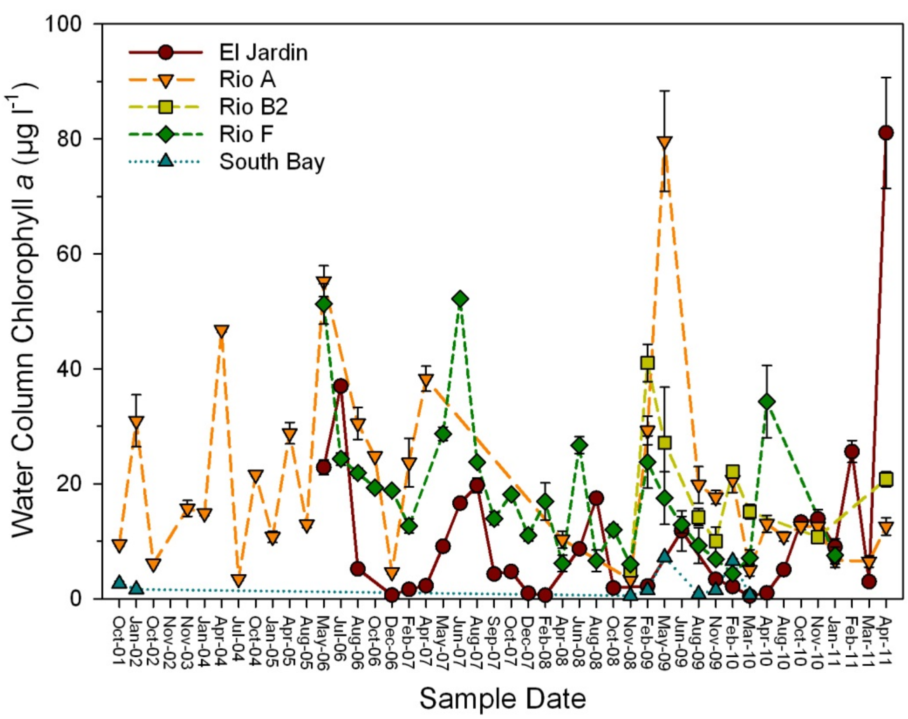


Figure 4.5.12. Tidal segment of Rio Grande surface water column chlorophyll from October 2001 to April 2011.

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).

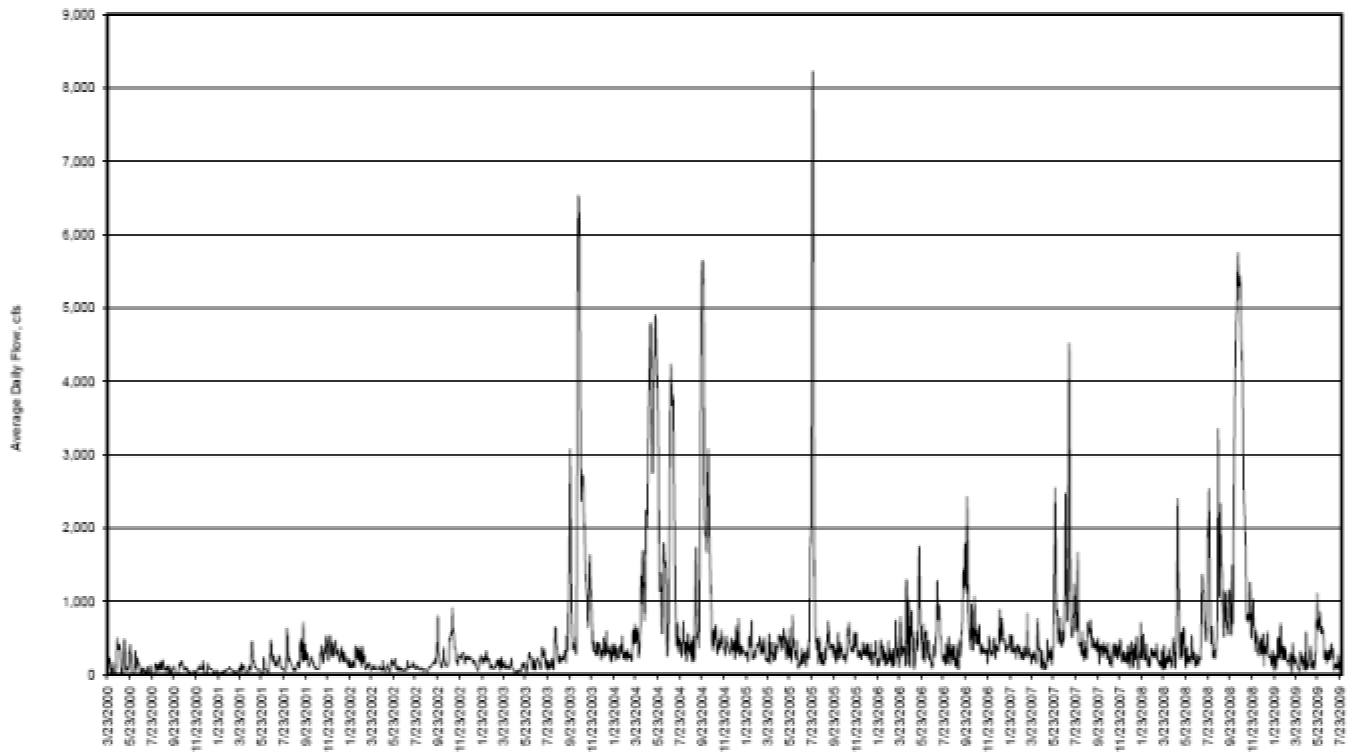


Figure 4.6.1. Rio Grande daily river flow at Brownsville gage at El Jardin dam (IBWC #08475000) from 2000 to mid-2009 (from IBWC database).

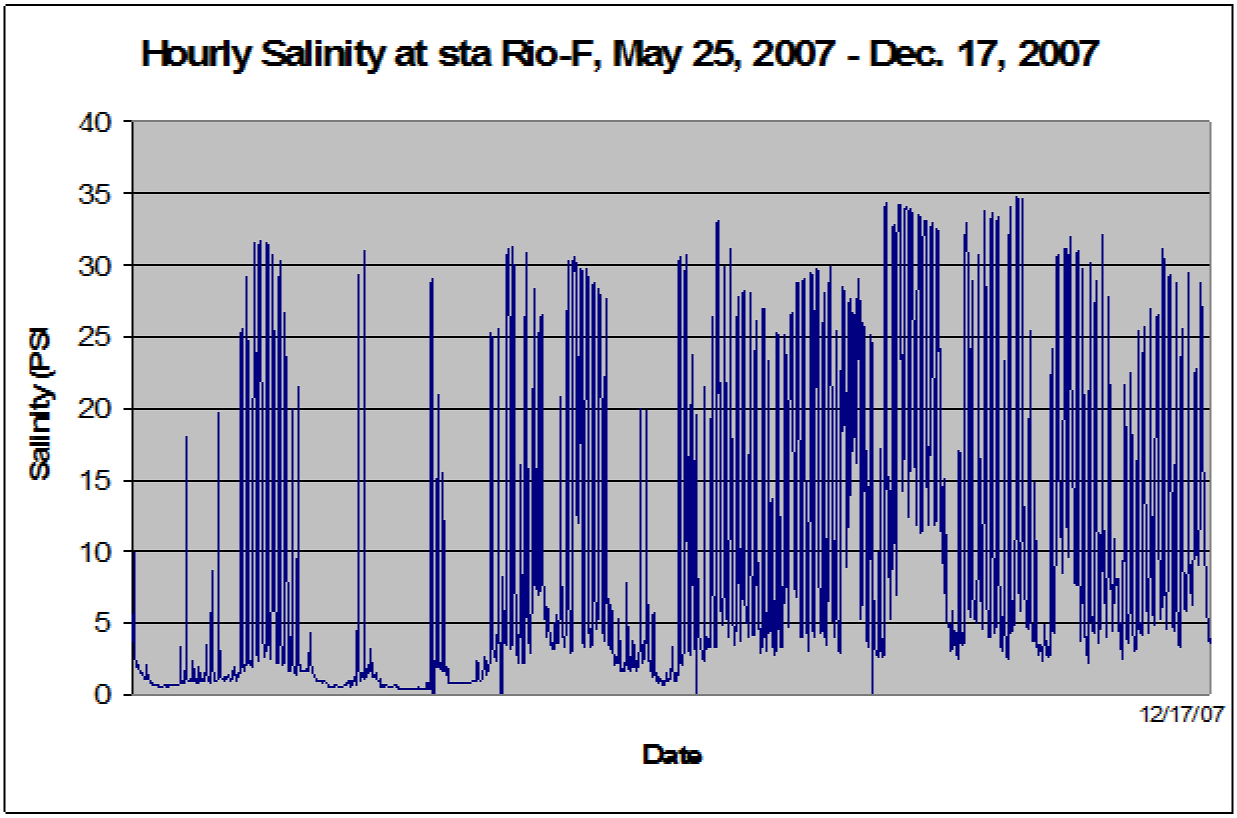


Figure 4.6.2. Hourly salinity datasonde record at Station Rio-F from May to December 2007

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.

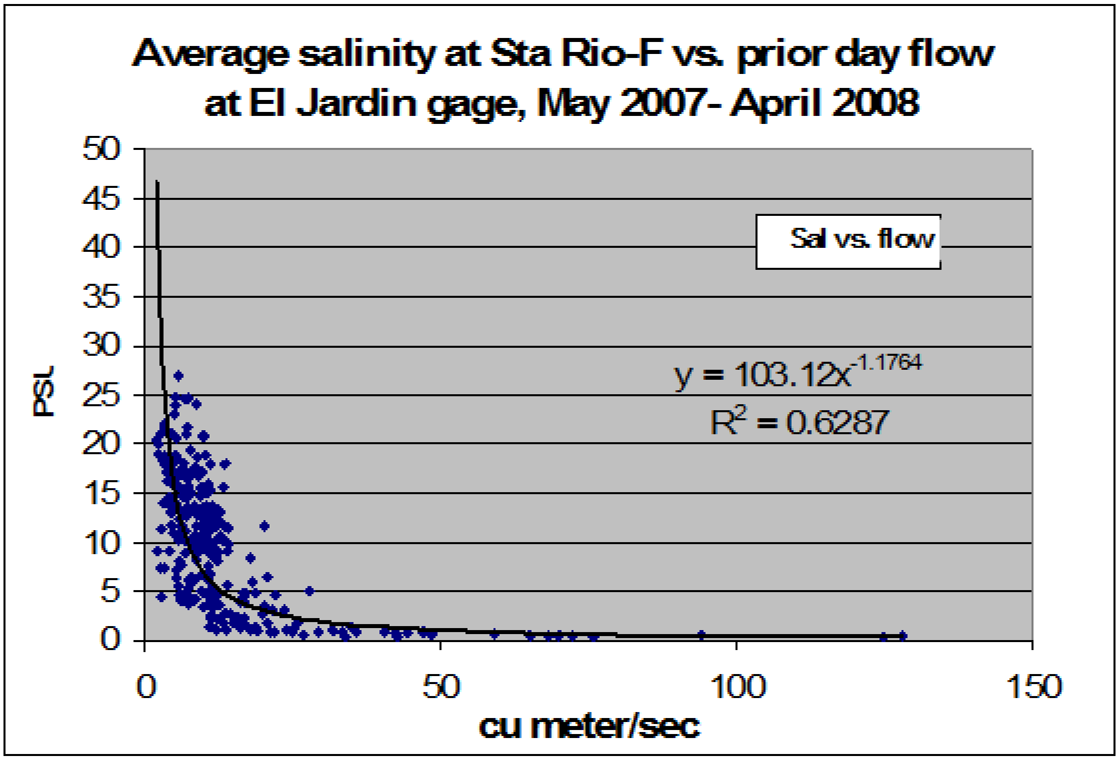


Figure 4.6.3. Daily Average Rio Grande flow at Brownsville gage near El Jardin dam, 2007 – 2008 correlated with next day average daily salinity as psu at Station Rio-F, 2.5 miles from the river mouth.

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. *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* *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.

Conclusion

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. *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,* 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)

> 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).

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).

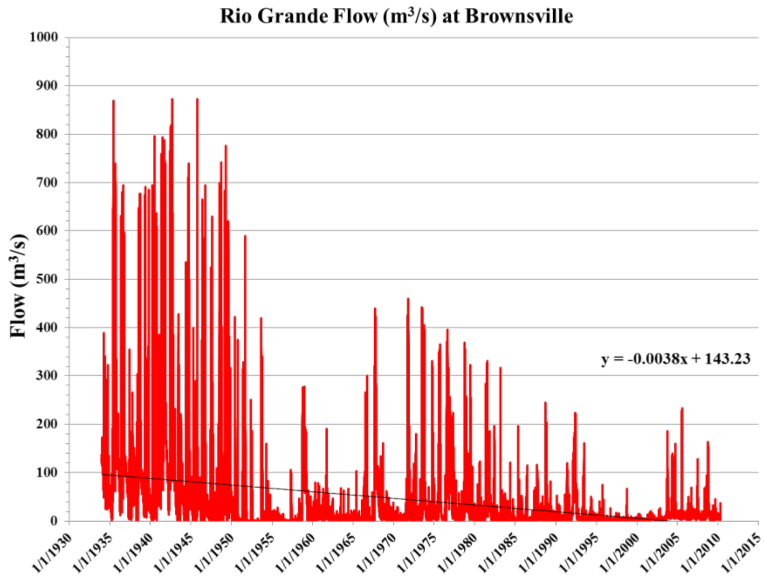


Figure. 5.3.1. Flow in Rio Grande at Brownsville gage measured by IBWC, 1935 to 2010.

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**).

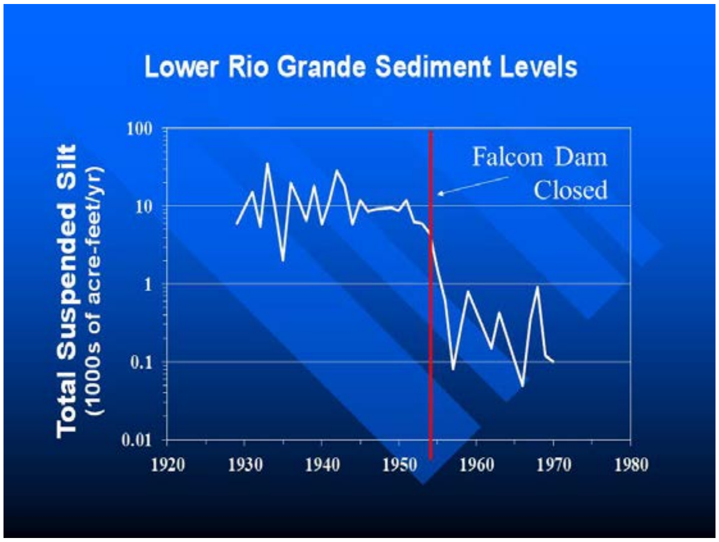


Figure 5.3.2. Suspended sediment loads in the Rio Grande below Falcon Reservoir from 1930 to 1972 showing the effect of the closure of Falcon Dam in 1954 on the passing of suspended sediments in the Lower Rio Grande. Data are from USGS.

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		**ºC**	**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.

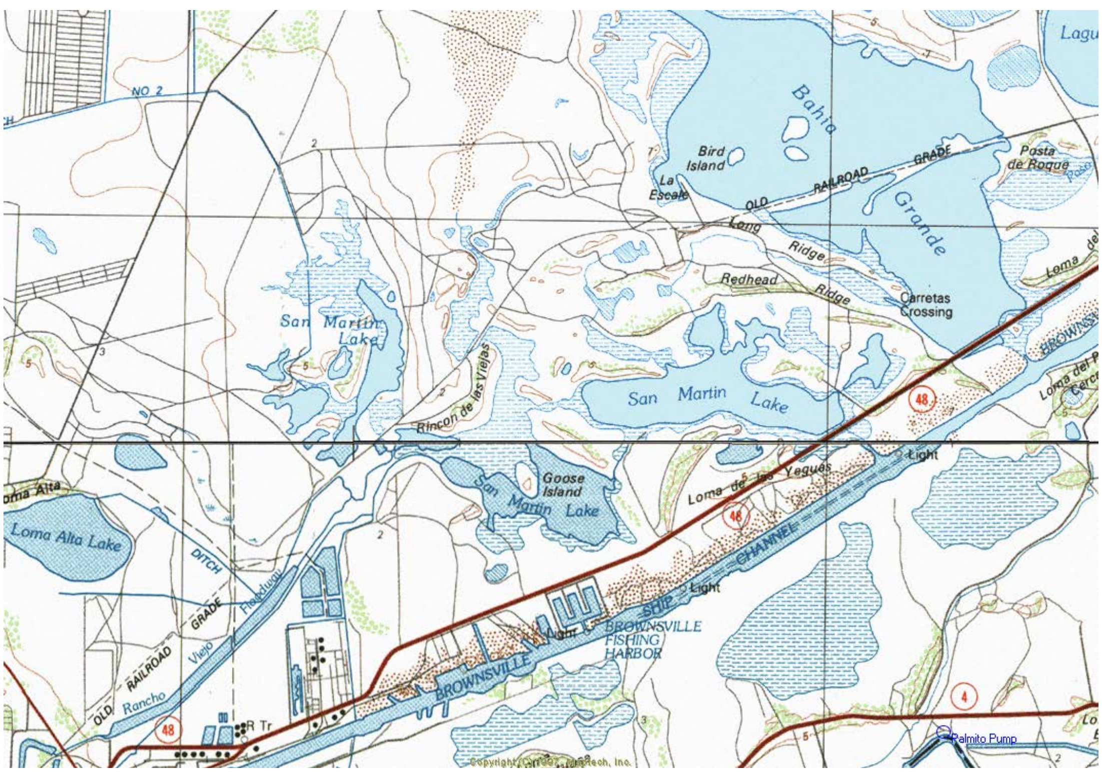


Figure 6.1.1. Map of the current Bahia Grande and San Martin Lake systems.

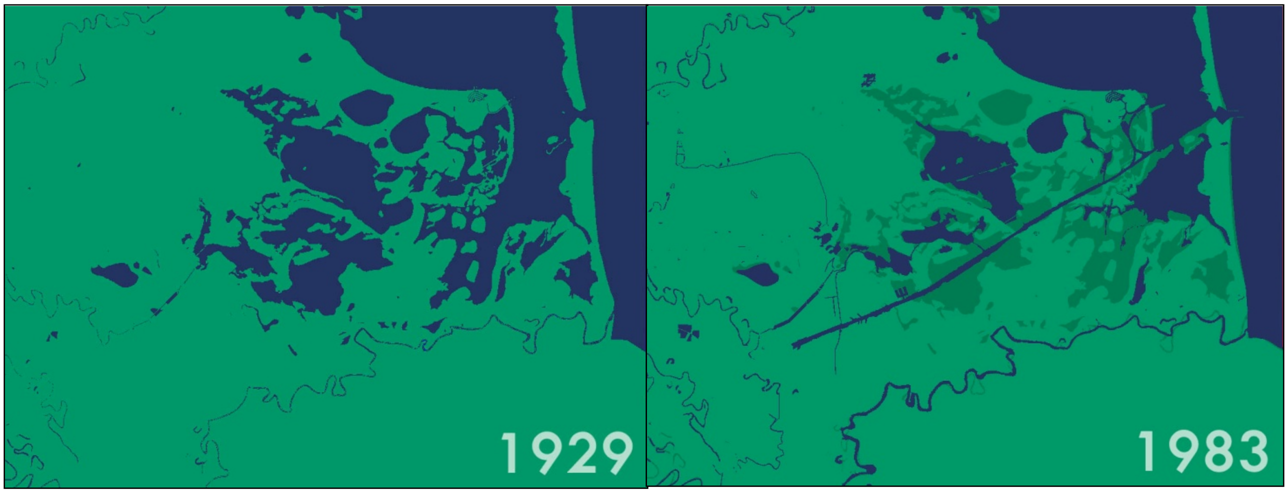


Figure 6.1.2. Changes in water surface area in the Bahia Grande/San Martin Lake area from 1929 to 1983. Maps courtesy of Jude Benavides and Anthony Reisinger, III.

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

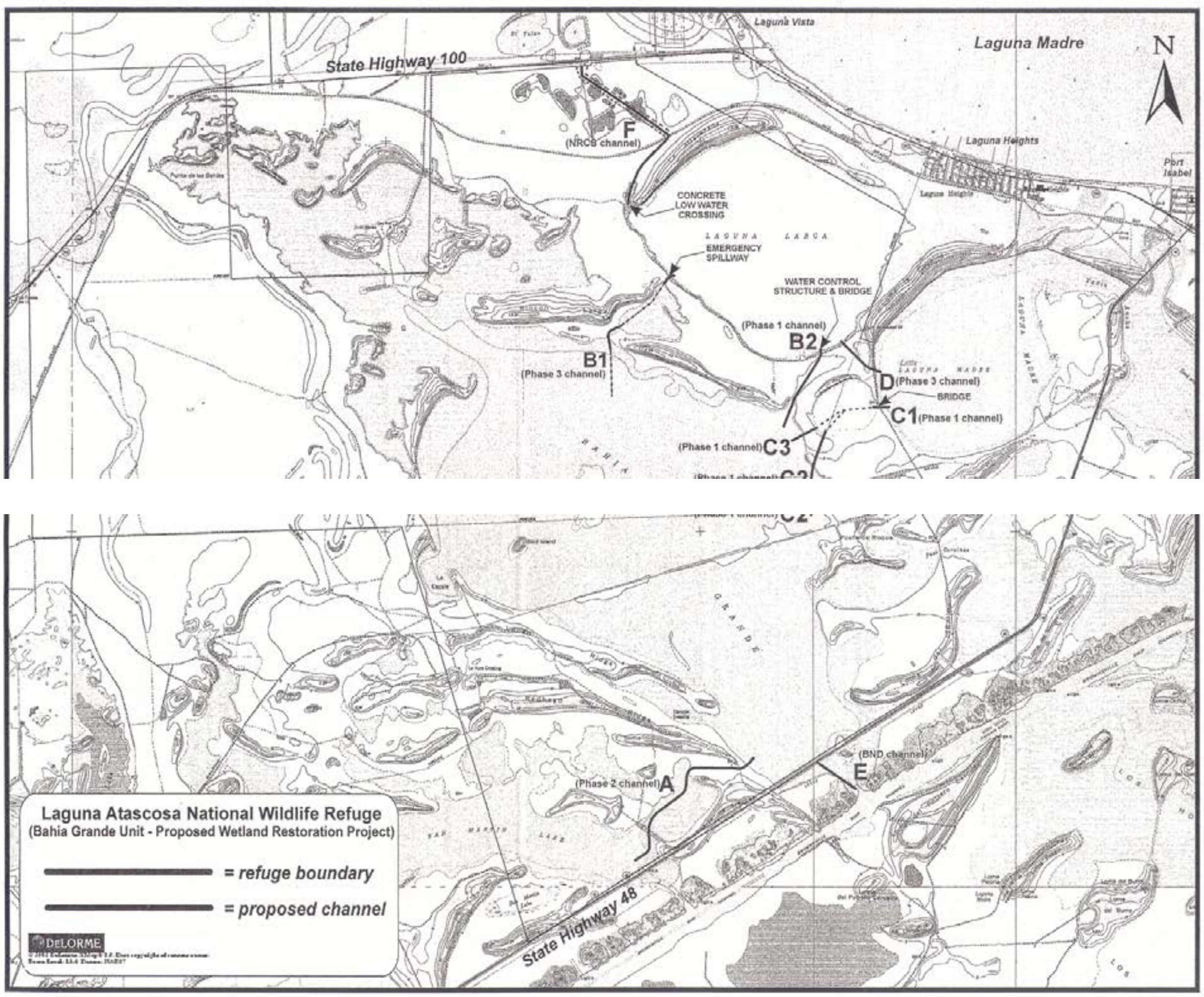


Figure 6.1.3. 2005 Map of Bahia Grande showing the location of the pilot (marked as channel "E") and internal channels, B, C and D. Channel A has not been constructed. To the west is one basin of the San Martin Lake system.

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.

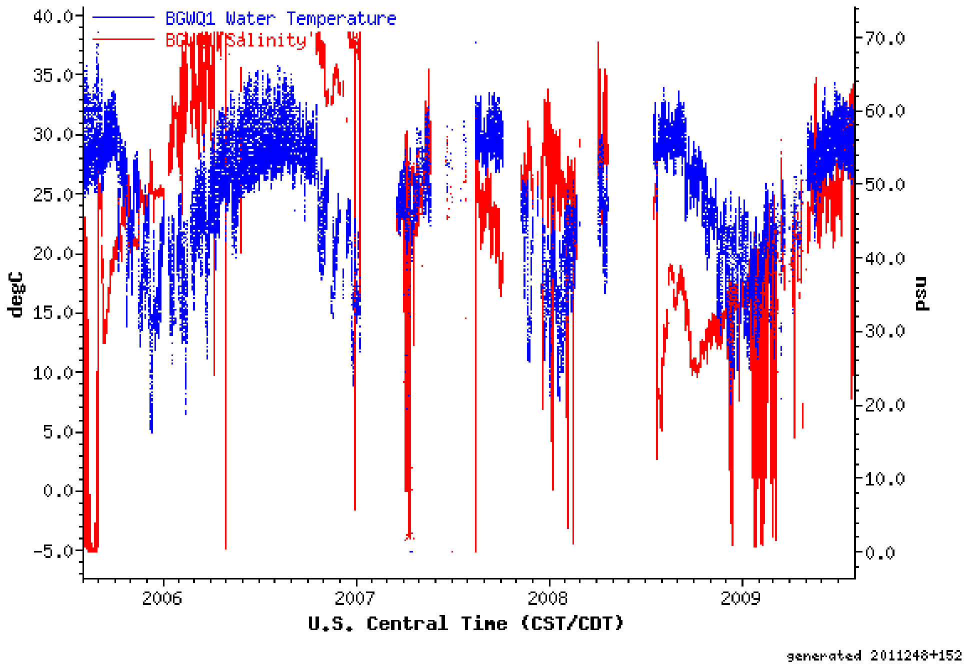


Figure 6.3.1. South sub-basin Bahia Grande water temperature and salinity, August 2005 to July 2009. Salinity date is truncated above 70 PSU. Data from TCOON (http://lighthouse.tamucc.edu/TCOON/ HomePage).

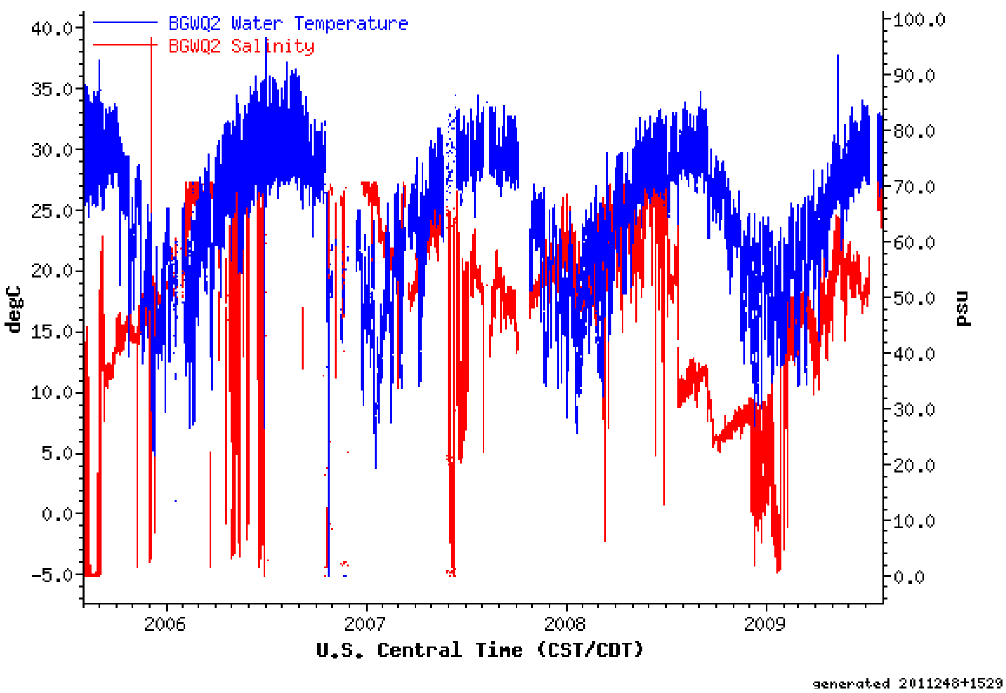


Figure 6.3.2. North sub-basin Bahia Grande water temperature and salinity, August 2005-July 2009. Salinity date is truncated above 70 PSU. Data from TCOON (http://lighthouse.tamucc.edu/TCOON/HomePage).

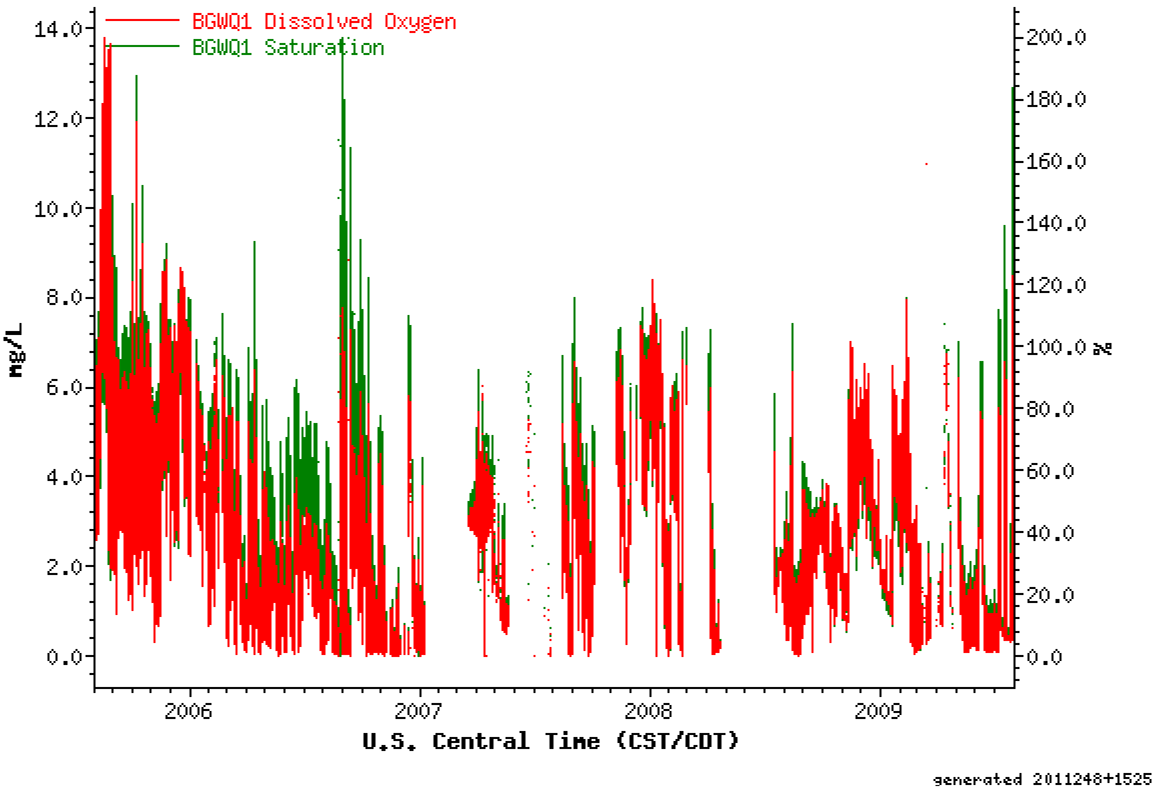


Figure 6.3.3. South sub-basin Bahia Grande dissolved oxygen and percent saturation, August 2005-July 2009. Data from TCOON http://lighthouse.tamucc.edu/TCOON/HomePage).

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.

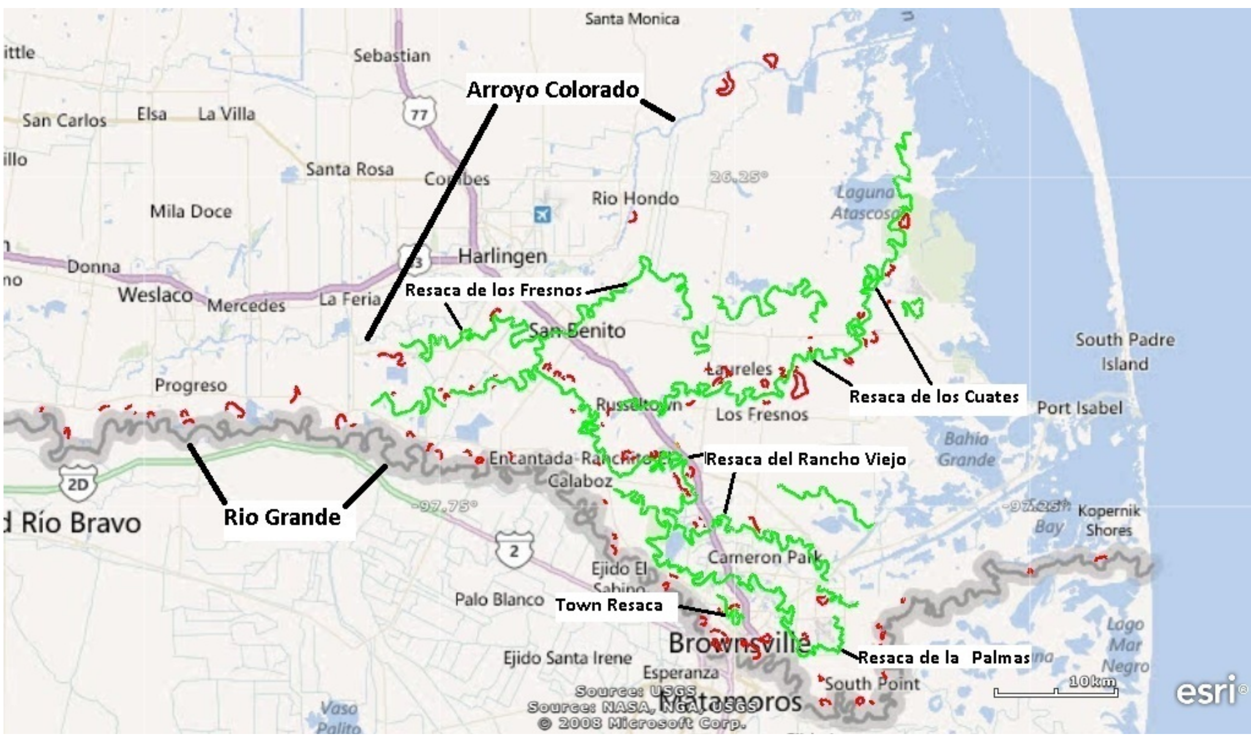


Figure 7.1.1. Resacas of Cameron and Hidalgo County, Texas.

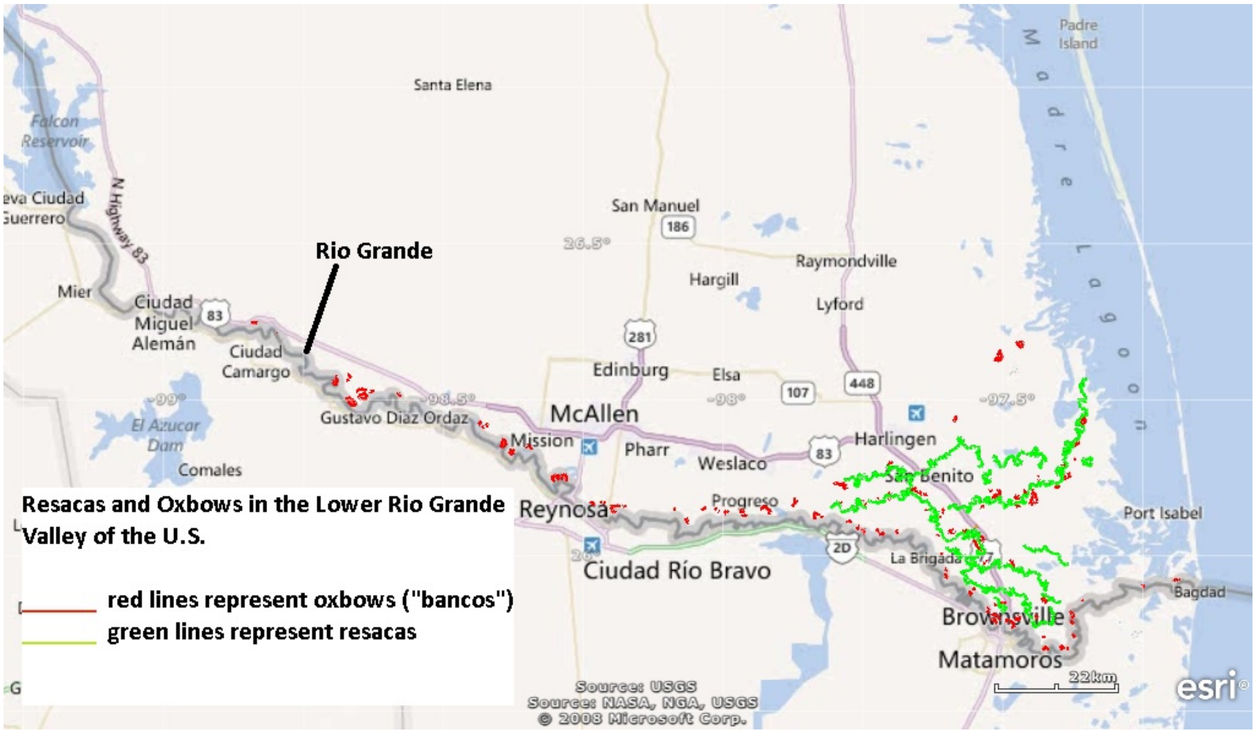


Figure 7.1.2. Resacas and oxbows of the Lower Rio Grande Valley, Texas.

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:

- Resaca de las Palmas: 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).
- Resaca del la Guerra: 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).
- Resaca de las Palmas in Resaca de las Palmas State Park: 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**).

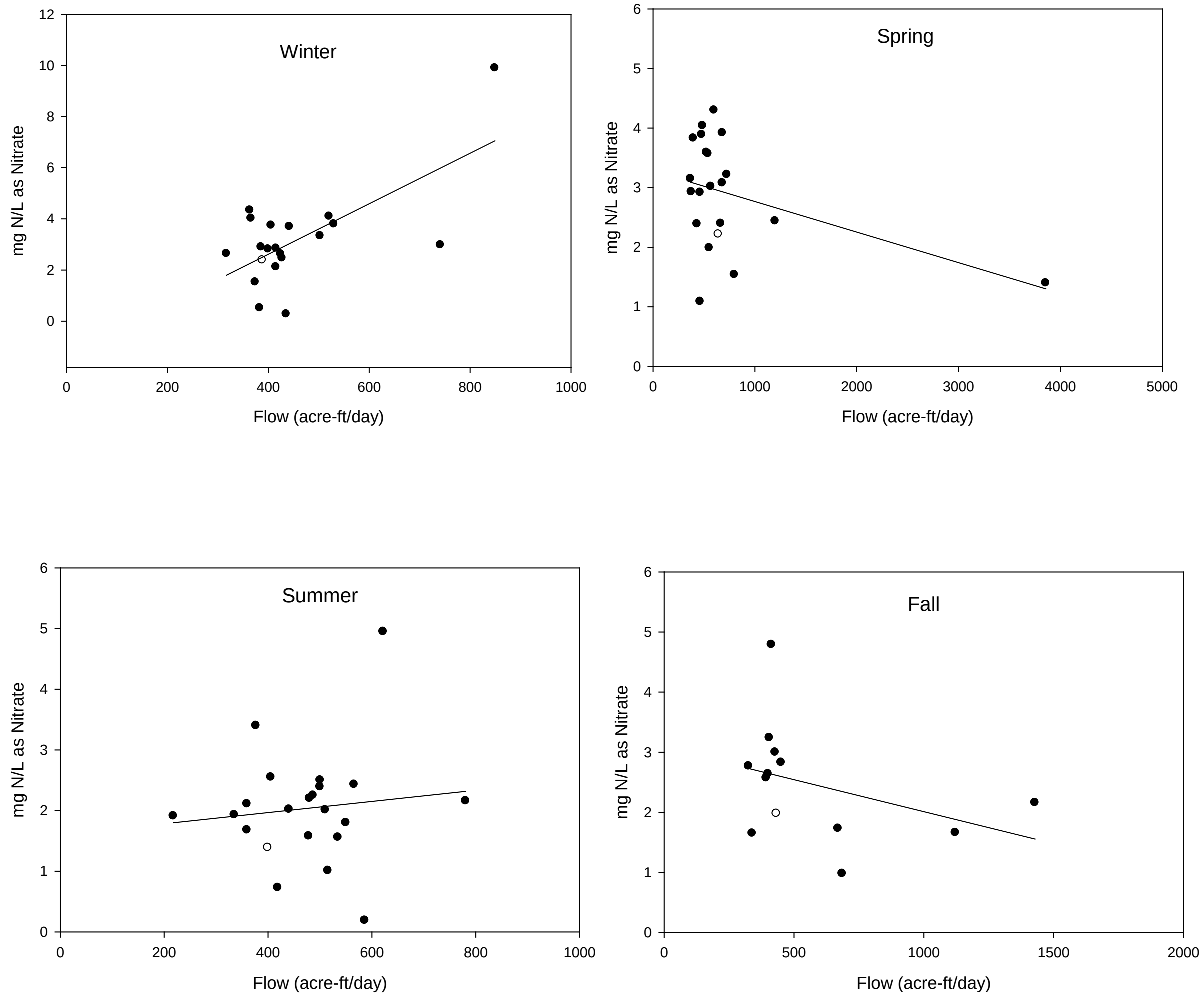


Figure 8.3.1. Seasonal relationships between nitrate-nitrogen concentration and flow in the Arroyo Colorado based on TCEQ water quality data from the Port of Harlingen and flow values from the Harlingen IBWC gage for the period 1978-2009. Note changes in scales of both X and Y axes.

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.

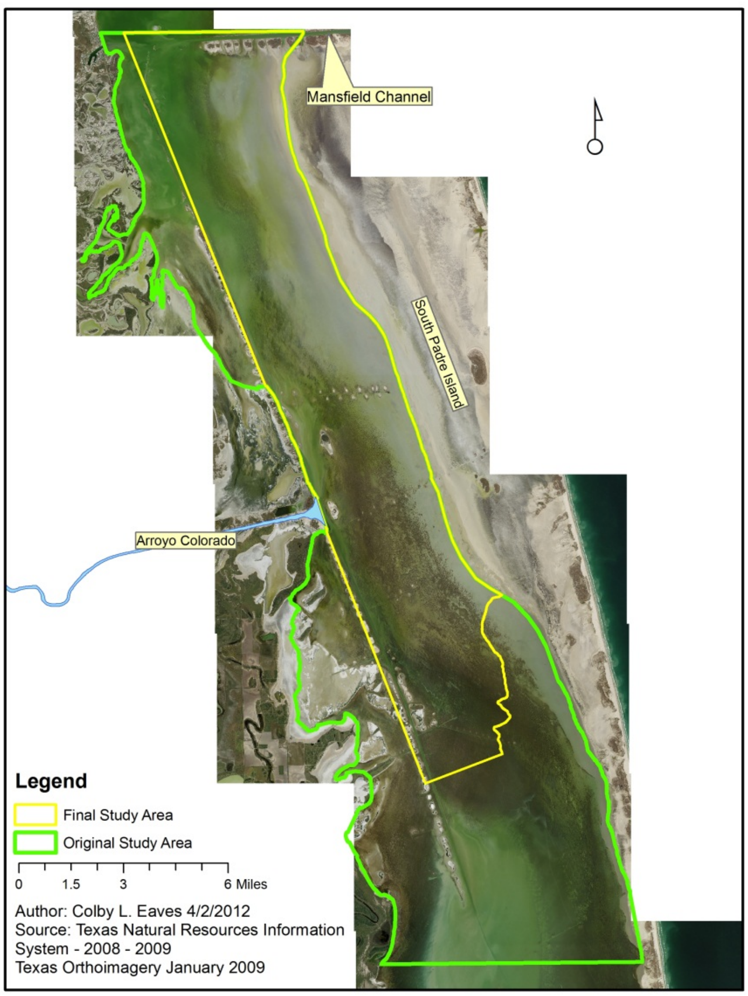


Figure 9.2.1. Lower Laguna Madre study areas outlined on 2009 NAIP color photography. Green area used initially, yellow area used later for change analysis.

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*.

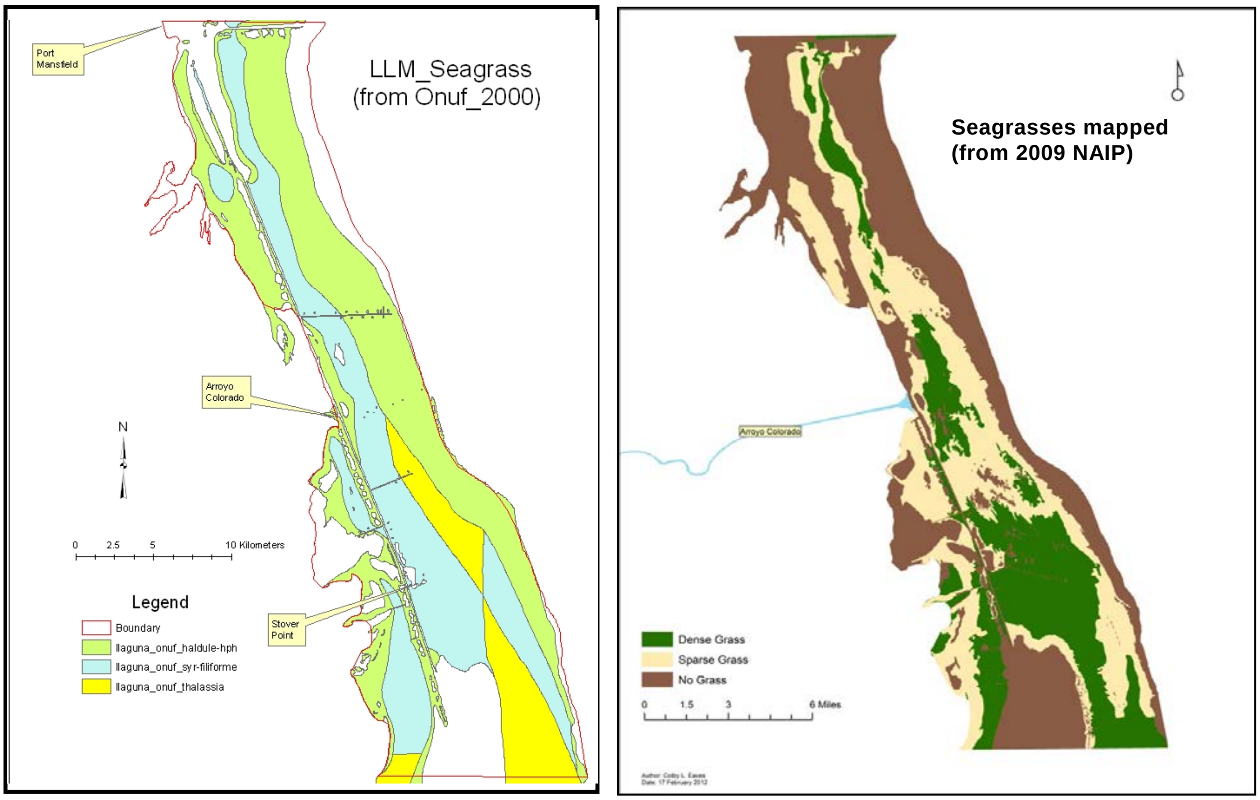


Figure 9.2.2. LLM maps of seagrass cover based on Onuf survey of 1999-2000 (left) and 2009 NAIP imagery (right).

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.

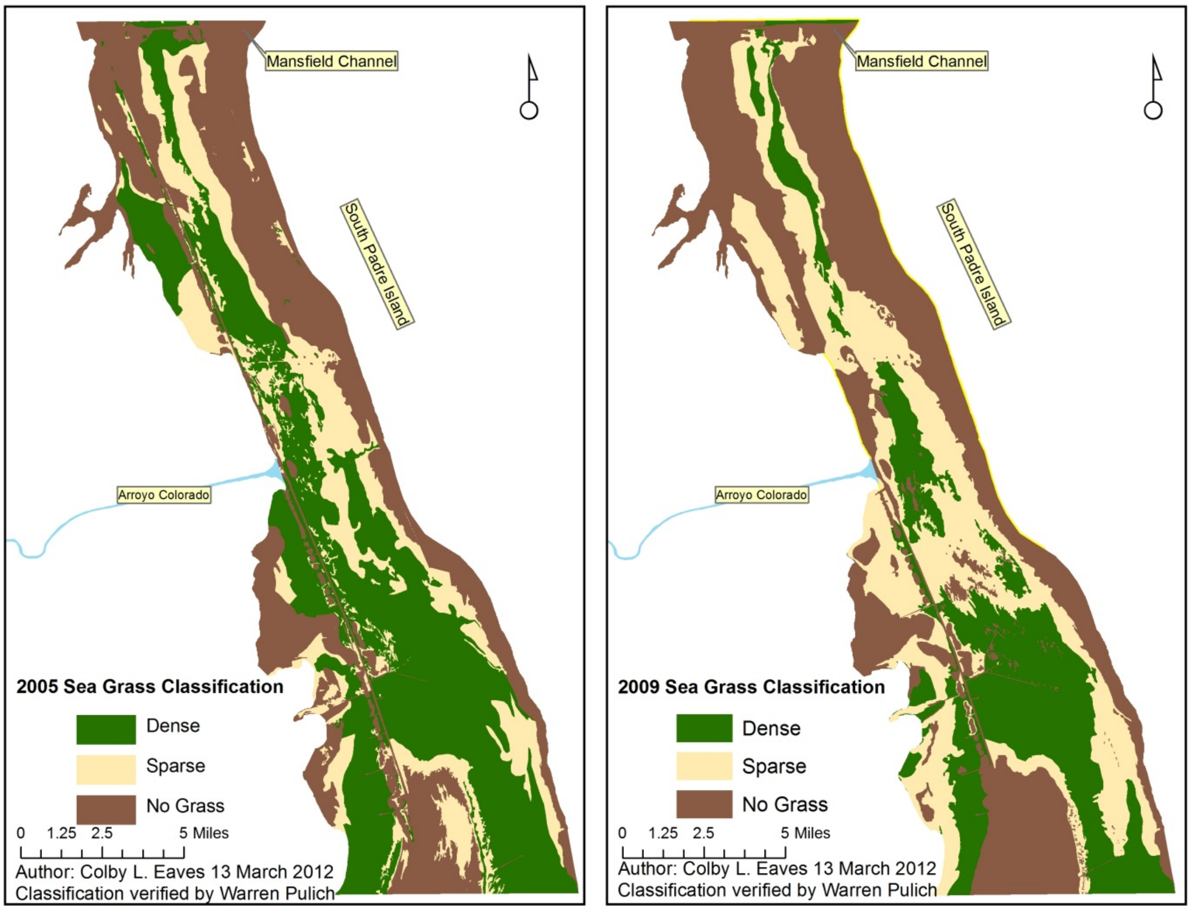


Figure 9.2.3. LLM seagrass distribution from 2005 USACE (left) and 2009 NAIP (right) imagery.

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**).

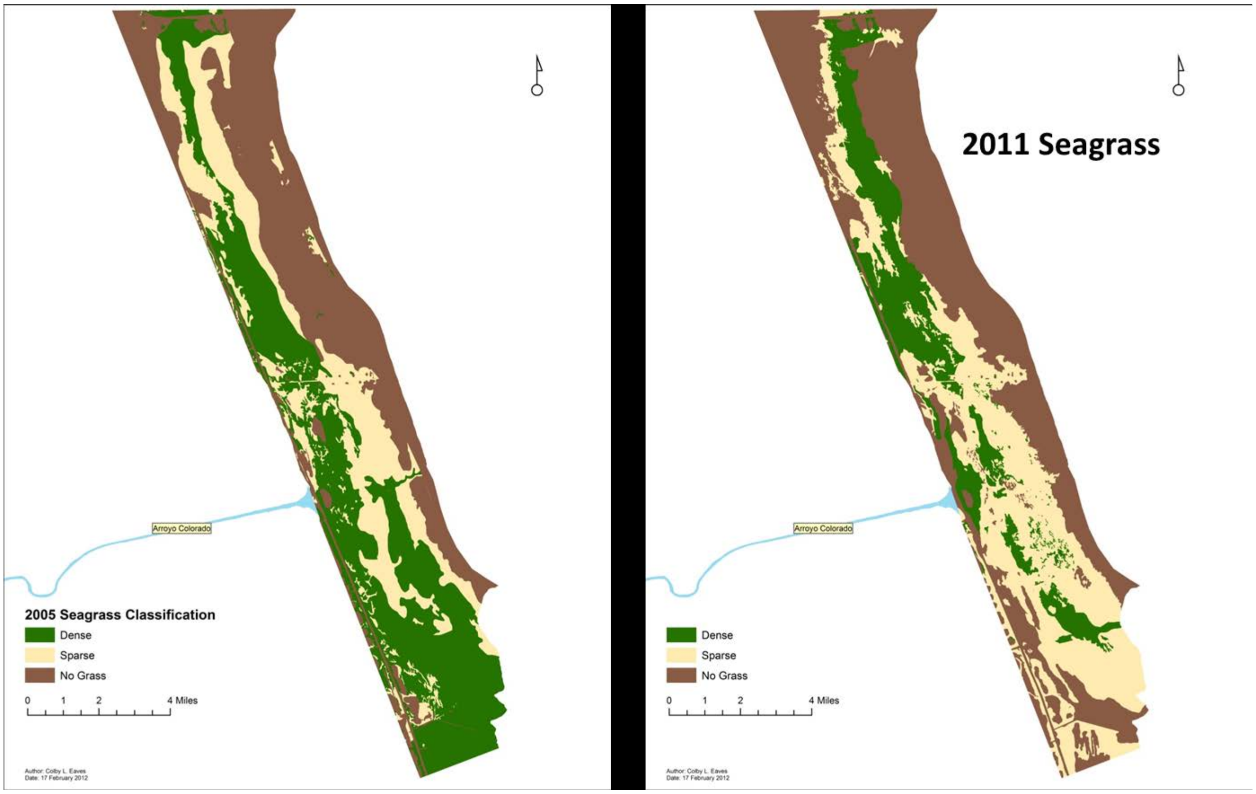


Figure 9.2.4. Comparison of seagrass areas in the northern portion of LLM mapped from 2005 USACE and 2011 TGLO photography. Modified study area used (yellow area in **Figure 9.2.1**).

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).

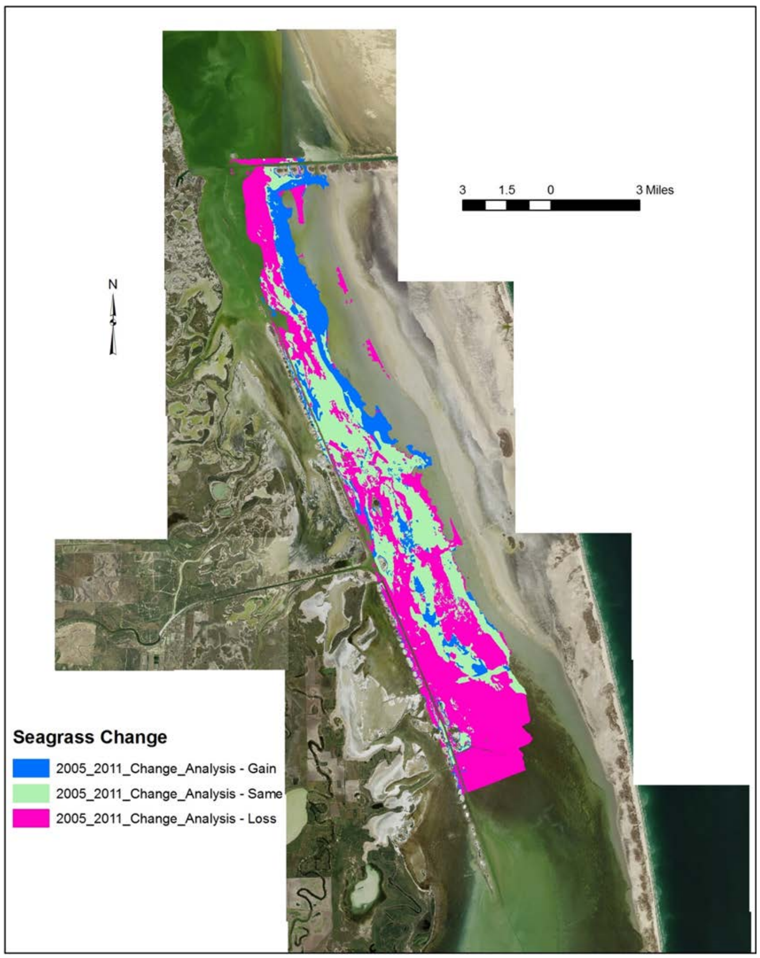


Figure 9.2.5. Change analysis map of LLM showing changes in seagrass areas between Nov. 2005 and Oct. 2011. Arroyo Colorado is on left in middle of map, and Mansfield Channel at top. Modified study area used from **Figure 9.2.1**.

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

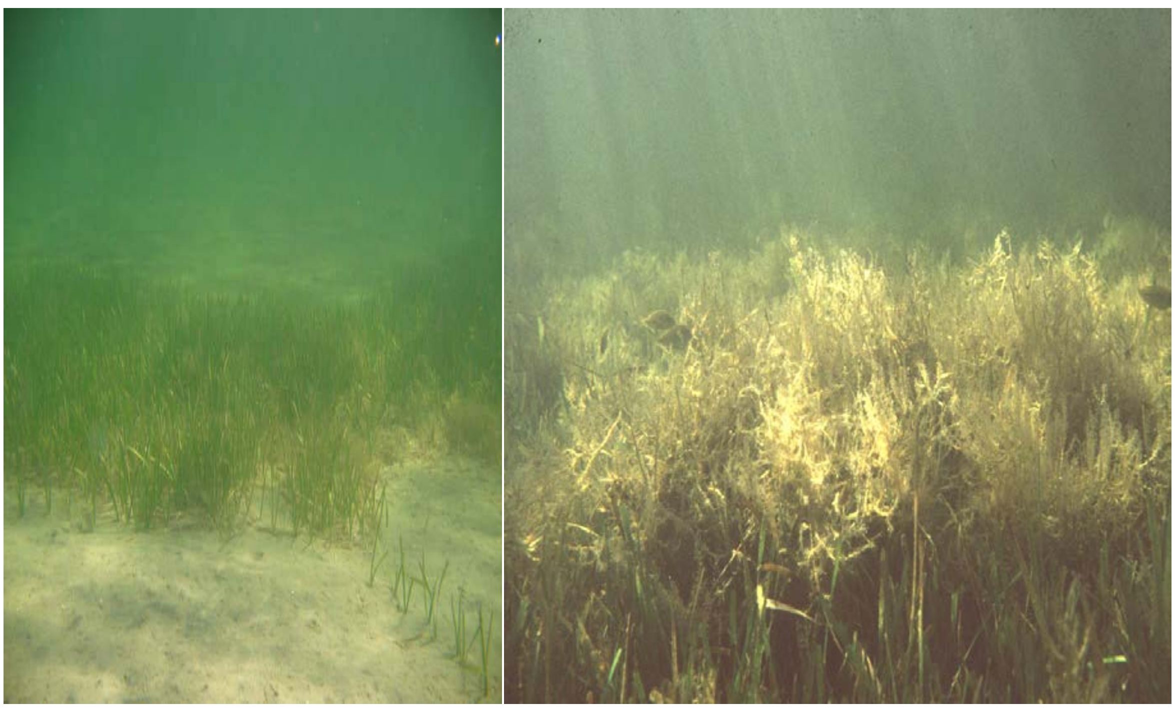


Figure 9.2.6. Examples of (left) healthy unimpacted *Thalassia* bed in LLM, and (right) *Thalassia* bed smothered by dense macroalgae and epiphytes. Photos by Hudson DeYoe.

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.

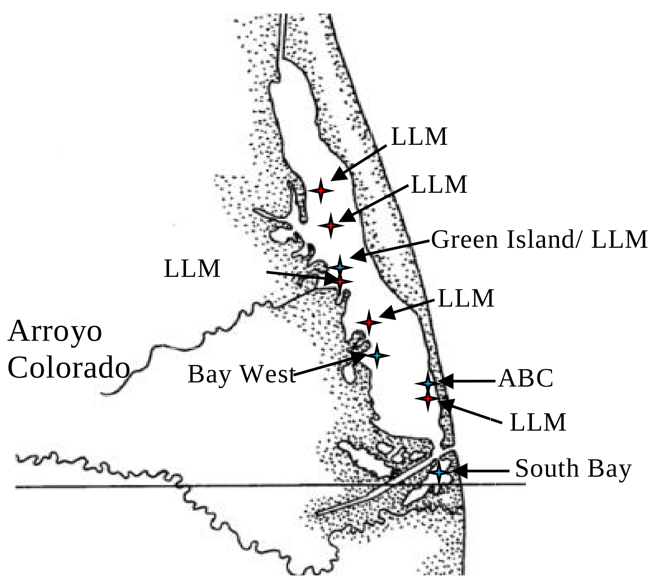


Figure 9.2.7. Study sites (Green Island, Bay West, ABC, South Bay) in the LLM for the *Thalassia* performance study (blue stars) and for the seagrass epiphyte study (LLM 050, 052, 053, 054, 055, 056)(red stars).

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**).

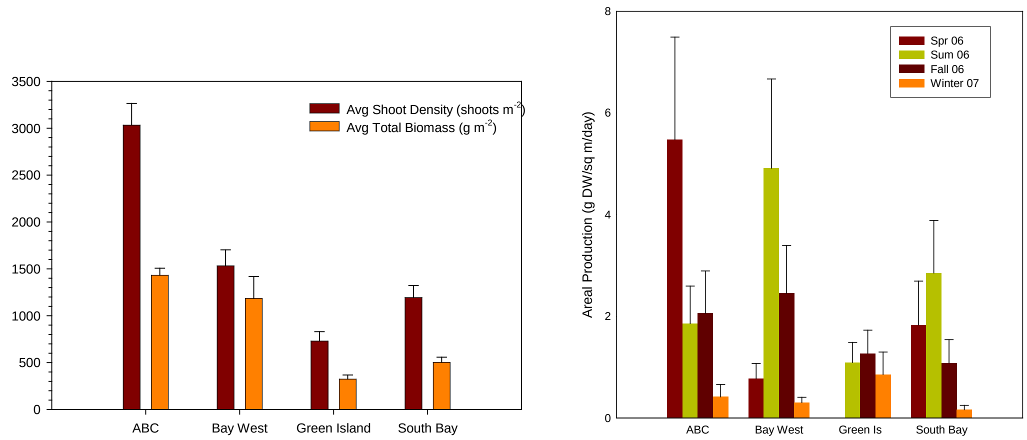


Figure 9.2.8. *Thalassia testudinum* shoot density, total biomass and areal production at four sites in the LLM from April 2006 to January 2007. No production data for spring 2006 at Green Island.

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)($p<0.05$).

Seagrass Epiphyte Study

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).

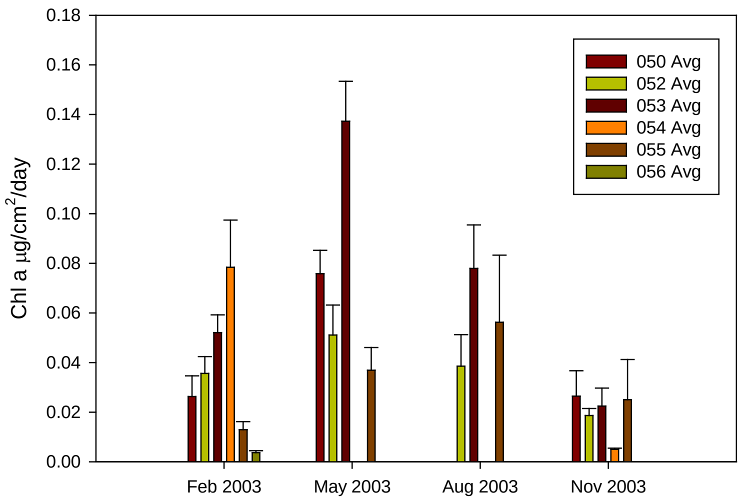


Figure 9.2.9. Epiphyte accumulation on artificial seagrass leaves at six locations in the LLM. Sites LLM 050 and 052 were south of the Arroyo Colorado. Sites 053 and 054 were nearest the Arroyo Colorado (near Green Island) while sites 055 and 056 were north of the Arroyo Colorado. There were no data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

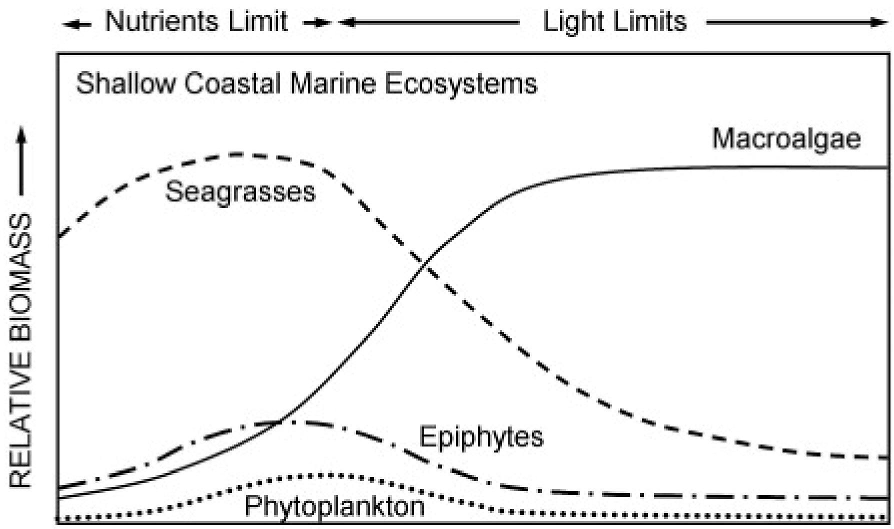


Figure 9.2.10. Generalized shift in the biomass of major groups of primary producers with increasing nutrient enrichment to shallow coastal marine waters. From Burkholder et al., (2007).

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).

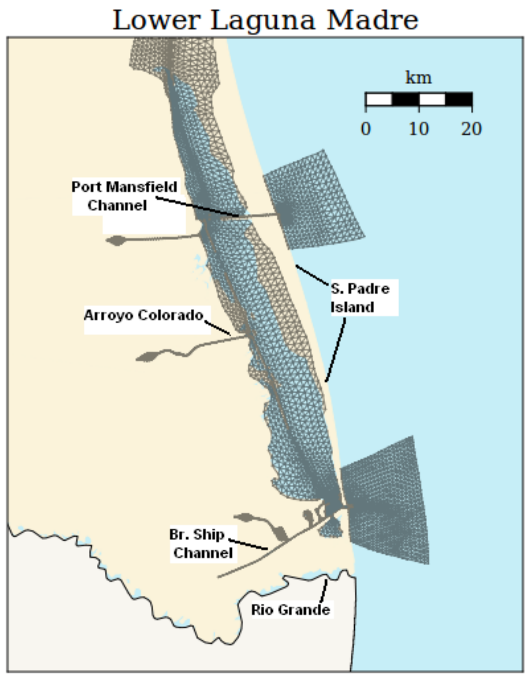


Figure 9.3.1 TxBLEND hydrodynamic model grid network applied to LLM.

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.

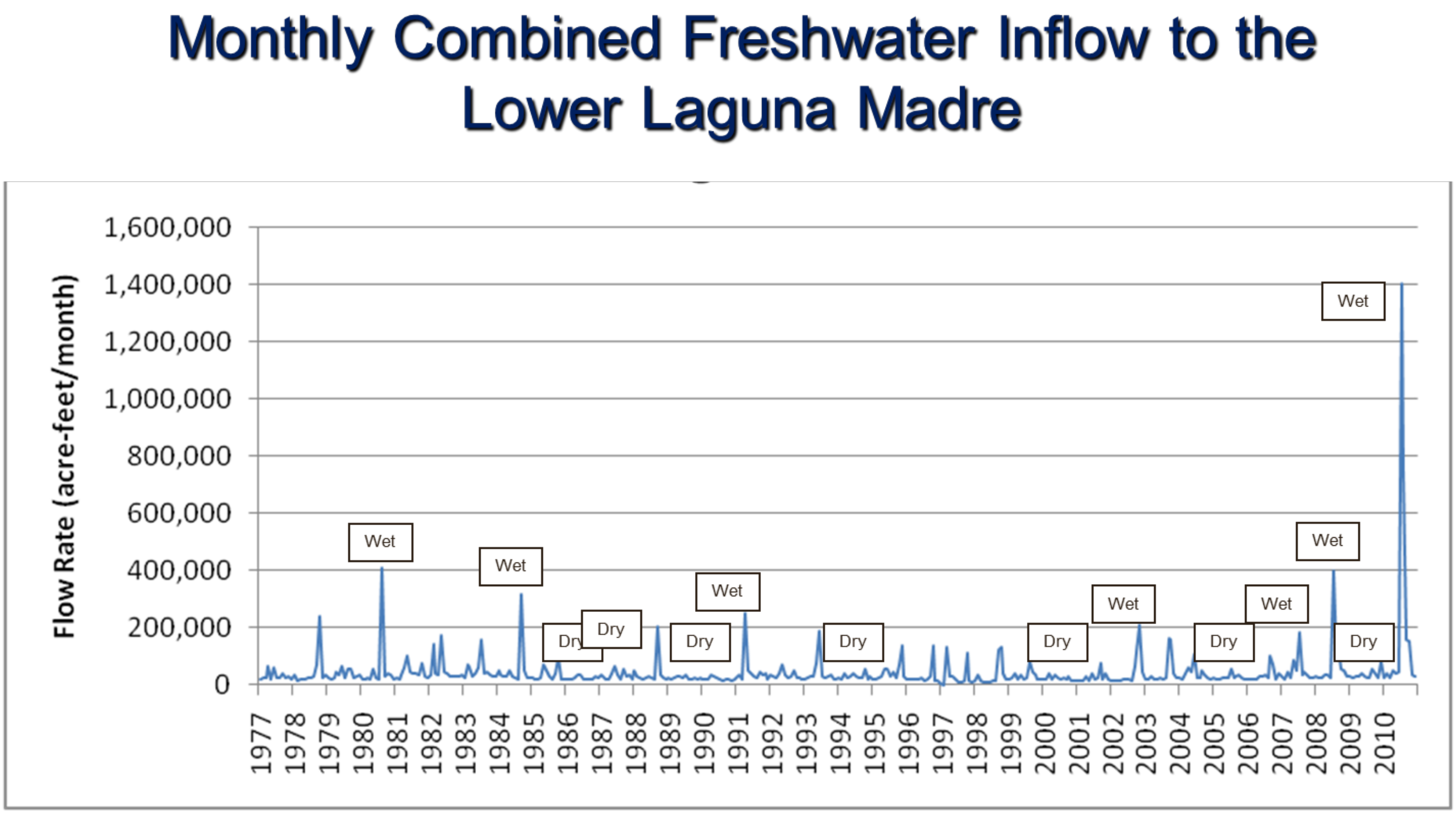


Figure 9.3.3. Monthly combined freshwater inflow to Lower Laguna Madre (graph from TWDB).

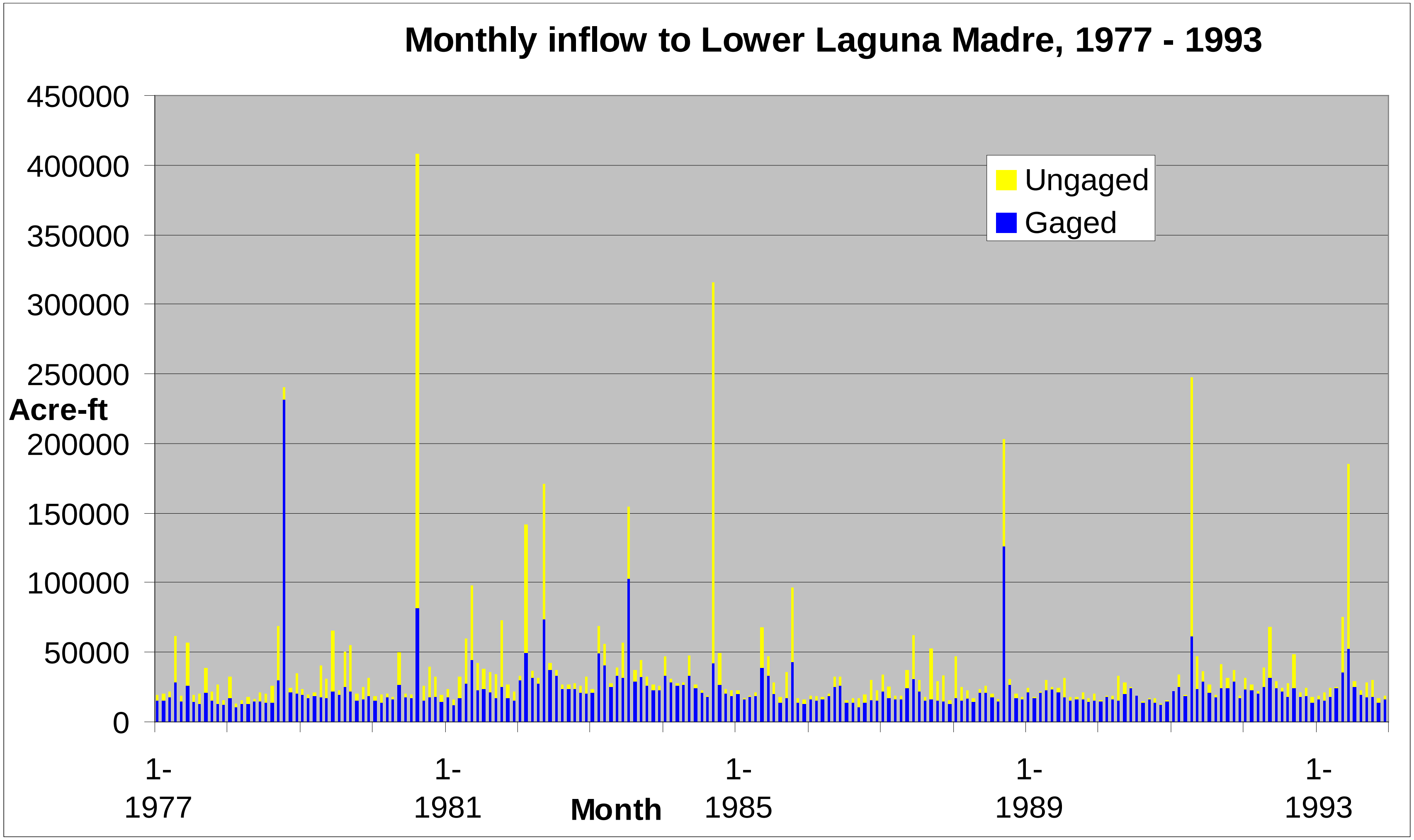


Figure 9.3.4. Monthly gaged and ungaged inflow to Lower Laguna Madre, 1977 – 1993 (data from TWDB).

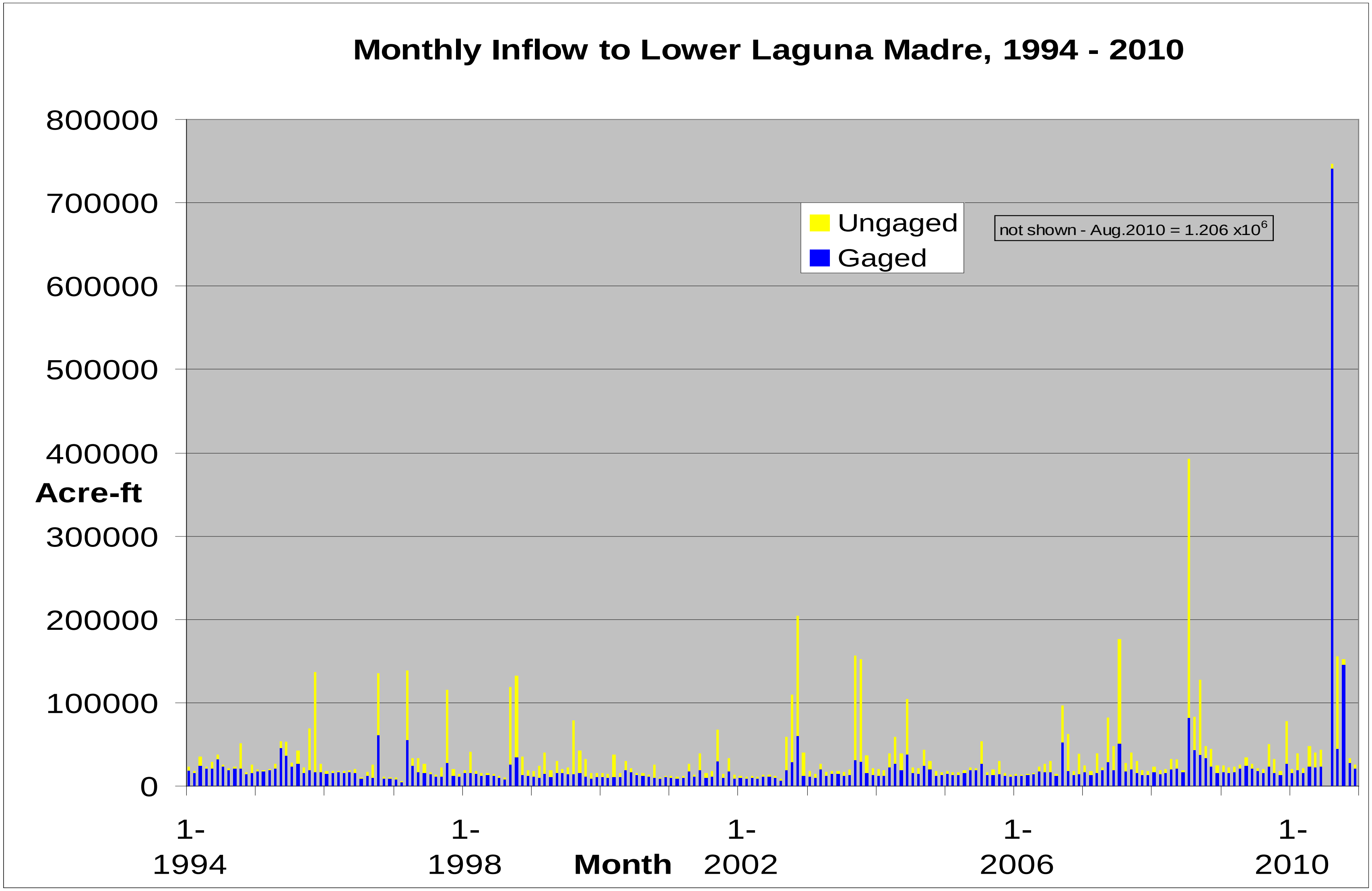
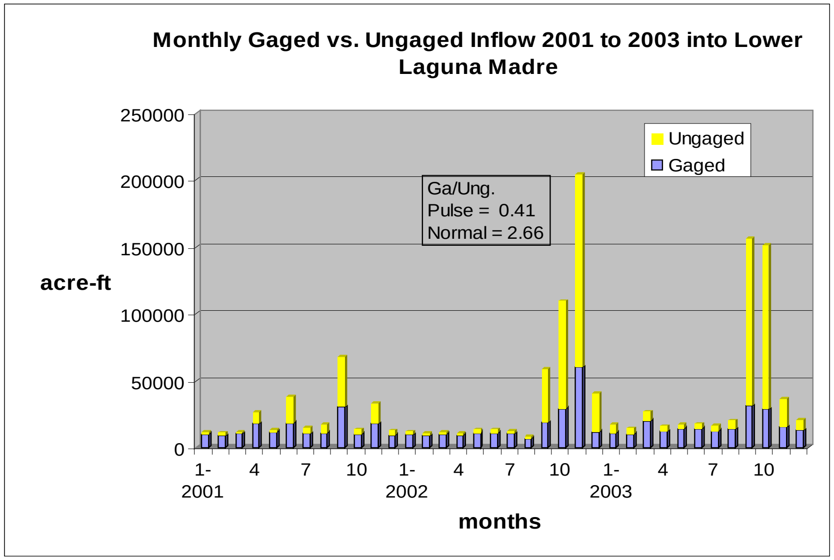


Figure 9.3.5. Monthly gaged and ungaged inflow to Lower Laguna Madre, 1994 – 2010 (data from TWDB).



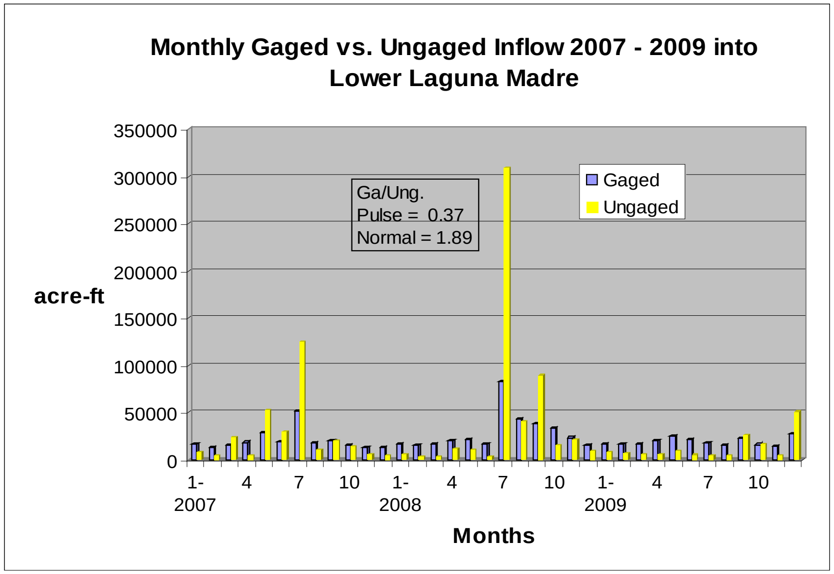


Figure 9.3.6. Separation of monthly inflows into gaged and ungaged flows for high flow years.

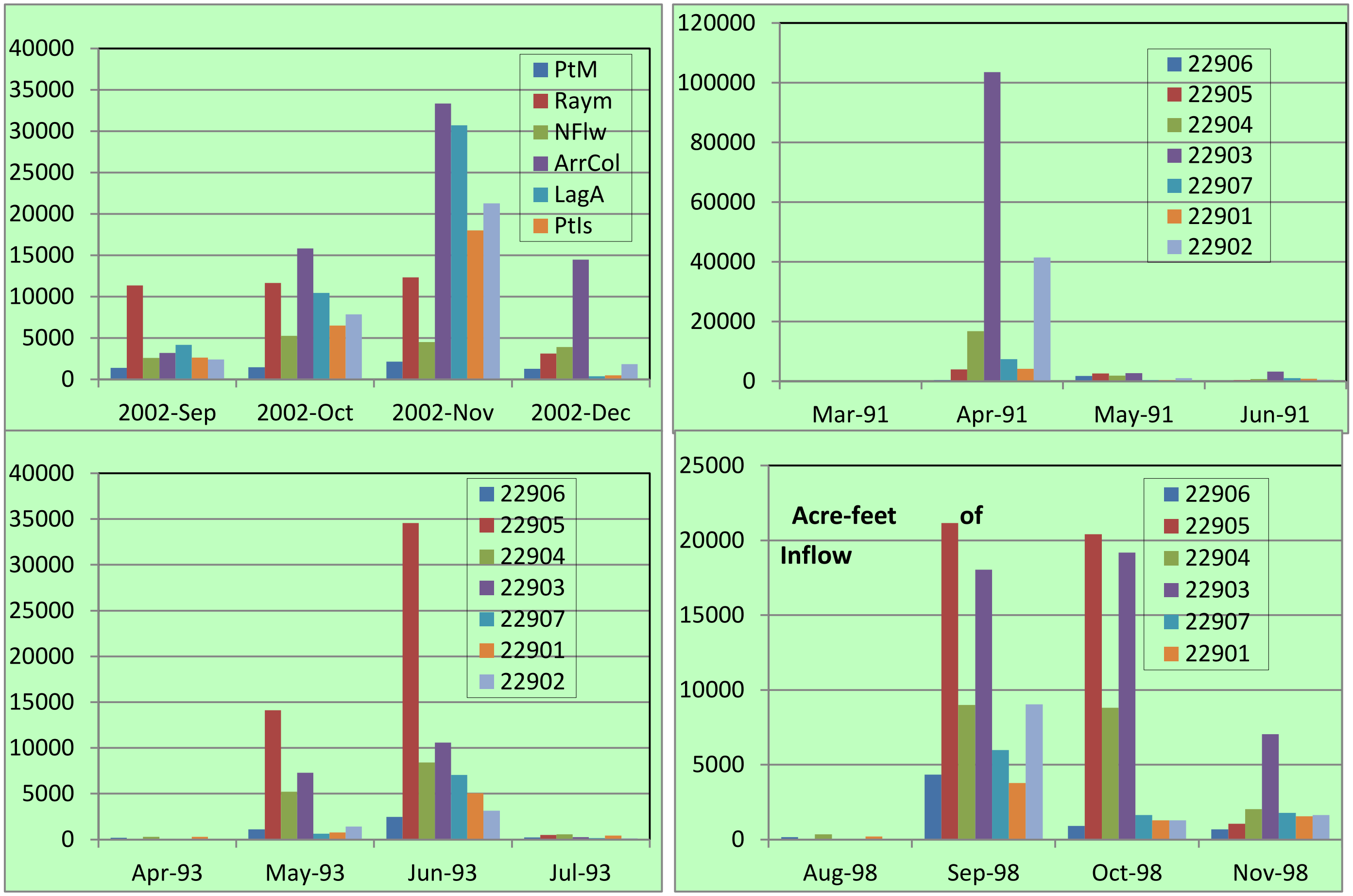


Figure 9.3.7. Volume of ungaged inflow pulses from seven LLM subwatersheds in 4 wet years. Legend numbers refer to ungaged subwatershed areas from Fig. IX.3 – 2. Top left figure uses local geographic names for subwatershed area numbers: PtM =Port Mansfield; Raym =Raymondville; NFlw =North Floodway; ArrCol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

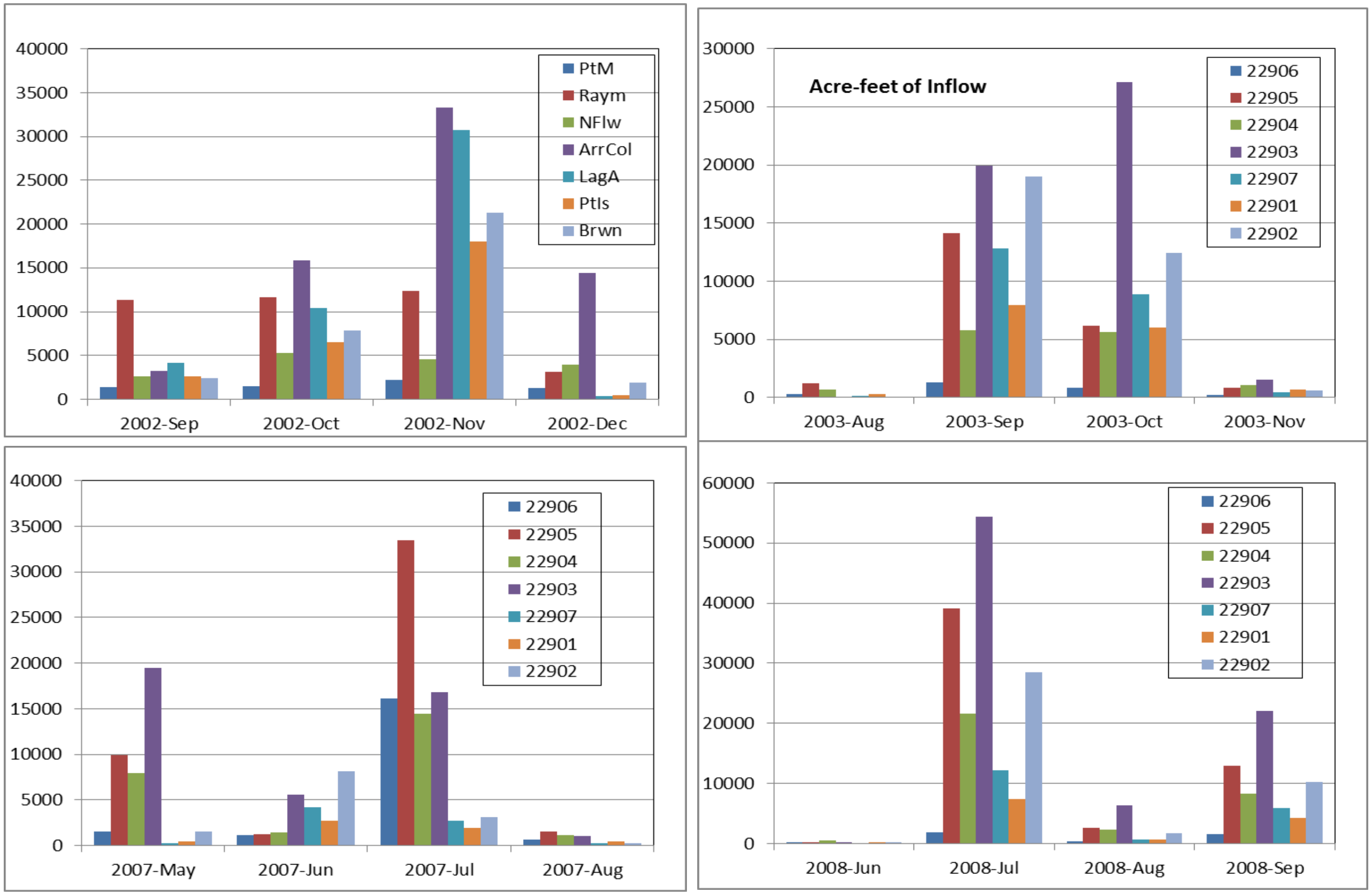


Figure 9.3.8. Volume of ungaged inflow pulses from seven LLM subwatersheds in 4 wet years. Legend numbers refer to ungaged subwatershed areas from Fig. IX.3 – 2. Top left figure uses local geographic names for subwatershed area numbers: PtM =Port Mansfield; Raym =Raymondville; NFlw =North Floodway; ArrCol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

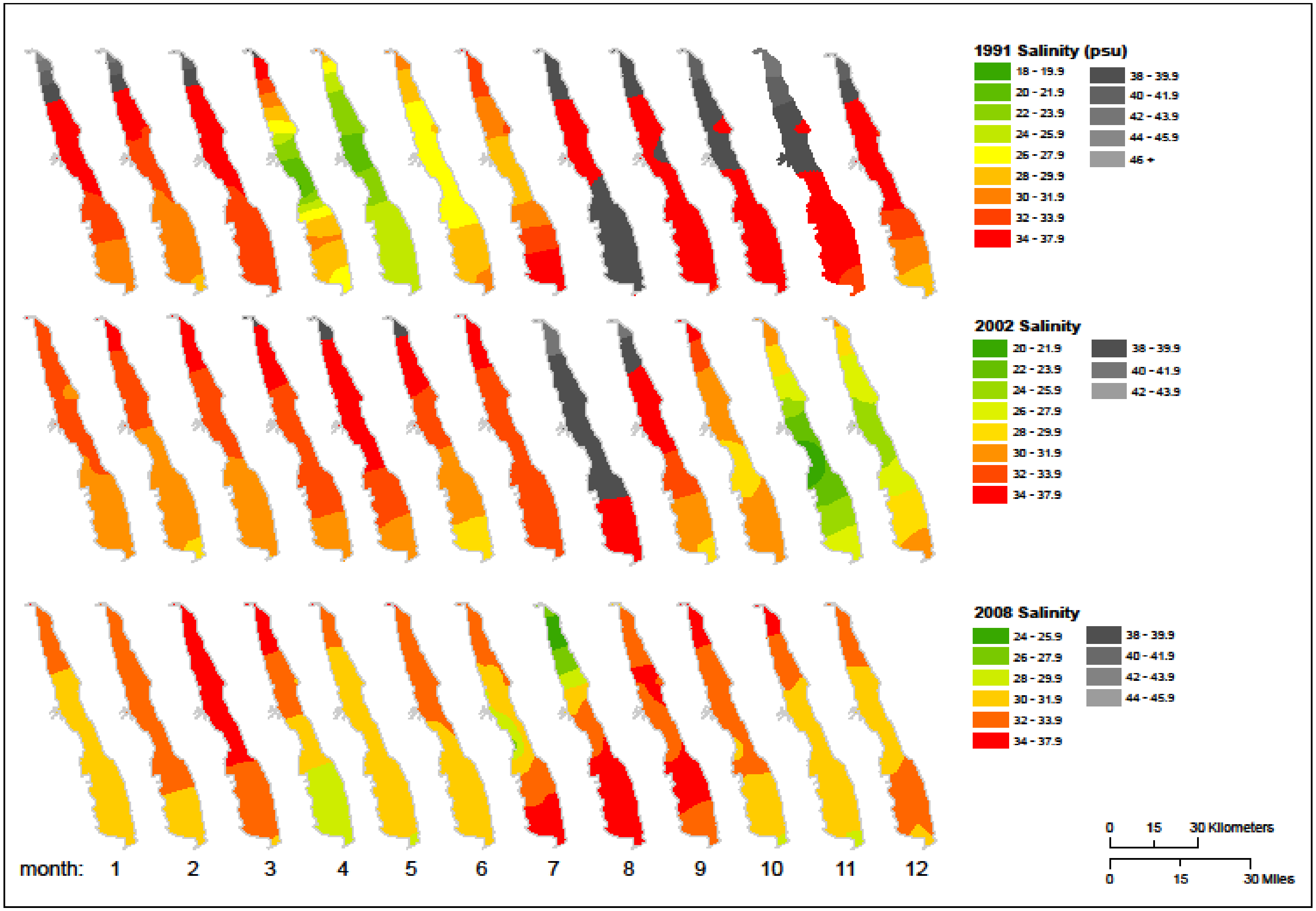


Figure 9.3.9. Salinity plumes during 3 Wet years (courtesy of L. Hamlin, TPWD).

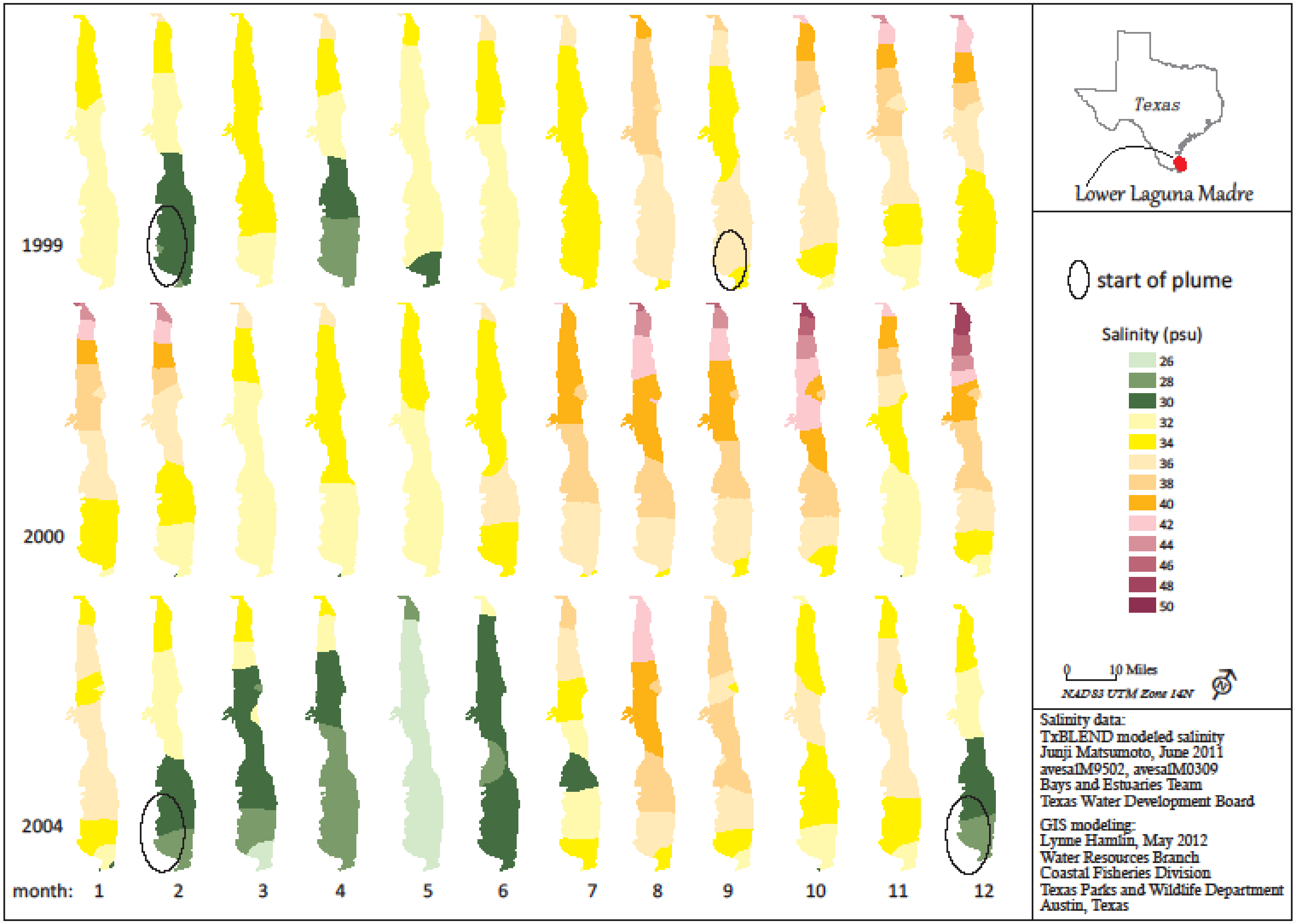


Figure 9.3.10. Salinity plume maps for LLM for 1999 Avg year, 2000 Dry year, and 2004 Wet year

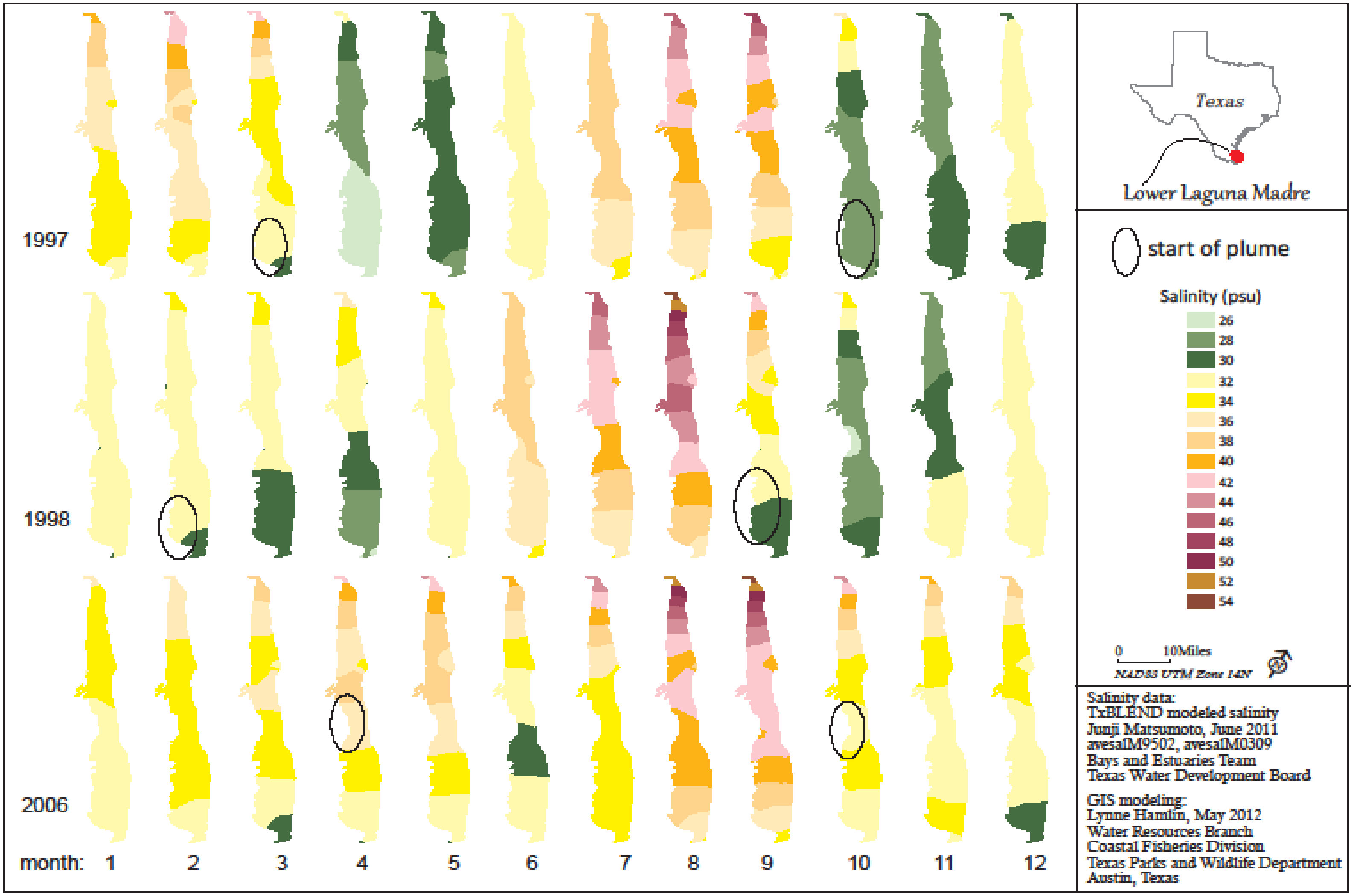


Figure 9.3.11. Salinity plume maps for LLM observed during three intermediate or Avg flow years

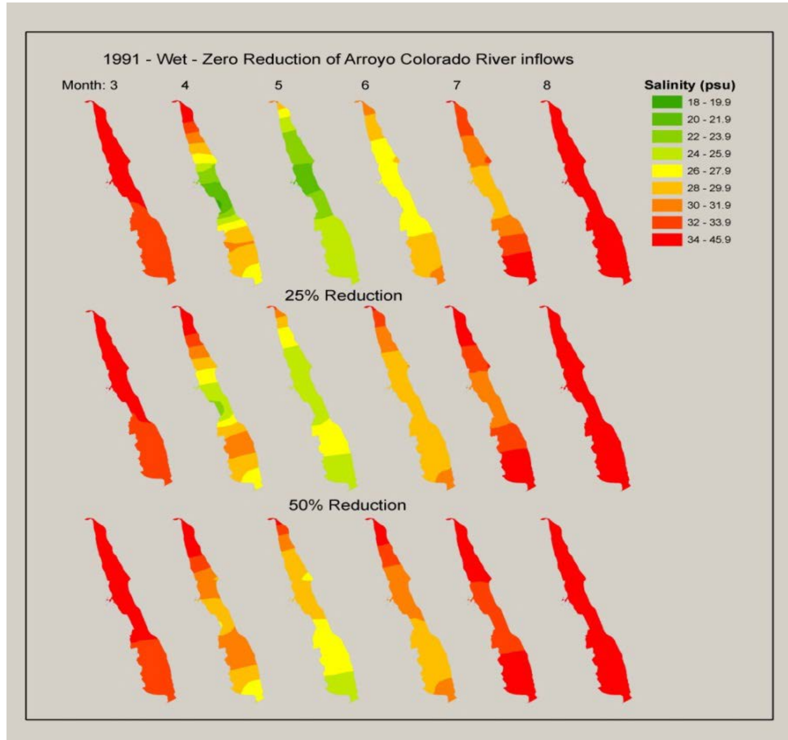


Figure 9.3.12. Salinity plume maps for LLM, 1991 (Wet year)

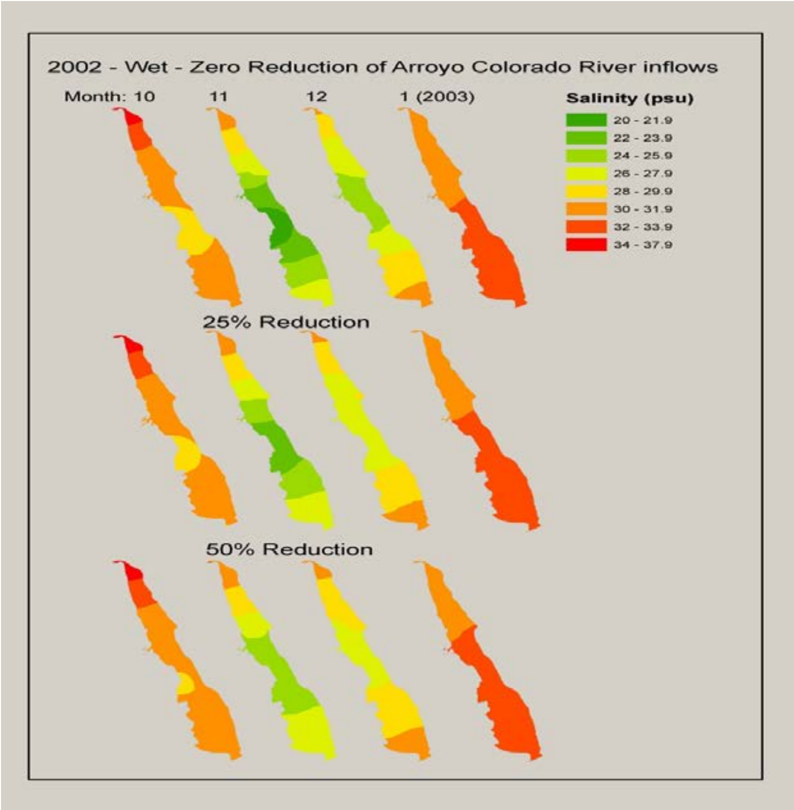


Figure 9.3.13. Salinity plume maps for LLM, 2002 (Wet year).

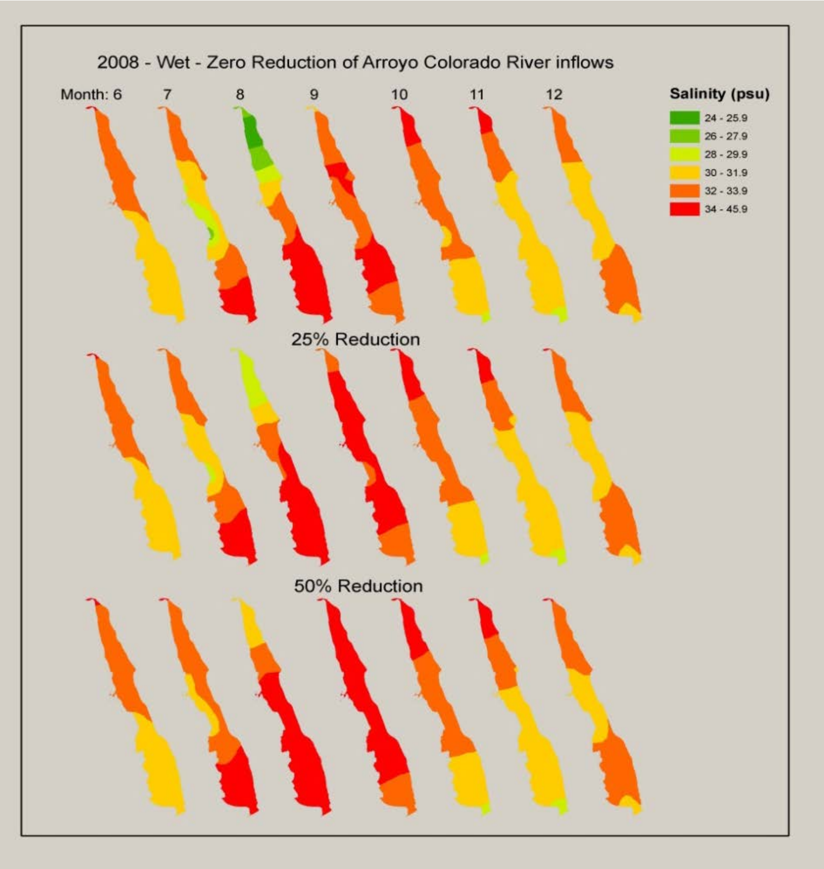


Figure 9.3.14. Salinity plume maps for LLM, 2008 (Wet year).

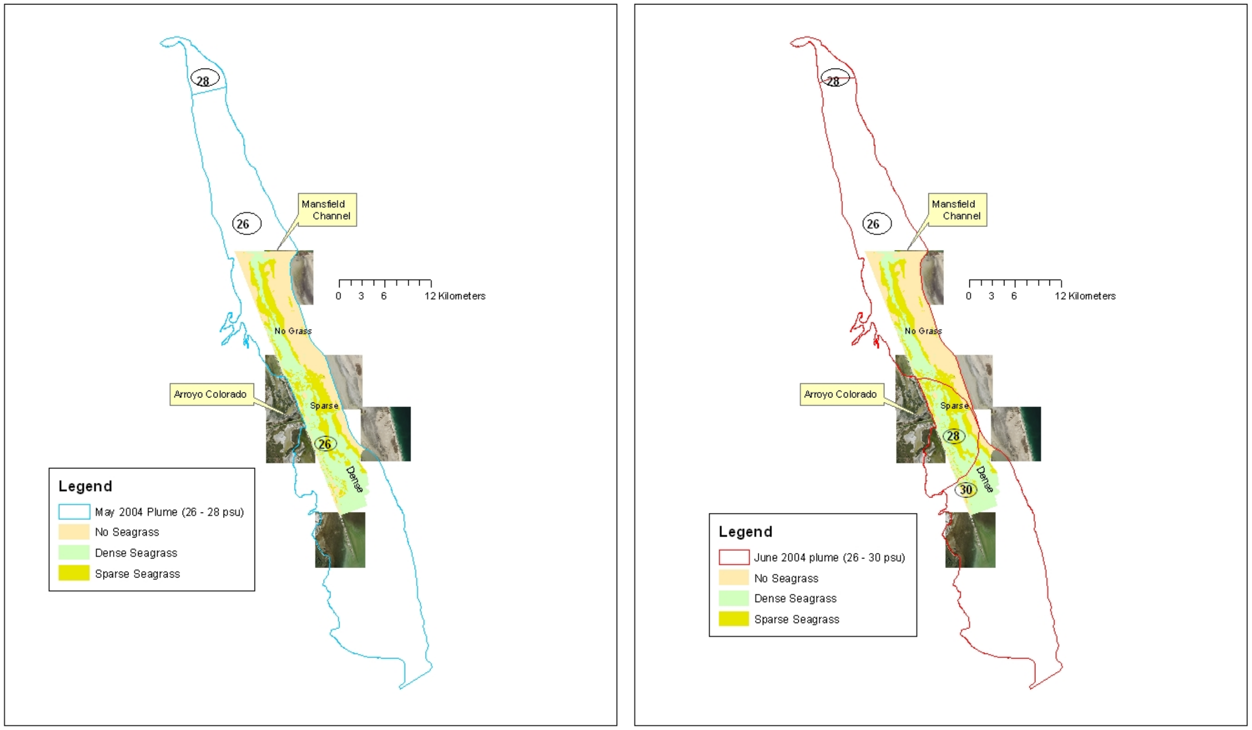


Figure 9.3.15. Salinity plumes in 2004 overlaid onto 2005 seagrass map.

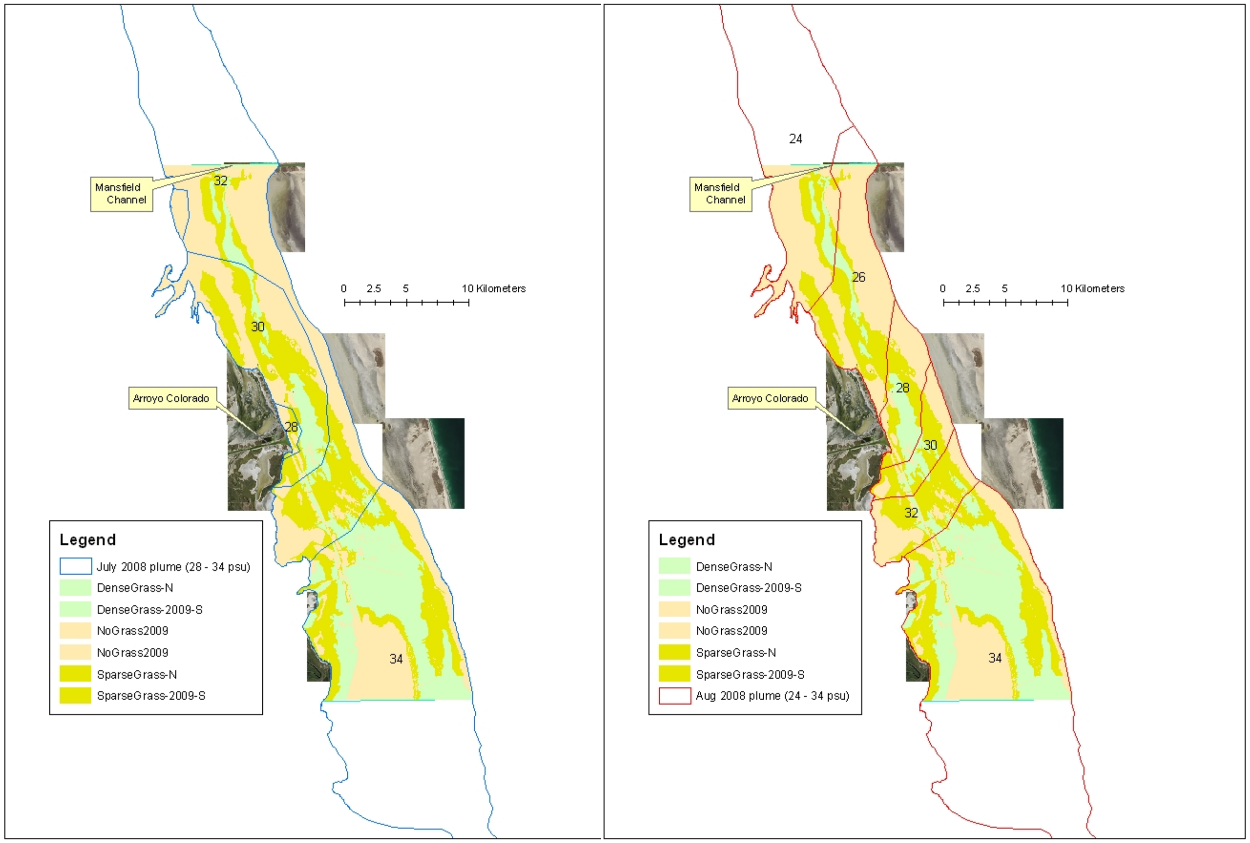


Figure 9.3.16. Salinity plumes in 2008 overlaid onto 2009 seagrass map.

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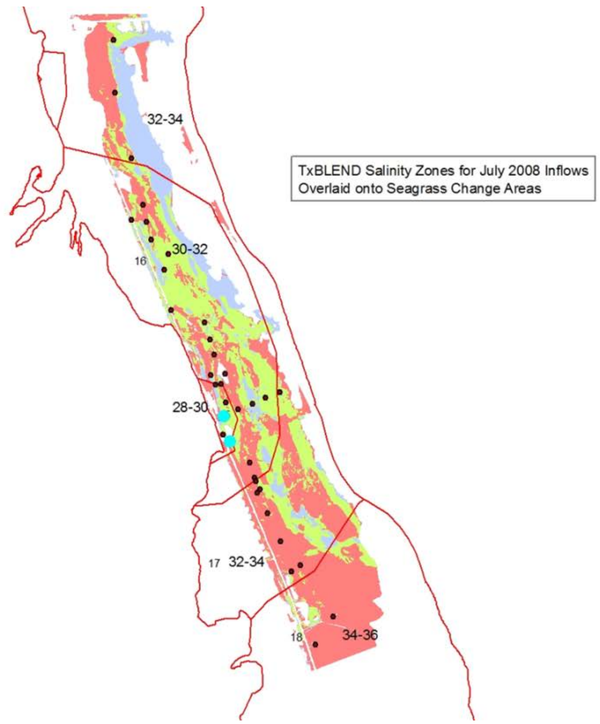

Figure 9.3.17. Salinity plumes in 2008 overlaid onto seagrass change map,between 2005 to 2011. Blue = Gain, Red = Loss, Green = no change in seagrass.

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:

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

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

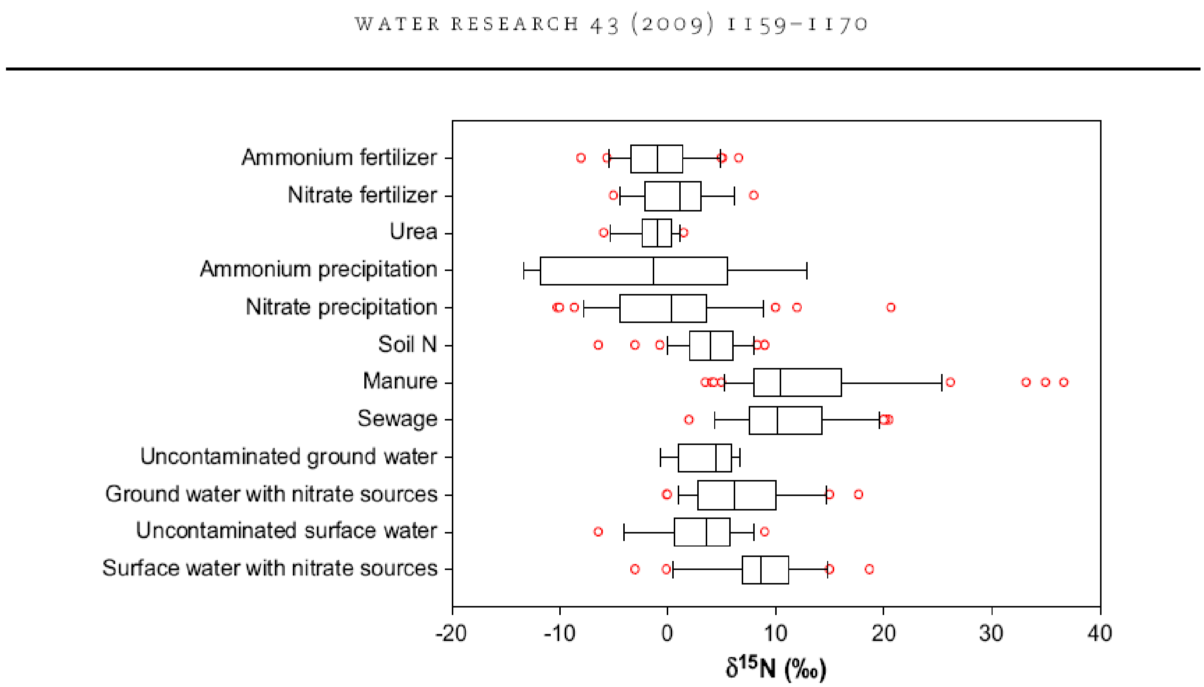

Figure 9.4.1. The range in $\delta^{15}N$ values for a variety of nitrate sources and sinks. Box plots illustrate the 25th, 50th and 75th percentiles; whiskers indicate the 10th and 90th percentiles; circles are outliers. From Xue et al. (2009).

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.

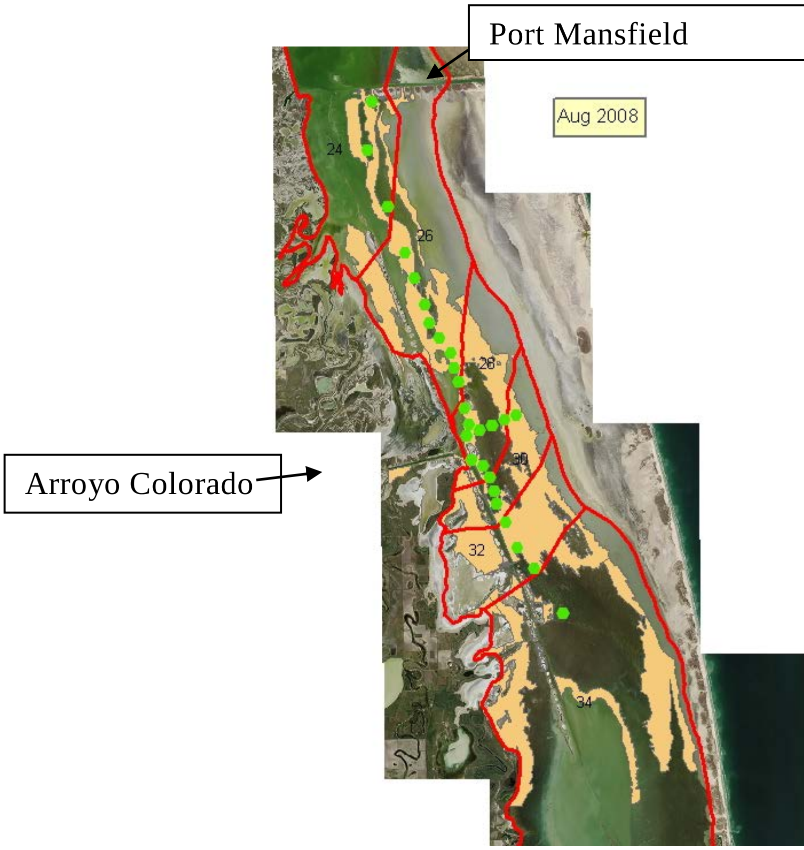

Figure 9.4.2. Green dots represent the sites in the Lower Laguna Madre visited on August 18, 2011 for collection of seagrass, drift algae and seagrass epiphytes analyzed for N isotopes. This isotope sampling design was laid out according to 2008 salinity plumes (red polygons in figure) observed as output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

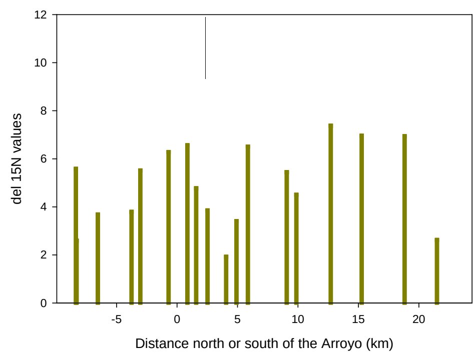

Figure 9.4.3. $\delta^{15}N$ values for the seagrass *Halodule wrightii* collected from the LLM along the north-south transect at varying distances from the Arroyo Colorado (at 0 km) on 18 August 2011. Negative values are south of the Arroyo while positive numbers are north of the Arroyo.

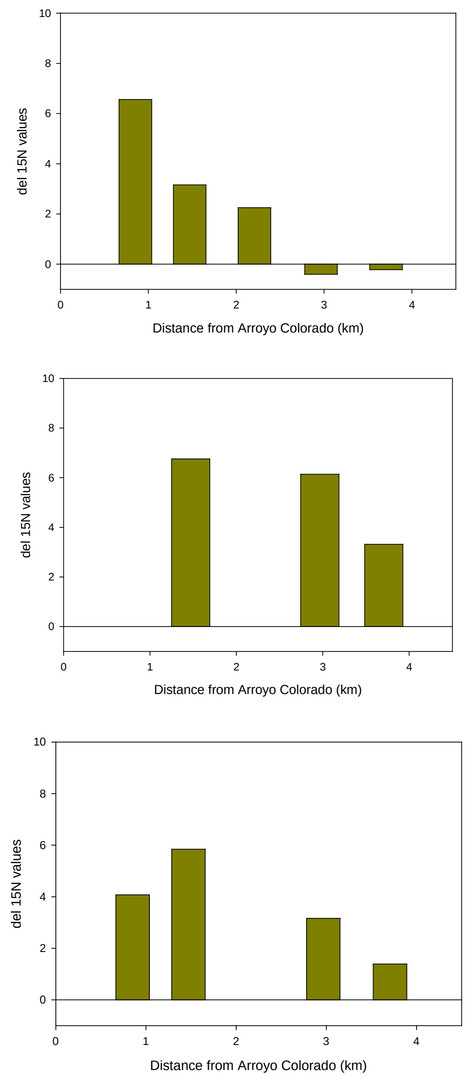

Figure 9.4.4. $\delta^{15}N$ values of the seagrass *Halodule wrightii* (top), the macroalgae *Palisada poiteauii* (middle) and epiphytes from *H. wrightii* (bottom) collected on August 18, 2011 in the LLM along the west to east transect starting near the Arroyo Colorado confluence.

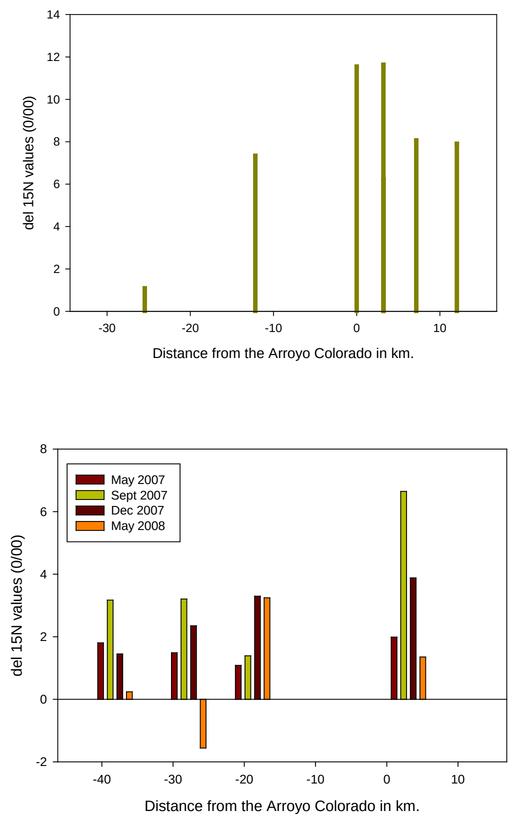

Figure 9.4.5. δ^{15}N values of the seaweed *Palisada poiteauii* (top) and the seagrass *Halodule wrightii* (bottom) collected from the LLM along a north-south transect in 2004 and 2007-08, respectively. Negative values along the X-axis indicate sites south of the Arroyo while positive numbers indicate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

<u>Direct Salinity Impacts</u>

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.

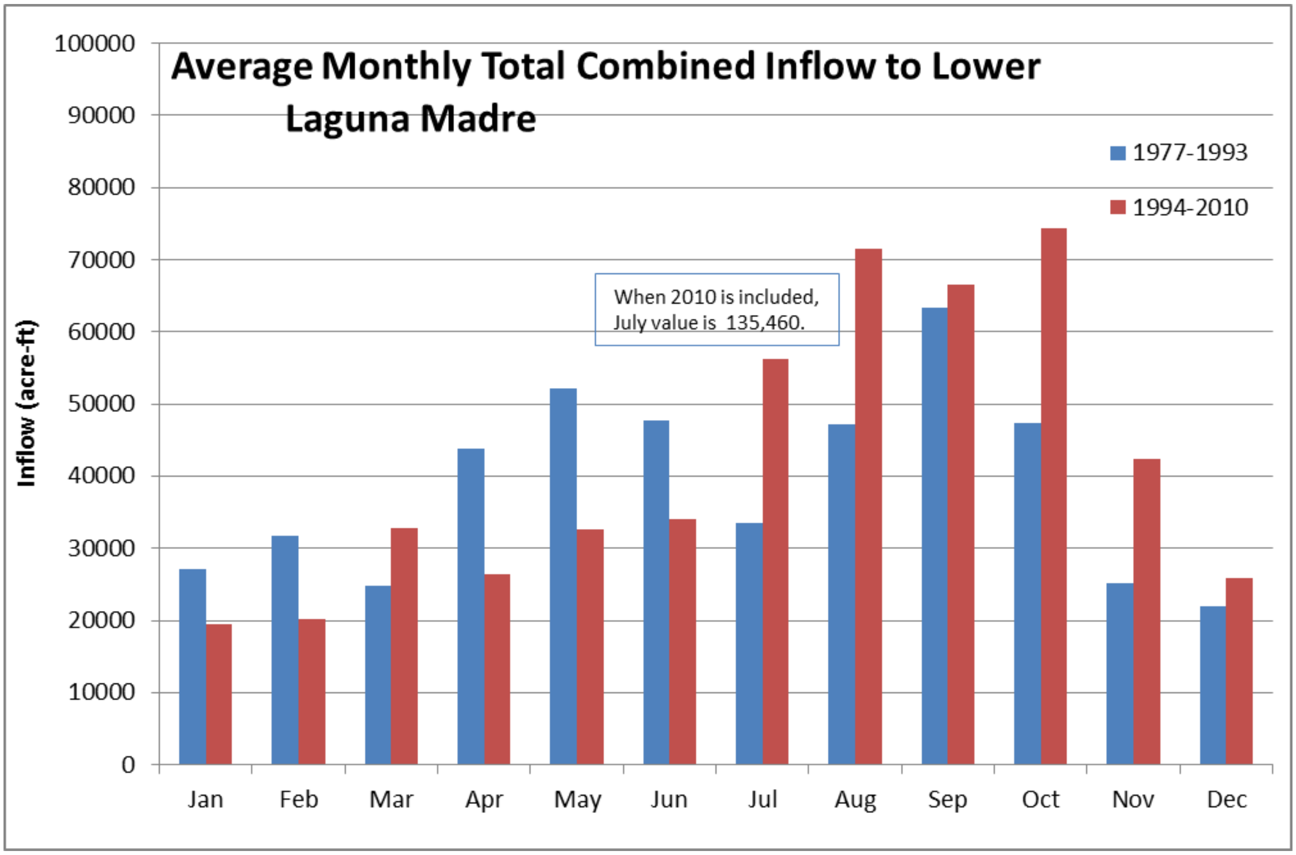

Figure 9.5.1. Average monthly total combined inflow to Lower Laguna Madre compared for two periods, 1977-1993 vs. 1994-2010. Value for July 2010 was excluded from the calculation because it greatly skews the average, being extraordinarily high at 1.4 x 10^6 ac-ft.

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 recommendation of flow regimes for the Rio Grande Estuary is focused primarily on keeping the mouth of the river open:

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

> <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).

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.

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."

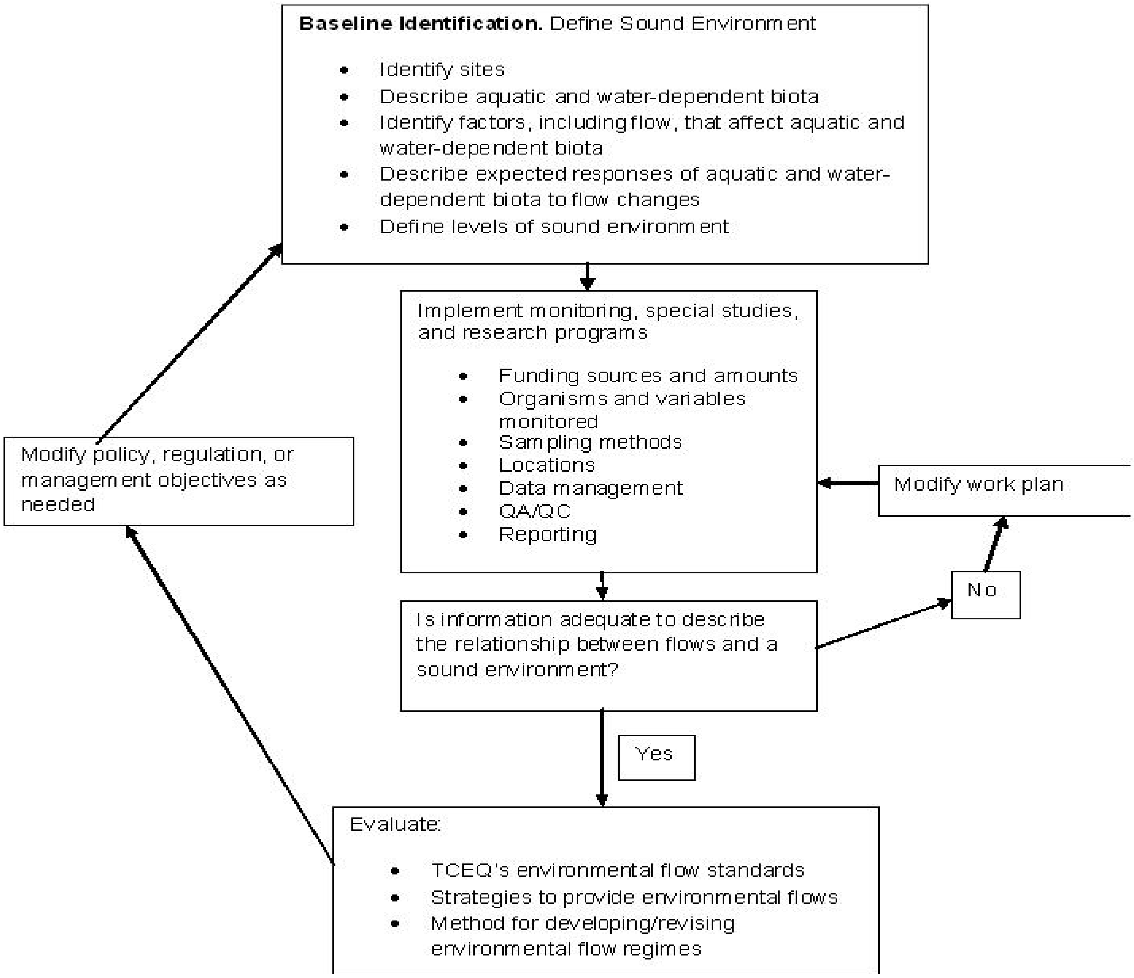

Figure 11.5.1. Adaptive Management Plan Flow Chart

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