MATAGORDA BAY FRESHWATER INFLOW NEEDS STUDY

Lower Colorado River Authority
Texas Commission on Environmental Quality
Texas Parks and Wildlife
Texas Water Development Board

August 2006

EXECUTIVE SUMMARY

Matagorda Bay

Freshwater Inflow Needs Study

Introduction

The primary purpose of this study is to reassess the freshwater inflow needs for Matagorda Bay based on more than eight years of new data collected since the completion of the 1997 Freshwater Inflow Needs Study. The earlier study was based on five years of data collected after the U.S. Army Corps of Engineers (USACE) opened a diversion channel in 1991 from the Colorado River into Matagorda Bay to increase freshwater inflows entering into the bay. The current study also reviews and modifies some of the 1997 study methodologies and assumptions. The results of this study indicate that higher freshwater inflows are needed to achieve the Target and Critical inflow needs than indicated in the 1997 study. This is largely due to the availability of additional, more variable data collected over a longer period of time.

Both the 1997 study and the current study represent a joint effort of the Lower Colorado River Authority (LCRA), the Texas Parks and Wildlife Department (TPWD), the Texas Water Development Board (TWDB), and the Texas Commission on Environmental Quality (TCEQ). Each study partner was represented on the study advisory committee and guided by a joint memorandum of agreement and scope of work (See Appendix A). A representative of the Lavaca-Navidad River Authority also attended the advisory committee meetings. The advisory committee meetings were open to the public and development of the study involved public meetings and workshops, a stakeholder process and public review and comment on the draft study.

Improvements in the Current Study

The current study builds and improves upon several areas of the 1997 study. Flow, salinity, and biological productivity data have been extended beyond what was used in the1997 study and are applied here. This includes the availability and use of independent fisheries data collected by TPWD rather than the reliance on commercial harvest data. As a result, improved equations have been developed for relating flow to salinity and to productivity. Biological equations for shrimp have also been improved resulting from more careful consideration of the influence of inflows on shrimp during the juvenile life stage. Sensitivity analyses were conducted on the TXEMP optimization model to provide better insight on the influence of constraints and other factors on the model results. As a result, limits on inflow and biological constraints were revised from the 1997 study. In addition to developing Critical and Target Flows as in the 1997 study, the current study presents options for use of TXEMP model results to develop intermediate flow solutions for use as a transition between the Critical and Target inflow needs. Model calibration of the TXBLEND hydrodynamic and salinity transport model benefited from additional data, and multi-year simulations were conducted in this study and provide better confidence in the model behavior.

The 1997 report identified a number of areas that would benefit from additional study. However, some areas could not be extended in this study due to lack of additional new data, including nutrients (related to primary productivity, offshore concentrations, loadings, and sediment), benthic dynamics and sedimentation needs of Lavaca Bay and East Matagorda Bay. In addition to the need to continue developing additional data and analysis, more information is needed on existing habitat conditions and their relationship to biological productivity. A comprehensive assessment of factors that may affect the overall ecological health of the bay is also being conducted as a part of the LCRA-SAWS Water Project (LSWP) Bay Health Study. The improvements and modifications to the State Methodology being done for this study in combination with the more comprehensive look at overall bay health and productivity by the LSWP Bay Health Study are expected to contribute to the development of improved methods and tools for assessing freshwater inflow needs for Matagorda Bay.

Target Flows and Critical Flows

Beginning with the 1997 study, two freshwater inflow needs (FINS) have been identified: the "Target" freshwater inflow need based on the application of the State Methodology; and the "Critical" freshwater inflow need. The "Target" freshwater inflow need seeks to optimize selected estuarine species productivity; the "Critical" freshwater inflow need is intended to provide a fishery sanctuary habitat during drier periods from which finfish and shellfish species are expected to recover and repopulate the bay when more normal weather conditions return.

The monthly Target flow needs estimated by the current study by source are summarized in Table ES.1. Monthly Target flows range from 480,100 acre-feet in May to 111,700 acre-feet in August. Compared to the 1997 study results, these results represent a maximum monthly increase of 267,600 acre-feet of freshwater inflows in the month of February to a maximum monthly decrease of 181,500 acre-feet of water in the month of May needed to deliver the Target inflow necessary to optimize selected estuarine species productivity.

Table ES.1 Monthly Target Flow Needs by Source.

Month	Colorado (1,000 ac-ft)	Lavaca (1,000 ac-ft)	Other (1,000 ac-ft)	Total Monthly (1,000 ac-ft)
January	205.6	77.0	37.2	319.8
February	194.5	68.9	44.5	307.9
March	63.2	15.6	42.3	121.1
April	60.4	30.3	51.1	141.8
May	255.4	139.4	85.3	480.1
June	210.5	86.0	80.2	376.7
July	108.4	29.2	66.4	204.0
August	62.0	18.3	31.4	111.7
September	61.9	37.3	107.2	206.5
October	71.3	42.9	100.7	214.9
November	66.5	23.0	47.4	136.9
December	68.0	24.9	35.7	128.7

During the 1997 study, 25 parts per thousand (ppt) was established as the desired maximum salinity level during drought or extended dry periods. This criterion was based on review of species tolerances with particular attention to the Eastern Oyster and its predators. The Eastern Oyster was chosen not only because it is a commercially important species, but because it cannot migrate to areas with lower salinity ranges to avoid predators. The 25 ppt salinity level is also the approximate dividing line between brackish estuarine waters and more saline marine waters and, thus, an appropriate threshold to use in determining whether estuarine species may become significantly affected.

Based on additional data and analysis, Critical inflow needs for the Colorado River increase from 14,260 acre-feet of water per month to 36,000 acre-feet of water per month over those calculated in the 1997 study. Lavaca-Navidad Critical inflow needs increase from 2,260 acre-feet of water per month to 4,290 acre-feet per month. Corresponding increases would also be needed from the other coastal basins that feed into West Matagorda Bay.

The primary reasons for the increases in Critical and Target inflow needs from the 1997 study include the following:

- More accurate statistical relationships based on additional data collected over a longer period of time since the USACE diversion channel was completed in 1991. For example, data was collected on a more continuous basis and data collection included fewer gaps and was subject to less frequent equipment failures.
- More variability of wet and dry years and corresponding salinities was captured by the statistical relationships; and
- Increased monthly inflow constraints were selected for use in the TXEMP modeling. Historic flows in the 70th percentile replaced the historic monthly mean used in the 1997 study or the monthly median flow (50th percentile monthly or median monthly historic flow), which has been widely used in other Texas estuaries. This constraint increase was necessary to allow the model to be solved without exceeding the selected salinity and biological productivity constraints.

Consistent with the 1997 study, the 2006 update continued to use the same salinity regimes and rationale for Critical and Target inflows, measurement locations, State optimization and hydrodynamic and conservative transport models (TXEMP and TXBLEND), target species (with one exception), and the relative weighting of species, as the 1997 study. In contrast to the 1997 study, the 2006 study also explored a range of intermediate inflow regimes that may be considered as a transition from Target to Critical inflow regimes.

Both the 1997 and the 2006 studies used the State Methodology, with some modifications. The State Methodology includes the use of the TXEMP model, a general purpose optimization model to find a minimum or maximum function (e.g., biological productivity) that satisfies constraints that are imposed (hydrology, salinity, biological). TXEMP results are bounded by the constraints. The State Methodology also includes the use of the TXBLEND model, a hydrodynamic and conservative transport model specific to water bodies such as lakes or bays. The conservation transport aspect of the model looks at the movement of salt through the water body. The TXBLEND model is used to verify that the inflow regime results identified by the TXEMP model as meeting all constraints will also provide the desired salinity regime throughout the Matagorda Bay system.

While the logic and equations of the optimization model itself are built on mathematical and engineering analyses, application of the model requires the inclusion of operative constraints, limits, and resource management objectives. These objectives are based more on policy than science and engineering. Other policy decisions include: the indicator species to be used, the relative weighting of the species; and the selection of inflow-response equations and inflow constraints (Longley, ed., 1994). Since many of these policy decisions are made by the state agencies responsible under state law for water permitting and planning, the 1997 study as well as this update are based on the existing State Methodology, with some modifications developed in consultation with the state resource agencies. It is expected that these policies and methodologies will continue to evolve based on the recommendations of the SB 1639 (78th Texas Legislature; 2003) Study Commission on Water for Environmental Flows.

It should be recognized that salinity is only one component in assessing the overall health and productivity of the bay. Other components of aquatic habitat such as the hydrodynamic regime, physical structure, food availability, and shelter/predator avoidance are also important. Salinity has been used as a primary measurement of beneficial inflows because it influences productivity, and it is easy to measure as a hydrologic variable. However, it may have only a secondary degree of influence. The indirect influence of salinity includes food availability (e.g. plankton) that thrive in freshwater – seawater mixtures found in estuaries. Higher productivity in terms of species richness and evenness is usually found in the fluctuating, mesohaline zone of the estuary.

Post-Diversion Productivity

The Colorado River was diverted into the eastern arm of Matagorda Bay in 1991 by the U.S. Army Corps of Engineers (USACE) to create habitat, increase nutrients and moderate salinity in order to improve productivity. Since the diversion, a functional deltaic marsh has developed at the end of the diversion cut that now forms the mouth of the river, creating habitat for many estuarine species. Over time it is expected that the delta marsh will increase productivity in Matagorda Bay because of increased physical habitat, increased nutrients, and moderated salinity. Comparisons of bay-wide biological monitoring data before and after the USACE diversion channel do not indicate a clear relationship between increased inflows and species abundance. However, the TPWD sampling effort in the bay does not directly sample this delta marsh, making it difficult to assess species utilization. Additionally, a major flood in 1992 and a severe drought in 1996 occurred during the post-diversion period, both of which have likely had negative short-term impacts on species productivity.

The current health and productivity of Matagorda Bay is generally good, according to TPWD studies and observations. Matagorda Bay generates approximately $63 million annually in commercial seafood harvests, and contributes toward an additional $115 million annually to the sport fishing industry (Loeffler and Balboa "Colorado Quandry," TWPD, The Outdoor Magazine of Texas, July 2003). Since the completion in 1991 of the USACE diversion channel, hundreds of acres of productive marshes have been created and newly created oyster reefs are flourishing. Id. Therefore, the health and productivity of the bay have been generally very good under the current freshwater inflows being provided to the bay.

Recent State Reviews

Since this update was initiated, the Texas Legislature established the Study Commission on Water for Environmental Flows under Senate Bill 1639 (2003). As a part of its task, the commission appointed a Science Advisory Committee to assess current methodologies and analytical tools for determining freshwater inflow needs. The Science Advisory Committee recommended improvements to the State Methodology, some of which have been incorporated into this study. For example, it criticized the State Methodology's use of commercial harvest data. This study relies on independent monitoring data. The Committee also criticized the State Methodology as relying too heavily on the premise that species abundance is dependent upon inflow and salinity, without adequately considering nutrients, sediments, energy, habitat and other measures of overall ecological health and productivity. In addition, the Study Commission's report recommended an "adaptive management" approach where adjustments to identifying or meeting environmental needs are made as new information and better science becomes available and endorsed the use of a peer review process and stakeholder involvement. LCRA is unique in the State of Texas in using this approach in the periodic review and revision of its Water Management Plan (LCRA, 1999). LCRA is also the only water right holder in the lower Colorado River basin that has specifically committed water for environmental water needs and has incorporated adaptive management principles.

Because of the recent criticism of the State Methodology, the uncertainty of what the legislative response may be to the SB 1639 Study Commission report, and the use of different modeling tools and approaches under the LSWP Bay Health Study, there remains the need to continue the periodic review and reassessment of freshwater inflow needs. Estimates of freshwater inflow needs for Matagorda Bay and the most appropriate means for delivering such flows should be updated and revised when new data, methods, and tools become available. The LSWP is also evaluating many factors that affect the overall ecological health of the bay and should be considered together with the FINS in any future water management decisions. Any lessons learned from other freshwater inflow needs studies being conducted in Texas should also be considered. For example, the Nueces Bay Study indicated that the timing and location of freshwater inflows were more important than an overall increase in the total amount of inflow for improving bay productivity.

Finally, models can predict only what may happen. In reality, only the passage of many years will demonstrate what effects freshwater inflows have on bay health and productivity. Like all coastal systems, Matagorda Bay's productivity is the result of a host of complex factors that are not yet fully understood.

ACKNOWLEDGMENTS

The LCRA expresses its appreciation to the Texas Water Development Board (TWDB), Texas Parks and Wildlife Department (TPWD), and Texas Commission on Environmental Quality (TCEQ) for their support during this study. Particularly, the members from these agencies that served on the study advisory committee provided valuable guidance and insight to the LCRA. The committee included Barney Austin (TWDB), Cindy Loeffler (TPWD), Bruce Moulton (TCEQ), and Mark Jordan, Chair (LCRA). In addition, Junji Matsumoto and David Brock (TWDB), David Buzan and Wen Lee (TPWD), and Doyle Mosier and John Botros (TCEQ) made invaluable contributions to the technical analyses in this study.

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TABLE OF CONTENTS

Chapter | **Page**

CHAPTER 1
Introduction

1.1 Purpose

The purpose of this study is to: (1) better understand the relationships between the volume and seasonal timing of freshwater inflows and important environmental conditions in the estuarine system; (2) better estimate the needs for freshwater inflows to maintain and preserve the bay's aquatic ecology; and (3) update the 1997 Freshwater Inflow Needs of Matagorda Bay System Study in accordance with the 2002 Memorandum of Agreement (MOA), as amended, between the Lower Colorado River Authority (LCRA), the Texas Parks and Wildlife Department (TPWD), the Texas Water Development Board (TWDB), and the Texas Commission on Environmental Quality (TCEQ).

A large part of this study seeks to help answer questions that were raised during the 2002 LCRA Water Management Plan stakeholder process regarding specific aspects of the 1997 Freshwater Inflow Needs Study results for Matagorda Bay. In particular, several stakeholders raised concerns about accuracy of the salinity –inflow relationship near the mouth of the Colorado River. These concerns and related discussions prompted LCRA and the participating agencies to revisit the 1997 Freshwater Inflow Needs Study.

The current FINS study is not intended to determine or suggest how the results may be implemented by any of the study participants. This study may be used by the TPWD, TWDB and TCEQ as a study prepared under Texas Water Code §§11.1491 and 16.058, along with any other relevant studies and information, and by TCEQ in the consideration of water right applications to store, divert or use state water pursuant to Texas Water Code §11.147. In addition, the TWDB may choose to use the study in the development and approval of state and regional water plans under Texas Water Code Chapter 16, subchapter C. The study will also be considered by LCRA in determining whether any changes to its Water Management Plan are needed, as provided under the MOA. This review process will assess the revised FINS with all other water demands, water availability, and with input from all affected interests. The review will also include the consideration of the Bay Health Study being performed as part of the feasibility study for the Lower Colorado River Authority-San Antonio Water System Water Project and any other relevant information and studies.

1.2 Study Components – State Methodology for Determining Freshwater Inflow Needs

The Target freshwater inflow needs for this update were estimated following as closely as possible the process developed by the TWDB and TPWD in their study of the Guadalupe Estuary (Longley, ed., 1994). This process involves a number of separate functions (Figure 1.1). The first major element is the development of statistical relationships for the varied and complex interactions between freshwater inflows and important indicators of estuarine ecosystem conditions. The key estuarine indicators considered were salinity, species productivity and nutrient inflows. Each of these indicators is related to inflows to the bay, which are developed in Chapter 2, Hydrologic Characteristics of Matagorda Bay. Chapter 3, Biology describes the species selected for use in this study and develops the equations relating abundance of these species to inflows. A description of the salinity characteristics of the bay is provided in Chapter 4, Matagorda Bay Salinity. This information is applied toward developing salinity-inflow relationships in Chapter 5, Development of Salinity Inflow Relationships for Use within TXEMP. Chapter 6, Nutrient Requirements of Matagorda Bay, describes the nutrient characteristics of Matagorda Bay and develops minimum nutrient requirements for later use in the analysis. A summary of the datasets used in these analyses is included in Appendix B.

The second essential process involves using statistical functions to compute optimal monthly and seasonal freshwater inflow needs. This is accomplished using the TWDB's TXEMP Model (Longley, ed., 1994). The TXEMP model estimates the freshwater inflow needs of an estuary by representing mathematically the interactions between freshwater inflows and salinity, species productivity and nutrient inflows. Sediment inflow constraints are excluded in TXEMP due to a lack of data concerning the volume of sediment needed to balance erosion and subsidence in the Colorado River and Lavaca River delta. Chapter 7, Estimation of Freshwater Inflow Needs, describes the application of the salinity, productivity, and nutrient information developed earlier in the report in TXEMP to develop Target and Intermediate inflows.

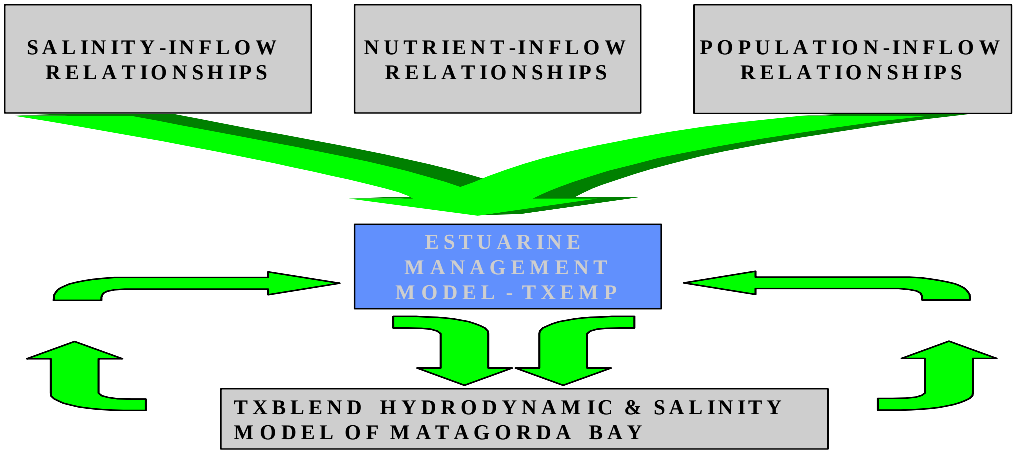


Figure 1.1 Process for Determining Freshwater Inflow Needs.

The third major component of the process of developing inflow needs is the simulation of the salinity conditions throughout the estuary using the TXBLEND model developed by TWDB and modified by LCRA. The simulated salinity is then compared to desired salinity ranges over broad areas of the estuary. If salinity is not within those ranges, then constraints in TXEMP are modified to achieve the desired salinity. Target flows developed in Chapter 7 are applied as inputs to TXBLEND in Chapter 8, Hydrodynamic and Salinity Transport Model, to evaluate the resulting salinity distribution throughout the bay. Chapter 9, Development of Critical Freshwater Flow Estimates describes the development of Critical Flows or flows required during low flow conditions in which the management goal is to provide sanctuary for species until more normal conditions return.

1.3 Improvements in the Current Study

The current study improves upon several areas of the 1997 study. Flow, salinity, and biological productivity data have been extended beyond what was used in the1997 study and are applied here. As a result, improved equations have been developed for relating flow to salinity and to productivity. Biological equations for shrimp have also been revised resulting from more careful consideration of the influence of inflows on shrimp during the juvenile life stage. Sensitivity analyses were conducted on the TXEMP optimization model to provide better insight on the influence of constraints and other factors on the model results. In addition to developing Critical and Target inflows as in the 1997 study, the current study presents options for use of TXEMP model results to develop intermediate flow solutions. Model calibration of the TXBLEND hydrodynamic and salinity transport model benefited from additional data, and multi-year simulations were conducted in this study and provide better confidence in the model behavior.

The 1997 report identified a number of areas that would benefit from additional study. However, some areas could not be extended in this study due to lack of additional new data, including nutrients (related to primary productivity, offshore concentrations, loadings, and sediment), benthic dynamics and sedimentation needs of Lavaca Bay and East Matagorda Bay. In addition to the need to continue developing additional data and analysis on nutrients, more information is needed on existing habitat conditions and their relationship to biological productivity.

1.4 Background

1.4.1 The Ecological Importance of Freshwater Inflows to Matagorda Bay

Bays and estuaries are critically important to the well-being of most marine shellfish and finfish species on the Texas coast and are vital to the state's commercial and sport fishing industry. Between 75 to 80 percent of the fishery species in the Gulf of Mexico are dependent upon estuaries during some portion of their life cycle. Many species are not permanent residents of the estuaries but migrate to them during different times of their lives. These migrations occur seasonally and are usually related to spawning cycles. Larval and juvenile organisms move from the ocean into estuarine marsh lands to find food and to seek the protection of lower salinity water. The young of many fishery species can tolerate lower salinity than their predators and parasites. When they mature to young adults, the individuals migrate back to the Gulf.

The life cycles of estuarine-dependent species require differing seasonal migratory patterns. Redfish, for example, spawn in the fall, and the young migrate into estuarine marshes shortly afterward to feed and grow. Estuaries are the permanent homes for many indigenous species that do not migrate. The most well-known of these is the oyster. The juveniles anchor upon natural reefs or other solid objects and remain in the same spot through their adult lives. This lack of mobility makes the oyster particularly susceptible to changes in water conditions. Oysters cannot tolerate freshwater (i.e. less than 5 ppt salinity) for more than a few days. On the other extreme, very salty water (i.e. over 25 ppt) for a prolonged period of time combined with high temperatures allows parasites (*Perkinsus marinus*) and oyster drills (*Thais haemostoma*) to attack the oysters, often destroying entire oyster reefs.

Many complicated interactions govern the biological productivity of Texas bays and estuaries other than the quantity of freshwater inflows. However, freshwater inflows and their associated nutrients and sediments are recognized by most estuarine biologists as one of the primary factors in estuarine productivity. Studies have demonstrated that these contributions from the freshwater inflows allow economically important fish and shellfish species to survive, grow and reproduce abundantly (LCRA, 1997).

Researchers have also discovered that periodic river floods inundate delta marshes, transport nutrients and other organic materials (food sources), and remove or limit many pollutants, parasites, bacteria and viruses harmful to estuarine-dependent organisms (LCRA, 1997). However, too much freshwater can stress or even severely damage these living coastal systems if their environment loses its marine character.

1.4.2 The Economic Value of Matagorda Bay

At approximately 350 square miles, the Matagorda Bay system is the second largest of Texas' seven major bay systems (Galveston Bay is the largest; other significant bay systems include Sabine Lake, San Antonio Bay, Aransas/Copano Bay, Corpus Christi, Nueces Bay and Upper and Lower Laguna Madre). This system is also known as the Lavaca-Colorado estuary, and its largest single body of water is Matagorda Bay. Major secondary bays in the estuary include Lavaca, East Matagorda, Keller, Carancahua, and Tres Palacios (Figure 1.2).

The current health and productivity of Matagorda Bay is good, according to TPWD studies and observations. The bay, with its estuaries nourished by freshwater inflows from the Lavaca and Colorado rivers as well as numerous, smaller streams and creeks, has been described as a "mother dynamo of sea life production." (Jim Anderson, "The Ocean's Nursery," TPWD, The Outdoor Magazine of Texas, July 2002) The abundant production of finfish and shellfish make this environmentally sensitive area important not only as an ecological resource, but also as a source of economically significant commercial and sports fisheries (Loeffler and Balboa, "Colorado Quandary," TPWD, The Outdoor Magazine of Texas, July 2003). Palacios calls itself "The Shrimp Capital of Texas," and is the home port to more than 400 shrimp trawlers. The Gulf of Mexico produces more than 40 percent of the total U.S. seafood harvest, and commercial boats based around Matagorda Bay bring in a major portion of the bounty, generating about $63 million annually. Id. The booming sportfishing industry on the bay generates $115 million annually. Id. "It's a healthy, diverse system now," according to TPWD biologist Bill Balboa, based at the Palacios Field Station. "The menhaden [a key forage fish] are thriving, shellfish surveys are up and new wetlands have formed." Id.

The economic importance of estuaries is shown in the value of estuary-dependent fish and shellfish. Commercial fishermen in Texas landed an estimated 95.2 million pounds of fish, shrimp, crabs and oysters in 1999. Shrimp are the most valuable resource along the Texas coast, accounting for 81 percent of the harvest and 88 percent of the dockside value in 1999 (Auil-Marshalleck et al., 2001). The dockside value of the shrimp catch was worth an estimated $219 million (in 1999 dollars). The economic impact of the industry is estimated at $330 million annually, which supports 30,000 full-time jobs (Texas Center for Policy Study, 2002).

Matagorda Bay has an important role in commercial fishing among Texas bays, especially with regard to shrimp. Commercial shrimpers in the Matagorda Bay system landed one-fourth of the total shrimp catch from all Texas bays, representing 27 percent of the dockside value, on average, from 1995 to 1999. Commercial crab landings from the Matagorda Bay system accounted for about 15 percent of the statewide catch and value. Gulf landings from ports located in the Matagorda system are important to the local and state economies. Palacios and Port Lavaca have gained major port status with the National Marine Fisheries Service. Major port status is assigned to a port with more than 5 million pounds of seafood landings per year. Palacios, in particular, has consistently been classified as a major port and ranked second among Texas ports for shrimp landings in 2000.

Texas A&M University modeled economic output for several Texas bays in 1995. The A&M study estimated that the statewide impact from commercial fishing (gulf and bay) for the Matagorda system was 1,847 jobs and $71.86 million in total output (Tanyeri-Abur et al., 1998). Increases in landings and value data indicate that this impact has grown over time. For example, Palacios landings recorded 6 million pounds of seafood worth $21 million in 1995; by 2002 that number increased 15 million pounds worth nearly $31 million.

Estuaries also provide important recreational benefits. The Texas coast provides abundant opportunities for fishing, wildlife and bird watching and other nature recreation. Marsh wetlands surrounding the estuaries are vital habitat for migrating waterfowl. The U. S. Fish and Wildlife Service estimated that expenditures for wildlife-related activities in Texas were $5.4 billion in 2001 (Underwood, 2003). Fishing and other nature tourism are dependent on healthy estuaries with adequate freshwater inflow.

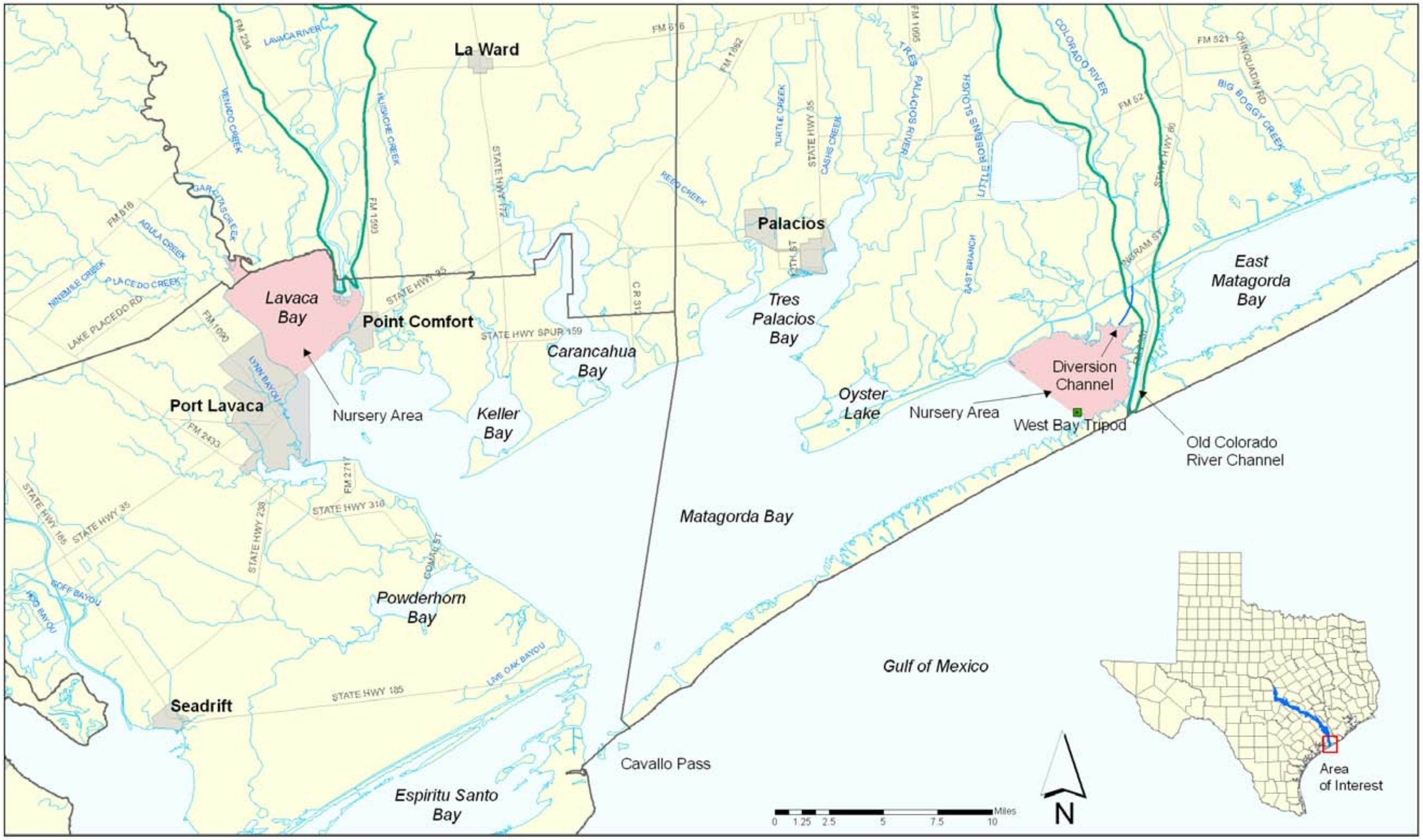


Figure 1.2 Matagorda Bay.

1.4.3 Historical Changes in Inflows

Natural as well as manmade changes have had a significant impact on the amount and pattern of freshwater inflows into Matagorda Bay. For centuries, the Colorado River emptied into Matagorda Bay, which then included what is now known as East Matagorda Bay. But tremendous floods during the past two centuries slowly created an obstacle of logs and debris that extended for several miles upstream of the mouth of the river. Several unsuccessful attempts were made to clear the log jam or build channels around it. Finally, in 1929, a great flood cleared this massive log jam and blew centuries of accumulated silt and debris into Matagorda Bay, building a new delta. This delta continued to grow until it finally cut the bay in half, separating Matagorda Bay from East Matagorda Bay (Figure 1.3). A channel was cut through this land bridge in 1935, allowing the Colorado River to flow directly to the Gulf of Mexico.

Federal maintenance of the river channel began in 1937, authorized under the U.S. Army Corps of Engineers maintenance authority for the Gulf Intracoastal Waterway (GIWW). The GIWW intersects the Colorado River just above the bay near the town of Matagorda through which some of Colorado River flow exchanges between East Matagorda Bay and Matagorda Bay. The GIWW also has affected the historical inflows to the bay, particularly from the smaller, upper bay tributaries.

In 1991, the Corps of Engineers dredged a diversion channel so that water from the Colorado River would once again flow into Matagorda Bay. The purpose of the diversion channel was to provide more freshwater inflows into the bay to reduce salinities, increase nutrient inflows and develop emergent marshlands to increase biological productivity and diversity. While emergent marshlands continue to develop, more years of data are needed to evaluate the relationship between altered flows and productivity. There is also some local concern that because of the amount of sediment being deposited, the diversion channel will cause that end of the bay to turn into a vast, shallow marshland, which will have an impact on recreational navigation and fishing (Underwood, 2003).

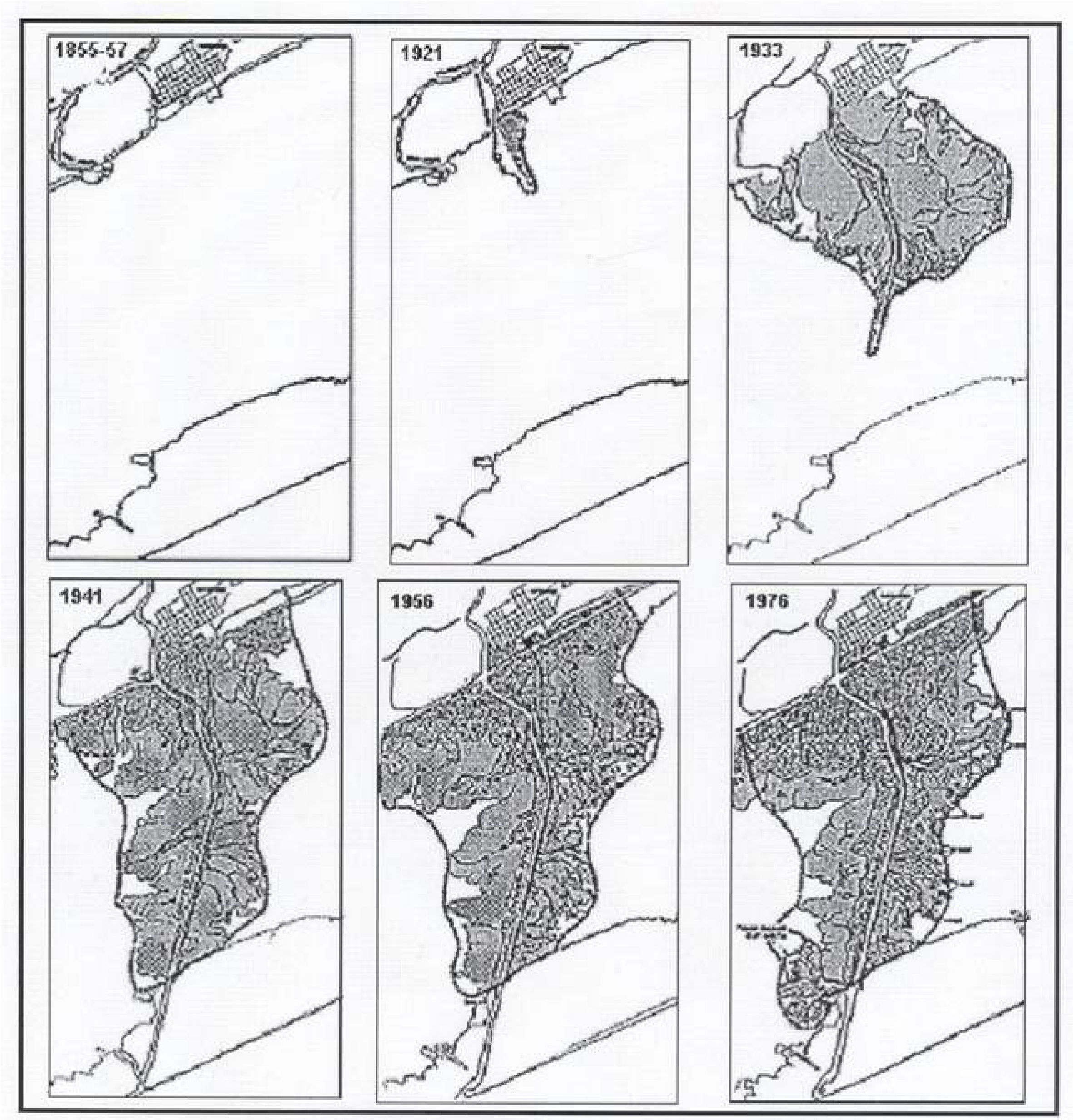


Figure 1.3 Development of Colorado River Delta[1].

1. Reference: Delta Development – Mouth of Colorado River Project Assessment Report, Coastal Technology Corporation (Adapted from USGS, Tobin & Kargl), 1980.

1.4.4 State Policy on Freshwater Inflow Needs for Bays and Estuaries

Water management in Texas has become increasingly more complex as population and economic growth continues at a rapid pace and environmental needs for water are becoming fully recognized. The use of freshwater for municipal, industrial, agricultural and other activities is often in direct competition with estuarine freshwater inflow needs. This competition of needs has generated much public interest in the water planning and permitting process over the past several decades.

Prior to the 1985 conservation and environmental amendments to the Texas Water Code, the State of Texas generally did not consider or provide for the assessment or protection of environmental water needs. Since most water rights in Texas were issued prior to 1985, most were issued without conditions for the protection of environmental water needs. In river basins that are fully or over appropriated, unused water rights and return flows are the primary sources of water for environmental flow needs, especially during dry periods. (Jordan, 1995) Therefore, a number of innovative strategies, both regulatory and non-regulatory, will be needed to fully meet environmental flow needs. Id.

In 1985 the Legislature amended Texas Water Code Section 11.147 to require consideration of freshwater inflows to bays and estuaries during water rights permitting decisions. Available studies to support these permitting decisions regarding freshwater inflows are limited. Further weight to be given to various factors in considering freshwater inflow needs during permitting decisions has been subject to considerable dispute over the appropriate environmental management goals and how water should be allocated to meet these goals while considering all other competing demands for water.

Presently, Texas law does not clearly define environmental management goals nor mandate protection of specific levels of freshwater inflows. However, state policy does require the state to "consider and provide for the freshwater inflows necessary to maintain the viability of the state's bays and estuary systems while balancing all other interests in the granting of permits" (Water Code §11.0235, enacted by SB1639). The first recognition of effects of permit issuance on estuaries came in 1975, with the passage of SB 137 by the 65th Texas Legislature. Later enactment of Texas Water Code §16.1331 requires that five percent of the firm yield of any state reservoir within 200 river miles of the coast that was built after September 1, 1985, be reserved for instream uses and estuarine inflow releases. The authorization of any new major new reservoirs will face significant challenges because of cost, environmental issues, lack of appropriate sites and availability of sufficient, unappropriated water. Id. In addition, for new water use permits within 200 river miles of the coast, “the commission shall include in the permit to the extent practicable when considering all public interests and the studies mandated [by law], those conditions considered necessary to maintain beneficial inflows to any affected bay and estuary system.” (Texas Water Code §11.147, 1985)

It is relatively easy to quantify the water needs for municipal, industrial, agricultural and other human uses of water. However, the influence of water on the complex interactions in estuaries is difficult to quantify. To more fully understand the implications of changes in freshwater inflows to estuarine ecosystems, state and federal agencies began studies of Texas’ bays and estuaries in the 1960s.

In 1985, the Texas Legislature directed TPWD and TWDB to continue studies of the estuaries and determine sufficient information so that the need for freshwater inflows to the estuaries could be considered in the allocation of the state’s water resources. These studies originally were to be completed by December 31, 1989. However, due to funding reductions, changes in priorities, the complexity of estuarine systems not fully understood at this time, and other factors, they were significantly delayed.

LCRA's ability to more effectively manage the Highland Lakes to meet the region's existing and future water needs, including the protection of environmental flow needs, was directly affected by the delay in completing these studies. LCRA was required by the Texas Water Commission, a predecessor of the TCEQ, to seek amendments to the LCRA Water Management Plan for its lakes Buchanan and Travis water rights to consider freshwater inflow needs of the Matagorda Bay from the Colorado River. Thus, establishing the freshwater inflow needs from the Colorado River is vital to LCRA's management of its lakes Buchanan and Travis water rights in the Colorado River basin for all beneficial purposes. LCRA is aware of its responsibilities in meeting competing water needs all along the river so that the Matagorda Bay system will receive adequate freshwater inflows and continue to be productive in its natural role.

1.4.5 The 1997 Matagorda Bay Freshwater Inflow Needs Study

To expedite the state's freshwater inflow needs study of the Matagorda Bay system, and to comply with requirements of its water rights, LCRA entered into a cooperative agreement with TPWD, TWDB and the Texas Natural Resource Conservation Commission (TNRCC) (a predecessor agency to the TCEQ) in 1993 to initiate a freshwater inflow needs study for Matagorda Bay. In 1997, the cooperating agencies (LCRA, TWDB, TNRCC, TPWD, and LNRA) completed their study of freshwater inflow needs of the Matagorda Bay system pursuant to the Memorandum of Agreement, the results of which are contained in a report titled, "Freshwater Inflow Needs of Matagorda Bay." In the study, LCRA adapted existing methods used by the TPWD and TWDB and applied those methods to estimate freshwater inflow needs for the estuary. The participating state agencies provided timely technical assistance to LCRA in completing the study.

The 1997 study focused on the estuary west of the Colorado River (Matagorda Bay) in quantifying the freshwater inflow needed from the Colorado and Lavaca rivers and adjacent coastal basins. To the extent possible, the impact of freshwater inflows on the environmental conditions in East Matagorda Bay was to be evaluated; however, full analysis of East Matagorda Bay was contingent on adequate external funding and sufficient additional data. The results of the study were subsequently considered during the 1999 revisions to the LCRA Water Management Plan.

Two freshwater inflow needs (FIN) were identified in the 1997 study – the "Target" freshwater inflow need, based on application of the State Methodology, and the "Critical" freshwater inflow need. The Target FIN seeks to optimize selected estuarine species productivity within various hydrological and biological constraints; the Critical FIN is intended to provide a fishery sanctuary habitat during the most severe drought from which finfish and shellfish species could be expected to recover and repopulate the bay when more normal weather conditions return.

At the time of the 1997 study, the use of a Critical inflow management strategy was a pioneering concept not yet generally adopted by the state. The purpose of this strategy was to balance the impacts of environmental water needs with other competing demands for water during times of water shortage. Also, the Target flow cannot always be met, even in the naturalized flow time series. The Critical FIN for Matagorda Bay was based on maintaining a salinity level of 25 ppt in an area of the bay (at the West Bay Tripod) near the mouth of the diversion channel from the Colorado River into Matagorda Bay (Figure 1.2). The area of this refuge is approximately 10,000 acres. The Critical salinity value was chosen to protect oysters, a commercially important species in Matagorda Bay, from the significant predation and mortality from parasites that occurs when salinities exceed 25 ppt and other conditions such as higher temperatures are present (Chu and La Peyre, 1993; King, 1989; Shumway, 1996). This salinity level was also chosen because oysters are stationary and cannot migrate in response to salinity changes. This salinity level is also an approximate dividing line between brackish water needed for bay species life cycle events and more saline marine water. Juveniles of other species are less tolerant to elevated salinity but are mobile and can move to less saline areas such as the mouths of rivers and creeks.

The salinity reference location for the oyster reefs is at the West Bay Tripod, 3.5 miles from the delta of the Colorado River near the southern shoreline (Figure 2.2), and almost as far away from the nearest oyster reefs which lie along the northern shoreline. The West Bay Tripod and the nearest oyster reefs are nearly equidistant from the river mouth. Inflow regression equations were used to estimate the inflows necessary to maintain desired salinity levels at the West Bay Tripod, and by implication, at the oyster reefs.

A salinity measuring device for the Lavaca River delta was also attached to an existing structure (Port Lavaca Causeway) located approximately 3 miles from the delta of the Lavaca River. The Lavaca River refuge or sanctuary encompasses about 13,000 acres. Including the Colorado River delta refuge area (10,000 acres), the total available refuge area is about 10 percent of the 353 square mile area within the Matagorda Bay estuary.

The 1997 report identified a number of areas that needed further study to verify the processes used and to develop improved relationships between freshwater inflows and important indicators of estuarine conditions. These included collection of more salinity data, re-examination of the salinity-inflow equations, and continued collection of secondary productivity data. These are addressed in this updated study. The 1997 report also called for more information/data collection on nutrients (related to primary productivity, benthic dynamics) and additional studies of sedimentation needs of Lavaca Bay and East Matagorda Bay. Efforts to obtain additional data through partnerships between the study agencies, federal agencies and academic institutions will continue to be undertaken.

1.4.6 The 2001 LCRA Water Management Plan Revision Stakeholder Group

During the LCRA Water Management Plan revision process[2] in 2001, some members of the Water Management Plan Stakeholder Group believed that LCRA should adopt a revised Critical FIN (36,700 acre-feet per month) to reflect the revised salinity-inflow relationship that was developed based on additional data gathered since the 1997 study. However, other stakeholders voiced concerns over adopting a new Critical freshwater inflow needs figure, raising questions about the methodology and the potential impacts of how such needs might be addressed in light of other competing demands for water. After considering this stakeholder input, LCRA technical staff identified eight specific concerns with adopting new FIN criteria, including:

1. Drought bias in the Colorado River salinity-inflow equation data set;
2. The need to update the Lavaca River inflow salinity equation;
3. The need to update the productivity equations for the nine target species;
4. The need to update the relationships between inflows from the Colorado River, Lavaca-Navidad River system, and ungaged flows (such as those entering the bay system through runoff from the irrigation districts);
5. The need to update the hydrodynamic model to account for sedimentation in the bay;
6. The need to factor in nutrients and algal production;
7. The location of the salinity measuring location relative to the stream gage; and
8. The need to consider other variables that may affect salinity such as water depth, wind and tidal flux.

2 The WMP revision process began in 2001. The LCRA Board accepted staff's recommendations regarding the WMP revision in 2002. The revised WMP was submitted to the TCEQ in 2003.

Given these concerns, in its March 13, 2002, memo to the LCRA Board of Directors relating to recommended changes to the Water Management Plan, LCRA staff recommended against any revisions at that time to the WMP based on new salinity-inflow calculations. In its memo, staff explained there were significantly more issues to be considered besides a single salinity threshold. The memo stated that the 1997 FIN study used a very preliminary salinity limit of 25 ppt as the critical threshold value based solely on limited information about oyster impacts. "It was never recognized as being a rigorous biological criterion for achieving conditions that would be truly critical for all the key plant and animal species in the bay near the mouth of the river." The memo also stated that there was a clear intent to develop a much more complete set of criterion whenever the study was revised in the future. "To revise the critical FIN now using only the improved salinity-inflow relationship would be an incomplete revision. Such a revision would not produce accurate freshwater inflow needs." The memo further recommended that developing the improved criteria for critical inflow needs could be a part of the revision of the 1997 FIN study. The memo adds that the TPWD, TNRCC and TWDB had expressed an interest in working with LCRA to revise the study.

As a result, the LCRA Board accepted staff's recommendation to maintain the existing Critical and Target FIN values contained in the 1999 Water Management Plan but to continue to refine the inflow reassessments. The Board also moved forward to incorporate a new Intermediate flow regime into the proposed Water Management Plan to ease the transition between Target inflows and Critical inflows. The proposed plan calls for Intermediate flows of 1.5 times the Critical inflow when storage in the Highland Lakes is between 50% and 80% of capacity on January 1. The LCRA Board also directed staff to conduct a comprehensive review and update of the 1997 FIN study with the assistance of the three state resource agencies. Updates based on new data and information collected since 1997 were to address all but item (5) of the eight specific concerns identified by LCRA staff and the Water Management Plan Revision Stakeholders Group. However, little additional data that may facilitate inclusion of nutrients and algal production, as suggested in item (6), has been collected in Matagorda Bay. Finally, additional information that might be useful in setting somewhat less arbitrary Intermediate flow goals and criteria is presented in this study for consideration in future revisions of the Water Management Plan.

1.4.7 Initiation of the Current Study

The 2002 MOA (Appendix A) between the LCRA, TPWD, TWDB, and TCEQ was entered into as a result of LCRA Board direction to work with the three agencies to review and revise the 1997 study. Using additional data and developing the appropriate biological criteria and resulting Critical and Target inflow needs to the bay are among the expressed objectives outlined in the MOA.

The MOA also provides that LCRA will adapt "or modify" existing methods to compute updated freshwater inflow needs. The scope of work attached to the MOA also provides that LCRA will use state optimization models including TXEMP and TXBLEND "or alternative methods if deemed appropriate" to compute monthly and seasonal inflow needs. If any party to the MOA disagrees with the final draft report, the MOA provides that LCRA must include a rebuttal statement in the final report. Also, there will be no recommendations in the draft or final report unless there is unanimous agreement among the four agencies.

To the extent the four agencies consider it appropriate based on the findings of the study, LCRA agrees under the MOA to initiate a process for amending its Water Management Plan within six months of completion of the study. However, the MOA does not prescribe whether or how the LCRA would revise the Water Management Plan in response to the results of the study and how any revised freshwater inflow needs should be balanced with other water demands. Under the MOA, the study is not intended to replace the requirements of the state agencies under Texas Water Code §11.1491, but it may be used to fulfill such provisions under this statute.

The MOA set up an advisory committee composed of representatives from each of the participating agencies with the LCRA representative serving as chair. Meetings of the advisory committee were held quarterly and were open to the public, with notice and opportunity for public comment provided. The committee also held several public stakeholder meetings to discuss the data, methods, status and results of the study and to receive comment.

1.4.8 SB 1639 Study Commission on Water for Environmental Flows

Since the initiation of this revision of the 1997 study, a number of events have occurred that could affect the use of the study results. In 2003, the 78th Texas Legislature passed Senate Bill 1639 establishing a Study Commission on Water for Environmental Flows (Study Commission). The primary goal of the Study Commission was to identify and evaluate options for providing adequate environmental flows and ways to consider environmental water needs in the state's water allocation process. SB 1639 also directed the 15-member Study Commission to conduct public hearings and study public policy implications for balancing the demands on the water resources of the state resulting from a growing population with the requirements of the riverine, bay and estuary systems.

In addition, the Study Commission was directed to evaluate granting permits for instream flows for bay and estuaries dedicated to environmental needs, of the Texas Water Trust, and any other issues that the Study Commission determined to have importance and relevance to the protection of environmental flows. In evaluating the options for providing adequate environmental flows, the Study Commission was directed to take notice of a strong public policy imperative recognizing that maintaining the biological soundness of the state's rivers, lakes, bays and estuaries is of great importance to the public's economic health and general well-being. The Study Commission was also directed to specifically address ways that the ecological soundness of these systems will be effectively addressed in the water allocation process.

The Study Commission appointed a Science Advisory Committee (SAC) to assist the commission in developing technical recommendations on the science and methodology of determining environmental flow needs. As a part of its activities, the SAC performed a peer review of the state methodology, including the use of TXEMP and TXBLEND models. That report was submitted to the Study Commission on October 26, 2004. The Study Commission submitted a report with its recommendations to the Texas Legislature in December 2004.

While recognizing that the State of Texas has pioneered tools to address freshwater inflow needs, the Study Commission's report pointed out limitations to the tools in light of both scientific and public policy evolution. In its report, the Study Commission identified several criticisms of the State Methodology identified by the SAC including:

- Over-reliance on target species abundance rather than an overall sound ecological environment;
- Use of or over- reliance on commercial harvest data rather than independent fisheries data;
- Questionable statistical methods, regression forms and definition of independent variables;
- Optimum flows determined by arbitrary constraints;
- Poor correlations between optimum solutions and harvest data;
- Optimum patterns did not occur in the natural hydrology;
- TPWD verification process is biased toward optimum solutions by comparing Min Q and Max H; and
- Absence of dry year viability flows

The Study Commission's report also recommended an "adaptive management" approach when adjustments to identifying or meeting environmental needs are made as new information and better science becomes available and endorsed the use of a peer review process and stakeholder involvement. LCRA is unique in the State of Texas in using an adaptive management approach in the periodic review and revision of its Water Management Plan. LCRA is also the only water right holder in the lower Colorado River basin that has specifically committed water for the protection of environmental water needs.

Some of the shortcomings of the State Methodology identified by the Study Commission are addressed in this revision of the 1997 Matagorda Bay FINS. For example, the current FINS update uses TPWD independent fisheries data rather than commercial harvest data. In addition, the constraints for Target flows were widened to allow more latitude with model runs and simulations. Also, dry year viability flows are addressed using the Critical FINS management strategy. LCRA also used an "adaptive management" approach and a substantial stakeholder involvement process with peer review by the state resource agencies and outside commenters. However, other concerns raised by the Study Commission are still applicable here.

1.4.9 Legislative Response to the Study Commission Report

In partial response to the Study Commission report, Senate Bill 3, authored by State Senator Kenneth Armbrister, chairman of the Senate Natural Resources Committee, was introduced during the regular session of the 79th Texas Legislature in 2005. Although it did not pass, the bill contained a legislative finding that "… while the state has pioneered tools to address freshwater inflow needs for bays and estuaries, there are limitations to those tools in light of both scientific and public policy evolution. To fully address bay and estuary environmental flow issues, the foundation work accomplished by the state should be improved." The bill went on to propose the establishment of an Environmental Flows Commission, assisted by a Texas Environmental Flows Science Advisory Committee as well as bay stakeholder groups and science advisory teams, to assess the current methodologies and tools and to develop environmental flow regime recommendations to be submitted to TCEQ for adoption and use in water right permitting. A similar bill, SB 15, was re-introduced by Senator Armbrister during the special legislative session called in June 2005. A companion bill, HB40, was filed in the House by State Representative Robert Puente, chairman of the House Committee on Natural Resources. However, these bills were outside the governor's call for the special session and no final action was taken on either bill. State resource agencies are currently reviewing the Study Commission report to determine what may be carried forward under SB 3 within their existing authorizations and budgets and in consultation with the State's legislative and executive leadership.

1.4.10 The Bay Health Study of the LCRA-SAWS Water Project

In 2002, LCRA and the San Antonio Water System (SAWS) entered into an agreement to study the feasibility of the LCRA-SAWS Water Project. The purpose of the LCRA-SAWS Water Project (LSWP) is to help satisfy long-term water needs in both the lower Colorado River basin and the San Antonio area while ensuring good stewardship of the environment. The project would conserve and develop up to 330,000 acre-feet of water per year. Of that, approximately 180,000 acre-feet per year of agricultural and other rural water needs would be met in the Colorado River basin through conservation of agricultural irrigation water, storage of river water, and supplemental groundwater for agricultural use. Up to 150,000 acre-feet per year of river water would be transferred to the San Antonio area for the term of the agreement. Groundwater would not be transferred to San Antonio as part of the Project. The cost of studying, designing, constructing and implementing the project would be paid by SAWS.

The studies for the project must address a number of legislative requirements to protect the interests and environmental needs of the lower Colorado River basin. They are contained in HB 1639 (77th Tex. Leg. 2001). The approaches for the studies were developed during a public process in 2002 and 2003. Following approval of the study period plan by the LCRA and SAWS boards, studies began in July 2004 to address key issues associated with the project. These issues include water quality, potential environmental effects, cost and implementation of conservation and water supply development methods. During the study period, the water supply potential, construction and operational costs and environmental effects of the proposal will be continually refined and evaluated.

The principal charge for the Matagorda Bay Health Evaluation component of the project is to assess the environmental effects that could result from changes in inflow patterns to the Matagorda Bay system. The study is to respond directly to the requirement in Section 222.030(n)(3) of the Texas Water Code, which codifies the LCRA Act, to "ensure that beneficial inflows remaining after any water diversions will be adequate to maintain the ecological health and productivity of the Matagorda Bay system." The LCRA Act further charges that the analyses use the best science available.

A Framework for Assessing Bay Health has been developed for the LSWP to guide the bay study and help provide answers to how bay health will be maintained after the project. The framework approaches bay health by focusing on three components: inflows and how they will be altered by LSWP; habitat, including salinity, vegetation, substrate and other components; and biology, which will attempt to link changes in inflow and habitat to biological changes. This approach focuses on the different functions of various parts of the bay (open bay, secondary bays, marshlands, deltas) to better determine how they might be impacted by varying inflows. The Bay Health Framework is shown in Figure 1.4.

The State Methodology and the framework are dealing with similar issues, namely bay health and productivity; however, the two approaches are designed to answer fundamentally different questions.

The framework directs a set of studies that will determine the health and productivity of Matagorda Bay today, as well as projecting what the health of the bay will be in the future, both with and without LSWP and in particular during suboptimal inflow conditions.

In contrast, the State Methodology was designed to determine the freshwater inflow patterns needed to optimize the productivity of the entire bay complex. A substantial amount of resources has been expended over the past ten years in applying the State Methodology to Matagorda Bay. Numerous insights about the bay have been developed as a result of those efforts. However, the State's optimization TXEMP (Texas Estuarine Mathematical Programming) model was not developed to answer the questions posed by the Project about the future health of the bay, and, therefore, may not be well-suited to answer the questions that the legislative mandate requires be addressed. The impact of the LSWP on the bay will most likely result from reduced freshwater inflows during higher inflow conditions, and/or changes in the timing of inflows. However, the quantification of such potential impacts and the environmental mitigation measures that would result to address any adverse environmental impacts are unknown at this time. Because the State Methodology cannot be readily adapted to assess the potential impacts on bay productivity resulting from such changed conditions, the framework was developed to help assess these impacts while building on the knowledge gained from prior and ongoing applications of the State Methodology to the Matagorda Bay system.

The framework is centered on an understanding of three primary elements: namely, inflow and modifications thereof, habitat, and biology. Said another way, the route to understanding and quantifying potential environmental effects on the bay system starts with a "driver"—Inflow, which could be affected by the project; continues with an understanding of the effect that inflow changes could have on bay physical, chemical and biological/vegetative makeup (habitat); and concludes with the potential changes in the biology of the bay system. This multi-faceted approach characterizes inter-related elements of the health of the bay, which collectively provide a basis for measuring overall bay health.

It is important to note that inflow is certainly not the sole driver of conditions in the bay. Many other factors, some controllable and others not, are potential drivers of bay health, and will be accounted for insofar as possible in the evaluation. The major components of the proposed approach are summarized below.

- Habitat provides a powerful framework for viewing the health of the ecosystem.
- Salinity is a fundamental component of habitat, along with many other factors.
- Salinity is driven largely by changes in freshwater inflow, and will be investigated using a hydrodynamic/salinity model.
- The framework also provides for improved understanding of direct relationships between inflow and species productivity and benthic diversity.

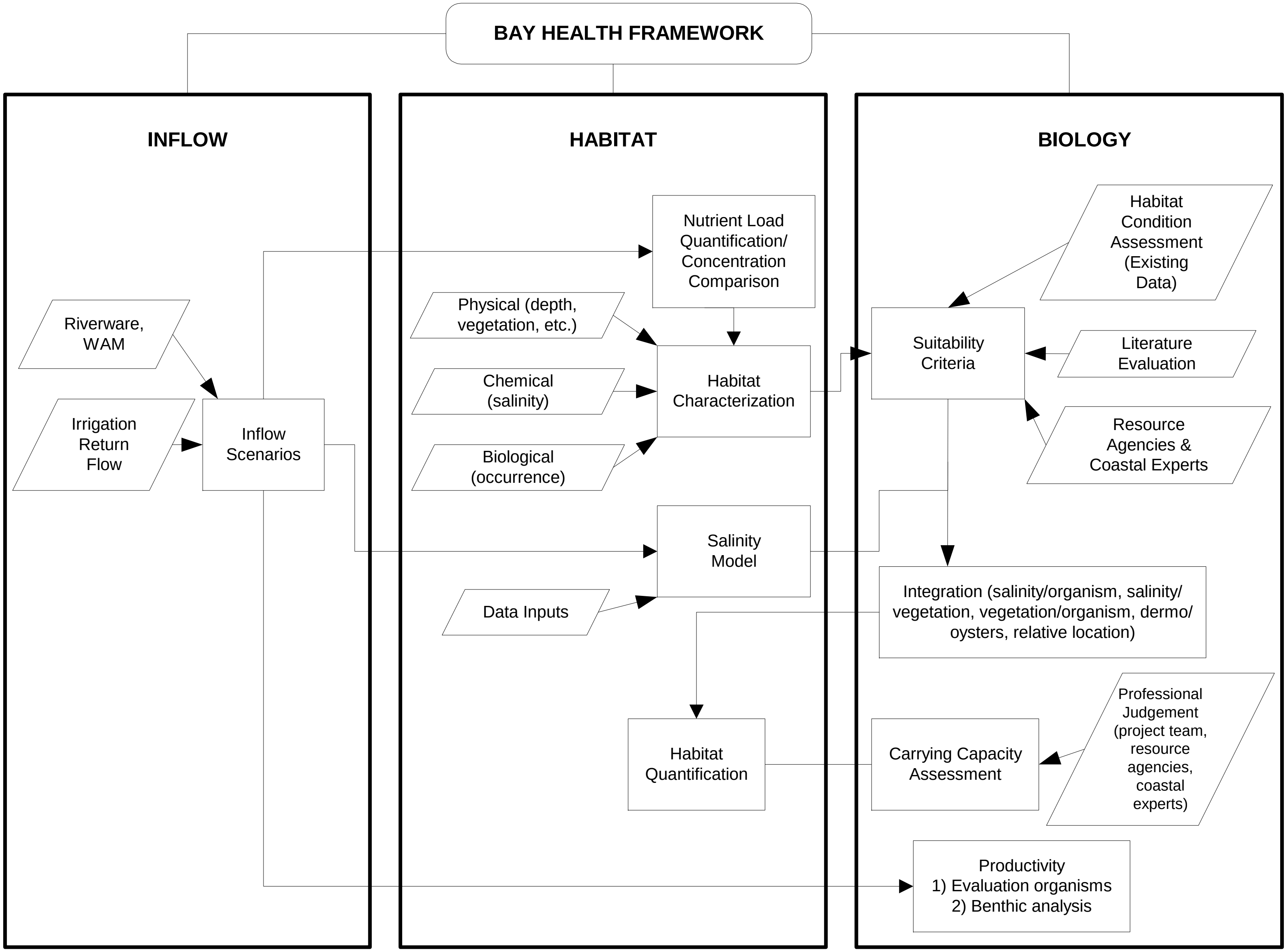


Figure 1.4 Bay Health Framework

The LSWP Matagorda Bay Health Evaluation is expected to be completed in 2007.

1.4.11 Recent Modeling Efforts by U.S. Army Corps of Engineers

The U.S. Army Corps of Engineers Research and Development Center (ERDC), Waterways Experiment Station (WES), recently completed the development of a hydrodynamic model for the Matagorda Bay area (Brown et al., 2003). The model was developed to help the Corps' Galveston District evaluate the effects associated with the potential reopening of Parker's Cut in Matagorda Bay and a potential new opening of Southwest Cut in East Matagorda Bay on currents, salinity and sediment changes. The focus of the model study was to determine if opening any or all of the cuts would improve navigation at the intersection of the Gulf Intracoastal Waterway (GIWW) and the Mouth of Colorado River bypass channel. Local interest groups also recently proposed that a number of other changes be made to the Mouth of Colorado River Project. The model was used to evaluate the existing system configuration and eleven proposed configuration designs to look into alleviating the navigation problems encountered at the intersection of GIWW and the Colorado River. The study included various data collection efforts, including a bathymetric survey of the immediate study area.

At about the same time, the Corps's Galveston District also undertook a modeling study of the Colorado River regarding the jetties, Parker's Cut and Southwest Cut (Kraus et al., 2000). The focus of this regional model study was more on circulation and navigation safety – to help with dredging operations, than on salinity. Multiple alternatives were evaluated in this modeling effort.

The Corps will likely base its decision to make changes to the various navigation cuts by addressing the navigation/transportation and economic benefits for this complex estuarine environment.

1.4.12 Review of State Methodology

As discussed earlier, the Science Advisory Committee of the SB 1639 Study Commission on Water for Environmental Flows has recommended improvements to the state's freshwater inflow methodology and models, which was reflected in the Study Commission's report to the Texas Legislature. A number of these recommendations have been incorporated in this study.

In its evaluation of 27 available hydrodynamic/salinity models including the state TXBLEND model, the LCRA-SAWS Project's Ecological Health Study Group recommended that the U.S. Army Corps of Engineers RMA suite of models be used. TXBLEND was dropped because it did not have the capability to model non-conservative constituents such as organic matter or nutrients.

1.5 Conclusion

This FINS study is intended to be part of an iterative process. When better information and methods become available, this study will also be updated. The USACE diversion channel into West Matagorda Bay, completed in 1991, significantly changed the ecological condition of the bay. Only a relatively short period of time has passed to collect and assess data to determine the impacts created by the channel.

Additional factors other than salinity that explicitly relate to overall biological productivity such as the location and quality of suitable physical habitat are not fully addressed in this study and may need to be further assessed in determining the amount, location and timing of freshwater inflows to effectively maintain and protect the overall ecological health of the bay. The recent example of Nueces Bay — where inflows were redirected to important upper bay marsh areas rather than simply increased to the bay proper, resulting in increased biological productivity (Bureau of Reclamation, 2000) — may provide lessons that can be applied to Matagorda Bay.

A comprehensive assessment of factors that may affect the overall ecological health of the bay is currently being conducted as a part of the LCRA-SAWS Project feasibility studies. The LCRA-SAWS studies should be considered together with the current Matagorda Bay freshwater inflow needs study (FINS) when making future water management decisions. In addition, the models and methodology used to assess freshwater inflow needs are currently being re-evaluated in the State of Texas.

Finally, models can predict only what may happen. In reality, only the passage of many years will enable us to see how changes of freshwater inflows may affect the bay. Like all coastal systems, Matagorda Bay's productivity is the result of extremely complex hydrological, meteorological and biological interactions that are not yet fully understood.

CHAPTER 2

Hydrologic Characteristics of Matagorda Bay

2.1 Purpose

This chapter describes the sources and statistical characteristics of inflow for Matagorda Bay. Total surface inflow is the sum of the inflows entering into Matagorda Bay from the Colorado River basin, Colorado-Lavaca coastal basin, Lavaca River basin, and Lavaca-Guadalupe coastal basin. In this study, total surface inflow is separated into two broad categories – river basin inflows and coastal inflow.

Total surface inflow estimates were obtained from the Texas Water Development Board's (TWDB) Coastal Hydrology database. This database has monthly total surface inflow estimates for the period January 1941 through December 2000. TWDB also has calculated daily inflow estimates for the period January 1, 1977 through December 31, 2003. This study used a combination of the TWDB's data sets, monthly inflow estimates for the period January 1941 though December 1976 and daily inflow estimates for the period January 1, 1977 through December 31, 2003. In these daily and monthly estimates of total surface inflow to Matagorda Bay, the portion from the Colorado River basin prior to June 1990 was based on a method developed by a predecessor agency to the TWDB (Texas Department of Water Resources, 1978).

River basin inflows for Matagorda Bay are estimated using gaged streamflows from the Colorado River basin and Lavaca River basin. Sources of data for gaged streamflows are the United States Geological Survey (USGS) and the Lavaca-Navidad River Authority (LNRA). In the Colorado River basin prior to June 1990, estimated inflow is based on a method of determining the inflow to Matagorda Bay based on gaged streamflow of the Colorado River at Bay City (TDWR, 1978). Beginning in June 1990, estimated Colorado River basin inflow is calculated as gaged streamflow for the Colorado River at Bay City minus diversions at the South Texas Project which is located downstream of the Bay City gage. The streamflow data for the Lavaca River measured by USGS and the streamflow for the Navidad River measured by USGS and LNRA are added together and used directly as estimated Lavaca River basin inflow to Matagorda Bay.

Coastal inflow is calculated in this study as the difference between the total surface inflow and the river basin inflows calculated in this study. The resulting coastal inflow includes gaged and unmeasured streamflows from the Colorado-Lavaca and the Lavaca-Guadalupe coastal basins and unmeasured streamflows from areas of the Colorado River basin and the Lavaca River basin downstream of the USGS and LNRA gage locations (Figure 2.1).

Inflows developed in this chapter are the basis for development of nutrient budgets, development of inflow-salinity and inflow-productivity relationships, development of constraints in TXEMP and calibration and execution of TXBLEND in later chapters of this report. Descriptions of how these data are used are listed in the subsequent chapters.

Future monitoring of meeting freshwater inflow needs would be simplified by using streamflow at commonly measured locations, such as USGS streamflow gages. For this reason, the salinity regression equations described later in this report use estimates of river basin inflows based on gaged streamflow from the Colorado River basin and Lavaca River basin. Since the primary sources of inflow are the Colorado River basin and the Lavaca River basin, the biological productivity regression equations described later in this report also use the estimates of river basin inflows. These regression equations do not explicitly include the other sources of inflow, the unmeasured portions of the river basins and all of the two coastal basins. The decision to use only the river basin inflows for the biological equations was made very early in the study and was agreed to by the cooperating agencies at that time. A significant factor in that decision was that at the beginning of the study, TWDB did not have values for the inflows for the last couple of years. This differs from the 1997 study in which these coastal inflows were explicitly included in the development of the biological productivity regression equations. Omission of the coastal inflow adds some degree of uncertainty to the equations.

2.2 Study Area

The study area for this report includes Matagorda Bay and its secondary and tertiary bays (hereafter referred to simply as Matagorda Bay), as shown in Figure 2.1. The largest sources of freshwater inflow to Matagorda Bay are the Colorado River basin and Lavaca River basin, which includes the Navidad River as a major tributary. Inflow to the bay also comes from the

Colorado-Lavaca coastal basin, with the Tres Palacios River as the major stream, and the Lavaca-Guadalupe coastal basin, with Placedo Creek and Garcitas Creek as major streams (Figure 2.1). There are also a large number of smaller ungaged creeks and streams that feed into the upper bay and marsh areas that provide a nursery and refuge for many species.

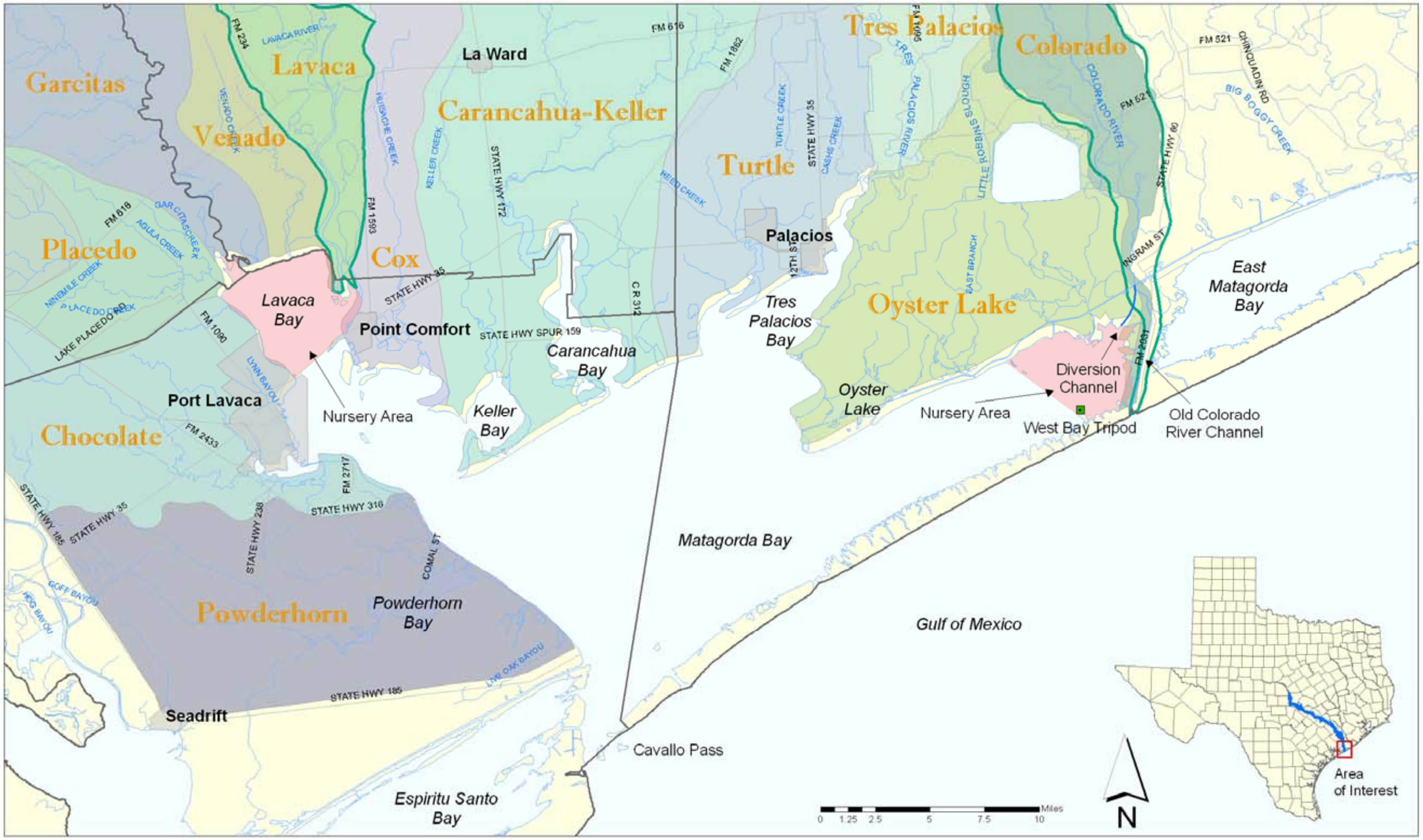


Figure 2.1 Colorado and Lavaca River Basins and Adjacent Coastal Basins.

2.3 Historical Changes

The hydrology of the Matagorda Bay system has undergone major changes. Over the years, log jams have historically occurred on the Colorado River, some of which have extended over many miles in length. Observers in the early 1800s noted an immense log jam that choked the mouth of the river and backed water for miles inland, restricting and diffusing inflows to the bay. Several unsuccessful attempts were made to remove the log jams or to build channels around them. But by 1928, the log jam was 40 miles long. Finally, in 1929, a great flood burst through this log jam and swept centuries of accumulated debris and silt into Matagorda Bay. This created a new peninsula out into the bay that eventually grew into a land bridge reaching to Matagorda Island, effectively cutting Matagorda Bay in half. After the land bridge occurred, some of the freshwater inflow dispersed laterally into the bisected bay and some into the Gulf of Mexico. Then, in 1935, a channel through this land bridge was cut connecting the Colorado River directly to the Gulf of Mexico. This was done to assist navigational access to the Gulf and relieve flooding. The cut, known as Parker's Cut, from the river channel westward to Matagorda Bay was made to allow better access to the oyster reefs in the bay.

Federal maintenance of the river channel near the bay began in 1937, authorized under the U.S. Army Corps of Engineers maintenance authority for the Gulf Intracoastal Waterway (GIWW). The GIWW intersects the Colorado River just above the bay and runs along the upper bay affecting the way inflows had historically entered the bay, especially from the smaller, upper bay tributaries.

The paragraph below describes the pre-diversion project condition, from page IV-1 of TDWR (1978). Tiger Island Cut is also referred to as Parker's Cut.

> *The flow routing and exchange patterns within the Colorado Delta are complex and result from the interaction of two land locked bay tides (both of which are affected by wind stresses), the Gulf of Mexico tide, and the various freshwater inflow patterns of the Colorado River. The avenues of difluence and circulation within the system include the GIWW at Matagorda, Culver Cut between the GIWW and Matagorda Bay, and Tiger Island Cut between the*

Colorado River and Matagorda Bay, as well as the junction of the Colorado River and the Gulf of Mexico. With so many interrelated components, the Colorado Delta represents an extremely complex system with respect to simulation model application.

However, the river channel significantly reduced any remaining inflows into the bay and by the 1970s, the bay's fisheries were suffering. In 1991, about ten years after the Corps of Engineers completed its studies, the Colorado River again flowed into Matagorda Bay through a new diversion channel dredged by the Corps. Many of the anticipated effects of the diversion channel included the increase of freshwater into the bay with resulting beneficial impacts to bay productivity and marsh habitat. Parker's Cut was also closed to prevent freshwater from flowing out of the bay or allowing higher salinity Gulf waters from entering the bay.

2.4 Freshwater Inflows

The following sections describe the methods and data used to determine the total surface inflow to Matagorda Bay, including river basin inflows and coastal basin inflow are described.

2.4.1 Total Surface Inflow

Monthly Total Surface Inflow

TWDB's calculation method for total surface inflow, including streamflow and runoff from all sources, is described below:

Freshwater inflow comes primarily from precipitation over each estuary's drainage basin. Runoff enters streams and rivers, makes its way to the mouth of each watershed, and eventually reaches the estuary. Along the way, some water is diverted for man's use. Diverted water that is not consumed can be returned to the streams.

Flow from larger watersheds and important rivers is monitored by United States Geological Survey (USGS) stream gages. USGS stream gages have historically been located far upstream from the estuary to remove them from the influence of tidal variations in flow and water level.

Downstream of these gages, between the gage and the point where the stream meets the estuary, streamflow is ungaged. In some estuaries, significant runoff originates in these ungaged areas.

Total flow from drainage basin runoff is found by summing flows originating in both gaged and ungaged watersheds. Gaged flows are obtained from USGS streamflow records. Ungaged runoff is the sum of i) computed runoff, using a rainfall-runoff simulation model, based on precipitation over the watershed, ii) flow diverted from streams by municipal, industrial, agricultural, and other users, and iii) unconsumed flow returned to streams.

Thus, total surface inflow reaching the estuary consists of:

Surface Inflow = (1) Sum over all gaged watersheds(USGS Gaged Flow)
+ (2) Sum over all ungaged watersheds(Modeled Flow)
- (3) Sum over all ungaged watersheds(Diverted Flow)
+ (4) Sum over all ungaged watersheds(Returned Flow)[1]

Monthly time series for categories (1) through (4) and for total surface inflow were obtained from the TWDB website for the period 1941 through 2000.

Daily Watershed Surface Inflows

TWDB also calculated more detailed information for the period 1977 through 2003. This consists of daily estimates of surface inflow for each of the 11 watersheds that comprise the total surface inflow to the Matagorda Bay for the period January 1, 1977 through December 31, 2003. The watersheds and their estimated annual average inflow (acre-feet per year, rounded to nearest hundred) for this period are listed below in Table 2.1.

[1] www.twdb.state.tx.us

Table 2.1 Annual Average Flow for 1977-2003 from Watersheds of Matagorda Bay.

Watershed	Annual Average Inflow (ac-ft/year)
Colorado	1,856,200
Oyster Lake	127,500
Tres Palacios	197,600
Turtle Bay	95,500
Carancahua Bay	227,500
Keller Bay	43,800
Cox Bay	40,000
Lavaca Delta	1,066,300
Garcitas Creek	254,400
Chocolate Bay	96,600
Powderhorn Lake	105,900
Total	4,111,300

The monthly and daily data sets have the period 1977 through 2000 in common. The annual average of the monthly total surface inflow for the period from 1977 to 2000 is 4,086,000 acre-feet per year. The annual average of the sum of 11 daily watershed surface inflows for the period from 1977 to 2000 is 4,089,000 acre-feet per year. The very small difference between this average and the corresponding value from the monthly data indicates that the same method was used in these calculations.

The total surface inflow data set used for the analyses in this report is the compilation of the monthly total surface inflow for the period from 1941 to 1976 and the sum of 11 daily watershed surface inflows for the period from 1977 through 2003. Annual total surface inflow for each year is listed in Table 2.2. The annual average for this entire period from 1941 through 2003 is 3,444,000 acre-feet per year.

Table 2.2 Estimated Annual Inflows to Matagorda Bay (acre-feet).

Calendar Year	Total Surface Inflow to Matagorda Bay (TWDB estimates)	Colorado River Basin Inflow*	Lavaca River Basin Inflow (USGS gage and LNRA data)	Coastal Inflow = Total Surface Inflow to Matagorda Bay - Colorado River Inflow – Lavaca River Inflow
1941	6,726,000	3,632,000	1,704,000	1,390,000
1942	2,674,000	1,445,000	540,000	689,000
1943	1,798,000	1,266,000	315,000	217,000
1944	3,937,000	1,740,000	906,000	1,291,000
1945	3,133,000	1,959,000	461,000	712,000
1946	4,682,000	2,139,000	1,207,000	1,336,000
1947	2,039,000	1,332,000	395,000	312,000
1948	1,364,000	600,000	313,000	452,000
1949	3,157,000	1,152,000	667,000	1,338,000
1950	1,317,000	892,000	220,000	205,000
1951	838,000	398,000	168,000	273,000
1952	1,381,000	435,000	497,000	449,000
1953	1,887,000	750,000	363,000	774,000
1954	441,000	274,000	31,000	136,000
1955	1,214,000	820,000	269,000	125,000
1956	448,000	301,000	24,000	123,000
1957	5,794,000	3,833,000	1,279,000	682,000
1958	3,582,000	2,334,000	597,000	651,000
1959	4,076,000	1,963,000	972,000	1,141,000
1960	5,990,000	2,358,000	1,512,000	2,119,000
1961	5,721,000	2,735,000	1,589,000	1,397,000
1962	1,007,000	578,000	279,000	149,000
1963	632,000	341,000	164,000	127,000
1964	1,069,000	283,000	211,000	575,000
1965	2,460,000	1,350,000	915,000	196,000
1966	2,452,000	850,000	571,000	1,031,000
1967	2,193,000	375,000	622,000	1,197,000
1968	5,230,000	2,390,000	1,315,000	1,525,000
1969	3,119,000	1,274,000	1,014,000	831,000
1970	4,016,000	1,729,000	779,000	1,508,000
1971	2,362,000	785,000	589,000	988,000
1972	2,668,000	660,000	914,000	1,094,000
1973	6,040,000	1,919,000	2,436,000	1,685,000
1974	4,204,000	1,922,000	1,276,000	1,006,000
1975	3,255,000	2,107,000	811,000	337,000
1976	3,057,000	1,374,000	980,000	703,000
1977	3,481,000	1,605,000	635,000	1,241,000

* LCRA calculated value based on USGS streamflow (see Section 2.4.2)

Table 2.2 (Cont.) Annual Inflows to Matagorda Bay (acre-feet).

Calendar Year	Total Surface Inflow to Matagorda Bay (TWDB data)	Colorado River Basin Inflow*	Lavaca River Basin Inflow (USGS gage and LNRA data)	Coastal Inflow = Total Surface Inflow to Matagorda Bay - Colorado River Inflow - Lavaca River Inflow
1978	2,297,000	542,000	774,000	981,000
1979	6,111,000	1,528,000	1,564,000	3,019,000
1980	1,727,000	580,000	443,000	704,000
1981	5,558,000	1,918,000	1,543,000	2,096,000
1982	3,066,000	936,000	900,000	1,230,000
1983	3,825,000	904,000	1,122,000	1,799,000
1984	1,740,000	580,000	384,000	776,000
1985	3,478,000	1,122,000	1,016,000	1,339,000
1986	3,095,000	1,515,000	518,000	1,062,000
1987	4,813,000	2,768,000	1,098,000	946,000
1988	726,000	445,000	75,000	206,000
1989	1,146,000	445,000	231,000	469,000
1990	1,250,000	369,000	110,000	770,000
1991	5,345,000	2,463,000	957,000	1,926,000
1992	14,897,000	9,603,000	2,514,000	2,780,000
1993	5,664,000	2,219,000	1,559,000	1,886,000
1994	4,021,000	1,463,000	1,513,000	1,045,000
1995	3,444,000	1,671,000	559,000	1,214,000
1996	1,490,000	595,000	272,000	623,000
1997	10,082,000	4,570,000	2,850,000	2,663,000
1998	7,626,000	3,443,000	2,469,000	1,713,000
1999	1,613,000	858,000	298,000	457,000
2000	1,649,000	718,000	353,000	578,000
2001	4,760,000	2,028,000	1,120,000	1,612,000
2002	5,639,000	2,651,000	1,250,000	1,738,000
2003	2,467,000	1,572,000	539,000	356,000
1941-2003 Average	3,444,000	1,578,000	850,000	1,016,000
1941-2003 Maximum	14,897,000	9,603,000	2,850,000	3,019,000
1941-2003 Minimum	441,000	274,000	24,000	123,000
1941-2003 Median	3,095,000	1,350,000	667,000	981,000
1979-1989 Pre-diversion Average	3,208,000	1,158,000	809,000	1,241,000
1993-2003 Post-diversion Average	4,405,000	1,980,727	1,162,000	1,262,273

* LCRA calculated value based on USGS streamflow (see Section 2.4.2)

2.4.2 River Basin Inflows

U.S. Geological Survey gages were used to calculate river basin inflows. The location of these gages and associated periods of record are listed in Table 2.3. In addition, release records from Lake Texana provided by the Lavaca-Navidad River Authority were used in determining inflow for the Navidad River watershed of the Lavaca River basin.

The streamflow data measured by the gages listed in Table 2.3 can be directly used as equivalent freshwater inflow to Matagorda Bay for the Lavaca River basin. However, prior to the construction of the Mouth of the Colorado River Project by the Corps of Engineers, only a portion of the streamflow in the Colorado River entered Matagorda Bay and the remainder flowed directly to the Gulf of Mexico.

Table 2.3 Measured Streamflow Locations in River Basins.

River Basin	River or Stream	Location	USGS Stream Gage #	Period of Record
Colorado	Colorado River	Wharton	08162000	October 1938 - Present
	Colorado River	Bay City	08162500	May 1948 - Present
Lavaca	Lavaca River	Edna	08164000	September 1938 - Present
	Navidad River	Ganado	08164500	May 1939 - April 1982
	Navidad River	Lake Texana Dam*	-	May 1982 - Present

* The Lavaca Navidad River Authority has measured flow on the Navidad River at the discharge structures for Lake Texana.

In 1978, the Texas Department of Water Resources (TDWR) developed a method of estimating the inflow to Matagorda Bay based on gaged flow of the Colorado River at Bay City (TDWR, 1978). This method makes various assumptions. The first is that the condition of the mouth of the Colorado River varied with streamflow in the river. During extended period of low streamflow in the river, siltation would occur and reduce the cross-sectional area. The second assumption involves the open/close state of the navigation locks. During periods of low streamflow (less than 5,000 cubic feet per second), the locks are assumed to be open with interaction between the river and the GIWW possible.

In a 1978 document (Report LP-79) the Texas Department of Water Resources (TDWR) established a method of estimating inflows from the Colorado River. The methodology seems to result in two simple equations that would calculate the flow from the Colorado River into Matagorda Bay. The equations were derived from a more complicated hydrodynamic model.

Below is an explanation of the methodology:

Q_1: Colorado River Flow above the GIWW;
Q_2: Colorado River Flow below the GIWW;
Q_3: Colorado River Flow entering the Gulf of Mexico;
I_1: Flow Entering Matagorda Bay through Culver Cut;
I_2: Flow Entering Matagorda Bay through Tiger Island Cut (Parker's Cut).

Obtain the flow Q_1 for the Colorado River above the GIWW from the USGS gage streamflow at Bay City.

Q1 and Q2 are related with these equations:

- *If $Q_1 \leq 250$ cfs then $Q_2 / Q_1 = 1.94$*
- *If 250 cfs < Q_1 < 5,000 cfs then*

$$Q_2 / Q_1 = 1 + (3.03 - 95.45 \cdot X_1 + 80.71 \cdot X_1^2 - 38.43 \cdot X_1^3) / 100$$

$$\text{Where } X_1 = \log_{10} (Q_1 / 1{,}000)$$

- *If $Q_1 < 5{,}000$ cfs then $Q_2 / Q_1 = 1.00$*

I_2 is related to Q_2 with these equations:

- *If $Q_2 < 9{,}000$ cfs then $I_2 / Q_2 = (93.05 - 7.067 \cdot 10^{-3} \cdot Q_2 + 3.9015 \cdot 10^{-7} \cdot Q_2^2) / 100$*
- *If $Q_2 \geq 9{,}000$ cfs then $I_2 / Q_2 = 0.61$*

The report discusses the flow through Culver Cut, but does not detail a method to determine flow through Culver Cut which is between the GIWW and Matagorda Bay.

This method was used by TWDB to calculate the monthly total surface inflow and the Colorado watershed of the daily watershed inflow data sets for the period prior to the construction of the Mouth of the Colorado River Project.

The same method was used in this study to calculate the daily estimated Colorado River basin inflow for the period prior to June 1990, the construction of the Mouth of the Colorado River Project.

For purposes of this analysis, Colorado River flow measured at the Bay City gage beginning in June 1990 minus diversions by the South Texas Project (STP) is considered to be the inflow that enters the estuaries. Beginning in May 1990, the Corps of Engineers first opened the diversion channel component of the Mouth of the Colorado River Project. This channel connects the junction of the Gulf Intracoastal Waterway and the Colorado River directly with Matagorda Bay (Figure 2.2). From May 1990 through June 1992, flow from the Colorado River entered into Matagorda Bay by means of both the new diversion channel and the existing Tiger Island Cut (Parkers Cut) off of the former Colorado River channel through the Colorado River Delta. In early July 1992, a barrier dam was completed that closed the former Colorado River channel at the junction of the river and the GIWW.

Colorado River flows currently enter Matagorda Bay through either the diversion channel or the GIWW. When the lock gates are closed at the intersection of the GIWW, virtually all of the Colorado River flow enters Matagorda Bay through the diversion. When the lock gates are open, some Colorado River flow can enter the GIWW. These flows can then enter East Matagorda Bay to the north and Matagorda Bay to the south through navigation cuts and to the Gulf of Mexico via the by-pass channel. The consensus of agencies that work in the area is that the majority of Colorado River water enters Matagorda Bay, rather than East Matagorda Bay, either through the GIWW or the diversion channel. The dynamics of the split in flow is an opportunity for more research. Ongoing sedimentation, delta formation, dredging, and gate operating procedures are likely to influence the split. The exact nature of the split is not known, however, it was not of fundamental importance to the regression equations developed in this study effort because the statistical relationships were based on the measured flows at Bay City, salinity and productivity.

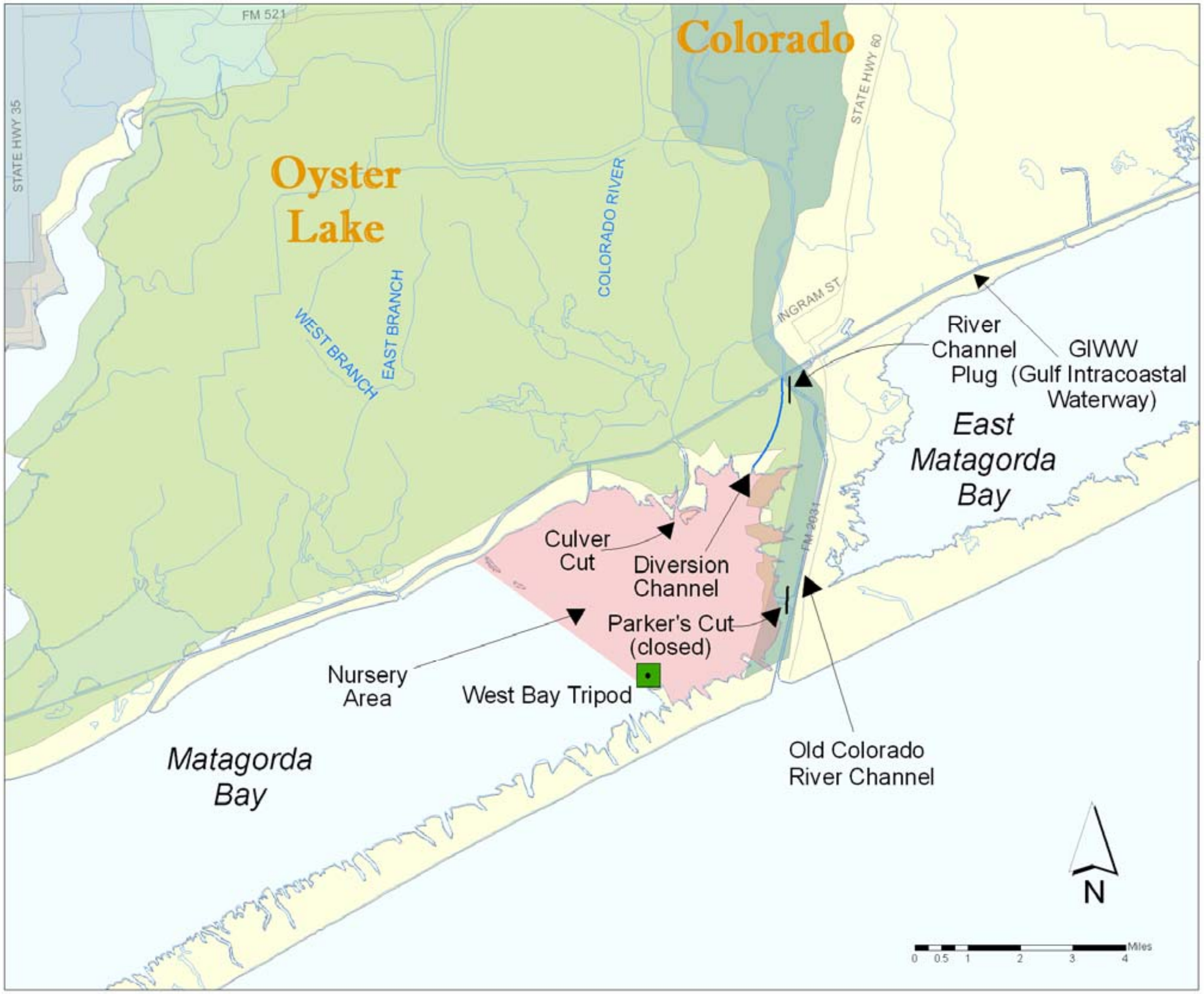


Figure 2.2 Location of the USACE Diversion Channel to Matagorda Bay.

Daily River Basin Gaged Streamflows and Estimated Inflows

Daily Colorado River basin streamflow was based on measurements from the Bay City gage from May 1948 to June 2005. This study does not use the period after December 2003 in any analyses. Data from the Wharton gage was adjusted to fill in the record prior to this period from January 1941 through April 1948 before the Bay City gage was installed. Over the 55-year period of whole calendar years for which streamflow was measured at both the Bay City gage and Wharton gage from 1949 through 2003, less 1992, the ratio of Bay City to Wharton flows from March through September (irrigation season) was 0.885. The similar ratio for the October through February period was 1.070. The flow at Wharton was adjusted by these ratios to provide estimated streamflow at Bay City prior to May 1948. The year 1992 was omitted from the calculation of these ratios as an outlier that would inappropriately skew the ratio. In 1992, the stream flow at Bay City was 9.61 million acre-feet and at Wharton it was 7.27 million acre-feet. Both these numbers were the largest recorded annual value at each of these locations. Their ratio of 1.32 is much larger then the next largest annual ratio of 1.21.

Lavaca River basin flows are comprised of flows from the Lavaca River and Navidad River. Flows on the Lavaca River are measured by a USGS gage near Edna (#08164000). The period of record used in this study for the Lavaca River gage near Edna is from September 1938 through June 2005.

Navidad River streamflow is estimated by LNRA using outflow from Lake Texana beginning in May 1982. Prior to the construction of that dam, June 1939 through April 1980, flows are based on the USGS gage near Ganado (#08164500) multiplied by the drainage area ratio of that gage to the Lake Texana, which is 1.322.

During the 24-month period of construction of Palmetto Bend Dam which impounds Lake Texana from May 1980 through April 1982, the Navidad River streamflow was estimated by using the Lavaca River near Edna gage multiplied by 1.532 as an estimate for streamflow near Ganado, and then multiplied by the drainage area of 1.322 as an estimate for streamflow at Lake Texana.

Monthly Distribution of River Basin Streamflows

Streamflow in the Colorado and Lavaca river basins varies seasonally. Figures 2.3 and 2.4 show the historical monthly distribution of streamflows in these major basins, respectively. The monthly distribution of streamflow is shown for the mean and 30th through 70th percentiles. The distribution of monthly streamflows shows the least variation during the late summer months, especially in August. The distribution is the greatest for both basins during the spring months. These figures demonstrate that there is a wide range of historical inflow that is contributed from each basin to the bay throughout the year.

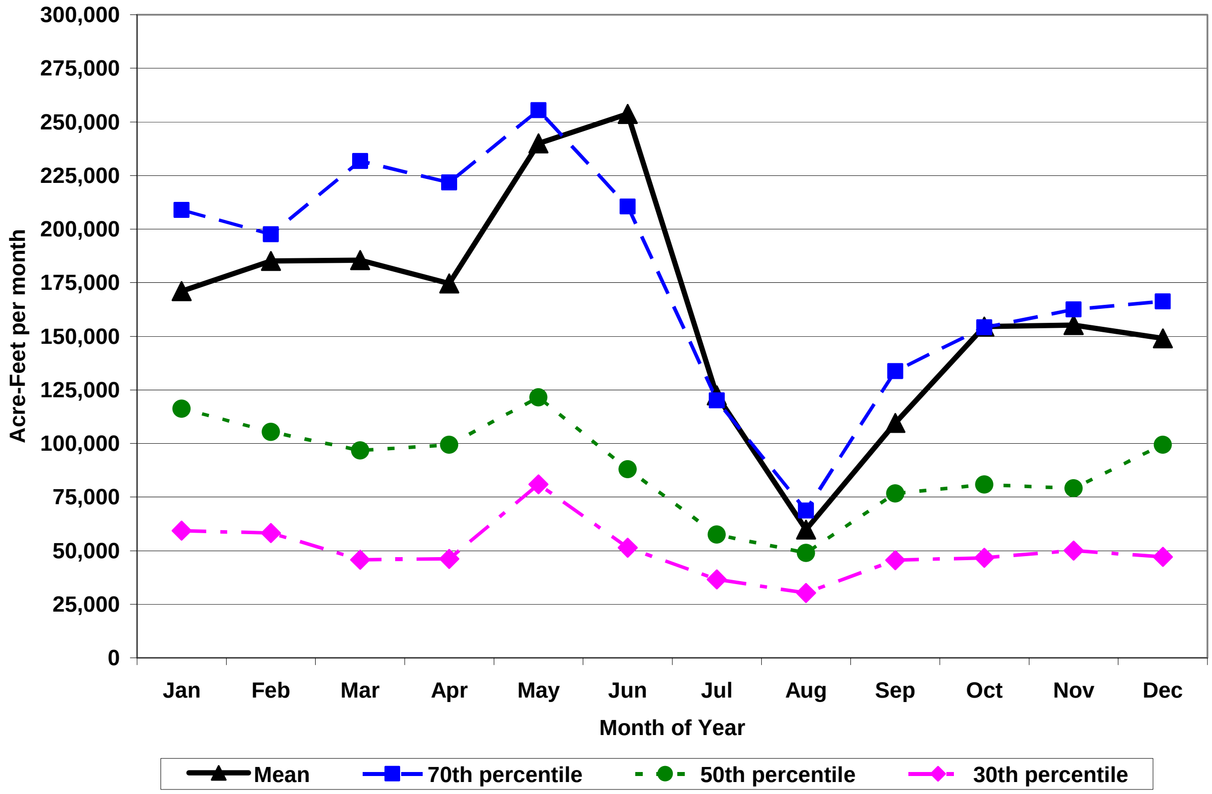


Figure 2.3 Distribution of Monthly Streamflow for the Colorado River Basin for 1941 to 2003.

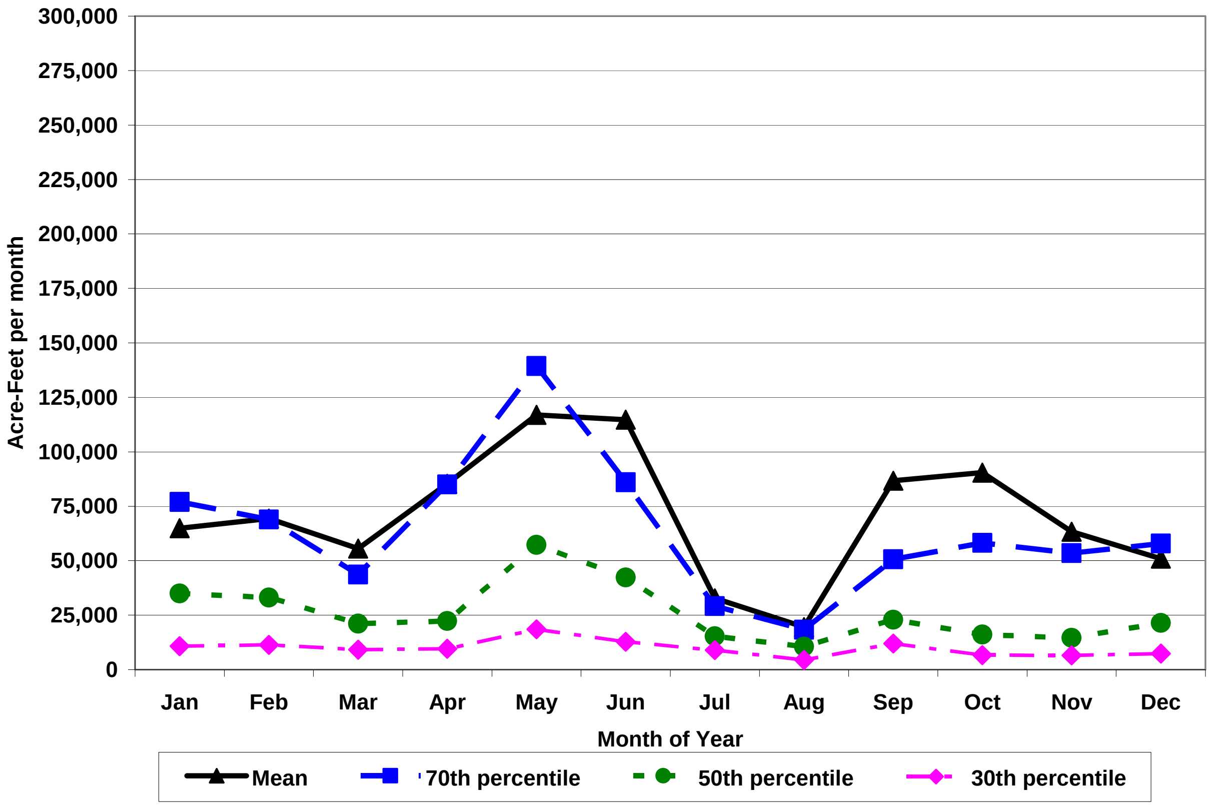


Figure 2.4 Distribution of Monthly Streamflow for the Lavaca River Basin for 1941 to 2003.

2.4.3 Coastal Inflow

In this analysis, the coastal inflow is defined as the unmeasured portions of the two major river basins (Colorado and Lavaca) and all of the coastal basins. The value of coastal inflow is calculated in this study as the difference between total surface inflow and the sum of the two river basin inflows.

The study area shown in Figure 2.1 includes the following four portions of the coastal inflow:

- Colorado River basin, unmeasured portion
- Colorado-Lavaca coastal basin
- Lavaca River basin, unmeasured portion
- Lavaca-Guadalupe coastal basin

The average estimated inflow from the unmeasured portion of Colorado River basin, for January

1977 through December 2003 is 37,200 acre-feet per year. This is the difference between the TWDB daily data for the "Colorado" watershed and the Colorado River basin estimated inflow calculated in this study.

The average estimated inflow from the Colorado-Lavaca Coastal basin, for January 1977 through December 2003 is 731,900 acre-feet per year. This includes the TWDB daily data for the following watersheds: Oyster Lake, Tres Palacios, Turtle Bay, Carancahua Bay, Keller Bay and Cox Bay.

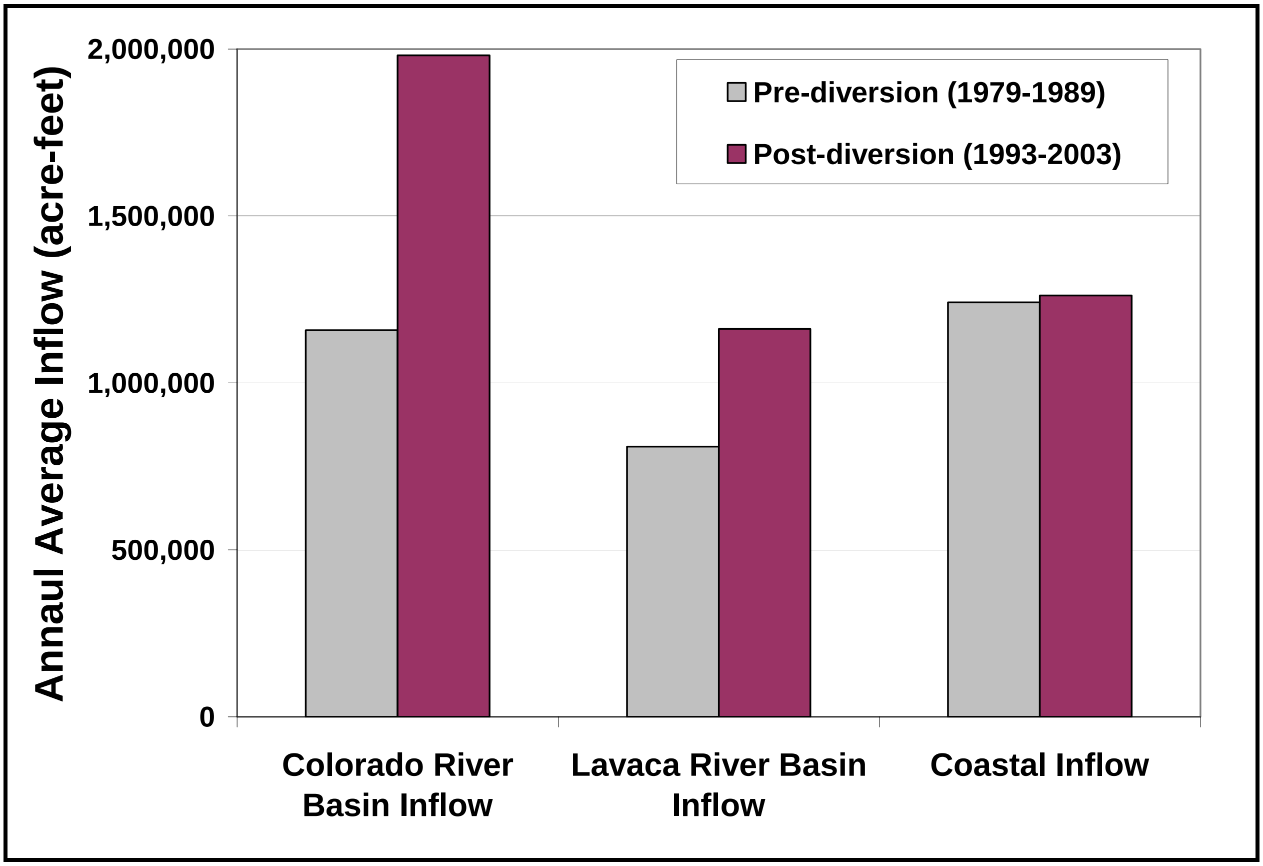
The average inflow for the unmeasured portion of Lavaca River basin, for January 1977 through December 2003 is 78,600 acre-feet per year. This is the difference between the TWDB daily data for the "Lavaca Delta" watershed and the Lavaca River basin estimated inflow calculated in this study.

The average estimated inflow from the Lavaca-Guadalupe Coastal basin, for January 1977 through December 2003 is 456,900 acre-feet per year. This includes the TWDB daily data for the Garcitas Creek, Chocolate Bay and Powderhorn Lake.

2.5 Hydrologic Changes Following Diversion Project

Following completion of the Corps of Engineers diversion channel project in 1991, flows from the Colorado River could reach Matagorda Bay directly. A comparison of the relative contributions of inflow from the Colorado River, Lavaca River, and coastal areas was made for the eleven year post-diversion project periods and the latest eleven year pre-diversion period.

Annual average estimated inflow to the bay from the Colorado River, Lavaca River and coastal area for the period prior to (1979-1989) and after (1993-2003) the Corps of Engineers diversion project on the Colorado River is shown in Figure 2.5. The 1992 flood year, during which the maximum inflow on record of 14.9 million acre-feet occurred, is not included. The annual average total estimated freshwater inflow to the bay from 1979 to 1989 was to 3,208,000 acre-feet per year and was 4,405,000 acre-feet per year for the 1993 to 2003 time period. The estimated annual average total surface inflow to the bay was higher during the post-diversion period, and the relative distribution of these flows among the three major sources demonstrate an increase in the portion from the Colorado River basin after the diversion project was completed as shown in Figure 2.6.



*The 1992 Flood Year is not included.

Figure 2.5 Annual Average Inflows to Matagorda Bay: Pre- and Post-Diversion.

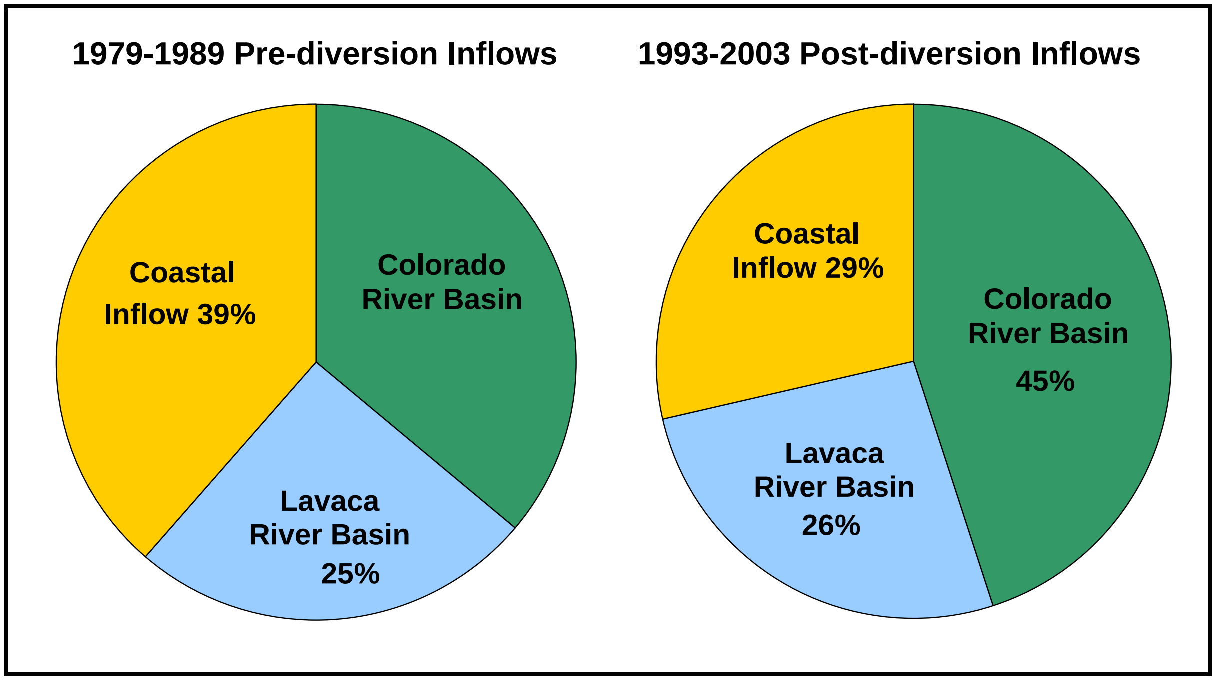


Figure 2.6 Distribution of Annual Average Inflows to Matagorda Bay: Pre-Diversion and Post-Diversion.

CHAPTER 3
Biology

3.1 Introduction

The relationship between freshwater inflows and biological productivity in Matagorda Bay is an essential component in developing Target freshwater inflow need recommendations. Fisheries equations relating freshwater inflows and species productivity were developed for nine target species in the 1997 Freshwater Inflow Needs study. The 1997 analysis used both TPWD Coastal Fisheries data and commercial harvest data to calculate annual productivity. Equations for seven species were developed using the bag seine subset of the Coastal Fisheries data, while equations for oysters and southern flounder were developed using commercial harvest data because bag seines are an ineffective sampling method for those species. Both data sets included data through 1992, the first full year of the diversion of the Colorado River into Matagorda Bay. The lack of post-diversion data is a potential limitation of the 1997 fisheries equations.

The primary purpose of this re-evaluation was to assess the relationship of inflows and fisheries productivity since the diversion of the Colorado River. This chapter also evaluates the spatial distribution, pre- and post-diversion abundance and salinity preferences of select species. Twelve candidate target species, considered economically and/or ecologically important to Matagorda Bay, were evaluated in this study, although viable statistical relationships were found for only seven of those species (Table 3.1). Statistically significant equations were not developed for five of the candidate species.

The biological productivity regression equations use estimates of river basin inflow from the two primary sources - the Colorado River basin and the Lavaca River basin. These regression equations do not include other sources of inflow including the unmeasured portions of the river basins and the remaining coastal basins (as discussed in Chapter2). This differs from the 1997 study in which these coastal inflows were included in the development of the biological productivity regression equations. Omission of these coastal inflows adds some degree of uncertainty to the equations.

Table 3.1 Species and Data Used to Evaluate Fisheries Equations in the 1997 and 2005 Freshwater Inflow Needs Studies.

Species	Data Used in 2005	Equation Developed	1997 Target Species
Blue Crab	Coastal Fisheries	Yes	Yes
Brown Shrimp	Coastal Fisheries	Yes	Yes
White Shrimp	Coastal Fisheries	Yes	Yes
Eastern Oyster	Coastal Fisheries	Yes	Yes
Gulf Menhaden	Coastal Fisheries	Yes	Yes
Striped Mullet	Coastal Fisheries	Yes	Yes
Red Drum	Coastal Fisheries	Yes	Yes
Black Drum	Coastal Fisheries	No	Yes
Southern Flounder	Coastal Fisheries	No	Yes
Grass Shrimp	Coastal Fisheries	No	n/a
Croaker	Coastal Fisheries	No	n/a
Spot	Coastal Fisheries	No	n/a
Spotted Sea Trout	Coastal Fisheries	No	n/a

3.2 Data Description

The two primary sources of data used to develop statistical relationships between freshwater inflows and fisheries productivity are commercial harvest data and TPWD Coastal Fisheries data. Commercial harvest data reports commercial fishing landings of finfish and shellfish by bay system. These data are influenced by factors including fishing effort, efficiency, harvest regulations and economic factors such as fuel prices. In addition, commercial data often reflect an advanced life stage for which many factors other than freshwater inflow can affect productivity.

The TPWD Coastal Fisheries program systematically samples Matagorda Bay using four gear types: bag seines, otter trawls, gill nets and oyster dredges. Bag seine samples are randomly collected monthly and otter trawls samples are collected monthly in a stratified random manner. Bag seine samples are collected only near the shoreline; otter trawls are collected in areas where water is at least one meter deep and free of obstructions. Gill nets, used in the spring and fall seasons, are placed so that they are perpendicular to the shore and left overnight. The oyster dredge program, which has changed over time, involves taking samples monthly at known reefs.

The TPWD Coastal Fisheries data was used in these analyses for all species. Except for oysters, the bag seine subset was determined to be the appropriate gear type for all species since the gear type selects for the juvenile life stage. Juveniles should provide less bias and better relationships to inflows because of their dependence on inflow for creating appropriate environmental conditions needed for proper growth and development. The adult life stage of many organisms can be significantly influenced by a variety of factors unrelated to freshwater inflow (e.g., commercial fishing pressure). The variation in annual productivity measured from the advanced life stages is more difficult to directly link to freshwater inflows, because adults are mobile and more tolerant to environmental conditions such as higher salinity. Thus, it is appropriate to measure the juvenile life stage, which is more sensitive to freshwater inflows.

The number of monthly bag seine samples collected by TPWD has increased over time (Table 3.2). The systematic change in collection effort has implications for fishery equation development. First, average annual density derived from six samples per month can be influenced by a single large catch. In addition, the variance of the average annual density derived from six samples per month will tend to be larger than the corresponding variance based on 20 samples per month. Second, there is a clear difference in the amount of coverage between six and 20 samples per month. Some portions of the bay were not represented when only six samples were collected, which is problematic to the calculation of annual productivity. For example, six samples located in prime habitat could lead to an inflated annual catch. Conversely, six samples during key months in suboptimal habitat could underestimate annual productivity. Ultimately, the difference in sampling efficiency could contribute to considerable variation in annual catch. Therefore, caution should be used when comparing annual averages derived from various collection efforts. Fortunately, there has been consistent sampling since 1992.

Table 3.2 Number of Bag Seine Samples per Month, since 1976.

	Month											
Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1976				4	4							
1977										6	10	6
1978	6	6	6	6	6		6	6	6	6	6	6
1979	6	6	6	6	6	6	6	6	6	6	6	6
1980	6	6	6	6	6	6	6	6	6	6	6	6
1981	6	6	6	6	6	6	6	6	6	10	10	10
1982-1987	10	10	10	10	10	10	10	10	10	10	10	10
1988	10	10	10	12	12	12	12	12	12	12	12	12
1989	12	12	12	12	12	12	12	12	12	12	12	12
1990	16	16	16	16	16	16	16	16	16	16	16	16
1991	16	16	16	16	16	16	16	16	16	16	16	16
1992	20	20	20	20	20	20	20	19	20	20	20	20
1993-2002	20	20	20	20	20	20	20	20	20	20	20	20

The annual density calculated from bag seine data for selected species are shown in Table 3.3. Most species show a large amount of inter-annual variation. For example, the annual density of Gulf menhaden ranges from 1838 individuals/acre to 28 individuals/acre. Several species show particularly low productivity during extended periods of low inflows. The annual density of white shrimp, Atlantic croaker, Gulf menhaden, striped mullet and spot were low during the drought in 2000.

Table 3.3 Annual Density of Various Species in Matagorda Bay (individuals/acre), 1978 – 2002.

Year	Blue Crab	Brown Shrimp	White Shrimp	Gulf Menhaden	Striped Mullet	Red Drum	Oysters (number /dredge)
1978	<u>8.28</u>	133.74	442.02	**3170.71**	31.72	3.23	
1979	21.85	155.56	434.26	693.52	78.52	6.67	
1980	18.89	114.26	417.96	92.22	17.04	7.22	
1981	34.76	125.24	642.38	278.10	43.65	8.73	
1982	25.00	165.33	**1399.67**	656.33	**450.56**	9.67	
1983	28.11	198.56	315.33	647.22	29.44	5.22	
1984	**39.11**	131.67	958.56	840.11	28.33	2.11	
1985	22.56	145.44	233.78	1527.44	27.00	4.33	
1986	20.67	**203.00**	270.11	1837.89	14.44	<u>1.33</u>	
1987	14.33	178.00	231.78	1434.11	16.56	7.00	
1988	11.50	<u>83.09</u>	136.43	145.12	21.35	2.22	
1989	18.06	147.78	153.43	74.63	11.67	2.78	
1990	29.44	168.68	180.49	206.04	11.88	6.11	
1991	23.13	180.28	248.26	1211.11	34.17	**15.00**	
1992	17.85	107.89	257.02	767.64	25.22	7.42	6.36
1993	20.50	93.00	234.00	196.89	17.94	4.83	<u>4.89</u>
1994	38.33	161.00	204.83	165.28	24.89	3.33	8.95
1995	25.44	137.78	242.83	287.11	11.00	3.22	13.51
1996	15.39	110.83	181.94	593.56	13.06	7.94	19.66
1997	25.11	96.17	192.50	918.83	28.39	7.72	16.70
1998	19.28	150.44	188.56	379.89	13.56	3.17	15.08
1999	13.94	192.44	594.11	159.72	<u>7.44</u>	5.11	19.14
2000	17.72	179.28	<u>77.33</u>	<u>28.67</u>	9.33	1.67	**19.92**
2001	14.39	141.89	137.72	1676.17	42.17	4.28	9.99
2002	15.56	99.78	309.22	97.56	14.11	4.44	10.10
Annual Average	21.57	144.04	347.38	723.43	40.94	5.39	13.12

Note: All organisms except oysters were collected in bag seine. The oysters were collected by dredging. **Bold indicates the maximum annual abundance,** <u>Underlined indicates the minimum annual abundance.</u>

3.3 Target Species

The life cycles of many marine organisms are complex because development from egg to adult often occurs through many stages, which are dependent upon appropriate temperature, salinity and other environmental factors (TWDB, 1994). Many marine organisms use marsh habitat located in the smaller bays and river deltas in estuaries for the development of their juveniles. Such organisms have co-evolved with the natural pattern of freshwater inflows. For example, the arrival of larval/juveniles in the spring or fall often corresponds to historic peak spring and fall inflows. These inflows create lower salinity conditions and provide nutrients that nourish developing juveniles in the marshes.

3.3.1 Brown Shrimp

Brown shrimp is one of the most commercially and economically important species in Matagorda Bay (Figure 3.1). Adult shrimp spawn in the deeper waters of the Gulf from September through May; February and March are considered peak months (Lassuy, Brown Shrimp, 1983). Development of eggs to the larval stage is similar to white shrimp, with several molts and life stages occurring in the offshore water (Lassuy, Brown Shrimp, 1983). Brown shrimp larvae use tides to emigrate into the estuary and seek shallow, soft bottom marsh habitat for development. Smaller shrimp appear to prefer salinity in the 20 parts per thousand (ppt) range and avoid areas of low salinity (LCRA, 1997). Brown shrimp migrate out of the bays during the summer months June and July on favorable tides.

Brown shrimp are caught throughout Matagorda Bay, with the largest densities occurring in the tertiary bays, such as Caracahua Bay and Powderhorn Lake (Appendix C, Figure 1). Brown shrimp have clear seasonal patterns in Matagorda Bay. Catch density for bag seines peaks in May and June, as shown in Figure 3.2.

Figure 3.1 Brown Shrimp (TPWD).

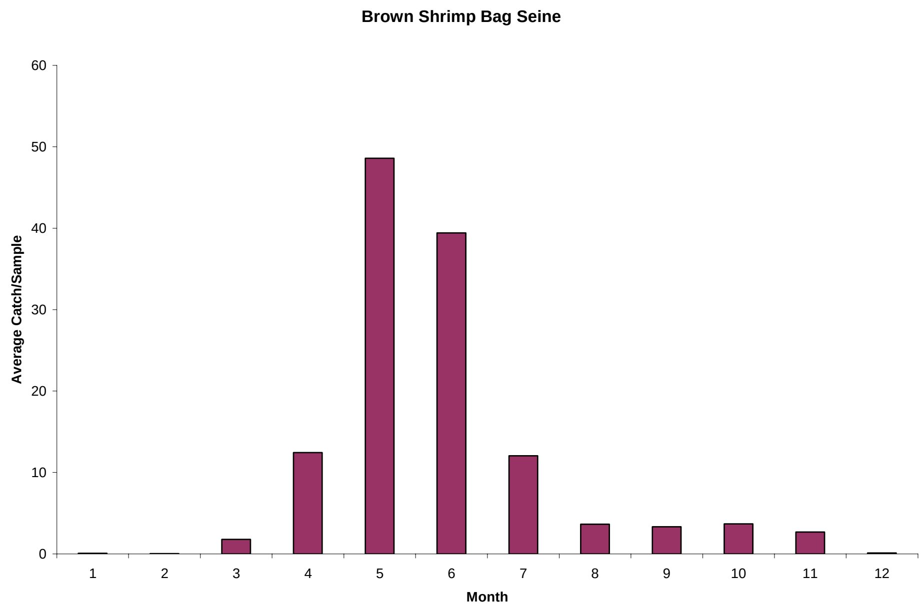


Figure 3.2 Average Catch of Brown Shrimp per Bag Seine by Month.

3.3.2 White Shrimp

Ecologically important white shrimp are also one of the most commercially important species in Matagorda Bay (Figure 3.3). White shrimp spawn in the Gulf of Mexico from April to August (Muncy, 1984). Eggs hatch about 12 hours after spawning and undergo a series of molts and life stages offshore before reaching the larval stage (Muncy, 1984).

Larval shrimp enter the estuary on flood tides and locate in the far reaches of the estuary (Muncy, 1984). White shrimp prefer shallow, low saline marsh while developing (TWBD, 1994). The shrimp develop rapidly in the nursery ground in the summer, stage in the open bay during fall and migrate to the Gulf late fall, typically when water temperatures drop (Muncy, 1984).

Figure 3.3 White Shrimp (TPWD).

The peak density of white shrimp collected with bag seines in Matagorda Bay occurs from July to November (Figure 3.4). White shrimp densities are highest in the secondary bays (Caracahua, Powderhorn) and far into the Tres Palacios and Lavaca bays (Appendix C, Figure 2).

The annual density of white shrimp strongly correlates to inflows during July-August. Decreased annual productivity is demonstrated when flows during this bimonthly period are extremely high or low. This response led to the selection of July-August flows for the white shrimp equation. As with brown shrimp, larger flows were eliminated to limit the data to a region where a linear response is justified.

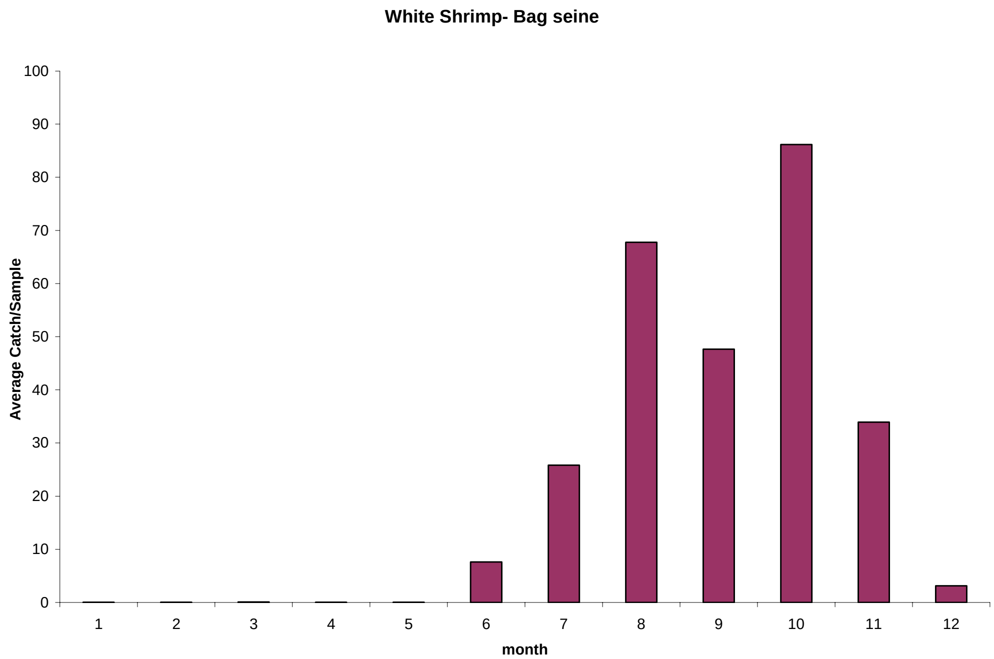


Figure 3.4 Average Catch of White Shrimp per Bag Seine by Month.

3.3.3 Blue Crab

Blue crab (Figure 3.5), an ecologically and economically important species in Matagorda Bay, occupies the estuary year round, although abundance in bag seines peaks in spring, as shown in Figure 3.6. Mating occurs in low salinity waters in the upper reaches of the estuary (Van Avyle, 1984). Females migrate to the Gulf to spawn during the fall (TWDB, 1994). Larvae return to the estuary on incoming tides and are distributed equally around the estuary during winter. Juvenile crabs tend to concentrate in the upper reaches of the estuary during the spring (Appendix C, Figure 3) (LCRA, 1997). Crabs can tolerate a wide range of salinities, although peak abundance appears to occur in intermediate salinities in the Matagorda Bay system (LCRA, 1997). Upon maturation, male and female crabs inhabit different portions of the estuary with males preferring lower salinity waters and females in higher salinity waters (Van Avyle, 1984).

Figure 3.5 Blue Crab.

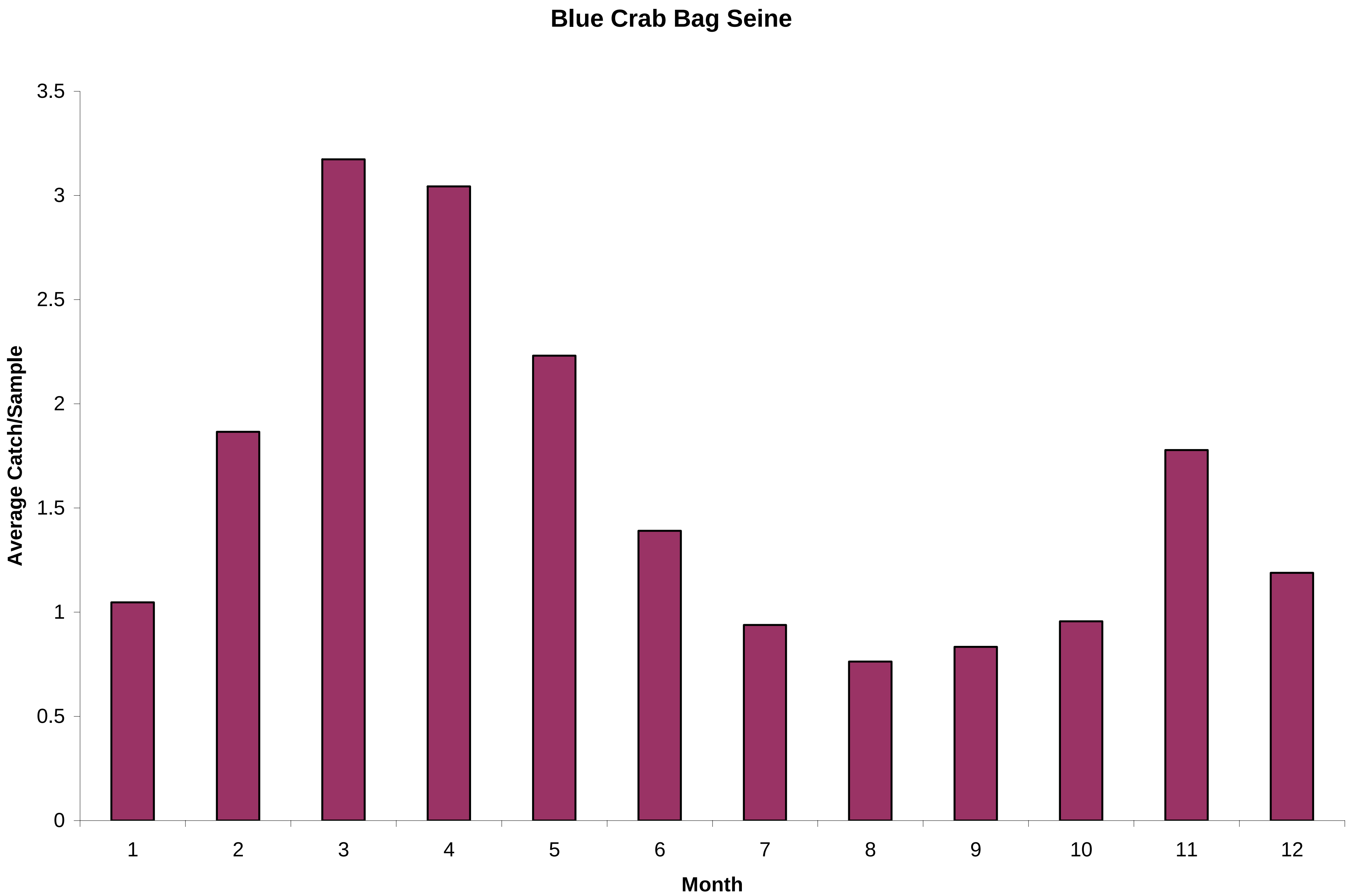


Figure 3.6 Blue Crab Bag Seine

3.3.4 Oysters

Oysters are ecologically and commercially important sessile mollusks that inhabit the estuary full time (Figure 3.7). Oysters live in groups known as beds or reefs and continue to re-establish in favorable areas. Spawning is a function of temperature and salinity. Temperatures above 20 degrees C and salinity above 10 ppt are favorable (Stanley and Sellers, 1986). Oysters spawn throughout the year, but peak in late spring and early summer in Matagorda Bay. Mass spawning occurs at a temperature above 25 degrees C (Stanley and Sellers, 1986). Larvae remain in the water column up to three weeks, when they attach to a hard substrate (preferably existing shell) and become spat (Stanley and Sellers, 1986). Growth depends on environmental conditions, such as salinity (LCRA, 1997). Oysters are subject to parasites and diseases, particularly at elevated salinity and temperatures. Increased salinities favor the oyster drill predator (LCRA, 1997). High salinities also increase the rate of infection and mortality by the parasitic oyster disease Dermo, especially at salinities over 25 ppt (Balboa, 2004). Fluctuations in salinity levels keep infection rates low.

The oyster equation was developed using market-sized oysters from the Coastal Fisheries oyster dredge data. Oyster density was low following large inflow events associated with the floods of 1992, when Matagorda Bay received nearly 10 million acre feet of inflow. The population steadily grew until 2000, when a drought and high salinities resulted in heavy oyster mortality associated with disease. The data from 2001 and 2002 were not used because the density of market sized oysters had not recovered from the high mortality in 2000. While the flows during 2001 and 2002 were favorable for oysters, the low population density resulted in poor correlations to inflows. Thus, excluding the years impacted by drought allowed for the period of growth (1992 to 2000) to be statistically modeled.

Figure 3.7 Oysters (TPWD).

3.3.5 Striped Mullet

Adult finfish are usually tolerant to a range of salinities from freshwater to seawater. However, juveniles of these species often depend upon estuarine environments for development. Striped mullet (Figure 3.8) are a common finfish in Matagorda Bay, present in the estuary throughout the year (Figure 3.9 and Appendix C, Figure 4). Striped mullet spawn offshore primarily during November and December, coinciding with the period of lowest density in the bay (Collins, 1985). Juvenile mullet distribute throughout the estuary during the spring, with the largest concentrations occurring in the upper reaches of the Tres Palacios, Caracanhua, Turtle and Lavaca bays. Adults migrate offshore to spawn during the fall and may return to the estuary, stay offshore or migrate up freshwater rivers (Collins, 1985).

Figure 3.8 Striped Mullet (TPWD).

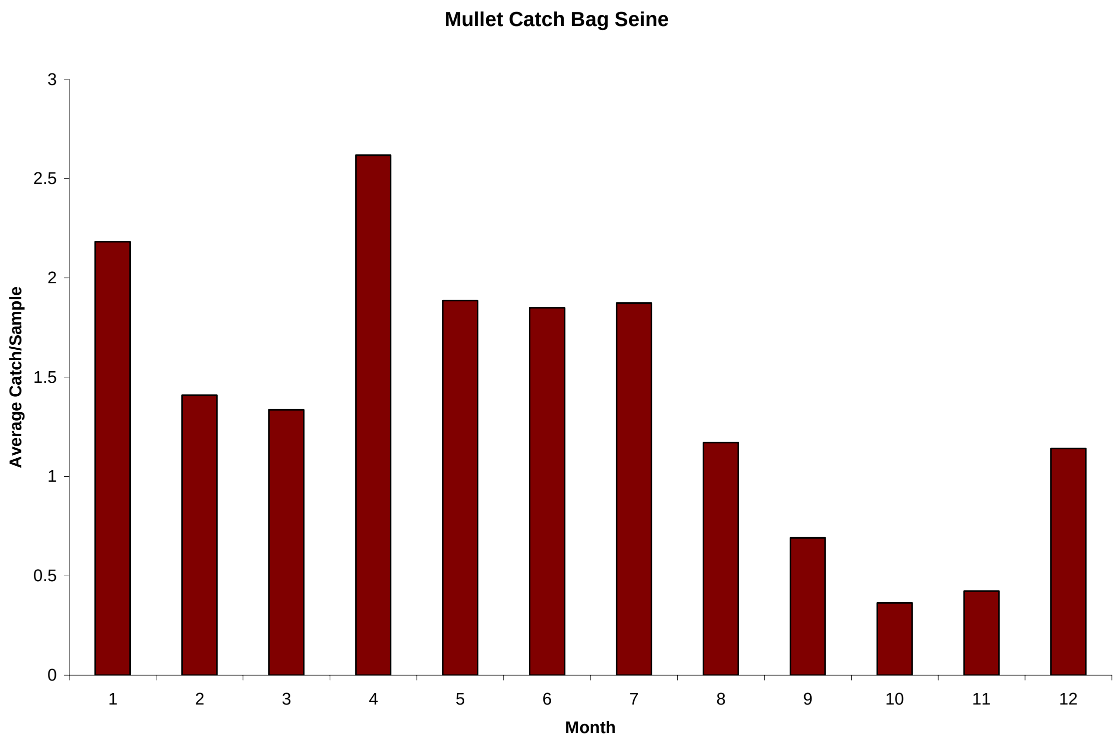


Figure 3.9 Average Catch of Striped Mullet per Bag Seine by Month.

3.3.6 Gulf Menhaden

Gulf menhaden is an abundant estuarine-dependant finfish species (Figure 3.10). Menhaden are commercially important in the upper Texas coast and Louisiana (Lussuy, Gulf Menhaden, 1983). Adult menhaden spawn in the Gulf of Mexico during the fall and winter, which coincides with the lowest density collected in bag seines (Figure 3.11). Spawning may occur up to five times in a single season (Lussuy, Gulf Menhaden, 1983). Larvae develop offshore for three to five weeks before entering the estuary on favorable currents (Lussuy, Gulf Menhaden, 1983). Larvae seek shallow, low salinity areas. Juveniles form large schools and remain in the low salinity areas until fall. Similar to mullet, the largest concentrations occurred in the upper reaches of the Tres Palacios, Caracanhua and Lavaca bays as shown in Appendix C, Figure 5. Young fish migrate to the Gulf with adults, but it is unclear whether they participate in spawning (Lassuy, Gulf Menhaden, 1983).

Figure 3.10 Gulf Menhaden (TPWD).

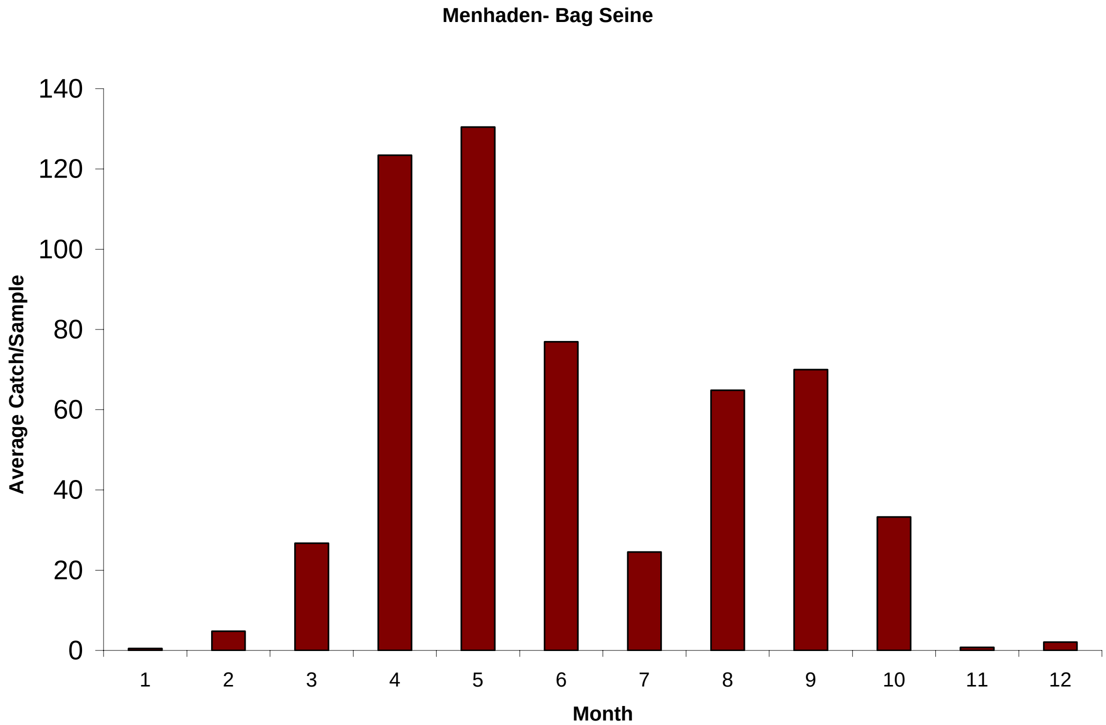


Figure 3.11 Average Catch of Gulf Menhaden per Bag Seine by Month.

3.3.7 Red Drum

Red drum are one of the most important sport fish on the Texas coast and historically an important commercial finfish as well (Figure 3.12). Juvenile red drum use the estuary for development, with peak density occurring during winter (Figure 3.13). Red drum spawn offshore during late summer and fall (Reagan, 1985). Eggs are carried into the bays on tidal currents where they develop in sea grass beds and wetland marshes (Reagan, 1985). Red drum were collected throughout the bay (Appendix C, Figure 6), and were apparently more abundant in the upper reaches of the estuary (LCRA, 1997). Red drum migrate to the Gulf after remaining in the estuary for four or five years (Reagan, 1985).

Figure 3.12 Red Drum (TPWD).

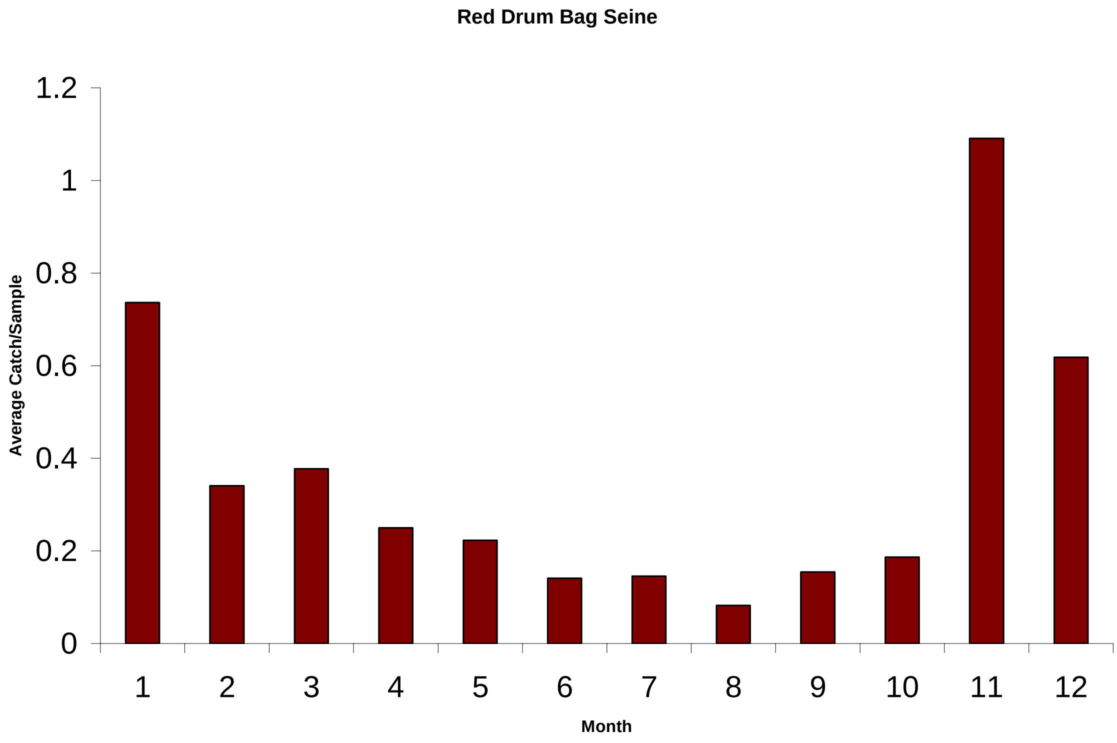


Figure 3.13 Average Catch of Red Drum per Bag Seine by Month.

3.4 Salinity and Species Abundance

Estuarine organisms are adapted to a wide range of salinity conditions. However, abundance of many estuarine organisms appears highest at intermediate salinities. Metabolic stress occurs when salinity is too high or low. Table 3.4 shows average annual salinity to average annual density for target species. Annual productivity is generally highest when annual average salinities are between 15 and 23 ppt.

Table 3.4 Salinity and Density of Selected Estuarine Organisms.

Species	Individuals/Acre			
	<15 ppt	15 – 18 ppt	18 – 23 ppt	> 23 ppt
Blue Crab	19.8	21.4	26.1	17.7
Brown Shrimp	134.4	145.9	144.9	147.0
White Shrimp	278.9	384.4	452.8	220.6
Gulf Menhaden	953.5	644.0	1130.2	201.3
Striped Mullet	37.2	76.6	26.7	12.5
Red Drum	9.2	6.2	4.3	4.3

Source: Calculated from Texas Parks and Wildlife Department, "Coastal Fisheries Data for Matagorda Bay Bag Seine1977 – 2002" database. (Austin, Tex. 2004).

3.4.1 Species Abundance Before and After the Diversion

A comparison of annual abundance of selected species in Matagorda Bay was conducted for the pre- and post-diversion period. The null hypothesis is that there are no differences in annual density of blue crab, brown shrimp, white shrimp, Gulf menhaden, mullet, and red drum in the pre- and post-diversion periods, based on a Student's *t* test. Although there are large differences in mean density between the periods, the null hypothesis was not rejected for any species (Table 3.5).

This is an unexpected result since there was more water and lower salinity concentrations on average since the diversion. Additional intertidal marsh habitat was created in the new Colorado River delta, thus, productivity was expected to increase. However, it should be noted that within the spring flows May-June period 1992, 1993 and 1997, the Colorado River discharged greater than 1.5 million acre-feet into Matagorda Bay. That volume is equivalent to the estimated target need for the entire year and such a large volume in a short time could have disrupted productivity.

Table 3.5 Average Annual Species Abundance (individuals/acre) Before and After the Diversion.

Species	Pre Diversion 1978 – 1990	Post Diversion 1992 – 2002	p value
Brown Shrimp	150	134	0.25
White Shrimp	447	238	0.07
Blue Crab	22.5	20.31	0.51
Striped Mullet	60	19	0.23
Gulf Menhaden	892	479	0.17
Red Drum	5.7	4.8	0.46

Source: Calculated from Texas Parks and Wildlife Department, "Coastal Fisheries Data for Matagorda Bay, 1977 – 2002" database. (Austin, Tex. 2004).

3.4.2 Importance of Location within Matagorda Bay

The Matagorda Bay system has several smaller secondary bays. The smaller bays can be the most productive areas in a bay system because they have optimal habitat (marsh) and salinity conditions. Table 3.6 compares species density at four sites. White shrimp, brown shrimp and menhaden were more abundant in Carancahua Bay than the eastern arm of Matagorda Bay or Tres Palacios Bay. Mullet, red drum and speckled trout showed little preferences between the systems. While Carancahua Bay and Tres Palacios Bay receive significantly less inflow than Lavaca Bay and the eastern arm of Matagorda Bay, it appears that the right combination of inflows and habitat is present to promote productivity. For example, the eastern arm of Matagorda Bay receives the most freshwater inflow but had the lowest abundance of most species. It should be noted, however, that sampling does not occur in the Colorado River delta proper, an area of newly created marsh habitat and potentially the highest abundance of organisms.

Table 3.6 Species Abundance at Different Locations in the Matagorda Bay System (individuals/acre).

Site	Eastern Arm Matagorda	Tres Palacios	Carancahua	Lavaca
Brown Shrimp	113.07	151.06	220.57	123.80
White Shrimp	157.76	208.33	529.27	202.01
Blue Crab	19.09	32.13	19.98	16.07
Striped Mullet	32.94	31.01	27.71	15.34
Gulf Menhaden	623.99	1381.99	1316.14	551.90
Red Drum	7.23	3.95	5.12	4.87

Note: Abundance is the average number of individual organisms per acre
Source: Calculated from Texas Parks and Wildlife Department, “Coastal Fisheries Data for Matagorda Bay, 1977 – 2002” database. (Austin, Tex. 2004).

3.4.3 Conceptual Model for Developing Flow-Productivity Relationships

The relationship between freshwater inflows and estuarine productivity is complex. A description of the full range of influences of freshwater inflows on productivity fell beyond the scope of this FINS analysis. The FINS analysis was limited to relating freshwater inflows to productivity using only available data on productivity, most notably the TPWD Coastal Fisheries data. Developing relationships, for example, between freshwater inflows (via nutrient loading) on algal (primary) productivity was not possible because of the minimal data available on nutrient loading and algal productivity for Matagorda Bay. While these and many other relationships are well recognized, their treatment was beyond the scope of the FINS study due to limited data. Further data collection is recommended and additional work to help support development of additional relationships is the focus of other studies (e.g. LCRA-SAWS Water Project). These and other studies will likely continue long into the future to help develop more reliable and new relationships.

In general, freshwater inflows moderate salinity, provide nutrients necessary for primary productivity, and build and maintain habitat. Depending on their timing, volume and location, freshwater inflows can either benefit or harm productivity. Under certain conditions, the impacts are immediately felt and short–lived; in other cases, the impacts are not evident for months but might last for years. The same level of freshwater inflows are not uniformly beneficial to all species because flow volumes that benefit one species can harm productivity of another. Flow volumes can also have a more direct impact on juveniles than adults of some species.

In general, the relationship between inflows and productivity becomes more complex and less certain the further in time, the farther up the food chain and the more mature the species one considers. The ultimate purpose of this analysis was to distill these complex interactions to a level that could be represented in the form of simplified mathematical equations relating flow to productivity. The form of these equations had to be compatible with use in TXEMP, the optimization model used to determine target inflows for Matagorda Bay. This requirement placed restrictions on the form of equations that could be used, and led to the need for simplifying assumptions. Because the relationships developed here are of a simple form, they are not meant to capture the full range of influences of inflows on productivity nor all the factors that contribute to productivity. This section discusses some of the assumptions inherent to the relationships and the conditions they are meant to represent.

Statistical Approach

Prior efforts (LCRA, 1997) to develop flow-productivity equations made use of the all-possible-subsets statistical approach, in which all combinations of the independent variables (bi-monthly flows) were regressed against the dependent variable (annual species productivity) in a broad search for statistically significant regressions. Only monotonic functional forms (linear, log, square root) were applied. (Monotonic functions continually either increase or decrease.) Similar attempts in the current study to develop flow-productivity equations with updated data sets were not uniformly successful.

Use of both the all-possible subsets approach and of monotonic functional forms applied over limited flow ranges allowed the development of the best available equations that related freshwater inflows to productivity. This recognizes that equations that describe species response to freshwater inflows need not be of the same type for all species, nor should they necessarily be expected to. Some species inhabit the bay throughout the year, thus using the all possible subsets approach selected the best statistical fits from all flow possibilities. Brown and white shrimp, however, are in the bay for very specific periods of time and also were shown to respond negatively to extremely large inflows. Thus, modeling their response over limited inflow ranges with monotonic (uniformly increasing) functions provided very strong correlations that correspond to the species life history requirements. However, there were not enough data points to capture the negative relationship of productivity with inflows, if any exists. Overall, the use of two approaches sought to utilize the best equations for all species.

Indeed, no statistically significant relationships were found for several species using these approaches. In some instances, relationships were weak, and the most statistically significant independent variables were not consistent with historical observations and what is believed to be the mechanisms of the bay. Rather than adhere to the use of the all-possible-subsets approach, alternate approaches were used in this study to develop the needed equations, particularly for shrimp.

Use of juvenile organisms to represent productivity

Except for oysters, productivity in this study is defined as the biomass of juvenile organisms of the size captured in bag seine sampling gear used in TPWD's Coastal Fisheries sampling program. Productivity for oysters is based on biomass of live oysters collected with oyster dredges in the Coastal Fisheries program. Use of juveniles reduces the influence of confounding factors that are magnified when considering adult organisms, such as fishing pressure, predation and disease. The assumption made in selecting juvenile species is that the inflow-productivity relationship is most direct and simple at the earliest stages of the life cycle, but is complicated by the pressures mentioned earlier as the animals mature. The response of juveniles to salinity is also more critical than that of adults. TPWD bag seine data from Matagorda Bay indicates juveniles prefer a narrow range of salinities until they mature, and extremely high or low salinities can lead to mortality.

In a sense, this approach treats potential productivity associated with juveniles, rather than productivity associated with fully realized adult biomass. While the use of adults as indicators of bay productivity would also be suitable, the use of juveniles would be expected to be less problematic.

Seasonal occurrence of species – selection of independent variables

Occurrence in the bay of some species, e.g., brown and white shrimp, is highly seasonal. Juvenile brown shrimp, for example, are found in the bay primarily from April through July, while few are found in the bay outside of these months. For brown shrimp to flourish, satisfactory salinity, nutrient and habitat requirements must be maintained between April and July. Assuming that neither nutrients nor habitat constrains productivity, salinity in the bay during these months has the most direct influence on productivity (e.g. energetics), while outside of those times, salinity and other factors are less important (Longley, ed., 1994). These assumptions support the selection of certain flow months, during or immediately prior to the time the species are present in the bay, as independent variables to be used in the flow-productivity equations.

Extreme inflows – need to filter data

Very low flows are assumed to have short-term (months to 1 to 2 years) negative impacts on productivity (see Figures 3.3 and 3.6 for brown shrimp and white shrimp productivity relative to a wide range of flows). Droughts are known to have an impact on productivity by both reducing nutrient input to the system and by elevating salinities to extreme levels. Extremely large flows provide beneficial nutrients and sediment but can also disrupt or reduce productivity in the short term. Floods reduce salinities to the other extreme, increase turbidity levels, and physically transport species away from desired habitat. Finally, moderate flows tend to support greater productivity than extreme flows. These assumptions about the effects of extreme flows (i.e. low productivity for small and large flows, and higher productivity for moderate flows) on productivity imply that quadratic or other higher order functions, rather than monotonic functions, are needed to represent this response. Alternatively, if monotonic functions must be used, , as required in the application of the TXEMP optimization model (Chapter 7) in this study, the range of flows used should be limited to that in which productivity is monotonic.

This alternate approach was taken in the development of equations for some species. Extremely high flows were eliminated with the reasoning that the monotonic functions used in the regression equations, as required in TXEMP, simply cannot represent the response of productivity to flow over the entire range of flows. Data were eliminated for years in which "large" floods occurred during the months (or immediately prior months) when the species are in the bay. The elimination of these data points was not based on the assumption that they were aberrant or anomalous due to measurement inaccuracies or other reasons, but rather that they did not fall within a range in which a monotonic response would be expected. While identifying "high" flows is subjective, it was felt to be necessary due to the above restrictions.

Conceptual model

The above assumptions are summarized below in a conceptual model for the flow-productivity equations:

1) Juvenile species are representative of potential productivity and good candidate measures since they are less influenced by other external pressures than more adult species. Simple models to relate inflows to productivity are more likely to succeed with juvenile species than with more mature species.

2) Freshwater inflows influence salinity, nutrient supply and habitat. The bay is not nutrient limited nor habitat impaired under the normal range of flows considered in TXEMP. The response of juveniles to salinity is a primary response relative to responses to nutrients and habitat.

3) Some juvenile species in Matagorda Bay have strong seasonal preferences (i.e., they are found in the bay during specific seasons). Simple equations that relate the response of these species to inflows should include flows during or immediately prior to the seasons during which the species are found in the bay. The beneficial effect of inflow in moderating salinity and in providing nutrients is assumed to be most influential during the months in which the species are observed to be in Matagorda Bay and decreases in significance away from that period.

4) The immediate effects on productivity of droughts and large floods are both assumed to be negative relative to “normal” flow conditions, since droughts and floods strongly influence salinity. Monotonic functions relating flow to productivity cannot adequately represent both the increasing and decreasing response of productivity to extreme inflow conditions. Since monotonically increasing functions are used to represent flow and productivity due to restrictions imposed by the application of TXEMP in this study, the range of data must be limited to a region in which a monotonic response is justified.

Application

Different species require different approaches to development of equations relating inflow to productivity. Although the all-possible-subsets approach succeeded with some species, it was not adequate for others. For these species, the above description provides a simple conceptual model for the equations that were developed. It attempts to limit the analysis to data meeting the monotonic-function model assumptions. It reduces the likelihood that data outside this range will generate spurious results simply because they do not meet the model assumptions. It simplifies the analysis and allows for immediate use in the existing TXEMP formulation. Finally, it can be accomplished in relatively short time.

The equations developed here are highly restricted in their applicability. It would be ideal if an equation relating inflow to all life stages of a species (based on data from the different gear types in the TPWD Coastal Fisheries database) and overall flow ranges could be developed. However, this is impractical given the available data and complexity of estuarine ecosystems. Instead, equations relating flow to a particular life stage (one gear type), and in some cases over limited flow ranges, were developed. Constraints in TXEMP limit use of the equations over specific flow ranges, so this was chosen as a more appropriate approach for this analysis. Further studies should investigate the development of quadratic or higher-order equations relating flow to productivity, and use of these forms of equations in TXEMP. Further basic studies on the effects of floods in providing nutrients to recharge the system are needed. Time series or other types of models should be pursued to allow for more complex descriptions of bay productivity.

3.5 Species Abundance Relationships

Statistically significant regression equations for mullet, menhaden, red drum, blue crab and oyster were developed using the all possible subsets approach for the post diversion period (Table 3.7). The equations estimate abundances based on bi-monthly seasonal inflow into the estuary. For example, the blue crab equation explains the annual catch based on freshwater inflows occurring in March-April, May-June, and September-October. Flows during March-April negatively influence annual catch, while flows in May-June and September-October bolster productivity. Statistically significant equations were investigated, but none could be identified, for black drum, spot, Atlantic croaker, grass shrimp or spotted sea trout with this approach. Flounder were not evaluated because they are not effectively captured with any gear type.

Equations for white shrimp and brown shrimp were developed using a simple linear technique relating bimonthly flows that were concurrent with peak abundance as seen in Table 3.7. Both species demonstrated strong seasonal occurrence in bag seines. Since the relationships were linear, a plot of the relationship between annual abundance and productivity is provided for brown and white shrimp. The relationship between freshwater inflow and species abundance for other species were described with multiple regression equations, making it difficult to demonstrate graphically.

The annual density of brown shrimp strongly correlates to inflows during May-June. Decreased annual productivity is demonstrated when flows during this bimonthly period are either extremely high or low (Figure 3.14). This behavior led to the selection of May-June flows for the brown shrimp equation (Figure 3.15). However, larger flows were eliminated from the analysis to limit the data to a region in which a linear response is justified. These flood flows are outside of the range of what would be considered optimal.

The annual density of white shrimp strongly correlates to inflows during July-August. Decreased annual productivity is demonstrated when flows during this bimonthly period are extremely high or low (Figure 3.16). This response led to the selection of July-

August flows for the white shrimp equation (Figure 3.17). As with brown shrimp, larger flows were eliminated to limit the data to a region where a linear response is justified.

Table 3.7 Catch as a Function of Inflow* for the Seven Target Species.

Target Species	**Discharges (Q)**						
	Constant	Jan-Feb	Mar-Apr	May-Jun	Jul-Aug	Sep-Oct	Nov-Dec
Brown Shrimp	85.63			.003			
White Shrimp	56.36				.001		
Blue Crab	-19.98		-3.38**	6.77**		3.86**	
Eastern Oyster	17.01			- .0000079	.000016		
Striped Mullet	7.00	10.20**				-7.51**	
Gulf Menhaden	-468.71	538.68**				-335.89**	
Red Drum	3.626				1.06**	.796**	-1.58**

* Post-diversion period data were used.
** Indicates the natural log of inflow. The September-October term was lagged 1 year for Menhaden and Striped Mullet.

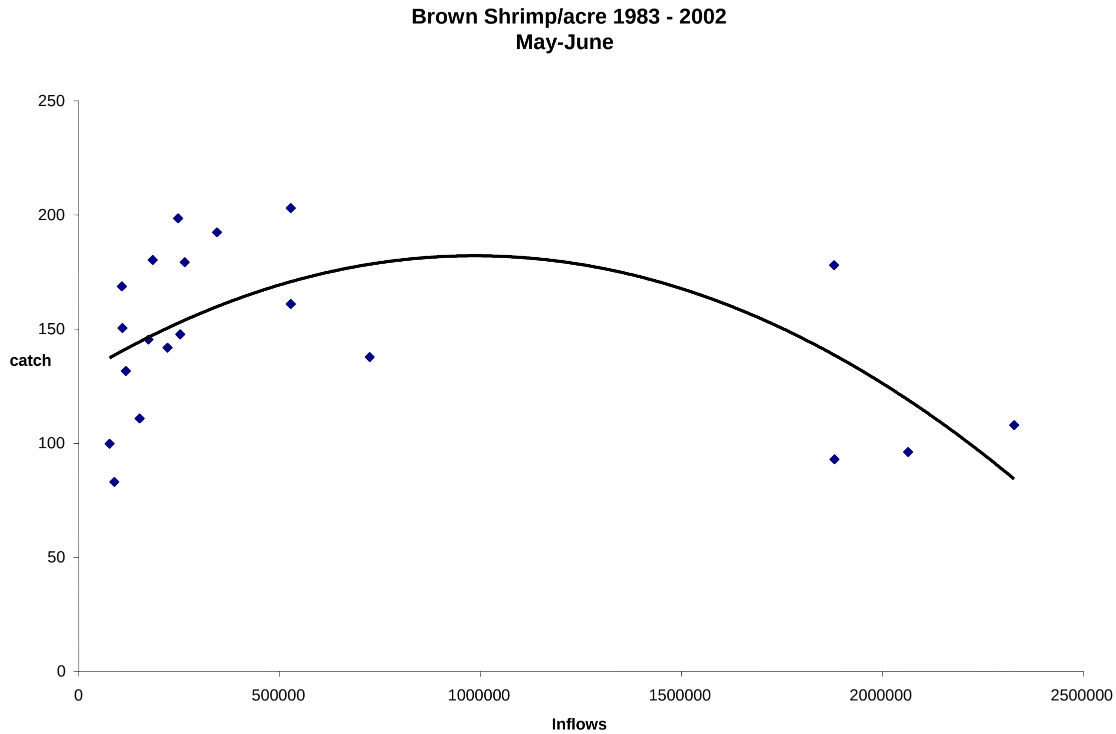


Figure 3.14 Annual Brown Shrimp Density (individuals/acre) to May-June Inflows.

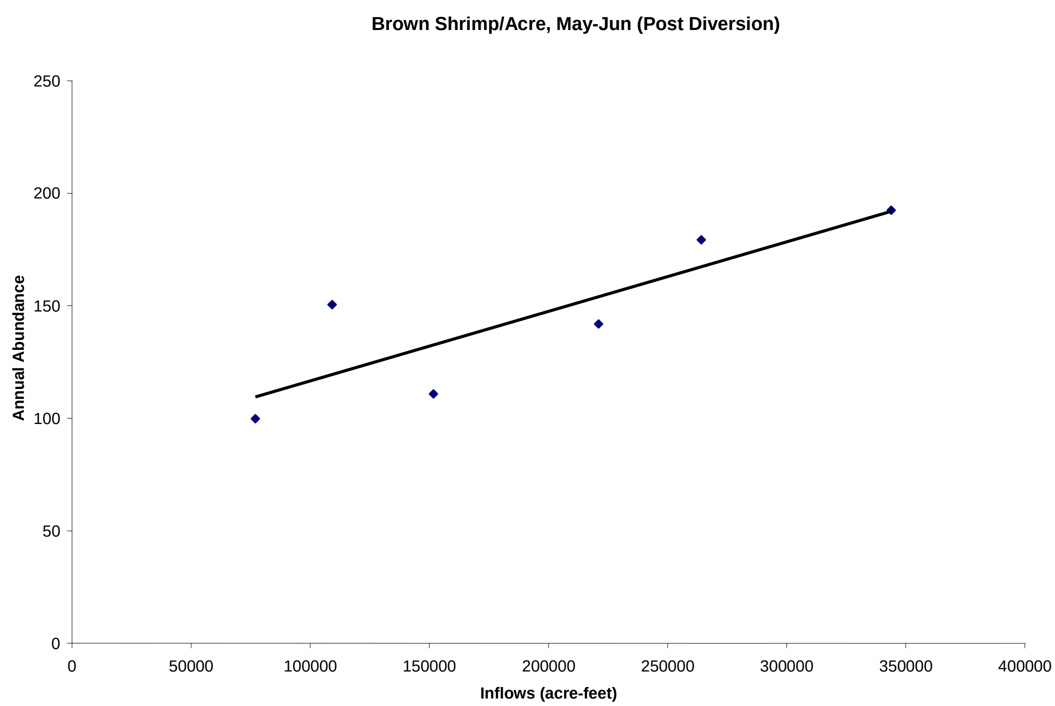


Figure 3.15 Relationship between Annual Brown Shrimp Abundance and May-June Inflows.

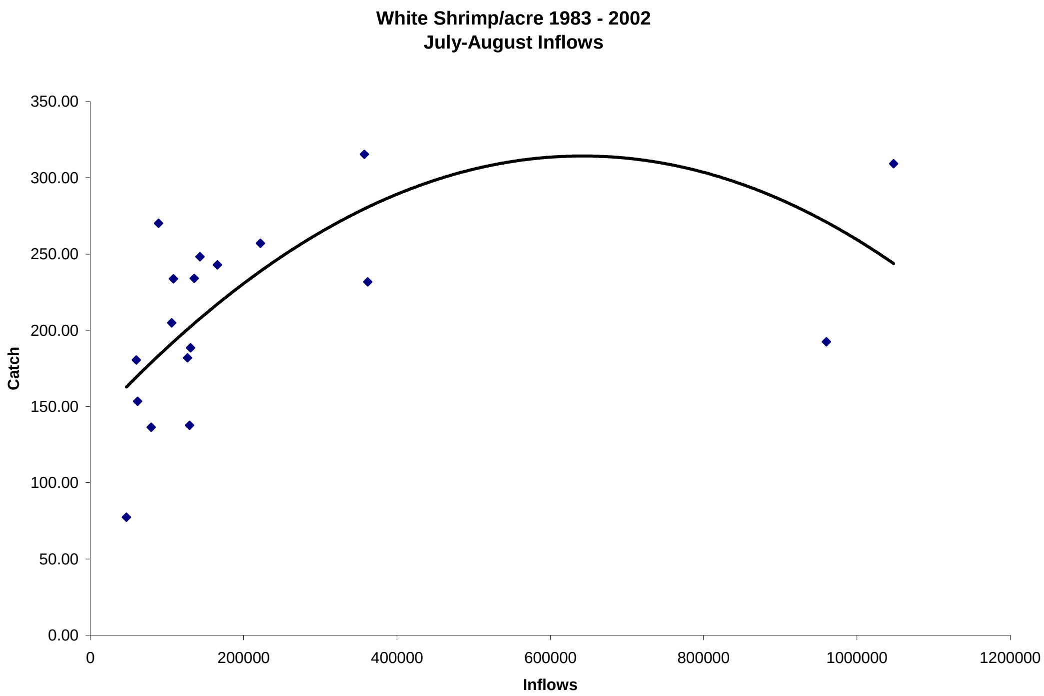


Figure 3.16 Annual White Shrimp Density (individual/acre) to July-August Inflows.

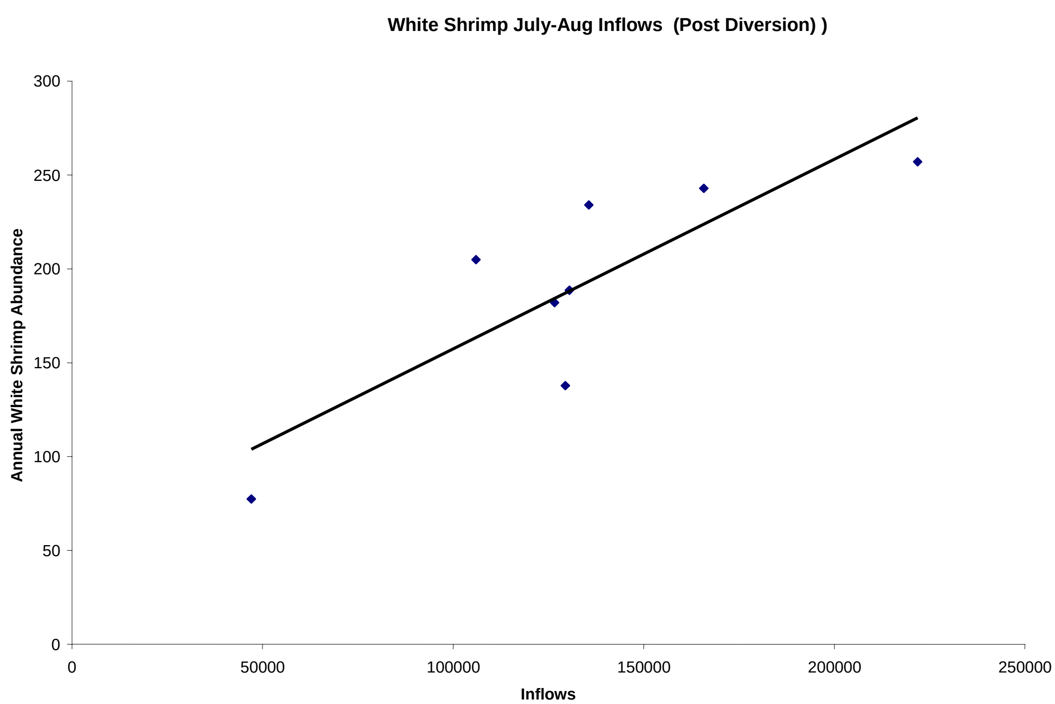


Figure 3.17 Relationship between Annual White Shrimp Abundance and July-August Inflows.

The statistical equations indicate a relationship between freshwater inflow and juvenile abundance. Freshwater inflows are important in establishing chemical and physical conditions in the estuary needed by many estuarine organisms. Thus, the simple multiple regression models attempt to capture this fundamental relationship between freshwater inflows and productivity of key species. Since freshwater inflows are the only independent variable, other potentially important factors to productivity are excluded from the models. The health and abundance of specific organisms rely on a healthy source population, ability to enter the system, and the availability of appropriate combinations of physical and chemical conditions and food resources (Ward, 1999). Thus, many factors unrelated to freshwater inflow affect abundance.

CHAPTER 4

Matagorda Bay Salinity

4.1 Introduction

The biological productivity of Matagorda Bay depends in part on maintenance of a salinity gradient between fresh and marine waters. This gradient is preserved by maintaining appropriate quantities of freshwater inflows (Longley, ed., 1994). Fortunately, a significant amount of salinity monitoring and historical data over much of Matagorda Bay is available. This data was used to derive relationships between salinity to changes in freshwater inflows from the Colorado and Lavaca rivers. These relationships are to be used for several aspects of this study, including the support and calibration of the TXEMP model and computation of the minimum flows needed to maintain critical salinity levels at select locations within the bay. Relationships for use in TXEMP are described in Chapter 5 and relationships for evaluating critical salinities are described in Chapter 6. This chapter describes the data sources and general characterization of salinity within Matagorda Bay.

4.2 Need to Update Salinity-Inflow Relationships

Salinity data used in the prior FINS study (LCRA, 1997) was limited to only five years following the Corps of Engineers diversion project. That leaves insufficient data to predict a relationship between salinity and bay health. Discrepancies were observed between the levels of salinity that had been predicted and what was observed at the West Bay Tripod in the eastern arm of Matagorda Bay during the drought in the summer of 2000. This led to a review of the relationships developed in the prior study. Data collection also has improved in recent years and now provides significantly more data with fewer gaps. The purpose of updating these equations is to develop relationships with fewer predictive errors.

4.3 Salinity Data

Salinity data in Matagorda Bay is collected by LCRA, TWDB and Texas Parks and Wildlife Department (TPWD) Coastal Fisheries Program. The analysis for this study primarily used the intensive site-specific data collected using automated measuring devices (datasondes) operated by TWDB in Lavaca Bay and data collected by LCRA in the eastern arm of Matagorda Bay. The datasondes operate continuously and sample hourly. Data collected by TPWD for the fisheries program began around 1976 with an increase in sampling around 1982. The data is collected from grab samples using a refractometer and is recorded to the nearest part per thousand (ppt).

4.3.1 Site-Specific Salinity Data

Site-specific salinity data is collected at three sites in Matagorda Bay. In late 1992, LCRA installed two datasondes to provide hourly measurements of salinity, dissolved oxygen, pH and other field parameters. The devices are located in Matagorda Bay (Figure 4.1), with one near the mouth of the Colorado River Diversion Channel, called West Bay Tripod (Site A), and the other on the GIWW called Channel Marker #4 (Site B). The data collected by this method is considered to be accurate to within +/- 2 ppt.

Prior to 1998, instrument malfunction and the need to temporarily relocate datasondes for other studies led to notable data gaps. However, improved maintenance and reliability of the LCRA datasondes resulted in significantly improved records after 1998. Salinity at the West Bay Tripod was recorded hourly during most of the period from 1993 through present.

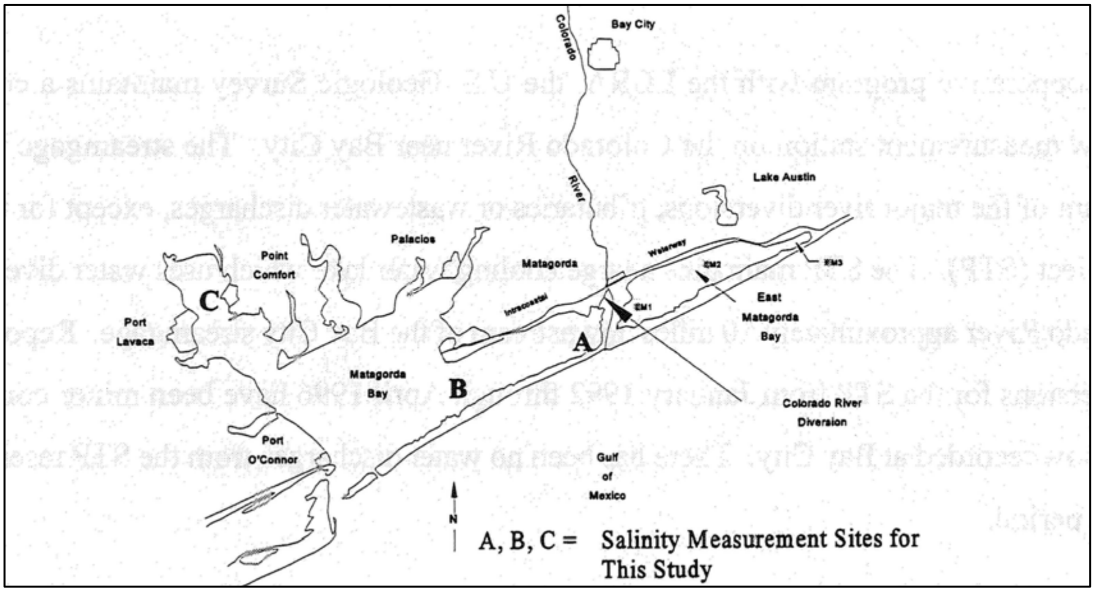


Figure 4.1 Locations of Site Specific Salinity Measurement Stations.

Beginning in 1986, TWDB installed a similar continuous monitoring station in upper Lavaca Bay (site C in Figure 4.1). This station has collected hourly measurements of field parameters, including salinity. Data from this source was used in developing relationships for Lavaca Bay.

The site specific data provides a consistent location and sampling methodology that is preferred for the development of statistical relationships to support TXEMP and critical flow conditions analysis.

Particular attention was given to the salinities in the eastern arm of Matagorda Bay as this is the area of greatest anticipated influence of the recent Corps of Engineers diversion project. Typical day to day variation in salinity at the West Bay Tripod is from 1 to 5 ppt. Salinity changes are influenced by tides, inflows, evaporation and mixing, among other factors. Figure 4.2 illustrates the frequency of positive and negative changes in salinity at the West Bay Tripod. As seen in the figure, the likelihood of salinity increase is about equal to the likelihood of a decrease. Salinity decreases more than 2.8 ppt in a day or 5.6 ppt in a week only 10 percent of the time. Conversely, about 10 percent of the time salinity increases more than 2.4 ppt in a day and 5.5 ppt in a week.

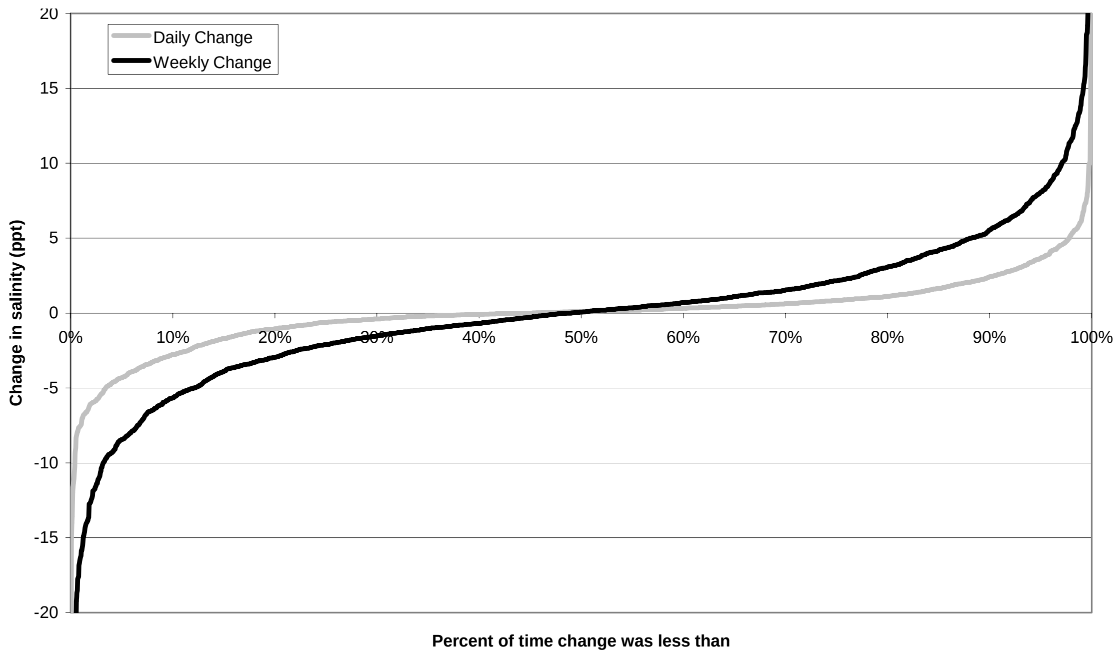


Figure 4.2 Frequency of Salinity Change at the Western Tripod 1993 to 2002.

4.3.2 Bay Wide Salinity Data

TPWD Coastal Fisheries data is useful in characterizing salinity in Matagorda Bay because of its spatial variability, good coverage and long period of record.

Spatial variation of monthly salinity averages were developed using GIS by interpolating between data observations using an inverse distance weighting (IDW) method to identify typical salinity neighborhoods and gradients.

Monthly bay-wide salinity observations are presented in Figures 4.3 through 4.14. Lower salinity is depicted in green and higher salinity is depicted in red. The clustering of low salinity readings near the mouths of major and minor tributaries is demonstrated, and the clustering of higher salinity near points of major tidal inflows is similarly identified. The variation in salinity patterns can be compared month to month. Salinity gradients for individual months may appear overly severe on a localized basis due to influence of isolated observations. Additional research into this area, such as upper and lower quartile spatial salinity gradients as well as other return periods and larger averaging areas, could also be informative.

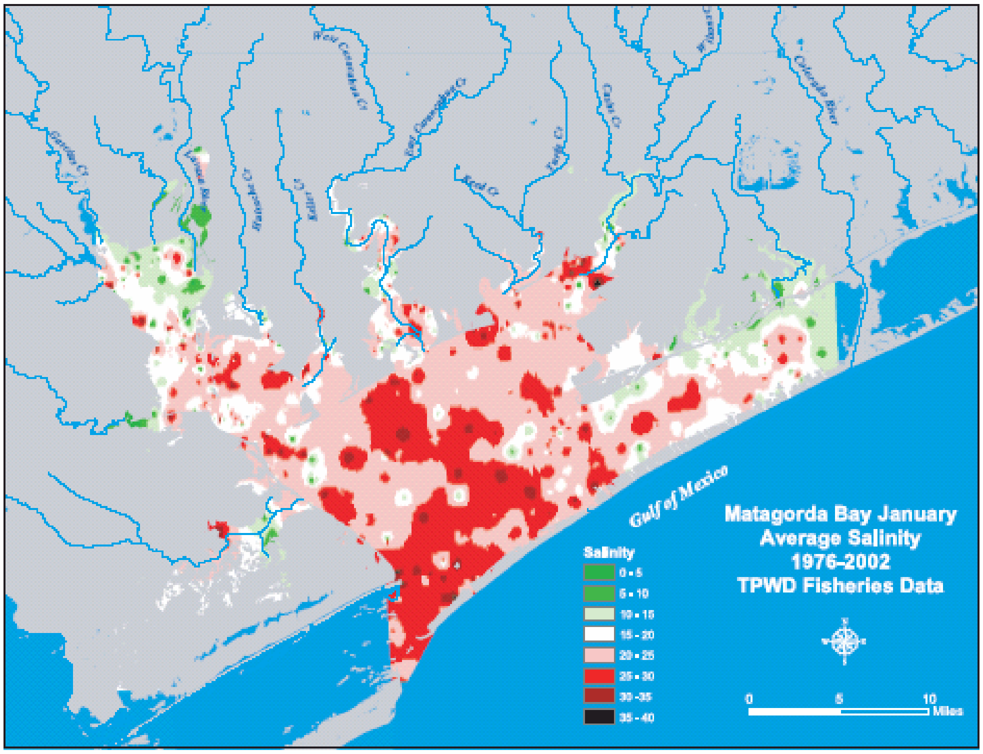


Figure 4.3 Average Salinity Zones for January.

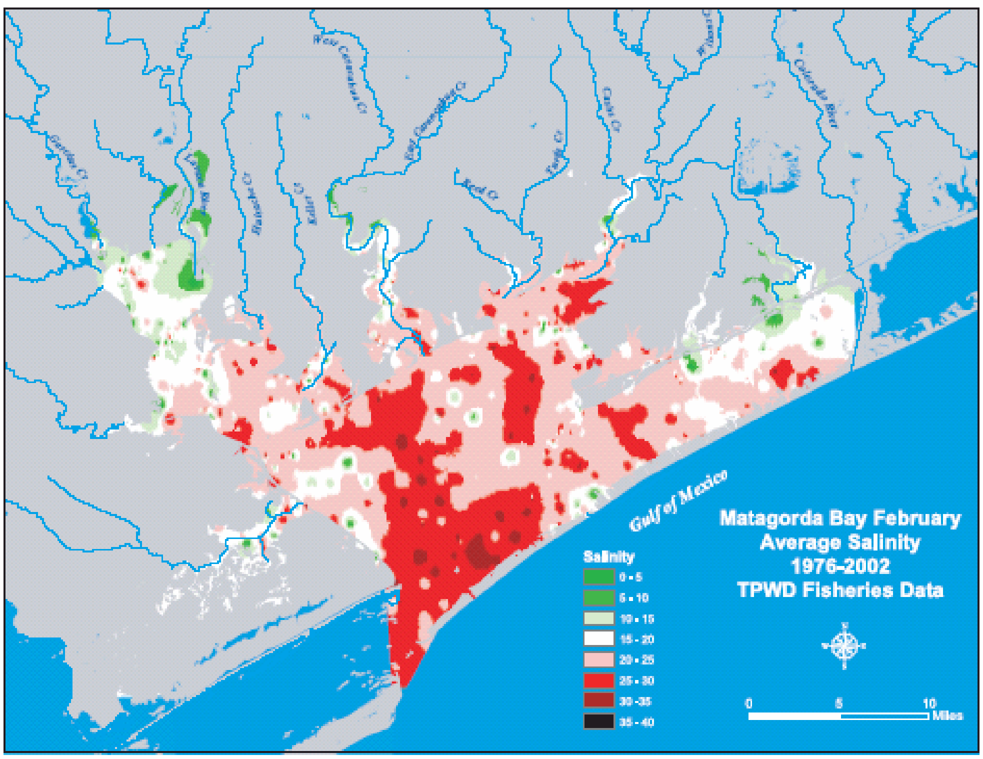


Figure 4.4 Average Salinity Zones for February.

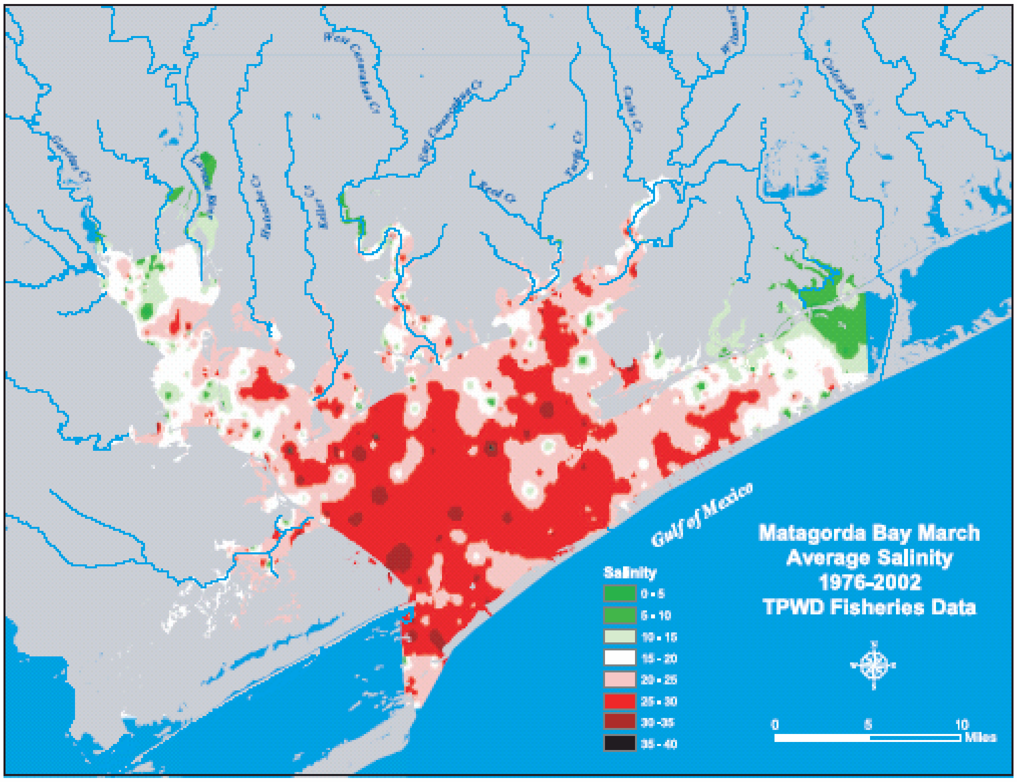


Figure 4.5 Average Salinity Zones for March.

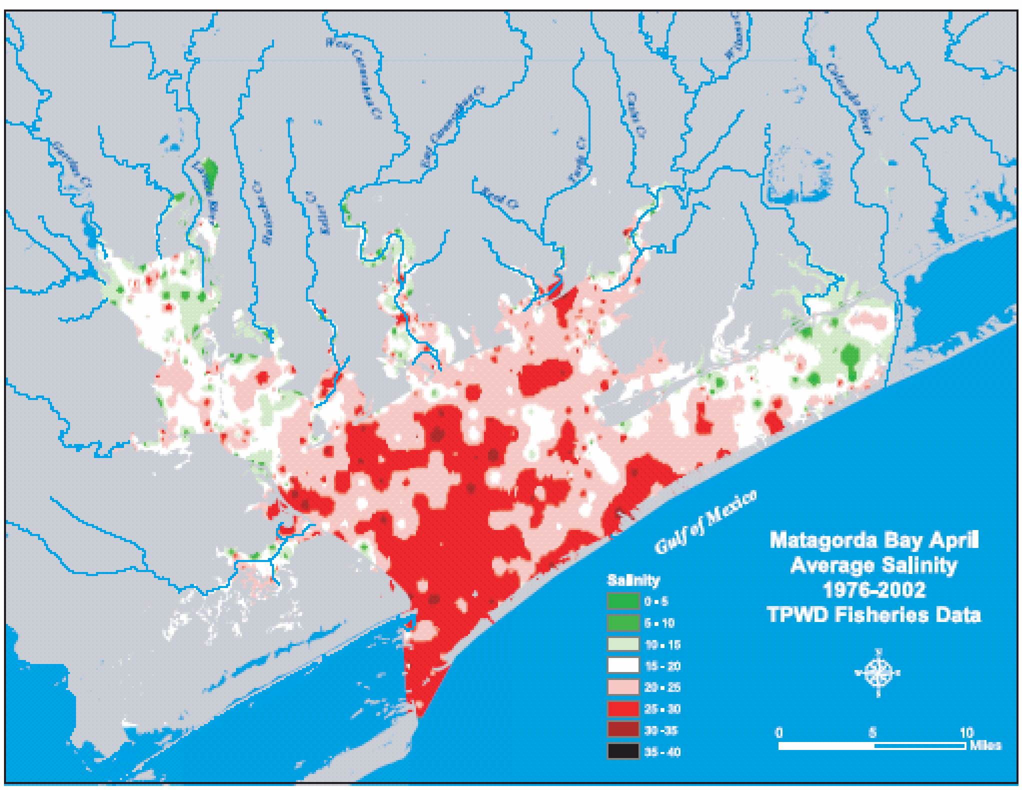


Figure 4.6 Average Salinity Zones for April.

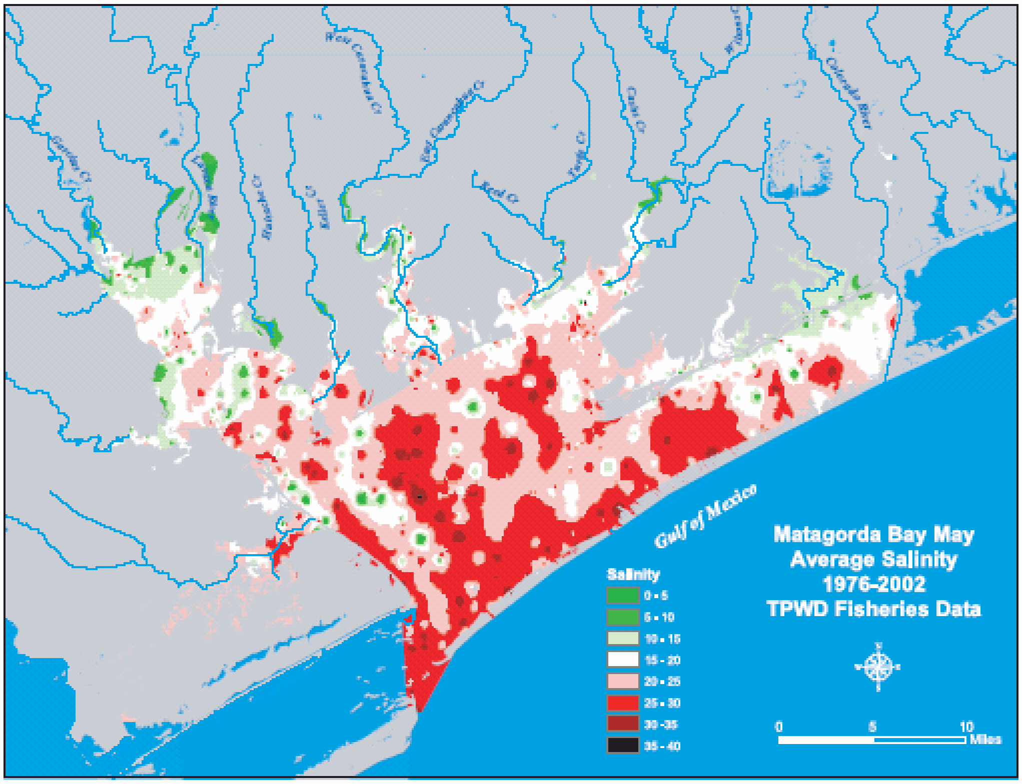


Figure 4.7 Average Salinity Zones for May.

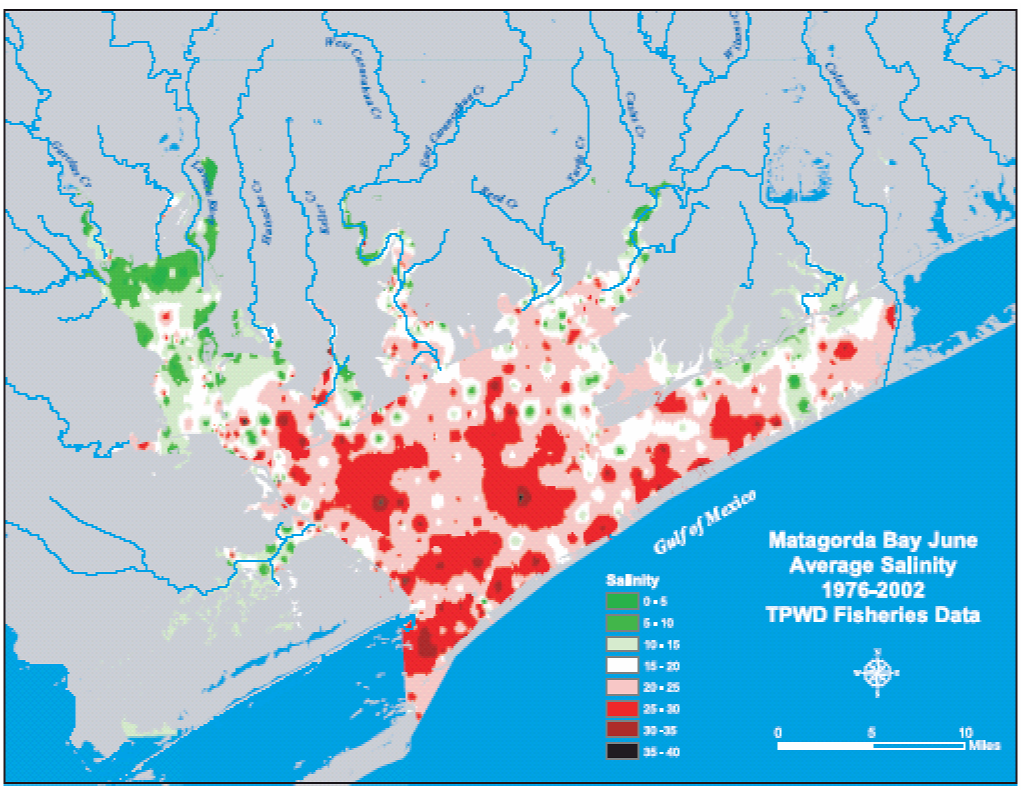


Figure 4.8 Average Salinity Zones for June.

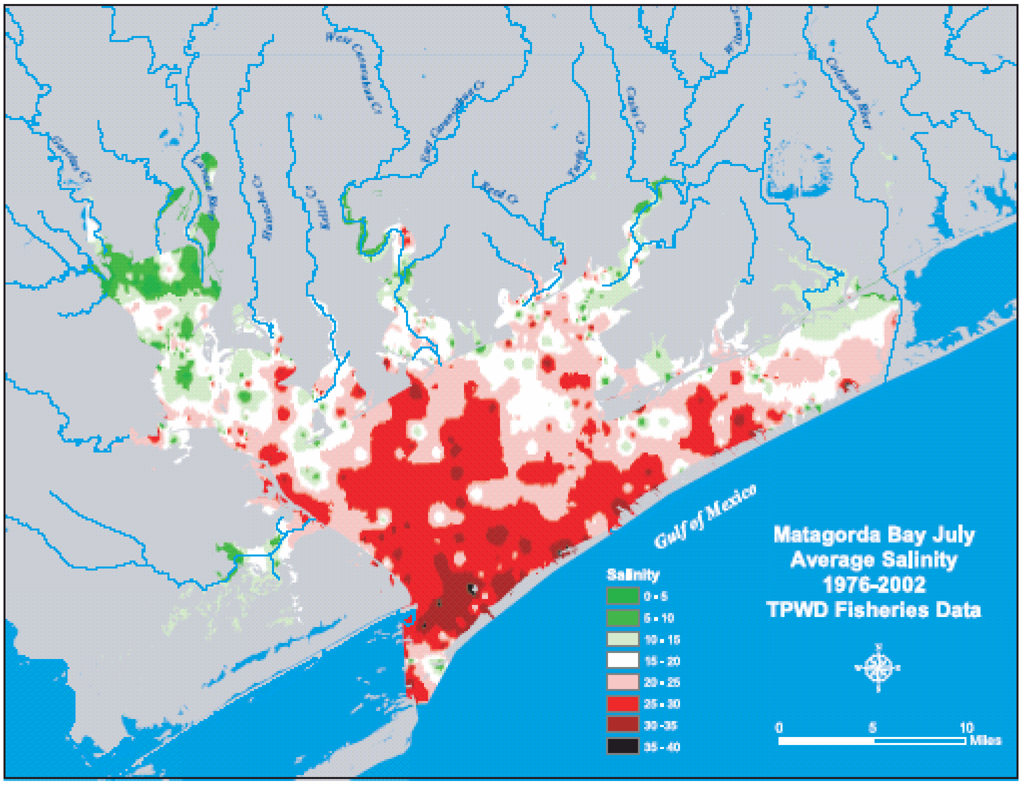


Figure 4.9 Average Salinity Zones for July.

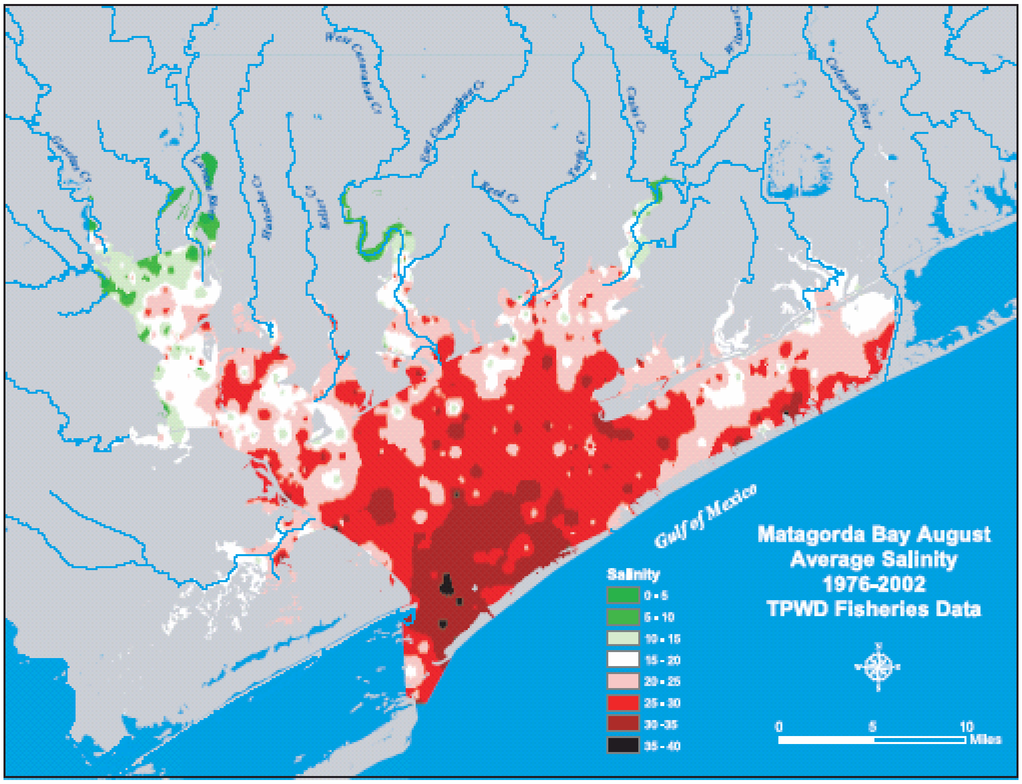


Figure 4.10 Average Salinity Zones for August.

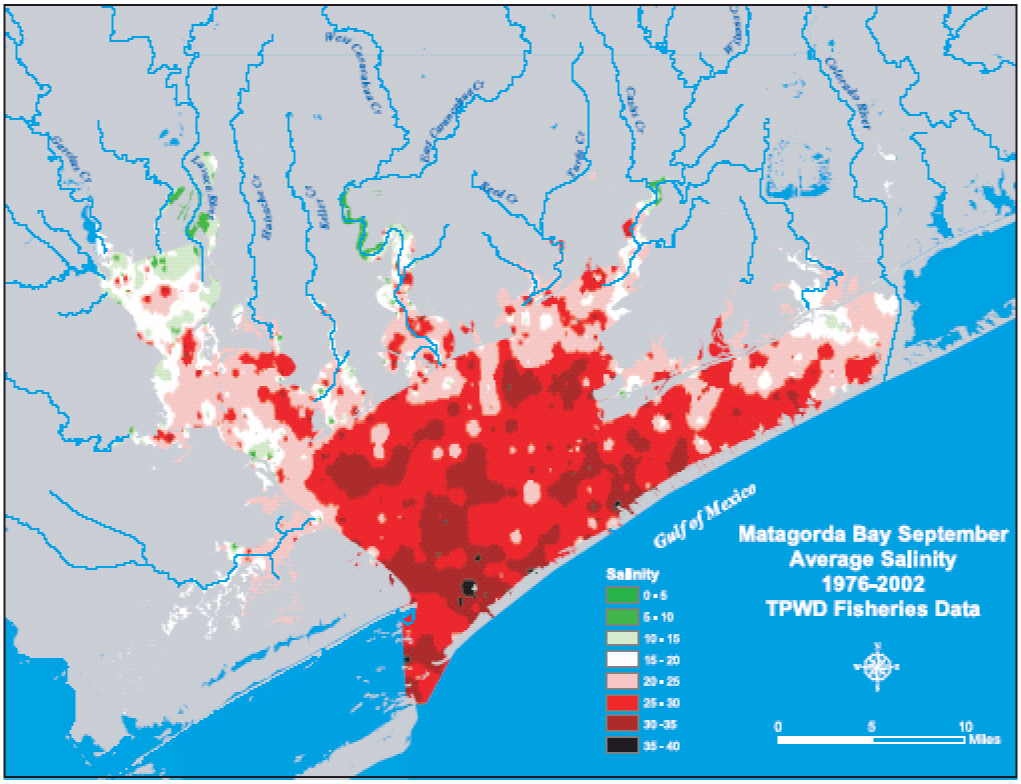


Figure 4.11 Average Salinity Zones for September.

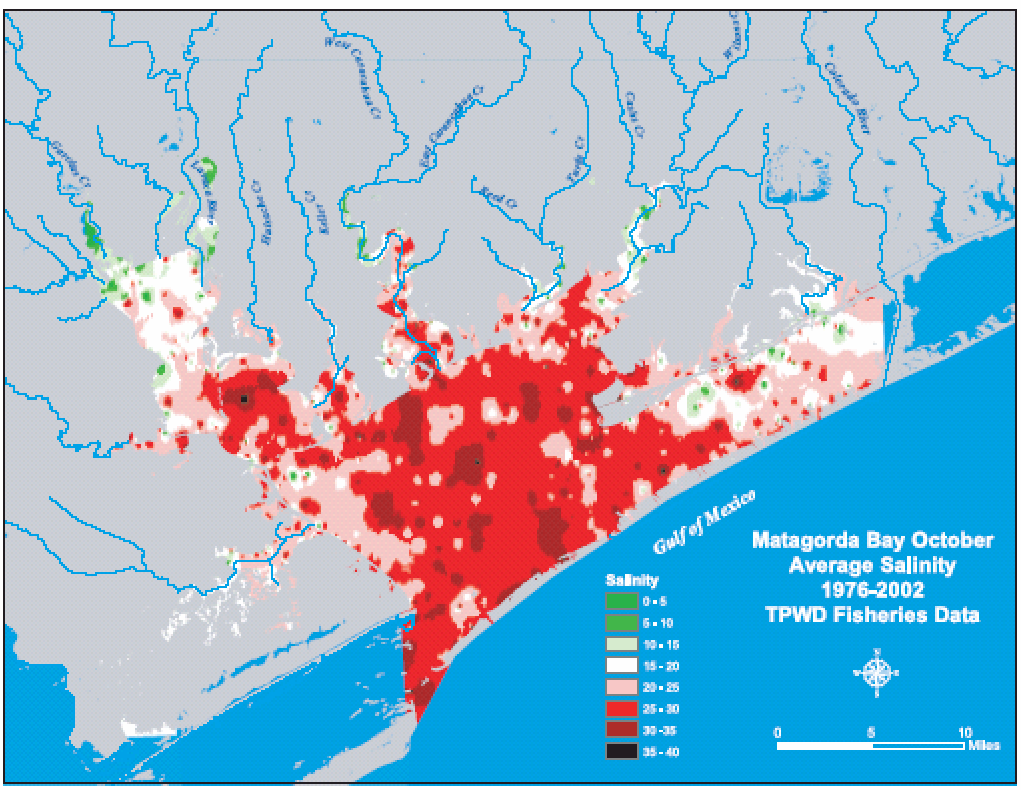


Figure 4.12 Average Salinity Zones for October.

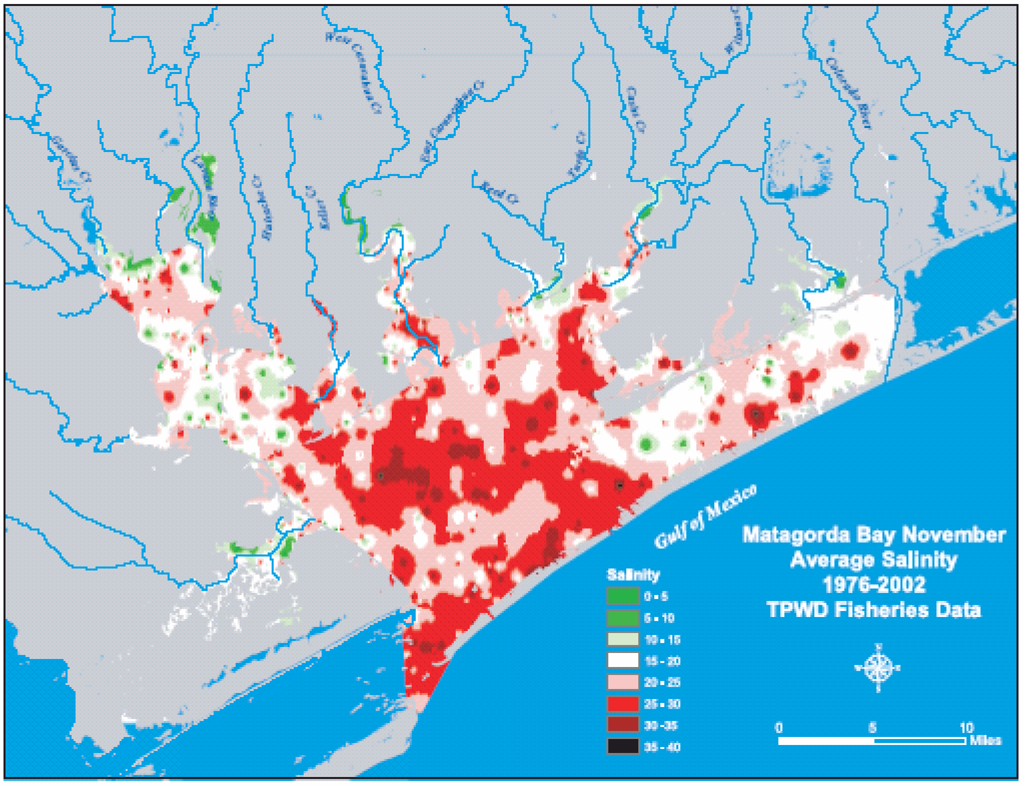


Figure 4.13 Average Salinity Zones for November.

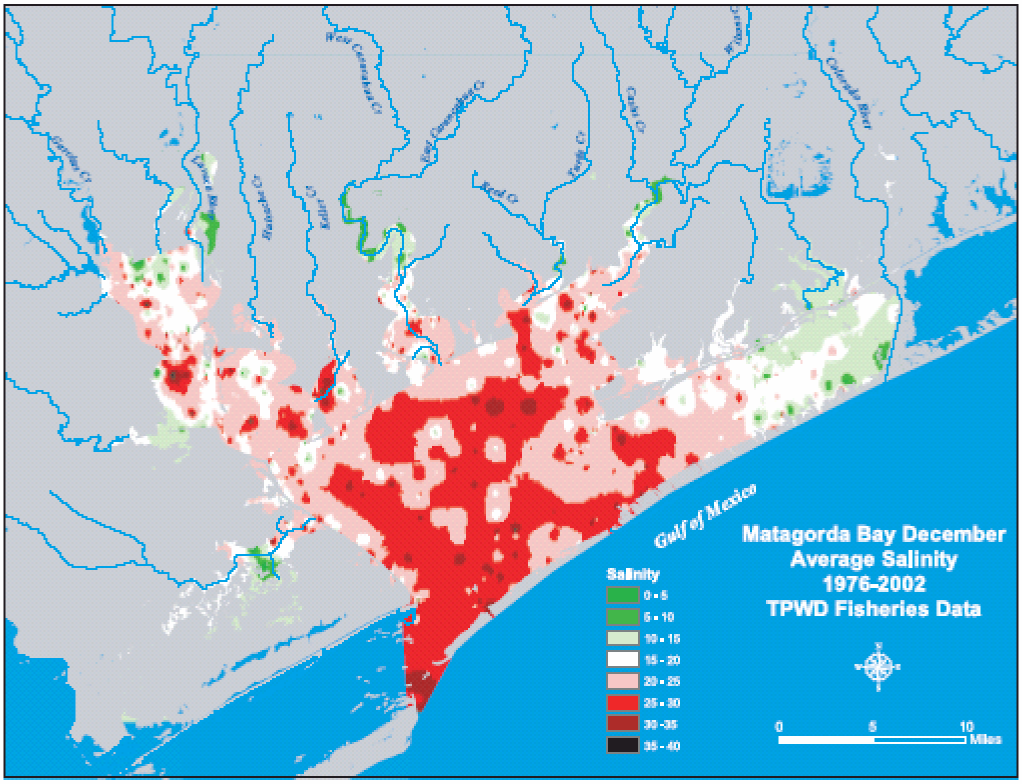


Figure 4.14 Average Salinity Zones for December.

Salinity frequencies for the secondary and tertiary bays of Matagorda Bay are depicted in Figure 4.15. Lavaca Bay is shown to be the freshest secondary bay, with the open bay and the western half of the eastern arm being the most saline.

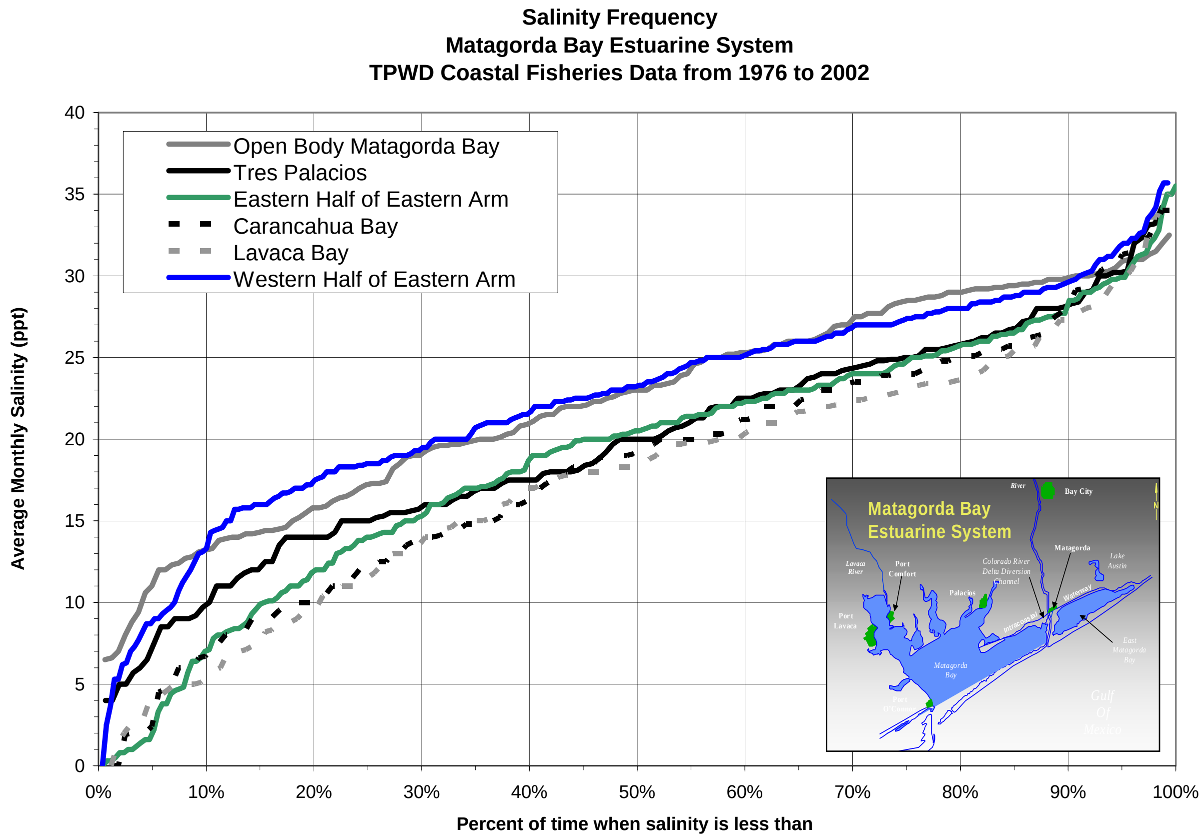


Figure 4.15 Salinity Frequencies in Matagorda Bay.

4.3.3 Matagorda Bay Eastern Arm Characterization

TPWD data was applied to evaluate salinity in the eastern arm of Matagorda Bay before and after the Mouth of the Colorado River Diversion Project. The average salinity for these periods is summarized in Table 4.1. The salinity is spatially described in four quadrants of the arm which are illustrated in Figure 4.16. Freshening of the bay after the diversion is likely due not only to the diversion but also to above normal inflows during this period, as illustrated in Figure 2.4 of the Hydrology Chapter.

Table 4.1 Average Salinity Pre- and Post-diversion in the Eastern Arm of Matagorda Bay-TPWD Coastal Fisheries Data.

Quadrant	1976 to 1990 (ppt)	1991-1998 (ppt)	Change (ppt)
Northwest	23.4	18.2	-5.3
Northeast	20.0	15.3	-4.7
Southwest	25.2	22.1	-3.1
Southeast	23.5	16.8	-6.7

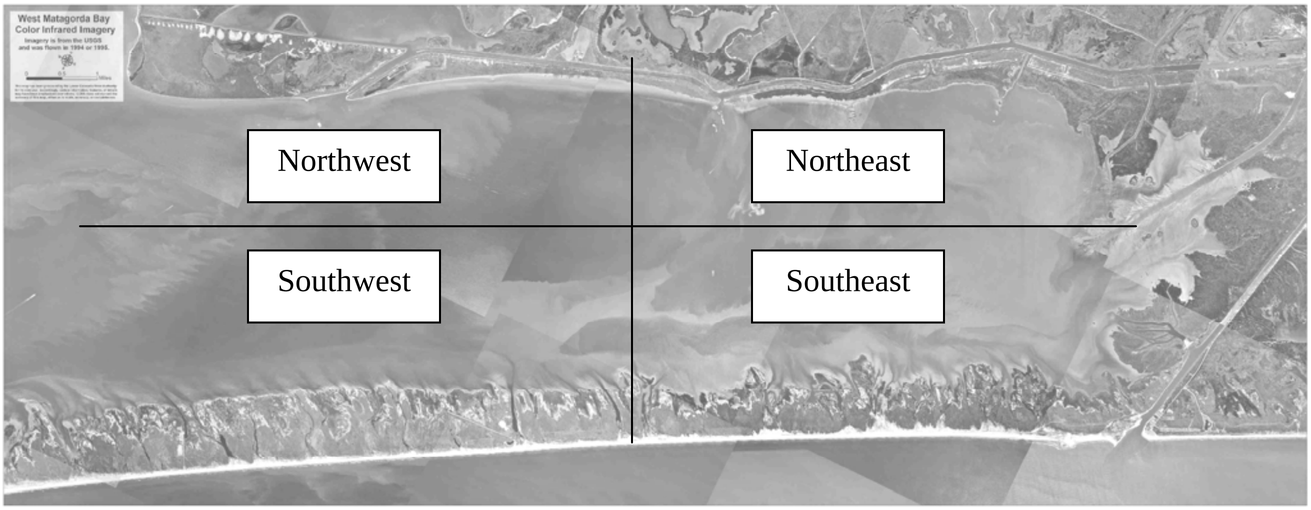
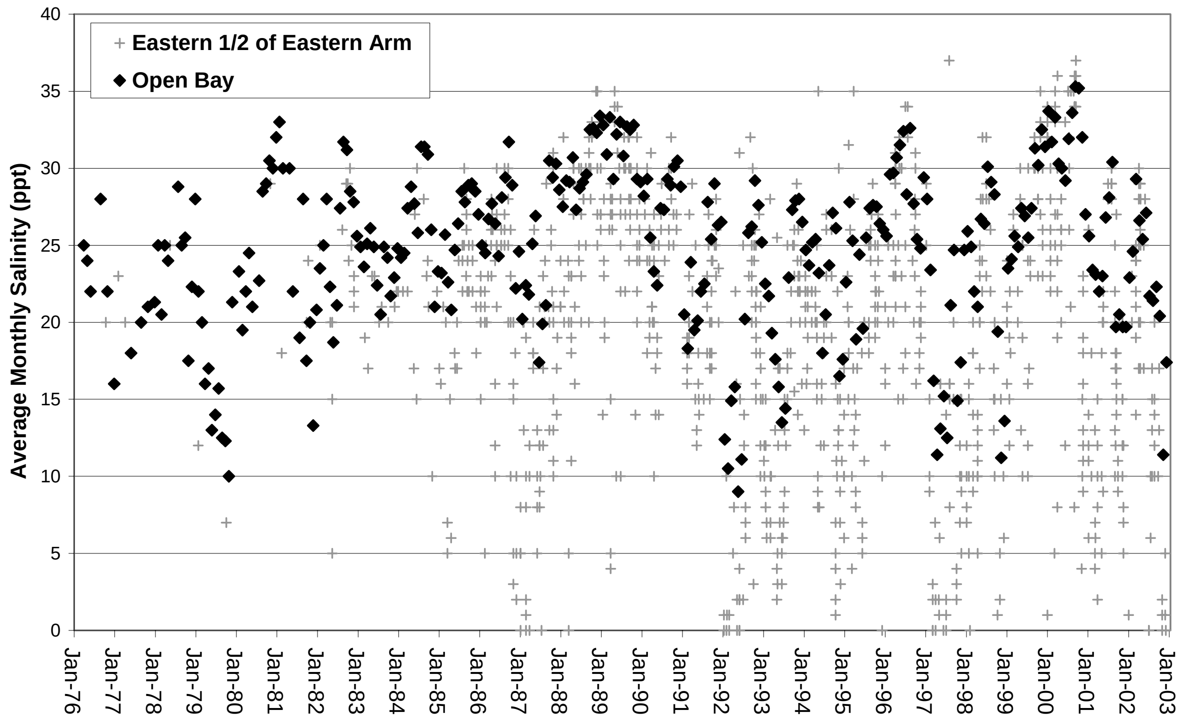


Figure 4.16 Quadrants of the Eastern Arm of Matagorda Bay.

Similarly data from the northeast and southeast quadrants were combined to examine salinities in the eastern half of the eastern arm. This area roughly approximates the region identified as a nursery and refuge during drought conditions. Salinity in this region has ranged from 0 ppt to 37 ppt over the period of March 1976 to December 2002 as shown in Figure 4.17. Summary statistics are also presented in Table 4.2.



*Diversion channel inflow to the Bay started in 1992.

Figure 4.17 Monthly Salinity in the Eastern Half of the Eastern Arm and Open Bay of Matagorda Bay - TWPD Coastal Fisheries Data.

Table 4.2 Comparison of Eastern Half of the Eastern Arm of Matagorda Bay to the Open Bay from 1976-2002.

Statistic	Open Bay Monthly Value (ppt)	Eastern ½ East Arm Monthly Value (ppt)
Mean	24.74	19.05
Standard Deviation	5.37	8.62
Median	25.40	20.00
Minimum	9.00	0.00
Maximum	35.30	37.00

CHAPTER 5

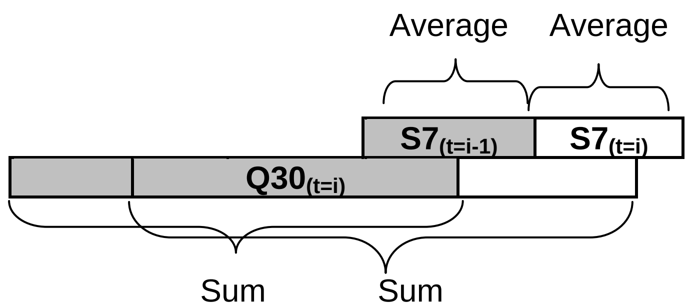
Development of Salinity Inflow Relationships for Use within TXEMP

5.1 Introduction

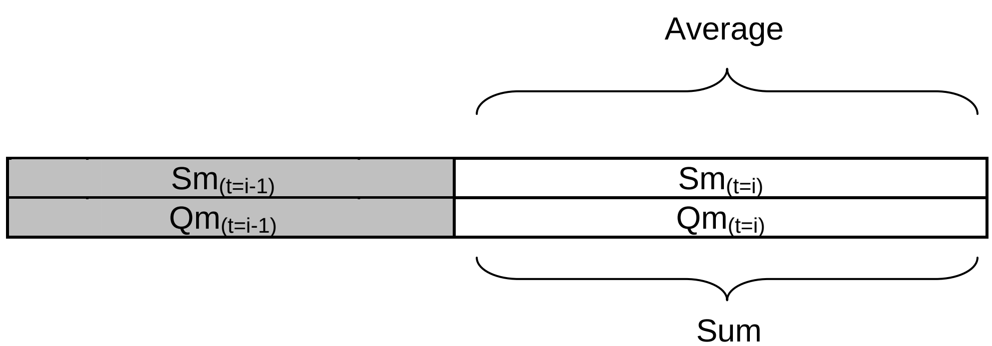
The purpose of this analysis is to determine the relationship between salinity at several locations in Matagorda Bay and changes in the freshwater inflows. Two equations are recommended, one for the West Bay Tripod related to the Colorado River inflow and one for Lavaca Bay related to the Lavaca River. These relationships are to be used within the TXEMP model for simulation of salinities at constraint locations. This analysis used salinity data presented in Chapter 4. The differences between prior study and current study results are also presented.

5.2 Methodological Differences from Prior Study

The prior study made use of a relationship between a straddled and lagged seven-day average salinity to a 30-day river flow. This strategy made effective use of limited salinity data but led to a high level of autocorrelation. It also served as a reasonable proxy for the monthly salinity and flow input requirements of TXEMP. However, with the benefit of increased monitoring intensity following the Mouth of the Colorado River Diversion Project, this proxy is no longer needed for Matagorda Bay. For purposes of this study, matched pairs of monthly average salinity and total monthly flows were used in all regression relationships. Both the 1997 and the current strategies are illustrated in Figure 5.1.



1997 Study straddled relationship



2005 Study matched pairs relationships

Figure 5.1 Development of Time Series Data Sets and Regression Equations.

5.3 Colorado River Influence at West Bay Tripod

5.3.1 Ordinary Least Squares (OLS) Regression: Monthly Salinity-Inflow Relationship

A variety of multivariate relationships were tested to discover patterns between monthly Colorado River flows passing the South Texas Project and observed mean monthly salinity at the West Bay Tripod. Seasonal, flow-range specific and salinity-range specific relationships were tested but did not perform better than a generic monthly model. This finding confirms the results of prior studies (LCRA, 1997).

A minimum threshold of 25 observations was applied for a given month before that monthly average salinity entered the model because the high quality salinity dataset was available at this location. The sample for the regression analysis consisted of 62 monthly average observations. Although the salinity data collected at West Tripod Bay started in 1992, instrument malfunction led to notable data gaps up to 1998. In all instances, a natural logarithmic transformation of the flow variables significantly improved the predictive equations results. The best fit equation is a multivariate equation of the form given by Equation 5.1 and includes the freshwater inflows for the current month and the two prior months.

Equation 5.1 Monthly Salinity-Inflow OLS Relationship for West Bay Tripod

$$SM_i = 106.62 - 4.13 \times LN(QM_i) - 2.05 \times LN(QM_{i-1})) - 1.53 \times LN(QM_{i-2)})$$

where: i = month
Qm_i = Total Monthly Flow past STP for month i (acre-feet)
Sm_i = Average Monthly Salinity at West Bay Tripod for month i (ppt)

Solving Equation 5.1 for flow in 1,000 acre-feet for use in TXEMP gives:

$$Sm_i = 53.37 - 4.13 \times LN(Qm_i / 1000) - 2.05 \times LN(Qm_{i-1} / 1000) - 1.53 \times LN(Qm_{i-2} / 1000)$$

The relationship suggests an adjusted R-square value of 78 percent and a standard error of 3.53 parts per thousand of salinity (ppt). Each of the independent variables is significant at the 95 percent confidence level. However, the relationship has a Durbin-Watson statistic of 1.45, which indicates some serial autocorrelation but is within the 1.3 to 2.7 range of acceptability (Hilton, 2004). Full regression results are provided in Appendix D. The presence of autocorrelation reduces the statistical inference and confidence in these traditional measures of fit.

5.3.2 Advanced Regression Techniques: Monthly Salinity-Inflow Relationship

The presence of autocorrelation in the residuals has been largely ignored in fields other than econometrics (Thejll, 2003). However, there was interest for the purpose of this study to investigate how the salinity relationship could be improved by better understanding the nature of the autocorrelation and possibly removing its influence.

The Durbin-Watson statistic of 1.45 revealed the presence of some autocorrelation, which was anticipated for time series data. Multi-lagged autocorrelation analyses revealed that the nature of the serial autocorrelation was greater than first order but diminished significantly with sequential lags. Nielsen (2004) identifies the following implications of an ordinary least squares (OLS) relationship with autocorrelation:

> *Because of auto-correlation:*
> *1. The OLS and true regression lines may differ sharply from sample to sample depending on the initial disturbance*
> *2. MSE {mean square error} may underestimate true variance of error term, thus standard errors of estimate of the regression coefficients may also be underestimated*
>
> *In general, auto-correlation of the disturbances may have the following effects with OLS estimation:*
> *1. Estimated regression coefficients are still unbiased but no longer minimum variance*
> *2. MSE (the OLS estimate of variance) may underestimate the true variance of errors may underestimate true standard error of estimate. Thus, statistical inference using t and F tests is no longer justified*

Nielsen identifies five methods of remediation for first-order serial autocorrelation. The first is to include missing independent variables. However, this was not practical for application with TXEMP. The four remaining methods are the Cochrane-Orcutt (C-O), the Hildreth-Lu (H-L), the first differences and regression model with autocorrelated errors. The C-O, H-L and the first differences approaches involve transformation of the current observation with the help of previous observation. These methods are reasonably tolerant to missing data. Finally, the regression with an explicit model for the error term is good for a dataset with minimal missing values so that the error term can be sufficiently characterized.

The first approach was not feasible for use in TXEMP but is employed for Critical Flow analyses of Chapter 9. The C-O and H-L transforming methods were also attempted. They showed that a first order autocorrelation correction was sufficient to remove undesirable effects of autocorrelation and that the autocorrelation was most problematic due to the salinity term and not the flow terms. Unfortunately, because application of these other methods requires use of prior period terms or errors, they were not useful for developing TXEMP compatible equations.

The final method investigated was regression with an explicit error model developed using the maximum likelihood estimate method. This method also requires the use of prior period terms and is similarly not useful for developing TXEMP equations but it was pursued to identify the potential error of not accounting for serial correlation.

A select portion of the dataset was chosen for the analysis to minimize missing values. This period was found from September 1999 to March 2004 for the West Bay Tripod salinity dataset.

Equation 5.2 Monthly Salinity-Inflow Regression with Error Model for West Bay Tripod

$$Sm_i = 108.93 - 3.84 \times LN(Qm_i) - 2.66 \times LN(Qm_{i-1}) - 1.34 \times LN(Qm_{i-2}) + 0.44 \times \varepsilon_{i-1}$$

where: i = month
Qm_i = Total Monthly Flow past STP for month i (acre-feet)
Sm_i = Average Monthly Salinity at West Bay Tripod for month i (ppt)
ε_{i-1} = error in salinity prediction for month i-1 (ppt)

Solving equation 5.2 for flow in 1,000 acre-feet for use in TXEMP gives:

$$Sm_i = 54.76 - 3.84 \times LN(Qm_i / 1000) - 2.66 \times LN(Qm_{i-1} / 1000) - 1.34 \times LN(Qm_{i-2} / 1000) + 0.44 \times \varepsilon_{i-1}$$

This model provided an adjusted R-square of 84.5 percent and a standard error of 3.05 ppt (Equation 5.2). The Durbin-Watson for the relationship with error correction improved to nearly 2.14, which is nearly free of autocorrelation. Each of the constant and the independent variables were significant at the 95 percent confidence level.

From this effort it has been learned that:

- First order error correction methods are likely sufficient remediation for autocorrelation at the West Bay Tripod,
- Three independent flow terms are statistically significant for the West Bay Tripod,
- The standard error may be reduced by as much as 0.50 ppt with the use of error corrections, and

- Modification of TXEMP so that it could utilize a prior period salinity could enable the C-O method, which should effectively eliminate any impact of serial autocorrelation and slightly improve predictive ability.

The OLS relationship and the OLS with error correction relationships are compared for the period of 1993 to 2003 against the 1997 relationship in Figure 5.2. Computation of salinity using the regression with error term is limited by lack of continuous data and therefore the line appears broken. The figure shows that both equations perform better than the 1997 relationship. When it can be applied (data is sufficient to compute prior month prediction error), Equation 5.2 appears to outperform the 5.1, particularly during the 2000 drought. However, the mean difference is less than 1.3 ppt. The estimated instrument error of salinity measurement is 2 ppt so there is not a significant loss in proceeding with the OLS model.

Figure 5.2 also shows that the predictive accuracy is not uniform. The error tends to be larger at high and low salinities. This suggests that the relationship may not be linear in the lower range or that important independent variables have not been captured in this analysis. However, for the purposes of this study the accuracy at extreme salinities is of less importance. Future studies may be able to develop nonlinear relationships with an improved error profile over a larger range of salinity that can still support TXEMP.

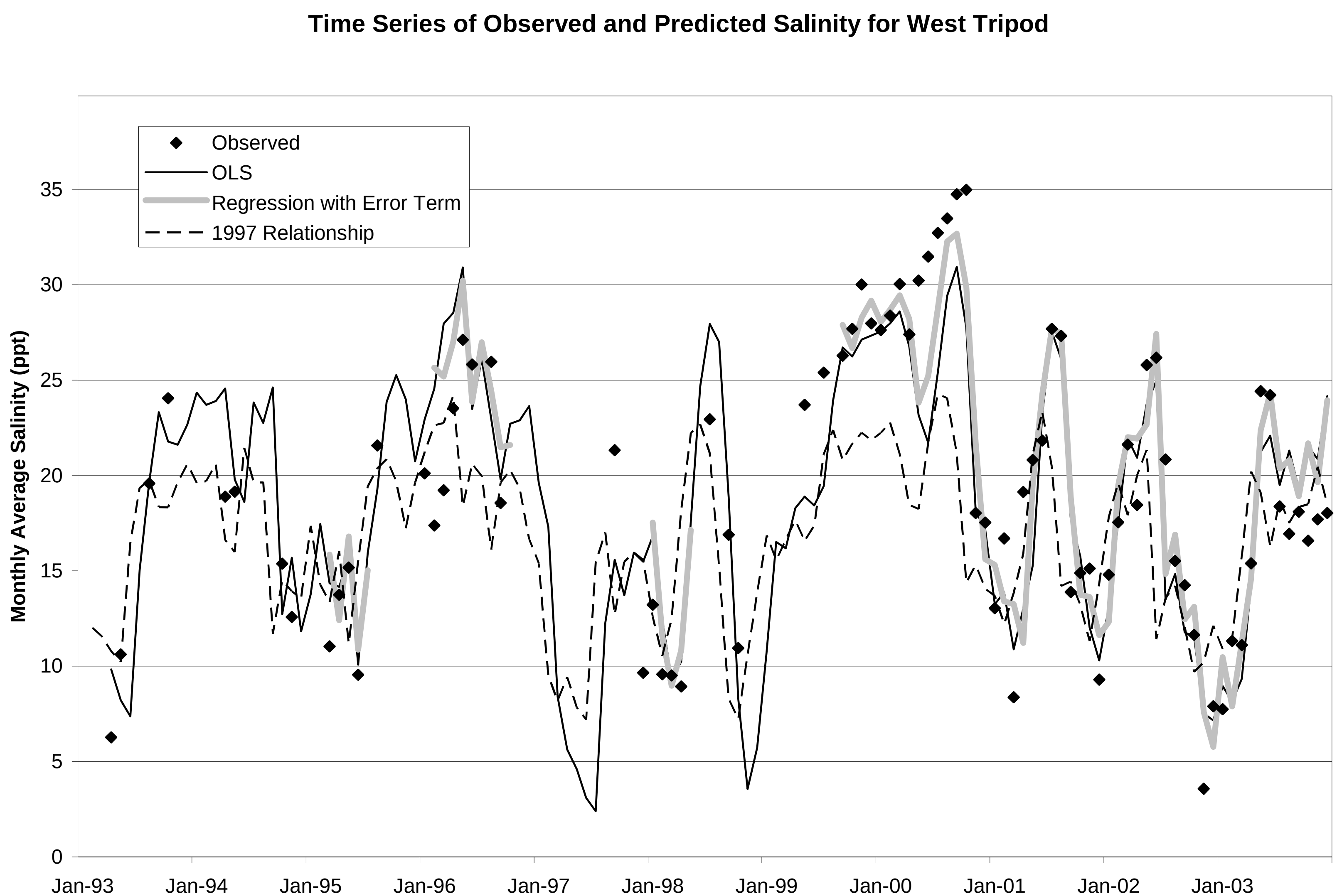


Figure 5.2 Observed and Predicted Salinity for Eastern Matagorda Bay near Mouth of Colorado River (West Bay Tripod) Using Three Models.

5.4 Lavaca River Influence on Estuarine Salinity at Lavaca Bay

5.4.1 Ordinary Least Squares (OLS) Regression: Monthly Salinity-Inflow Relationship

A variety of nonlinear relationships were tested to discover patterns between cumulative monthly inflows (Qm) and observed mean monthly salinity (Sm). Factors other than flow were not investigated for use in TXEMP due to requirements of the model. Both Ordinary Least Squares (OLS) regression and more advanced statistical techniques were employed. A variety of multivariate relationships were tested to discover patterns between monthly Lavaca flows and observed mean monthly salinity (ppt) in Lavaca Bay. A minimum of 25 daily observations was applied before a monthly average salinity entered the model. The sample for the regression analysis consisted of 125 average monthly observations that met this criterion. In all instances, a natural logarithmic transformation of the flow variables significantly improved the predictive equation's results.

The best fit equation is a multivariate equation of the form given by Equation 5.3 and includes a term for freshwater inflows for the current month and the three prior months.

Equation 5.3 Monthly Salinity-Inflow OLS Relationship for Lavaca Bay

$$Sm_i = 64.77 - 1.74 \times LN(Qm_i) - 1.77 \times LN(Qm_{i-1}) - 0.64 \times LN(Qm_{i-2}) - 0.77 \times LN(Qm_{i-3})$$

where: i = month
Qm_i = Total Monthly Flow Discharging from Lake Texana for month i (acre-feet)
Sm_i = Average Monthly Salinity at Lavaca Bay for month i (ppt)

Solving Equation 5.3 for flow in 1,000 acre-feet for use in TXEMP gives:

$$Sm_i = 30.78 - 1.74 \times LN(Qm_i / 1000) - 1.77 \times LN(Qm_{i-1} / 1000) - 0.64 \times LN(Qm_{i-2} / 1000) - 0.77 \times LN(Qm_{i-3})$$

The relationship suggests an adjusted R-square of 72 percent and a standard error of 4.02 ppt of salinity. Each of the constant and independent variables is significant at the 95 percent confidence level. However, the relationship has a Durbin-Watson statistic of 1.33, which indicates some autocorrelation but is within the acceptable range of 1.3 to 2.7 (Hilton, 2004).

Full regression results are provided in Appendix D. The presence of autocorrelation reduced confidence in these traditional measures of fit, but the performance of the relationship as seen in Figure 5.3 suggests it is acceptable for use in TXEMP.

5.4.2 Advanced Regression Techniques: Monthly Salinity-Inflow Relationship

The Durbin-Watson statistic of 1.33 revealed the presence of some autocorrelation, which was anticipated for time series data. Multi-lagged autocorrelation analyses revealed that the nature of the serial autocorrelation was greater than first order but diminished significantly with sequential lags. Refer to Section 5.2.2 for discussion of the implications of serial autocorrelation and its potential treatment.

Cochrane-Orcutt (C-O), the Hildreth-Lu (H-L) and regression with explicit error term models were all developed for this site and each was sufficient remediation for first order autocorrelation. Only the regression with error and explicit error models using the maximum likelihood method is presented. This was performed for a select portion of the dataset to minimize missing values. More gaps are found in salinity data for Lavaca Bay than for the West Bay Tripod, therefore, determination of an error correction term was more difficult. Even after relaxing the data quality to only 15 daily observations per month, only 22 continuous monthly observations could be obtained. Instead, a reasonably continuous period with only short periods of missing data from January 1992 to October 2000 was chosen and missing observations were ignored. Since autocorrelation of the errors exceeds the first order, this technique may have some merit. The regression model with error correction is shown in Equation 5.4.

Equation 5.4 Monthly Salinity-Inflow by Regression with Error model for Lavaca Bay

$$Sm_i = 67.11 - 1.69 \times LN(Qm_i) - 2.02 \times LN(Qm_{i-1}) - 0.83 \times LN(Qm_{i-2}) - 0.59 \times LN(Qm_{i-3}) + 0.49\varepsilon_{i-1}$$

where: i = month
Qm_i = Total Monthly Flow past Lavaca Reservoir in month i (acre-feet)
Sm_i = Average Monthly Salinity for month i at Lavaca Bay (ppt)
$\acute{\varepsilon}_{i-1}$ = error salinity prediction for month i-1 (ppt)

Solving Equation 5.4 for flow in 1,000 acre feet for use in TXEMP gives:

$$Sm_i = 31.66 - 1.69 \times LN(Qm_i / 1000) - 2.02 \times LN(Qm_{i-1} / 1000) - 0.83 \times LN(Qm_{i-2} / 1000)$$
$$- 0.59 \times LN(Qm_{i-3} / 1000) + 0.44 \times \varepsilon_{i-1}$$

This model provided an adjusted R-square value of 85 percent and a standard error of 3.19 ppt. The Durbin-Watson for the relationship with error correction improved to nearly 2.04, which indicates that the residuals are free of auto-correlation. The constant and each of the independent variables were significant at the 95 percent confidence level. Detailed statistical analysis is included in the appendix.

From this effort it has been learned that:

- Error correction methods are likely sufficient remediation for first order autocorrelation at the Lavaca Bay site;
- Four independent flow terms are statistically significant for the Lavaca Bay site; and
- The standard error may be reduced with the use of error corrections

Equation 5.3 and 5.4 are compared for the period of 1987 to 2003 against the 1997 equation in Figure 5.3. It shows very little difference in performance between the 1997 relationship and either of the newer equations. For consistency Equation 5.3 will be used in further efforts of this investigation.

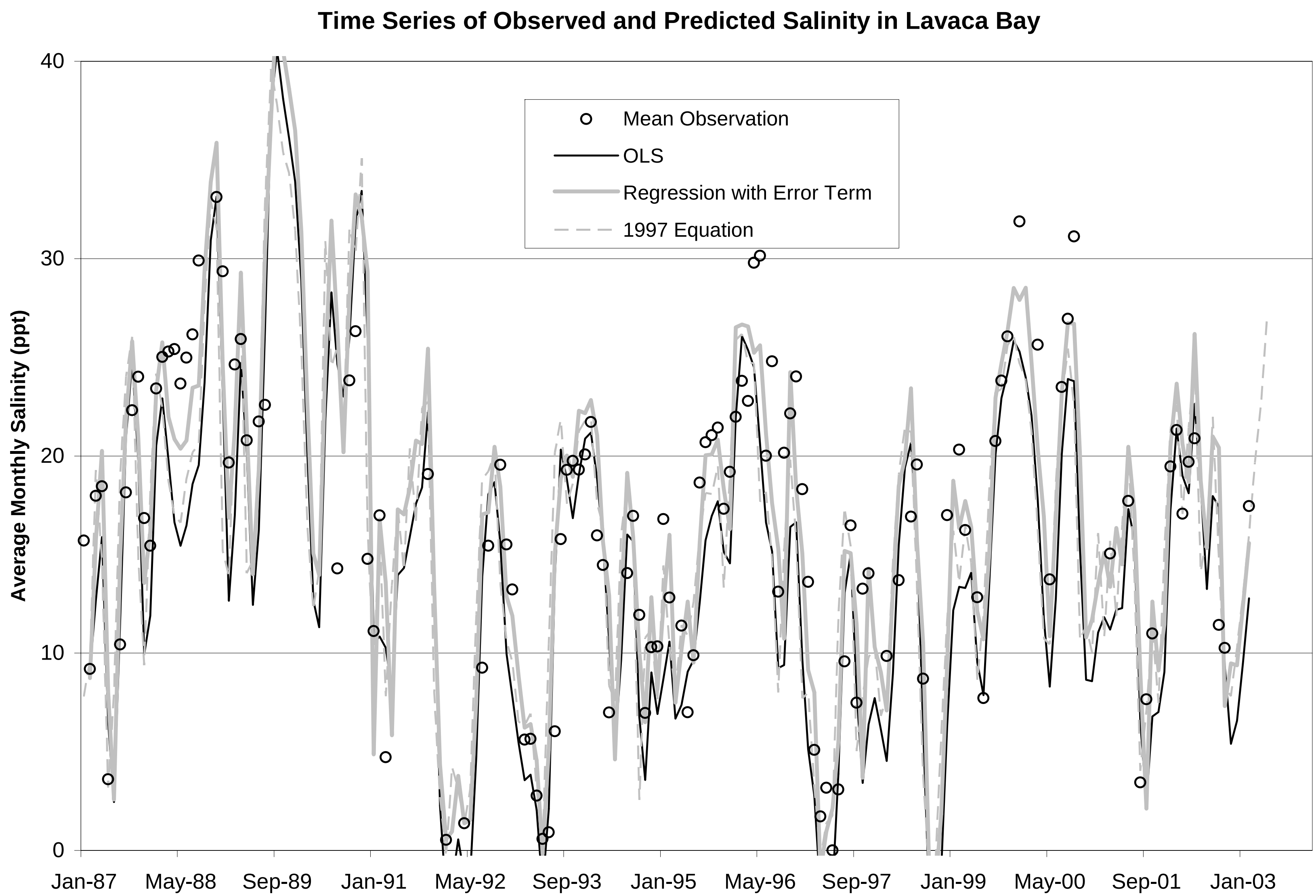


Figure 5.3 Observed and Predicted Salinity for Lavaca Bay Using Three Models.

The OLS relationship and the OLS with error correction relationships are compared for the period of 1993 to 2003 in Figure 5.3. Computation of salinity using the regression with error term is limited by lack of continuous data and therefore the line appears broken. When sufficient data exists to employ the regression with error term, it appears to be a slightly better predictor than the OLS. However, the mean difference is less than 2 ppt, which is the limit of the data collection methods so there is not significant loss in proceeding with the OLS model.

5.5 Conclusions

5.5.1 Mathematical Relationships for Use in TXEMP

For the West Bay Tripod site, the autocorrelation of the first order residuals was found to be present but not extreme. Time series prediction plots reveal notable improvement for the eastern arm to slight improvement in Lavaca Bay of the ordinary least squares models developed in this investigation over those developed in the prior study. However, in spite of the minor improvement offered by the error term models and that tests demonstrate some autocorrelation, it is recommended that the ordinary least squares models (Equations 5.1 and 5.3) be applied in TXEMP to determining salinity from inflows. This recommendation is due primarily to the fact that TXEMP does not currently have the capability to handle the prior period terms. Additionally, correction for autocorrelation appears to lead to only marginal improvement in the model's performance which did not justify major modifications to the TXEMP code at this time.

The number of months for which flow was a statistically significant independent variable differed among the regression relationships. The Lavaca Bay regression included four periods and the West Bay Tripod included three. The number of months or periods may also be influenced by the bay residence time and by physical access of ocean water to the site. Residence time of fresh water in the bay zones is related to the bay volume/inflow ratio. Lavaca Bay, with its shallow depths and small volume, has a smaller residence time than the West Bay Tripod. It is also less physically accessible to ocean inflows than the other site. Large freshening events would tend to linger for longer periods of time in Lavaca Bay due to these two factors. This would in turn lead to more significant periods in the regression equation.

This investigation showed serial autocorrelation in the residuals of flow and salinity predictive relationships to be a common problem. Future development of the TXEMP method to support use of the prior month salinity prediction could enable use of first order correction methods such as the Cochrane-Orcutt or similar, which would effectively eliminate influences of autocorrelation. However, for practical purposes, the first order autocorrelation does not seem to be problematic for the locations investigated in this study. Sensitivity analysis of the model to the less than 2 ppt improvement in relationships could indicate if this improvement is worthwhile.

CHAPTER 6

Nutrient Requirements of Matagorda Bay

6.1 Introduction

The nutrient income to Texas estuaries has become an important part of the freshwater inflow needs debate. Nutrients include nitrogen, phosphorous and organic matter and are a basic food source for many organisms that are critical to overall bay health and productivity. These nutrients are fed into the bay and estuary with the freshwater inflows. A review of existing bay monitoring data confirms the expected spatial relationships and responses to changes in inflows. To ensure Texas estuaries receive nutrient loads sufficient to maintain their health and productivity, a nitrogen budget is an important yet poorly understood component of the freshwater inflow studies. Bay data collected by the University of Texas Marine Science Institute suggests that nitrogen is the nutrient that appears to be limiting in most situations. This finding is consistent with that of the 1997 FINS.

This chapter reviews the nutrient status of Matagorda Bay, the relationship of nutrients to biological productivity and nutrient delivery from freshwater inflows that may result in reasonable biological productivity. The 1997 report included an analysis of nitrogen loadings and losses combined into a nitrogen budget. However, because nutrient water quality data is extremely limited for Matagorda Bay, the contributing rivers and coastal watersheds as well as the adjacent marshes, a new nitrogen budget was not compiled as part of the current study. Instead, insights from previous efforts make up the evaluation of nitrogen dynamics observed in Matagorda Bay for this update. Currently, the Bay Health Study of the LCRA-SAWS Water Project is underway to conduct an evaluation of the impact of nutrients on the health and productivity of the Matagorda Bay System.

6.2 Productivity and Nutrients

Almost all life is supported by plants because they have the unique ability to turn energy from the sun into organic matter, which serves as food for other living organisms. In doing so, plants also produce oxygen. These plants are producing energy the rest of the ecosystem can use and therefore are called the primary producers. The energy they produce is called primary production and the rate at which they produce energy is called productivity. In an estuary, most of the primary producers are microscopic single-celled algae or phytoplankton. Phytoplankton need light and nutrients to drive primary productivity. Because phytoplankton are designed to float, they stay near the surface and receive ample sunlight. However, a lack of nutrients can be a limiting factor in their growth. Nitrogen and phosphorus are usually in the greatest demand by phytoplankton but are typically scarce in the marine environment. Dissolved inorganic nitrogen (DIN) represents the form of nitrogen most available to promote phytoplankton production. The composition of the phytoplankton community in the bay varies seasonally and, to some extent, as the salinity gradient changes. Turbidity, seasonal temperature variation and flushing rate are physical parameters that are also important in determining primary production in estuaries (Boynton et al. 1982).

6.3 Nutrient Status of Matagorda Bay

Nitrogen is often considered the controlling nutrient in estuaries (Nixon, 1983; Nixon and Pilson, 1983). Ryther and Dunstan (1971) demonstrated that additions of nitrogen stimulated growth of marine algae. Dortsch and Whitledge (1992) found that algae growth is limited when inorganic nitrogen concentrations are lower than 0.014 mg/l. Scott Nixon (1983) took results from several estuary studies and compared the inorganic nitrogen load with the amount of productivity for each system. He concluded that a pattern of increasing productivity with increasing inorganic nitrogen load exists.

Table 6.1 presents the loading of major nutrients to the Matagorda Bay system as reported in Longley (1994). Similar data are presented from Ward and Armstrong (1980) and from Gorham-Test (1997).

Table 6.1 Inputs of Major Nutrients to Matagorda Bay System (millions grams per year).

Element	Gaged	Ungaged	Wastewater	Subtotal	Precipitation	Total
Longley, 1994						
TN	3,950	2,130	369	6,450	370	6,820
TP	520	300	200	1,020	-	1,020
TOC	27,600	13,600	700	41,900	-	41,900
Ward and Armstrong, 1980						
N	17,890	3,870	140	21,900		
P	890	200	40	1130		
C	10880	4780	730	16390		
Gorham-Test, 1997						
TN 1984	1,300	1,290	110	2,700	1,280*	3,980
TN 1987	7,820	1,580	110	9,510	1,470*	10,980

* Precipitation for 1984, 1987 includes dry deposition.

Given the standards used to judge estuaries on the national scale, Matagorda Bay has been classified as moderately eutrophic. That is, it exhibits concentrations of nutrients and chlorophyll that are on the high end of normal. Those are conclusions drawn from the National Oceanic and Atmosphere Administration's (NOAA) National Estuarine Eutrophication Assessment (Bricker, et. al, 1999). It is enlightening to consider the nutrient data from Matagorda Bay in the context of NOAA's criteria.

The following observations are based on 1993 through 2004 TCEQ regular monitoring data, with instances of less-than-detection-limit values reported as one-tenth the threshold. TCEQ collects quarterly samples at 12 locations within the Matagorda Bay System. Nutrients collected are Nitrite + Nitrate-N, Ammonia-N, Orthophosphorus (as P), Total Phosphorus (as P), Total Kjeldahl Nitrogen (as N), Chlorophyll-a, and Pheophytin.

In most years, the maximum dissolved inorganic nitrogen (DIN) concentration is above 1.0 mg/l, placing Matagorda Bay in NOAA's high nitrogen category. In all years, maximum concentration of total phosphorus (TP) is above 0.1 mg/l, placing Matagorda Bay in the high phosphorus category. It should be noted that NOAA's standard is based on total dissolved phosphorus, not total phosphorus as measured in recent years. However, prediversion dissolved phosphorus maxima were above 0.1 mg/l in most years. In most years, maximum chlorophyll-a concentration are between 20 and 60 micrograms/l, again within NOAA's high category.

Evaluating the concentration data using volume-weighted average concentrations may be more suitable, considering that many sampling stations represent small secondary bays not within the main freshwater flow paths. Matagorda Bay was subdivided into areas with one TCEQ monitoring station each and a bay volume assigned to that station. Bay-wide average concentrations were computed giving more weight to stations representing larger volumes (areas). Considering the nutrient status of Matagorda Bay using this TCEQ data and NOAA standards, the following is observed:

- Most years have maximum chlorophyll-a concentrations between 5 and 20 micrograms/l, NOAA's medium category.
- Most years have maximum total phosphorus above 0.1 mg/l, NOAA's high category.
- Most all years the DIN are above 0.1 mg/l, but below 1.0 mg/l, placing Matagorda Bay in NOAA's medium nitrogen category.

The above exercise indicates that the nutrient status of Matagorda Bay, at least for nitrogen and phosphorus, is typically within the range NOAA would consider sufficient to promote biological production. Therefore, current nutrient loading rates appear to be sufficient to support medium to high biological productivity.

6.4 Statistical Relationship between Inflows and Nutrients

With respect to freshwater inflows, a concern would be whether there are inflows below which nutrient loading rates are not sufficient to fuel typical productivity. In other words, the bay's productivity becomes limited due to a lack of nutrients. Previous evaluations of nutrient limitation for estuaries have been made on the basis of the concentrations of nutrients in freshwater inflow on the basis of the ratio of major nutrients dissolved in estuarine waters and on the basis of enrichment experiments, which are tests to determine which nutrients produce significant algal response (for further discussion, see Hecky and Kilham 1988).

To investigate the relationship between inflows and bay concentrations, tests were performed on volume-weighted bay concentrations, for which non-detect data were assigned a value one-tenth the threshold or 0.01 mg/l. Concentration-inflow relationships were based on cumulative three- and six-month inflows preceding the sample date. A nonparametric ANOVA (Kruskal-Wallis) test was used to test whether concentrations differed between inflow categories, defined by inflow quartile breaks. Tables 6.2 and 6.3 present the results.

Table 6.2 Average Nutrient Bay Concentrations (mg/l) at 90 - day Inflow Quartiles.

90 day Inflow Quartile	DIN mg/l	TN mg/l	TP mg/l
First	.109	.937	.119
Second	.266	1.075	.118
Third	.139	.771	.126
Fourth	.100	1.225	.214
Significance	ns	ns	ns

ns – not significant

Table 6.3 Average Nutrient Bay Concentrations (mg/l) at 180 - day Inflow Quartiles.

180 day Inflow Quartile	DIN mg/l	TN mg/l	TP mg/l
First	.087	1.209	.133
Second	.419	.844	.121
Third	.137	.946	.148
Fourth	.195	1.124	.173
Significance	.049	ns	ns

ns – not significant

These tests suggest that low bay DIN may be associated with low inflows. However, the general pattern in the tests does not give an indication that variation in medium time-scale inflows is associated with low bay nutrient concentrations.

The Kruskal-Wallis test was performed on nutrient concentrations grouped by one-year inflow quartiles (Table 6.4). At this level there are fewer low-quartile periods, which may reduce the validity of the results. However, nutrient concentrations were not found to be associated with inflow level.

Table 6.4 Average Nutrient Bay Concentrations (mg/l) at 360 - day Inflow Quartiles.

360 day Inflow Quartile	DIN Mg/l	TN mg/l	TP mg/l
First	.024	.807	.141
Second	.230	.831	.126
Third	.226	1.209	.162
Fourth	.108	1.041	.142
Significance	ns	ns	ns

ns – not significant

Even though the above tests do not show a strong relationship between inflows and nitrogen concentrations in the water column, this may not preclude nutrient limitation at low inflow volumes. The limited amount of water quality data may mean that significant times and areas of production are not covered.

6.5 Nitrogen as the Indicator Nutrient

Nitrogen is usually considered to be the nutrient most often limiting to estuarine production. However, other nutrients such as phosphorus and silica have been found to limit primary productivity in other estuaries. Previous studies have utilized enrichment experiments to indicate which element may limit production. In his assessment of the primary ecological interactions in four Texas estuarine systems, Davis (1973) reports studies that show that nitrogen was usually limiting to chlorophyll production in Matagorda Bay, although phosphorous was also limiting.

Dortch and Whitledge (1992) found silica often to be the limiting nutrient in the Mississippi River plume. Unfortunately, there is no recent data for the Matagorda system to test the adequacy of silica concentrations. However, limited data from the early 1970s shows silica concentrations typically higher than the 0.0056 mg/l threshold suggested by Dortch and Whitledge.

Jones et al. (1986) from a study of Lavaca Bay and the associated area of Matagorda Bay concluded that nitrogen was often limiting. However, they considered phosphorus to be ultimately limiting to biological productivity because nitrogen fixation in the system seemed to be able to compensate for some nitrogen losses, whereas phosphorus concentrations would be directly linked to the actual phosphorus loading.

Data on dissolved inorganic phosphorus (DIP) is very limited in the 1990s through 2003. Analysis of data collected for the TWDB monitoring program, 1983-1989, showed 7% of all measurements reported at the detection threshold (0.01 mg/l), and an additional 2% reported below threshold. According to the Redfield ratio (Redfield, 1958), DIP would have to be at a level of 0.0062 mg/l for limitation of phytoplankton growth. Thus, the data suggest potential phosphorus limitation occurs less than 10% of the time.

Given that silica and phosphorus appear adequate to maintain biological productivity, nitrogen remains a suitable focus for investigation of potential impacts of an altered inflow regime. However, phosphorus monitoring should continue, as phosphorus limitation might become important depending on changes in upstream nutrient processes and wastewater treatment.

6.6 Nitrogen Budget

A budget approach is a means to comparatively assess changes to nutrient loadings in the context of all nutrient sources and sinks. A detailed nitrogen budget was presented in the 1997 report for conditions of high and low inflows. The objective was to look for a potential link between major budget components and inflows that would allow the estimation of a nitrogen requirement to sustain production.

Table 6.5 is the nitrogen budget from the 1997 report, including adjustments for post-diversion loadings. The negative balance for the budget in both years and lack of certainty regarding major terms limited its interpretation for the use in assessing the Matagorda Bay system nitrogen requirements.

Table 6.5 Total Nitrogen Budget (millions of grams) for the Lavaca-Colorado Estuary.

Direct Inputs	**1984 Low inflow**		**1987 High inflow**	
Colorado River	716	*592	8339	*5992
Navidad River	420		1021	
Lavaca River	68		465	
Tres Palacios River	190		207	
Garcitas/Placedo Creeks	28		137	
Wastewater Return	111		111	
Ungaged Flow	1290		1585	
Precipitation	951		875	
Atmos. Dry Deposition	330		596	
Nitrogen Fixation	487		487	
Subtotal	4591	4467	13822	11476
Water Exchanges In				
Ship Entrance Channel	1322		4239	
Ship Entrance Channel, Entrained	3880		7137	
Pass Cavallo	1017		2825	
Pass Cavallo, Entrained	2840		5263	
Subtotal	9059		19464	
Loses				
Water Column Storage	625		1897	
Water Exchanges Out				
Ship Entrance Channel	2674		14762	
Ship Entrance Channel, Entrained	6010		7187	
Pass Cavallo	2007		7227	
Pass Cavallo, Entrained	4398		5299	
Subtotal	15713		36372	
Bio-geochemical Losses				
Denitrification	2438		2438	
Burial in Sediments	60		410	
Fisheries Harvests	82		97	
Escapement	104		208	
Subtotal	2685		3153	
Total In	13649	13526	33286	30940
Total Out	18398		39525	
IN/OUT	0.74	0.74	0.84	0.78
* Adjusted to Colorado River nitrogen input prior to the construction of the Diversion Channel				
REMAINING	-4748	-4872	-6239	-8585
Water Balance Error	-44		5833	
Total In. Adjusted for Water Balance Error	13605	13482	39119	36773
In/Out with WB Correction	0.74	0.73	0.99	0.93

In concept, using the budget approach to predict the nitrogen needs of the system requires information about biological and geochemical mechanisms that may affect budget terms. A major consideration in this regard is a budget component that now has to be largely inferred: system storage. During times of high nutrient loading, the various living and non-living components of the system probably store significant nutrients. There is data to estimate water column storage, but that may not be the major storage. Benthic organic and inorganic storage should be considerable, for example, but is practically unknown. So during times of high nutrient loading, one would expect significant storage in the system; whereas during months or years of low input, the storage should be depleted. With a more complete or accurate budget for other components of gains and losses the size of system storage can be inferred and used as a means of recommending an inflow that sustains the systems productivity.

Some new information suggests that some of the terms of the nitrogen budget may need revising. Gardner et al (2005) summarizes data from a number of more recent studies of Texas estuary nitrogen processes and shows that nitrogen fixation and denitrification are often balanced. Further, these studies offer evidence that at increasing salinities, nitrogen processes shift from denitrification (loss) to pathways that recycle nitrogen back into biological availability. Getting more information about those processes would be important to our understanding of how changes in nitrogen loading would affect productivity. A nitrogen budget may still offer a means to estimate or validate a nitrogen requirement for the system. However, for now other avenues may have to be investigated.

6.7 Approaches Used for Determining Nitrogen Loading Requirements

Several approaches to determining nitrogen loading requirements were investigated in the 1997 report. These are revisited or augmented in view of new data or new perspectives from recent literature.

6.7.1 Maintaining Current Levels of Productivity

The nitrogen loading to the system should be adequate to maintain the trophic state near the present status quo. That is, the nutrients should be sufficient to fuel the present level of productivity. Concerns about eutrophication in many estuaries on U.S. and European coasts have spawned most of the work on relationships between loading and productivity. Nixon (1995) proposed a definition of eutrophication related to the amount of increase in organic carbon in the system and proposed thresholds for oligotrophic, mesotrophic and eutrophic estuaries based on rates of organic carbon increase. Based on the information present at the time that the 1997 report was written, it appeared that Matagorda Bay would be classified as mesotrophic and that nitrogen loading sufficient to maintain phytoplankton organic carbon production at that level should be an appropriate objective. Applying this concept, Gorham-Test (1997) determined that 13,360 x 10^3 grams nitrogen per year from all sources would maintain appropriate productivity. This translates to approximately 1.71 million acre-feet freshwater inflow per year as determined in the 1997 FINS. However, there is confusion over whether Nixon's definition of eutrophication really considered all sources of organic carbon that drive estuarine production and what measure of productivity should be used for Matagorda Bay. Matagorda Bay, like most other Texas bays, receives significant organic carbon from riverine and wastewater sources and from fringing wetland production as well as from phytoplankton production. The summation of carbon loading from phytoplankton, return flow and riverine sources would place Matagorda Bay at a much higher trophic level than seems correct. Therefore, more consideration may be required in applying Nixon's definition of trophic status to Matagorda Bay and using that as a basis for quantifying nitrogen needs.

6.7.2 Nutrient Limitation

An approach that seems to offer promise is to quantify a loading that would maintain concentrations of nitrogen at levels above which phytoplankton production would be limited. This is complicated by the findings above that show no or little relationship between freshwater inflow (and associated nitrogen loading) and bay nitrogen concentrations (Section 6.4). The problem appears to be that internal mechanisms of storage and recycling are sufficient to maintain nitrogen concentrations at times of low loading between pulses of higher loading. So it is hard to determine from present data how the bay would respond to loadings significantly less than at present. To remedy this problem, it is proposed that we take advantage of information from sister bays along the coast, which comprise a gradient of inflows and loadings. Of course, each system has characteristics that may complicate comparisons. In particular, a portion of Sabine Lake inflows skirt the main bay and so system loadings and system concentrations may not be as tied as in other systems; the isolation of the main part of the Guadalupe Estuary from direct Gulf exchange also may give it special characteristics.

In general, the concentration of a non-conservative substance, such as a nutrient, in the bay is related to the loading, the flow-through and the rate of removal by biological or geochemical processes (eg. Dortch, 1997). Rates of removal of nutrients are generally assumed to be influenced by the hydraulic residence time of the system. For the major bays of the Texas Coast, except Laguna Madre, relationships were examined between loading per unit volume, residence time and average DIN concentration.

Residence time within an estuary is a function of freshwater inflow and tidal exchange; however, for this analysis residence time was based just on freshwater replacement from data given by Armstrong (1982) to simplify interpretation. Average bay concentrations were compiled from routine monitoring data from TCEQ, 1990-2001. Nutrient loading data were taken from Longley (1994) or from datasets used to create those tables and from more recent updates (in appendices to Pulich, et al., 1998; Lee, et al., 2001; Pulich, et al. 2002; Kuhn and Chen, 2005). Sabine Lake was dropped from the analysis because its residence time is so much different than the other systems. The data suggest there is a general relationship between residence time and DIN concentrations in the bays. Linear regression produced the following:

$$\text{DIN} = 0.264 - 0.103 * \text{Res} \qquad R2 = 0.667,\ p = 0.062$$

In this relationship, residence time (Res) is the bay volume divided by average net freshwater inflow per year.

This relationship can then be used to predict a bay-wide average DIN that would limit phytoplankton growth. The prediction has a great degree of uncertainty, not least because it would be extrapolating past the bounds of data in the relationship. Therefore, the following is offered only as a guide. From this relationship, the bay-wide average DIN should approach the productivity-limiting threshold of 0.014 mg/l (Dortch and Whitledge, 1992) when inflows are 714,000 acre-feet per year.

6.7.3 Historic Loading

Prior to growth of the urban areas, farmland, and irrigated agricultural development in the basin, inflows to the bay would have had lower nitrogen concentrations than what is found today. Those concentrations should be similar to concentrations now found in streams not impacted by human activities. Twidwell and Davis (1989) documented nutrient concentrations in stream segments identified as relatively unaffected. These data are similar to those compiled by Omernik (1976) for land use categories comparable to what was characteristic of the basin. From these data, a reasonable estimate of natural stream concentrations would be on the order of 0.7 mg/l N. Actually, the recent flow-weighted average TN concentration for all sources to Matagorda Bay is near 1.50 mg/l N.

An unimpacted inflow TN concentration was combined with median inflow volume to produce an estimate of historic nitrogen loading to Matagorda Bay. Using an unimpacted stream concentration of 0.7 mg/l N and 3,076,000 ac-ft median inflow, a historic annual TN load would be $2{,}655 \times 10^6$ g N /y from the drainage basin. This rate is proposed as a minimum target nitrogen load, capable of supporting Matagorda Bay's productivity at historically characteristic levels for the system. At today's typical input concentrations from all sources, 1.50 mg/l N, an equivalent TN load would be supplied by 1,440,000 ac-feet.

6.8 Preliminary Findings

The amount of inflow necessary to continue to maintain a healthy estuarine system is difficult to determine due to the limited understanding of many of the interacting processes. Nitrogen appears to be sufficient as a nutrient indicator for determining the nutrient requirements to sustain biological productivity for Matagorda Bay. If this is the case, as much as approximately 1.71 million acre-feet freshwater inflow per year may be sufficient to provide the nutrient loading necessary to maintain optimum productivity of the bay. In addition, minimum inflows of approximately 714,000 acre-feet per year may be necessary to avoid nutrient (nitrogen) limitation. However, determination of a nutrient requirement to sustain productivity in Matagorda Bay is compromised by lack of data on non-riverine sources of nutrients to the system.

Recent studies [e.g., Gardner et al. (2005)] suggest nitrogen fixation may be more important than anticipated. Sources of nutrients from atmospheric dry-deposition are also poorly known. Allochthonous carbon inputs may make important contributions to productivity of many Texas bays, but isotope studies show that the picture is complicated (Kaldy, Cifuentes and Brock, 2005). There are measurements of riverine TOC, but fewer measurements of contributions from delta and fringing wetlands.

To explore the degree to which estuary freshwater inflow recommendations can be made on the basis of comparisons among sister estuaries, more information would be needed to ensure such comparisons could be done correctly. In addition, parameters and processes that could contribute to cross-system analyses should be given particular study, such as nutrient dependence patterns among similar bays. For Matagorda Bay, additional information is needed on which major nutrient is limiting productivity seasonally and at very low inflow conditions. It has been suggested that imbalances in nutrient ratios can lead to growth of noxious or undesirable algal species. The nitrogen budget exercise illustrated the need for more study of many processes and components. Further modeling or study of Gulf-bay exchange, for example, would help. Studies to determine whether or not nutrients are stored in an exchangeable way in sediments, wetlands and biota would be needed to help enable deductions concerning changed conditions based on a budget-type approach.

CHAPTER 7
Estimation of Freshwater Inflow Needs

7.1 Introduction

This chapter describes an application of the State Methodology for determination of freshwater inflow needs (Longley ed., 1994) to determine Target inflow needs for Matagorda Bay. The discussion related to Critical Flows, is presented later in Chapter 9.

The primary management objective of the State Methodology is to maintain existing ecologically and economically important species in Matagorda Bay at near historical levels[1]. A secondary objective, and the purpose in applying an optimization model, is to make the most efficient use of the water. TXEMP computes the maximum productivity that can be obtained for a given annual amount of inflow.

Model results from multiple runs of TXEMP meeting all of the imposed constraints[2] are used to develop a response curve of viable solutions. Target Flows are described in the 1997 study (LCRA) as attempting to achieve the maximum productivity found on this curve subject to prudent consideration of "marginal benefits to biomass with additional freshwater inflows". The same approach is taken in this study to determine Target flows.

In searching for flows that meet the above objectives, TXEMP assumes that flows can be distributed throughout the year as required by the solution. TXEMP does not recognize restrictions due to other competing demands for water, nor does it take into account limitations in the ability to control flows, during floods or droughts for example. These additional restrictions and limitations make the Target flow solution difficult to achieve in practice. Nonetheless, TXEMP does provide the best solution possible for getting the greatest productivity for a given amount of water. How best to utilize the information provided by TXEMP solutions is left for later management and regulatory decisions.

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[1] See Section 7.4.6, Limits on Individual Species Productivity. Lower limits at 80% of mean species productivity were applied to each species to achieve this objective.
[2] See Section 7.4, Key Model Constraints, for further description of the imposed constraints.

In addition, although specific recommendations for Intermediate flows are not provided in this study, information related to the potential use of TXEMP as a tool to assist in the development of Intermediate flows is provided in this chapter.

7.2 Optimization Model

7.2.1 Purpose of TXEMP Model

TXEMP is a mathematical optimization model used to estimate freshwater inflows required to optimize productivity in Matagorda Bay. The objective in applying TXEMP is to determine the monthly flow distribution required to maximize productivity of key species in Matagorda Bay subject to hydrological and biological constraints. Productivity for each of the key species is related to monthly inflows through equations developed and described in Chapter 3 and presented in Table 3.7. Hydrological constraints are based on historical (1941-2003) flows in the Colorado River basin, the Lavaca-Navidad River basin and the remaining coastal basins that contribute inflow to Matagorda Bay. Biological constraints are based on physiological requirements for each of the species modeled and on the observed abundance of each species.

7.2.2 Differences from the 1997 Study

Several key aspects of the current study differ from the 1997 study. First, physical alterations to the Matagorda Bay system, primary of which are the diversion of the Colorado River into Matagorda Bay in 1991 and the closing of Parker's Cut in 1992, have created a physical, chemical and biological system that differs significantly from the system as it existed prior to these changes. The current study estimates inflow requirements for the current configuration of the system, i.e. the system following the completion of the diversion channel and the closing of Parker's Cut.

In the application of TXEMP, the current study uses productivity and salinity regression equations that are related to flows from the Colorado and Lavaca-Navidad river systems, but does not include drainage from the coastal watersheds. This differs from the 1997 analysis in which coastal watersheds were included in the development of the regression equations.

In the current study, seven key species identified in Chapter 3 are modeled in TXEMP. The seven target species include brown shrimp, white shrimp, menhaden, red drum, striped mullet, blue crab and oyster. This differs from the 1997 study that included nine species, including the above seven species, as well as black drum and southern flounder. The use of seven instead of nine species led to a reduction in optimal biomass computed in the current study in comparison to the biomass compiled in the 1997 study. The approach taken in developing the productivity equations in the current study is somewhat different as well. Rather than applying a statistical “all possible subsets” approach for all species as in the 1997 study, different approaches were adopted for the shrimp equations than for the finfish or oysters.

The salinity-inflow regression equations were based on data extending through March 2004 and included periods of both extreme flood and drought conditions. The equation for the eastern arm of Matagorda Bay (West Tripod) contains three flow terms, while the equation for Lavaca Bay contains four flow terms. In the 1997 study, both equations were developed with just two terms, representing flows for the current and antecedent months. The use of highly variable data sets and the use of additional terms in the equations have led to equations that are considerably more robust than those used in the 1997 study.

In the current study, an attempt was made to use the same model parameters in TXEMP that were applied in the 1997 study. For example, both the salinity and harvest probabilities used in the current study were the same as those used in the 1997 study. However, for parameters and constraints based on the statistics of hydrological or biological data (upper monthly flow constraints, e.g.), the parameters and constraints were changed to reflect the updated data sets. A significant difference in the development of Target flow estimates in the current study is the use of 70th percentile monthly flows for upper monthly flow constraints and the use of slightly higher salinity constraints. In the 1997 study, the upper monthly flow constraints were set to the mean monthly flows, and the upper salinity constraints were set 1 ppt lower than in the current study. Input files used to develop Target flows in this study are provided in Appendix E.

The rationale for use of higher flow and salinity constraints in this study are discussed in Appendix F.

7.3 Model Variables

The key decision variables that TXEMP solves for are the twelve monthly inflows each from Colorado River basin and from the Lavaca River basin. Annual coastal basin inflow is estimated as a fixed fraction, 0.361, of the combined Lavaca and Colorado river basin annual flows. Total flows are computed by combining the Lavaca and Colorado river basin flows with the coastal basin inflow.

7.4 Key Model Constraints

7.4.1 Upper and Lower Limits on Monthly Inflows for Colorado River Basin.

The lower limits on monthly flows for the Colorado River basin are defined as 10th percentile monthly flows based on historical data for the USGS streamflow gage on the Colorado River at Bay City (#08162500) from January 1941 to December 2003 less the diversion at the South Texas Project (Table 7.1). The upper limits are defined as 70th percentile monthly flows based on the same data.

Table 7.1 Flow Constraints on the Colorado River Basin Inflows (1000 acre-feet/month).

Month	Lower Constraint	Upper Constraint
January	30.6	208.9
February	26.8	197.6
March	22.3	231.7
April	22.9	221.7
May	28.4	255.4
June	22.0	210.5
July	20.0	120.1
August	17.3	68.7
September	25.3	133.8
October	33.1	154.2
November	26.2	162.5
December	23.8	166.2

7.4.2 Upper and Lower Limits on Monthly Flows for Lavaca River Basin.

Lower and upper limits for the Lavaca River basin monthly inflows are based on flow records for USGS gage on the Lavaca River near Edna (#8164000) and the Navidad River near Ganado (#8164500) from January 1941 through December 2003, and on releases from Lake Texana (Table 7.2). As with the Colorado basin, the lower limit is the 10th percentile monthly flow and the upper limit is the 70th percentile monthly flow.

Table 7.2 Flow Constraints on the Lavaca River Basin Inflows (1000 acre-feet/month).

Month	Lower Constraint	Upper Constraint
January	2.2	77.0
February	3.5	68.9
March	3.3	43.7
April	3.7	85.0
May	5.9	139.4
June	4.8	86.0
July	4.6	29.2
August	2.0	18.3
September	4.9	50.6
October	1.7	58.1
November	1.5	53.4
December	1.9	57.9

7.4.3 Upper and Lower Limits on Monthly Lavaca Basin Inflows Used to Develop Lavaca Salinity Equation.

Lower and upper limits for the Lavaca River basin inflows are based on flow records for the USGS gage the Lavaca River near Edna (#8164000) and the Navidad River near Ganado (#8164500), and on releases from Lake Texana. The minimum constraint was set to 1.0 thousand acre-feet/month, and the upper constraint was set to 1043.0 thousand acre-feet/month. These constraints are less restrictive than those in Table 2 and therefore do not come into play in the optimization, but are included for the sake of completeness.

7.4.4 Ratio of the Lavaca Basin to Colorado Basin Flows.

Means and standard deviations for "seasonal" flows, defined as bimonthly flows for January and February, March and April, May and June and so on, were computed for the Lavaca and Colorado basins. Upper and lower constraints were applied for each season on the ratio of the average seasonal flow for the Lavaca basin to the average seasonal flow for the Colorado basin. The constraint about the mean for each season is in proportion to the standard deviation of the seasonal flows. The intent of this constraint is to ensure inflow contributions from the Lavaca and Colorado basins are in proportion to historically observed inflows.

7.4.5 Upper and Lower Limits for Seasonal Flows

Upper and lower constraints were set for the combined Lavaca and Colorado basin "seasonal" flows. The upper and lower constraints are based on the minimum and maximum values used in developing the productivity equations. The purpose of this constraint is to prevent use of the equations to extrapolate beyond flows used in the development of the equations.

7.4.6 Limits on Individual Species Productivity

Lower limits on individual species productivities were set to 80% of the mean productivities. The mean productivity for each species was based only on data used in developing the productivity equations (Appendix B, Table B.2) applied in TXEMP. This includes data from 1992 through 2002, although data for some species and some years in this period were eliminated during development of the equations. Upper limits on all species were high enough to prevent these constraints from influencing the solution.

7.4.7 Upper and Lower Limits for Nutrients

A lower limit on total annual inflow was set at 1.710 million acre-feet. This limit is based on the nutrient budget described in Chapter 6 and is intended to limit conditions to which the system is not nutrient limited.

7.4.8 Salinity

Upper constraints on salinity were set to 16 ppt for May, June and July and to 21 ppt for all other months. Lower constraints on salinity were set to 1 ppt for May through August and to 5 ppt for the remaining months. The same constraints are applied to the Lavaca Causeway (Lavaca basin flows) and West Tripod (Colorado basin flows) sites.

Salinity constraints in the State Methodology are based on multiple studies that have been conducted to determine species viability limits (see, e.g., TDWR 1980a, Table 9-1 and Longley 1994, Table 6.7.3). However, this information is site specific and is variable and there remains the need to apply subjective judgment in using it for a particular bay, as pointed out in TWDR (1980a): "Since universal consensus is not evident for precise salinity viability limits, the seasonal bounds were established subjectively based upon the results available from scientific literature." Judgment is also needed in applying information from past studies because salinity reference locations have varied. For example, the salinity reference locations for the eastern arm of Matagorda Bay used in the 1980 study (TDWR, 1980a) were "… line 330 site 2, line 333 sites 1,2,3, line 340 sites 2, 3, and line 350 site2 …," referring to multiple locations in that region of the bay. The equivalent reference location in the present study is the West Bay Tripod.

The salinity constraints in the current study were based on constraints developed in the 1997 study, which in turn were based on "limits selected by the TWDB and TPWD in their study of estuarine inflow needs of the Guadalupe estuary." This refers to constraints developed in the example application of the State Methodology in Longley (1994). The Longley (1994) report presents salinity constraints based on earlier studies by TDWR (1980b) and Espey Huston and Associates (1986), but ultimately used constraints recommended by TPWD. Judgment and consensus between the state resource agencies and LCRA was applied in using this information to develop constraints particular to Matagorda Bay for the 1997 study.

7.5 Target Flow

Multiple runs of TXEMP over a range of total annual flows were used to create the response curve shown in Figure 7.1. The curve represents Matagorda Bay productivity as a function of total inflow, where productivity is defined as the sum of the computed biomasses for each of the seven species modeled. Total annual inflow is the sum of the annual inflows from the Colorado River basin, the Lavaca-Navidad River basin and the coastal basin.

Each point on the curve in Figure 7.1 represents the optimal productivity attainable for a particular total annual flow subject to the hydrological and biological constraints described above. TXEMP provides the monthly distribution of flows for both the Colorado and Lavaca basins needs to attain those levels of productivity. As described in the Appendix 6, overall system productivity could be made to increase by relaxing the constraints applied to this problem. However, the more restrictive hydrological and biological constraints applied here in estimating a Target flow are a means of obtaining solutions that are considered more reasonable and feasible from the perspectives of water management and biology.

Peak productivity (subject to the flow and salinity constraints applied for the target solution) of 236 thousand pounds occurs for a range of flows between 2.75 and 3.50 million acre-feet/year. Productivity drops to 72% of peak productivity (169.4 thousand pounds) at flows of 2.05 million acre-feet/year. Following the approach taken in the 1997 study, since no appreciable increase in productivity is provided for flows greater than 2.75 million acre-feet/year, the prudent choice for the Target flow is 2.75 million acre-feet/year. This flow is estimated to result in peak productivity for the least amount of water. This Target flow is less than the average annual inflow to Matagorda Bay from 1941 to 2003 (3.44 million acre-feet/year), and is also less than the median inflow for the same period (3.095 million acre-feet/year) (Table 2.2).

The total annual inflow is distributed between the Lavaca River basin (593 thousand acre-feet), the Colorado River basin (1.428 million acre-feet) and the coastal basins (729 thousand acre-feet). Table 7.3 provides monthly distributions for each of these annual inflows.

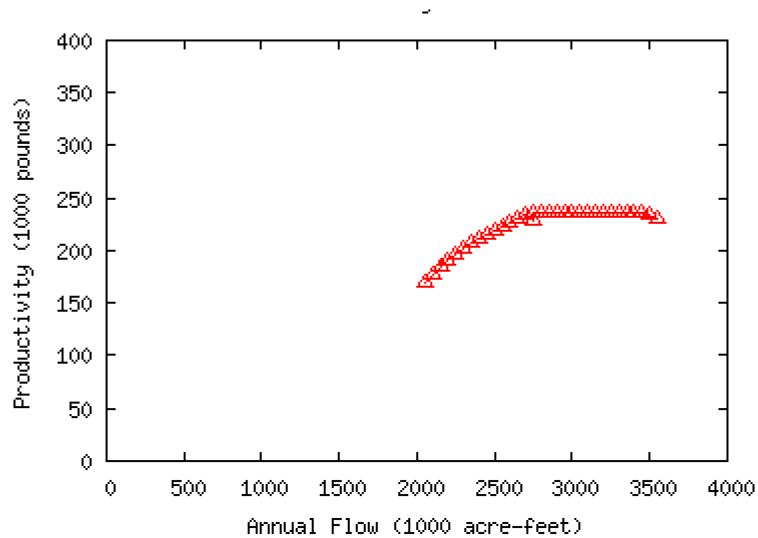
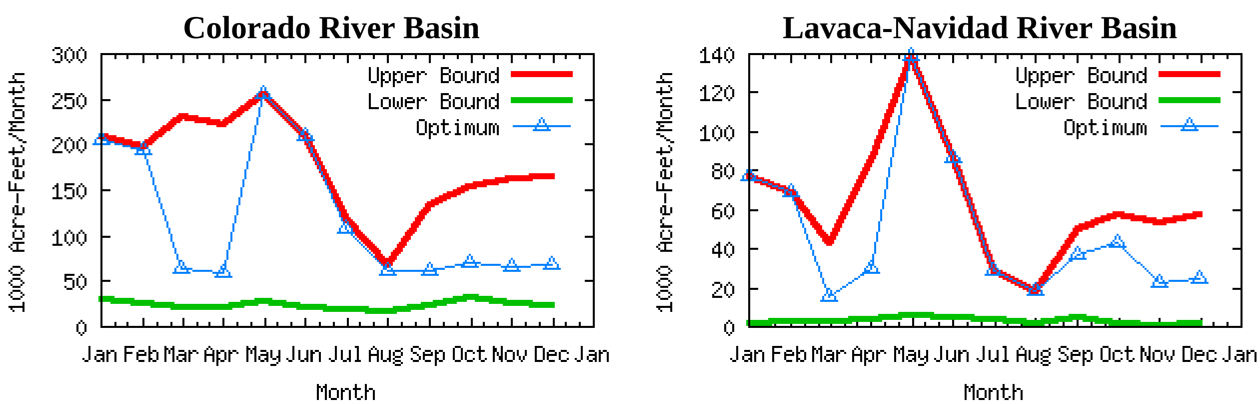


Figure 7.1 Total System Productivity versus Total Annual Inflow for Target Flow Runs.

The monthly solutions are shown in Figure 7.2 relative to upper and lower flow constraints for both the Colorado and Lavaca basins. Corresponding salinities relative to the upper and lower salinity constraints are presented in Figure 7.3. For both the Colorado and Lavaca basins, the solutions are confined by the upper flow constraints in January, February and May through August. Upper salinity constraints for Colorado basin flows (West Bay Tripod) affect the solution primarily during September through December.

Table 7.3 Monthly Inflows Corresponding to Target Solution (1000 acre-feet/month).

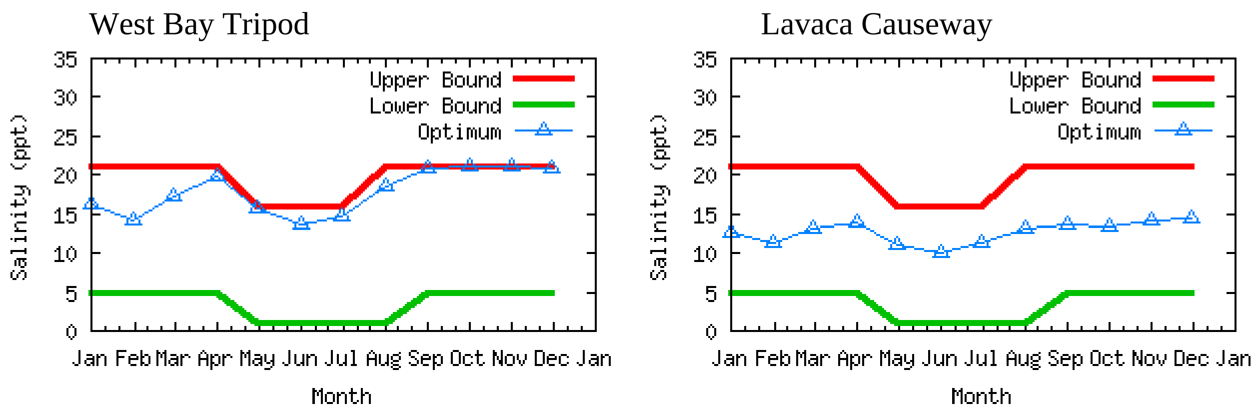
Month	**Colorado**	**Lavaca**	**Coastal Basins**	**Total Monthly Inflows**
January	205.6	77.0	37.2	319.8
February	194.5	68.9	44.5	307.9
March	63.2	15.6	42.3	121.1
April	60.4	30.3	51.1	141.8
May	255.4	139.4	85.3	480.1
June	210.5	86.0	80.2	376.7
July	108.4	29.2	66.4	204.0
August	62.0	18.3	31.4	111.7
September	61.9	37.3	107.2	206.5
October	71.3	42.9	100.7	214.9
November	66.5	23.0	47.4	136.9
December	68.0	24.9	35.7	128.7
Total	1427.8	592.8	729.4	2750.0
Percent%	51.9	21.6	26.5	100.0



Upper bound – red line. Lower bound – green line. Optimum solution – blue line.

Figure 7.2 Distribution of Monthly Flows for Colorado River Basin and Lavaca-Navidad River Basin.

Mean productivities, based on the 1992-2002 TPWD data used to develop the regression equations, and productivities corresponding to the Target flow solution are presented in Table 7.4. The mean total productivity is 126.5 thousand pounds. Mean productivity resulting from Target flows is significantly higher at 236.2 thousand pounds, but significantly less than the maximum total productivity (again, based on the 1992-2002 TPWD data) of 258.9 thousand pounds. The distribution of total biomass among species is maintained with slight percentage increases in brown shrimp and menhaden and small percentage decreases in the remaining species. The ratio of target to mean productivity is influenced by the use of a limited (1992-2002) data set. Relatively low productivity for many species during this period was possibly influenced by high flows in 1992 and 1997, and low flows in 1996, 1999, and 2000. Observed productivities for the selected species prior to the diversion in 1992 were higher than for 1992-2002, so it is expected that higher productivities will occur in the future, thereby reducing the target to mean productivity ratio.



Upper bound – red line. Lower bound – green line. Optimum solution – blue line.

Figure 7.3 Monthly Salinity Distributions Corresponding to Target Flow Solutions for Colorado River Basin and Lavaca-Navidad River Basin.

Table 7.4 Mean Productivity (1,000 pounds), Percent of Total Mean Productivity, Target Productivity (1,000 pounds), and Percent of Total Target Productivity. Mean productivity is based on the 1992-2002 TPWD productivity data.

Species	Mean	% of Total	Target	% of Total
Brown Shrimp	37.6	27.9	77.4	32.8
White Shrimp	29.0	22.9	42.1	17.8
Menhaden	40.4	31.9	94.9	40.2
Red Drum	0.5	0.4	0.6	0.3
Striped Mullet	1.2	0.9	2.0	0.8
Blue Crab	2.0	1.6	2.5	1.1
Oyster	15.9	12.6	16.8	7.1
Total	126.5	100	236.2	100

7.6 Intermediate Flow Ranges

This report identifies the total Target inflow need at 2.75 million acre-feet per year and the annual Critical inflow need (Chapter 9) at 483,600 acre-feet (432,000 ac-ft from the Colorado River and 51,600 ac-ft from the Lavaca River basin). However, further work is needed to develop appropriate Intermediate freshwater inflow needs to bridge the gap between wet and dry hydrological conditions. No guidelines currently exist in the State Methodology to assist in developing criteria for Intermediate flows. This section provides TXEMP results for runs in which salinity and hydrological constraints were relaxed from those used to develop Target flows. While this study does not develop a specific Intermediate flow recommendation, it does provide TXEMP model results to help any possible future development of Intermediate flow recommendations.

7.6.1 Intermediate Flows Management Objective

While the broad management objective for Target flow is to optimize productivity within historical ranges and the objective for Critical flow is to provide refuge for important species until more normal conditions return, as indicated above, there are no guidelines currently in the State Methodology for developing criteria for either Intermediate or Critical flows. One approach to developing Intermediate flows may be to provide flows to achieve a particular level of productivity. Another may be to determine the best distribution of flows so as to maximize productivity for a particular annual flow. Another may be to vary between Target and Critical objectives. During wetter than normal conditions, for example, this could be achieved by trying to maintain productivity in an optimal fashion and, during drier than normal conditions, gradually moving towards maintenance of refuge conditions. The variation in objectives could be tied to reservoir storage and inflow conditions and may also include the use of water use and supply forecasts. TXEMP can be used to help determine appropriate management objectives and to evaluate the flows and flow distributions required to meet them.

A crucial question in setting management goals for Intermediate flows is whether or not excess and available water for bay needs can indeed be stored for use at other times of the year. If so, then this water might be managed to optimize productivity for a given amount of available water. Another question is whether or not a single or small number of discrete Intermediate flow targets should be identified or if solutions should be provided for a continuous range of flows. Answers to these questions will determine if and how the information provided here can be used to help develop guidelines or criteria for Intermediate flows.

7.6.2 TXEMP Runs with Widened Constraints

Several additional TXEMP model runs were completed to develop information useful for determining a range of possible Intermediate flows. These are similar to runs described in Appendix F in which sensitivity analyses were performed on TXEMP by varying flow and salinity constraints. One possible solution taken from these runs is described here. This suggestion does not imply a recommendation and is offered for demonstration purposes only. In this run, inflow and salinity constraints were widened relative to the constraints used in the Target flow runs. The minimum inflow constraint was lowered from 1.71 million acre-feet/year to 0.50 million acre-feet per year. The upper salinity constraint for both the Colorado and Lavaca basins was set to 23 ppt for all months. By lowering the minimum annual inflow constraint and increasing the upper salinity constraint, conditions less than ideal relative to target conditions but better than conditions represented by critical, are simulated. This appears to be a reasonable approach to setting constraints for intermediate conditions.

The TXEMP solution with these altered constraints is presented in Figure 7.4. This curve is similar to that for Target flows in Figure 7.1. Total system productivity is plotted versus total annual inflow. As in simulations for Target flow conditions, each point on the curve represents the maximum productivity possible for a particular annual inflow. Solutions in this case are found down to 1.3 million acre-feet/year, well below the minimum inflow of 2.05 million acre-feet in Figure 7.1 for Target flow conditions. This is significant because it provides inflow recommendations well below target (2.75 million acre-feet/year) and closer to critical (0.667 million acre-feet/year). Solutions for even lower total annual inflows are possible by increasing the upper salinity constraint, although at the lowest inflows the solutions become questionable because of the limits on the data used to develop the productivity equations.

Monthly inflows for the Colorado basin corresponding to the total annual inflows in Figure 7.4 are presented in Figure 7.5. The Colorado basin monthly median inflows are also shown in red as a basis for comparison (the sum of the Colorado basin median monthly flows is 1.07 million acre-feet). Figure 7.5 shows that when water is available, it is preferentially distributed by TXEMP to months where productivity is enhanced (January, February, May, June and July), and is removed when possible from months where productivity is harmed (March, April). As water availability decreases, model inflows are gradually adjusted as needed to achieve the greatest possible productivity. At the lowest inflow volumes, the monthly inflows become more uniformly distributed throughout the year, and the information provided by TXEMP regarding optimal inflow distribution loses its importance.

During some months, inflows remain well below the median monthly inflow (March, April, and September through December). In other months, inflows can exceed the median monthly. Providing these flows in an operationally ideal manner might be possible if excess inflows could be stored for later delivery during other months. For example, excess inflows stored late in the year might be delivered to provide most benefit during January, February or May through July. The volume of water available would determine the amount and distribution to be provided at that later time.

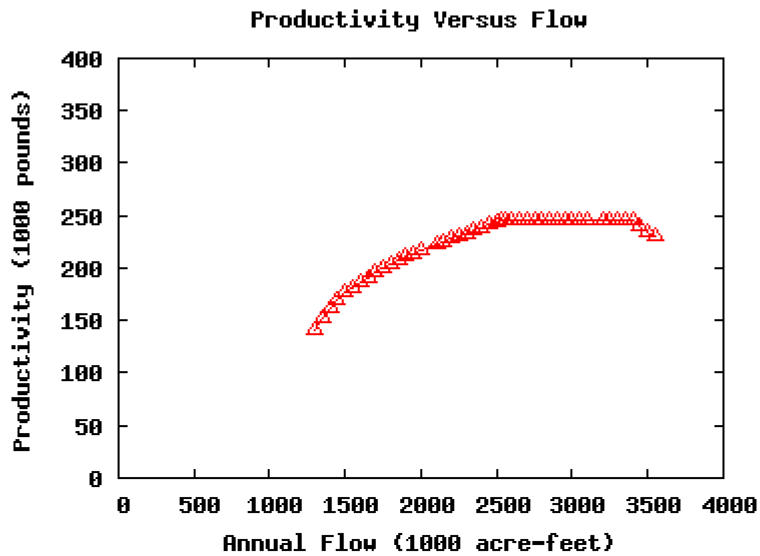
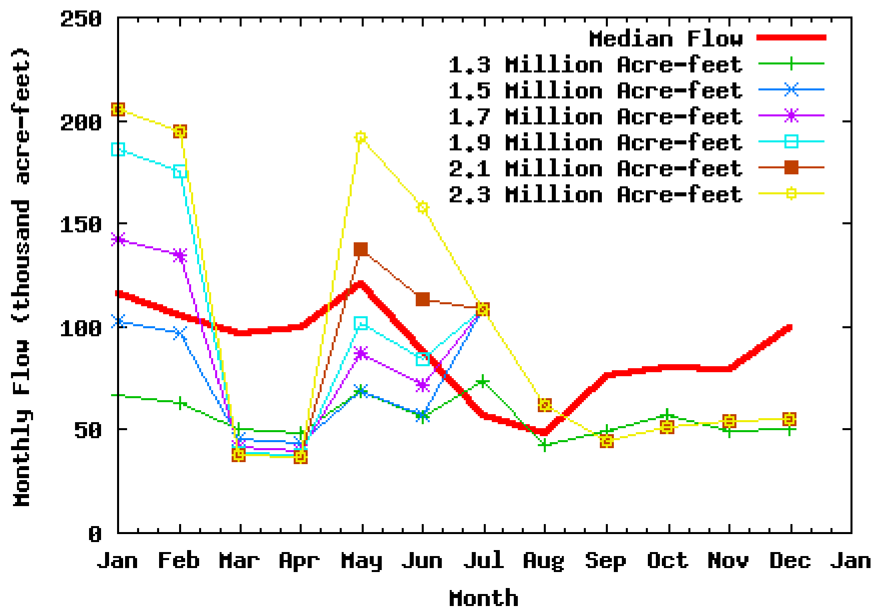


Figure 7.4 Total System Productivity versus Total Annual Inflow for Intermediate Flow Runs.



Note: Median monthly flows for the Colorado River Basin shown in red for reference.

Figure 7.5 Intermediate-Flow Solutions – Colorado Basin Monthly Flow Distributions for Selected Total (Colorado, Lavaca and Coastal Basins) Annual Flows from 1.3 to 2.3 Million Acre-Feet per Year.

7.7 Findings

The current application of the State Methodology has led to a calculation of a Target flow of 1.428 million acre-feet/year for the Colorado River basin, 593,000 acre-feet per year for the Lavaca River basin, and 729,000 acre-feet per year for the coastal basin. Over the past three decades there have been three other studies addressing the freshwater inflow needs of Matagorda Bay. The first was completed in 1980 by the Texas Department of Water Resources (TDWR, 1980) (now Texas Water Development Board) and proposed monthly inflows from the Lavaca and Colorado rivers to "maintain the fisheries harvest." Matthews and Mueller (1987) presented their recommendations at "Coastal Zone '87" in Seattle, Wash. Ten years later in 1997 LCRA, TWDB, TCEQ and TPWD finished the first Freshwater Inflow Needs of the Matagorda Bay System utilizing the State Methodology. Each successive study illustrates the need to continue to use an adaptive management approach when assessing freshwater inflow needs. Figure 7.6 depicts the total annual inflows recommended for Matagorda Bay from these four studies. Figures 7.7 and 7.8 depict the recommended river inflow volumes by month for the Lavaca and Colorado rivers, respectively. Lastly, Figure 7.9 provides a summary of the 1997 FINS and the current 2006 FINS Target recommendations plotted with the historical monthly average flows for the Colorado River at the Bay City gage.

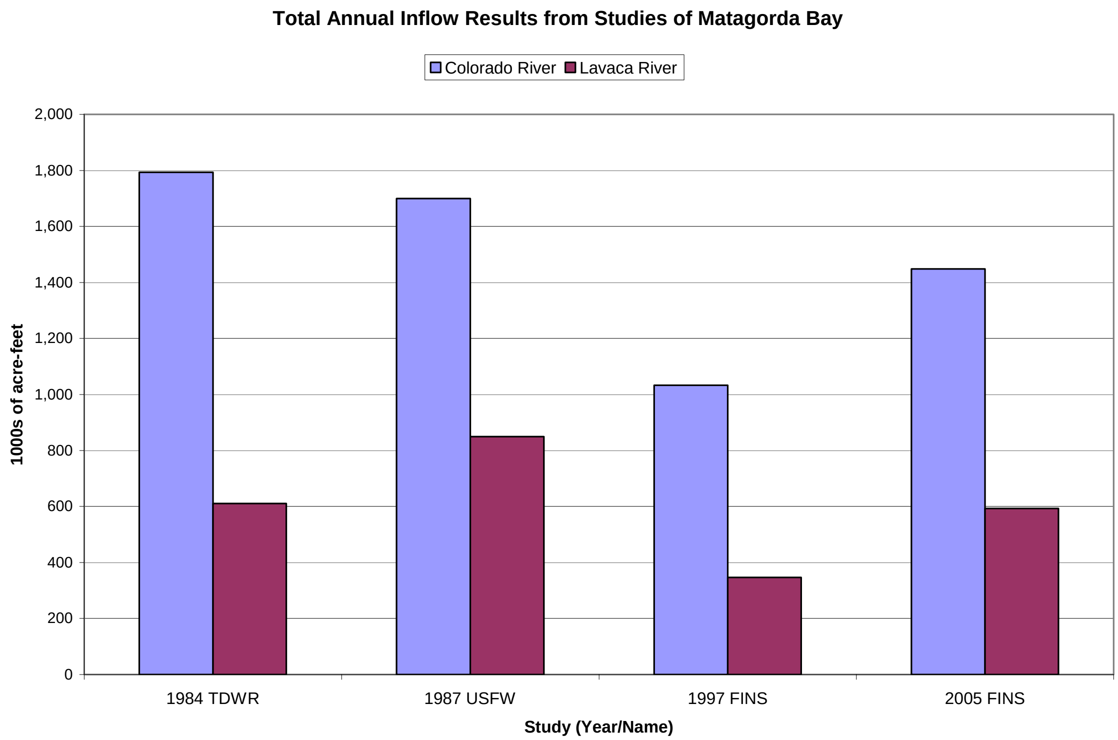


Figure 7.6 Comparison of Matagorda Bay Target Flows for Four Studies.

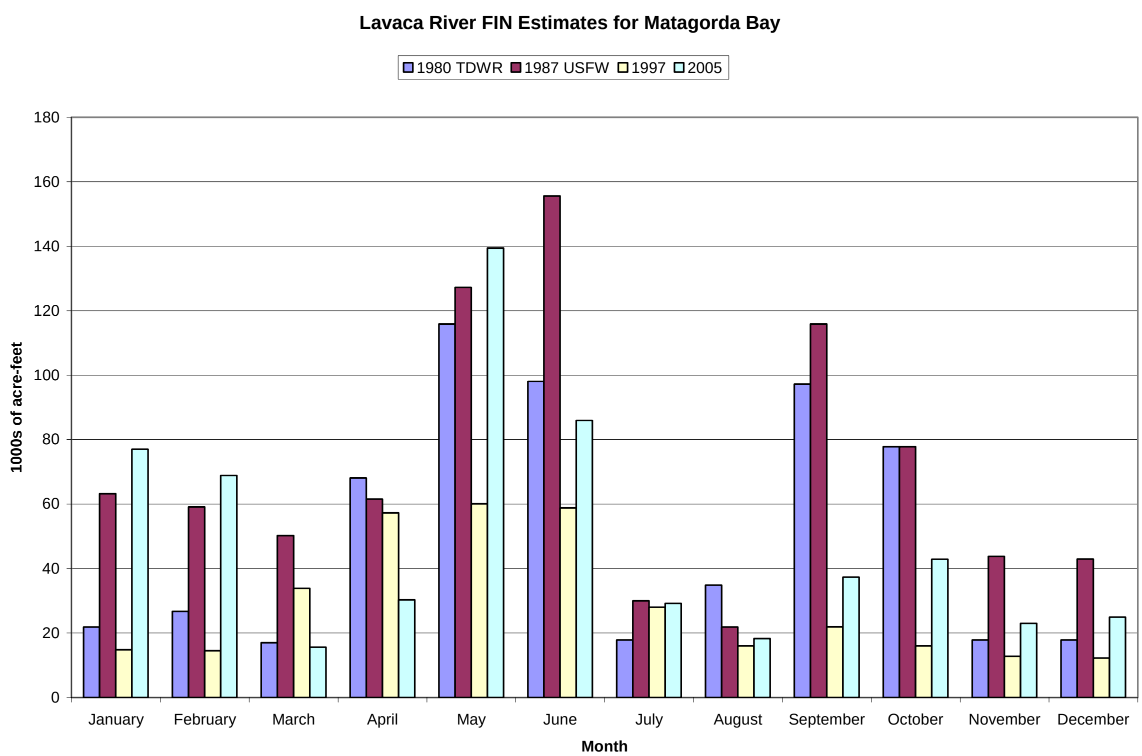


Figure 7.7 Lavaca River Freshwater Inflow Needs Estimates for Matagorda Bay.

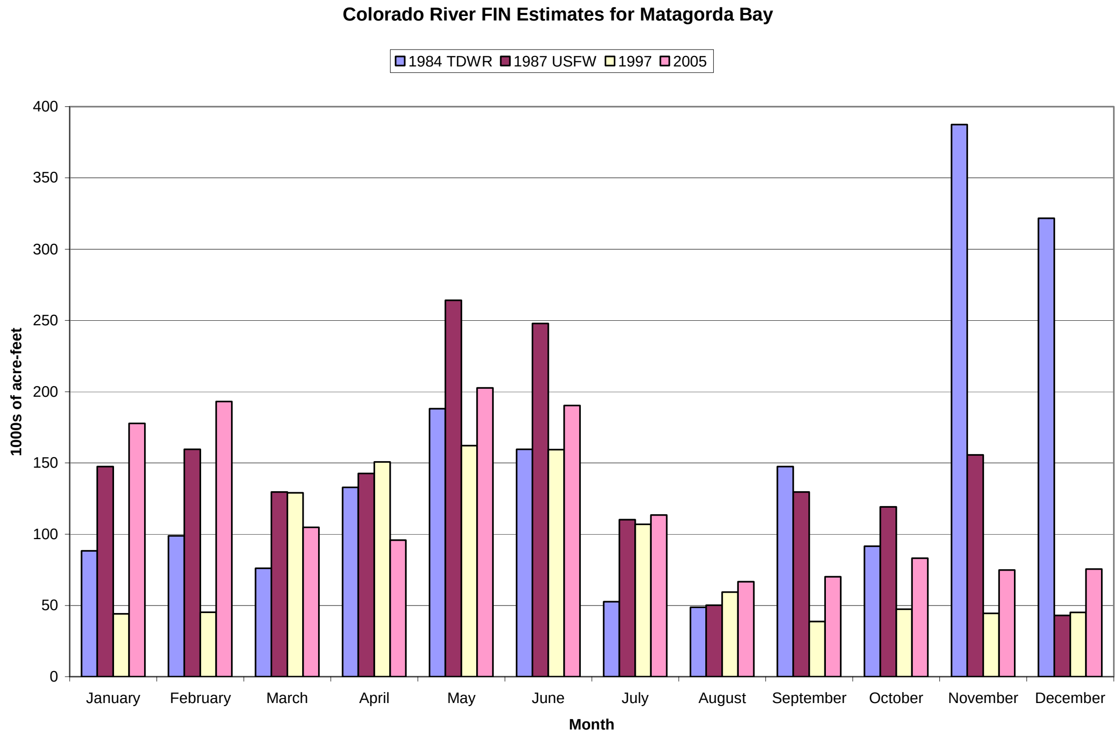


Figure 7.8 Colorado River Freshwater Inflow Needs Estimates for Matagorda Bay.

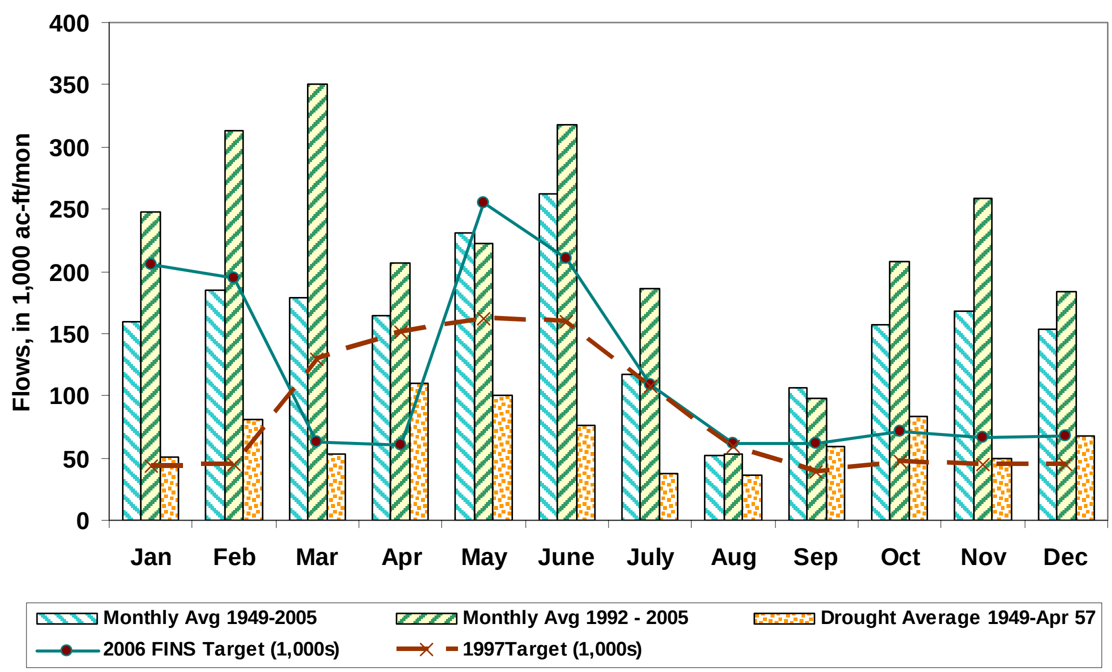


Figure 7.9 Comparison of 1997 and 2006 FINS Estimates for Matagorda Bay with Colorado River Historical Monthly Average Flows at Bay City.

Each study had different methodologies and results. The original inflow recommendations were designed to "maintain the fisheries harvest," while the recommended river flows in 1987 were designed to "maintain the mean shrimp harvest." The stated objective of the past two FIN studies has been to "optimize biological productivity at least at 80 percent of historical levels." While the monthly inflow distribution from each of the studies varies, there is consistency in the overall flow patterns (freshest in the spring and again in the fall). It has been hypothesized that the spring "freshet" has an immediate benefit to the estuary by lowering salinities and providing nutrients that drive the primary productivity of the bay for the current year-class juvenile organisms. Fall flows appear to act as a flushing mechanism to push the current year-class from the marshes and nursery areas into the open bay and Gulf. The fall flows are also thought to benefit the next year's juvenile year-class.

While management objectives for Intermediate flows have not been clearly developed, monthly flow solutions derived from TXEMP using widened constraints were presented in this section. Several Intermediate flow solutions, i.e. solutions representing annual inflow amounts lying between Target and Critical, were presented for consideration when developing Intermediate flow objectives and solutions.

Chapter 8
Hydrodynamic and Salinity Transport Model

8.1 Introduction

The TXEMP optimization model (Chapter 7) was used to compute monthly target flows for Matagorda Bay. Statistical equations were used (Chapter 9) to develop critical flow requirements. This chapter describes the use of a hydrodynamic and salinity transport model, TXBLEND, to evaluate the effect on bay salinity of providing these flows. The model calculates temporal and spatial variations in salinity using inflows, tides and meteorological inputs.

8.2 Model Description

TXBLEND is an adaptation of a finite-element hydrodynamic and conservative transport model developed in the 1980s (Gray, 1987) to simulate tidally driven circulation in estuaries. The model has been applied to freshwater inflow needs studies of estuaries in Texas (LCRA, 1997; Kuhn and Chen, 2005), and is currently used to predict currents in Galveston Bay, Corpus Christi Bay and Sabine Lake to support the Texas General Land Office's Oil Spill Prevention and Response Program[1].

TXBLEND solves the two-dimensional, vertically averaged form of the equations of motion for a fluid, the equations for conservation of mass and the advection-diffusion equations applied to transport of salt. Model inputs include inflows for major rivers and streams that drain into Matagorda Bay and adjacent bays, Gulf of Mexico tidal elevations, wind, rainfall and evaporation. Given these inputs, the model computes the temporal variation of water velocity, water depth and salinity at each point in the numerical grid that describes the system. The computational time step applied in this study was 180 seconds. Model outputs were provided at hourly intervals.

[1] http://hyper20.twdb.state.tx.us/data/bays_estuaries/bhydpage.html

8.2.1 Model Domain

The numerical grid describing the model domain contains 10,608 triangular elements and 6,799 nodal points (Figure 8.1). The grid represents San Antonio Bay, Matagorda Bay, East Matagorda Bay and the Gulf of Mexico. It includes 15 inflow locations including the Colorado River, Lavaca River, Guadalupe River and major coastal tributaries (Figure 8.2). Bay bathymetry (Figure 8.3) was based on bathymetry data used in a modeling study by the Corps of Engineers (USACE, 2003). This data was provided to TWDB and subsequently modified using Surface Water Monitoring System (SMS) software to extend the grid westward to include San Antonio Bay and to make the Gulf of Mexico one continuous boundary.

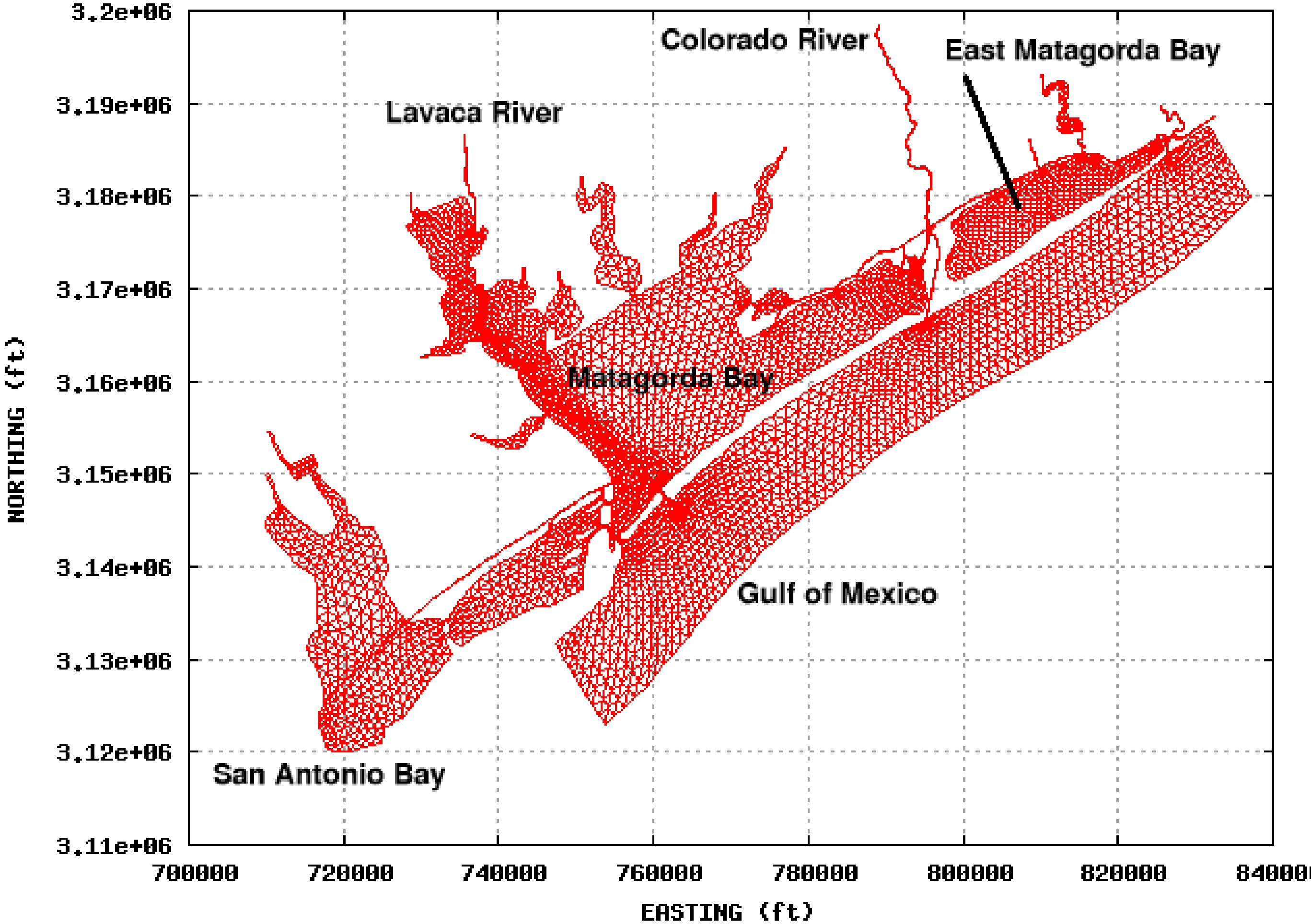


Figure 8.1 TXBLEND Numerical Grid.

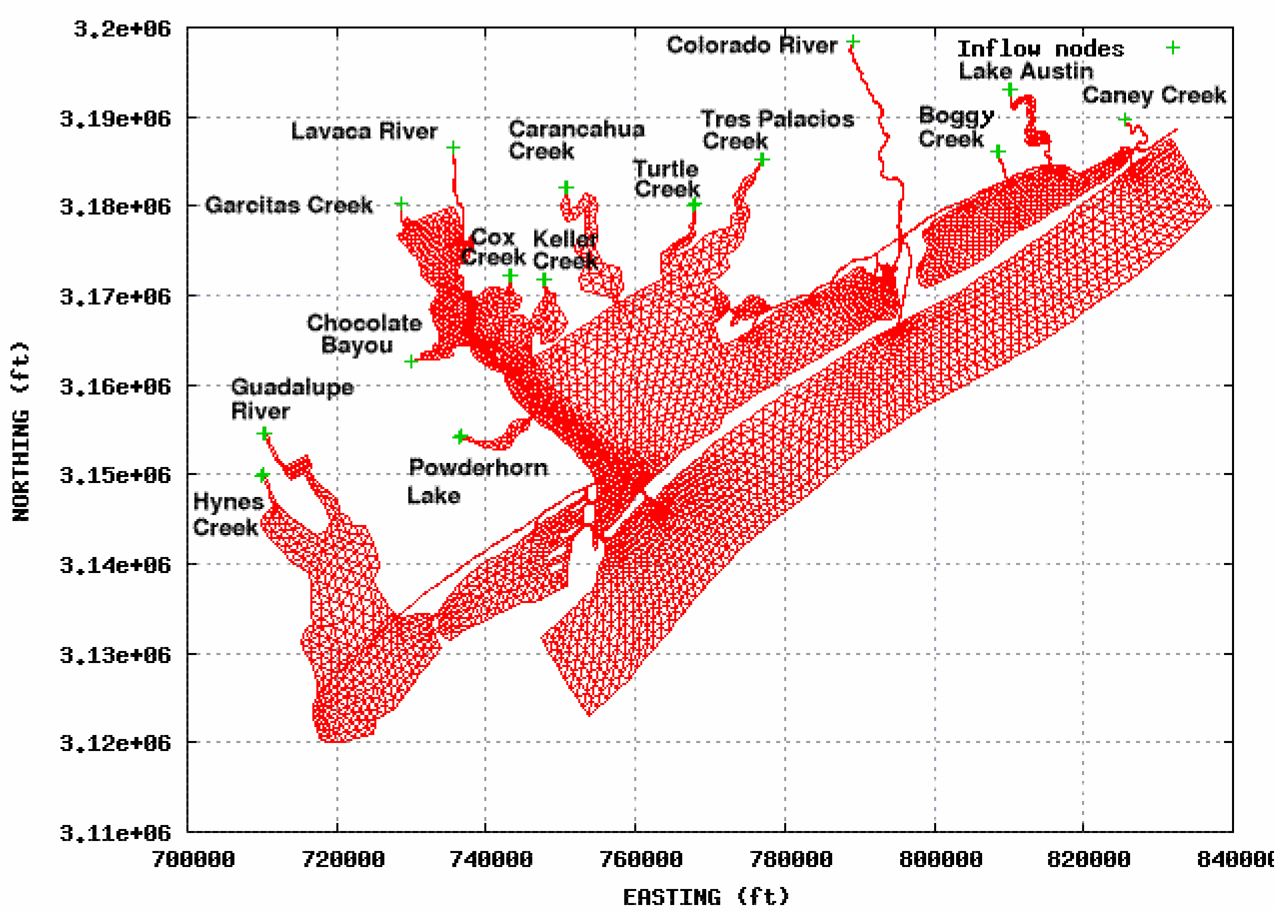


Figure 8.2 Inflow Locations (green markers) Used in Matagorda Bay TXBLEND Model.

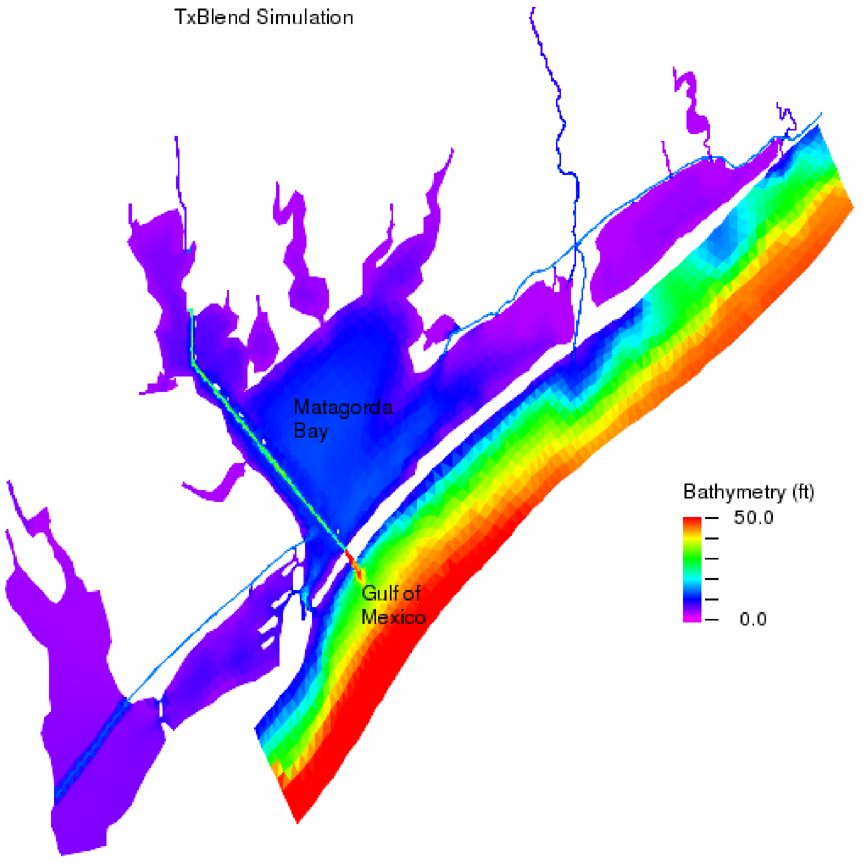


Figure 8.3 Bathymetry for Matagorda Bay used in TXBLEND.

8.2.2 Inflows

Daily inflow data for the fifteen inflow sites in the Matagorda Bay model grid was provided by TWDB. Inflows from 1997 through 2003 were used to calibrate TXBLEND (Figures 8.4.a to 8.4.o). Flows for the Colorado River and Guadalupe River were based on USGS streamflow gages at Bay City and Victoria, respectively. Flows for the Lavaca River were based on releases from Lake Texana. Daily inflows from the coastal watersheds for adjacent to the bay were computed with the TxRR rainfall runoff model with adjustments for known diversions and return flows in the watersheds.

Flows from 1997 through 2003 were highly variable. The second and third largest annual inflows to Matagorda Bay occurred in 1997 and 1998, respectively, surpassed only by flows in 1992 (Table 2.1). Flows for the two year period from 1997 through 1998 rank at the 95th percentile for bi-annual flows, and flows from 2001 through 2002 rank at the 90th percentile of bi-annual flows. Flows in 1999 and 2000 rank as the 22nd and 23rd percentile flows. Flows during this two year-period represent the 16th percentile flow for bi-annual flows. The large variability of flows during this period makes it well-suited for the purpose of calibrating TXBLEND.

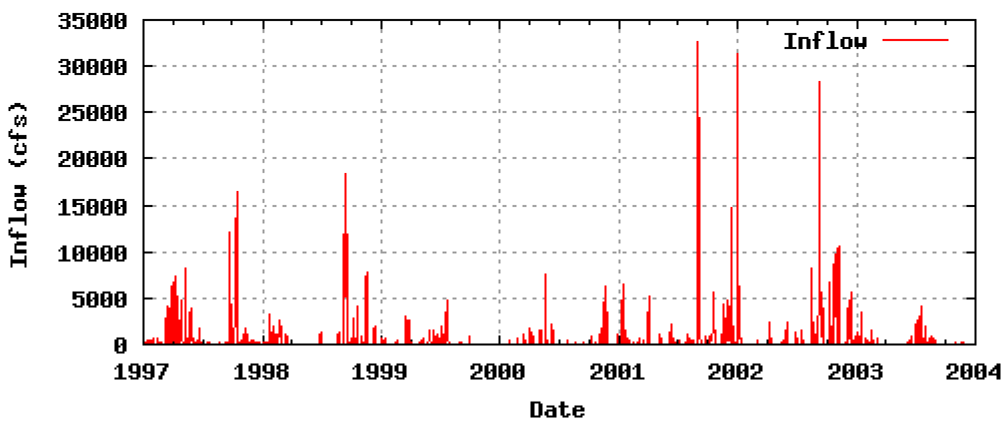


Figure 8.4.a Inflow Hydrograph for Caney Creek.

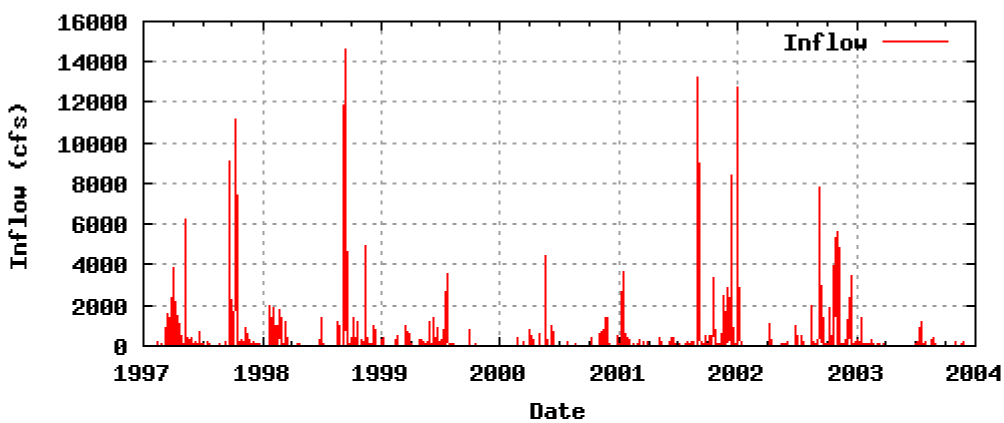


Figure 8.4.b Inflow Hydrograph for Lake Austin.

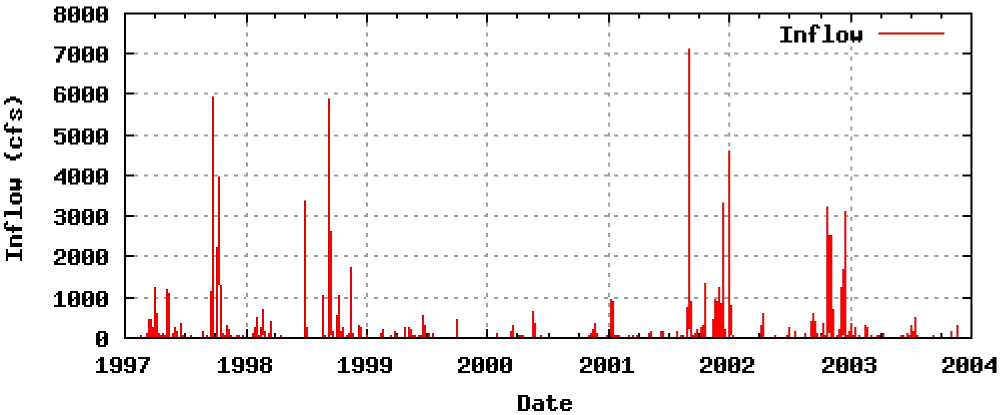


Figure 8.4.c Inflow Hydrograph for Boggy Creek.

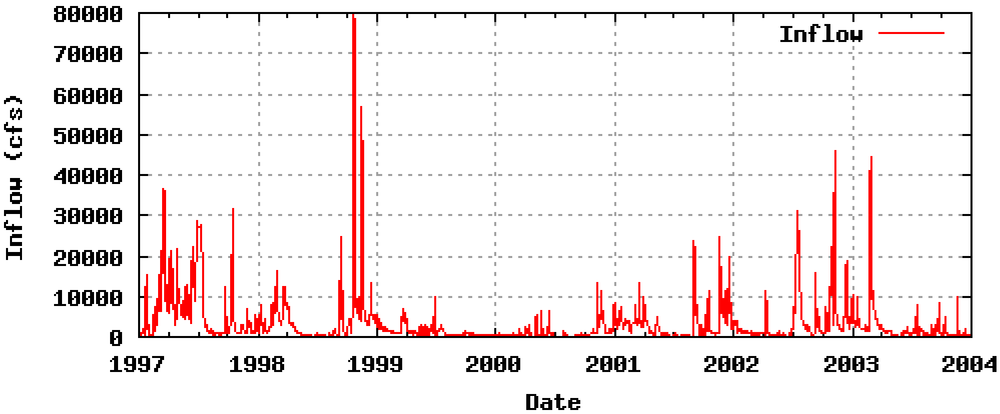


Figure 8.4.d Inflow Hydrograph for Colorado River.

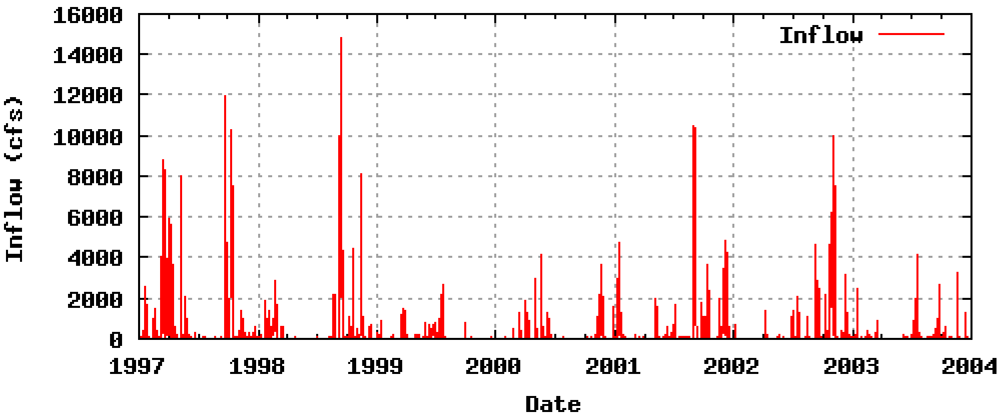


Figure 8.4.e Inflow Hydrograph for Tres Palacios Creek.

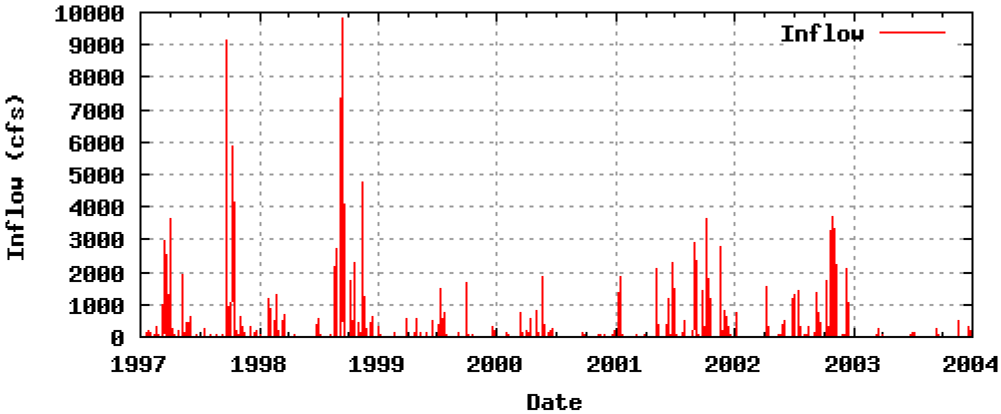


Figure 8.4.f Inflow Hydrograph for Turtle Creek.

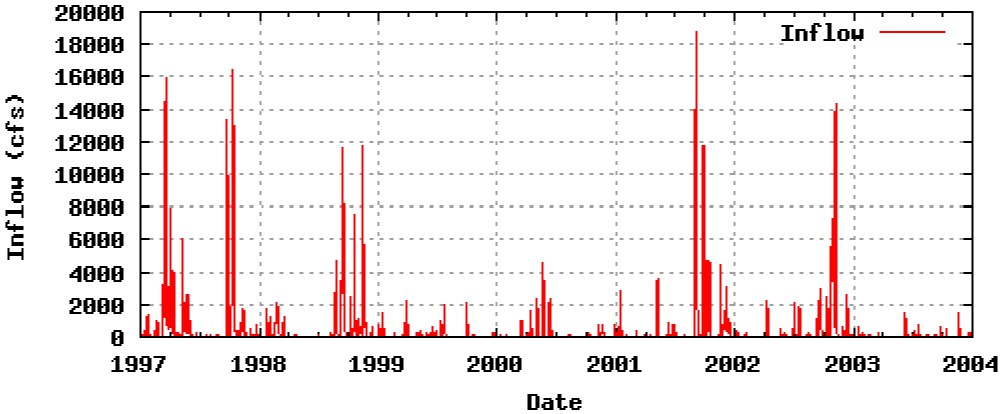


Figure 8.4.g Inflow Hydrograph for Carancahua Creek.

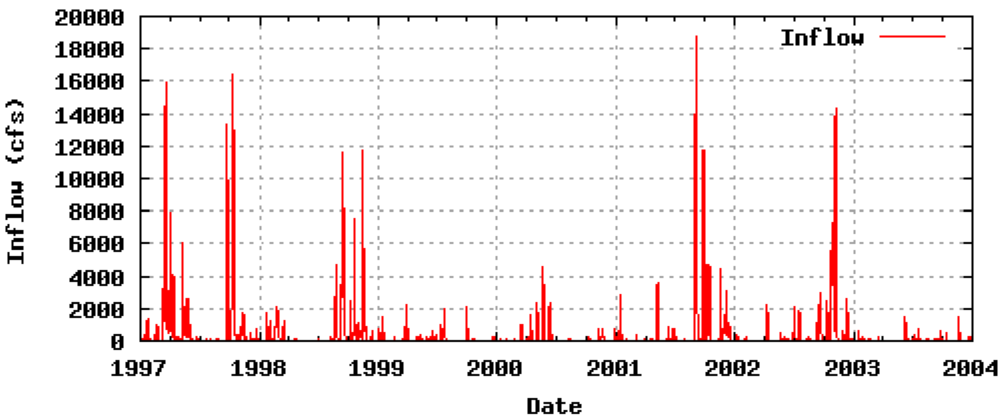


Figure 8.4.h Inflow Hydrograph for Keller Creek.

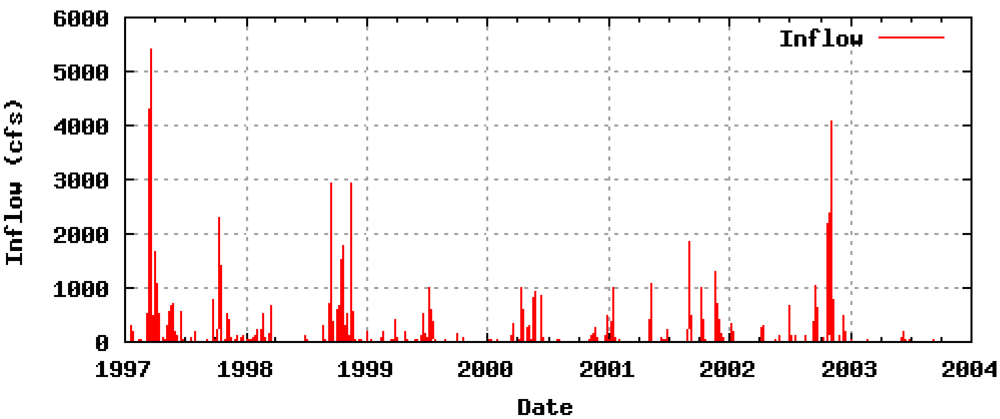


Figure 8.4.i Inflow Hydrograph for Cox Creek.

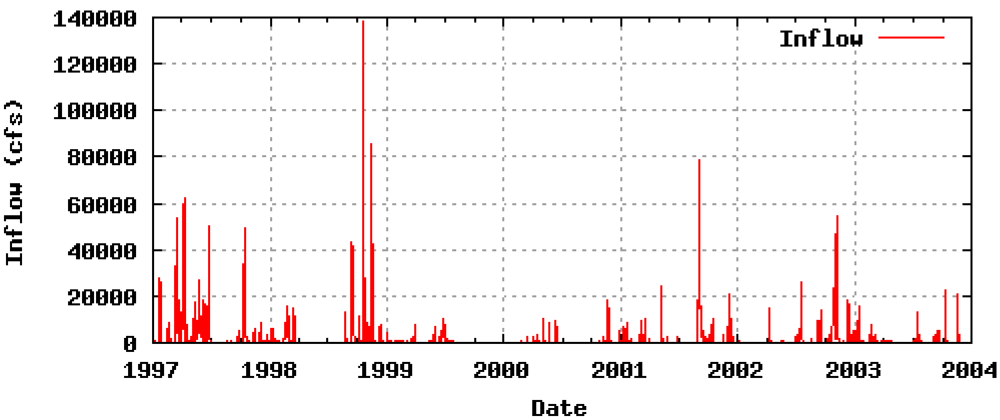


Figure 8.4.j Inflow Hydrograph for Lavaca River.

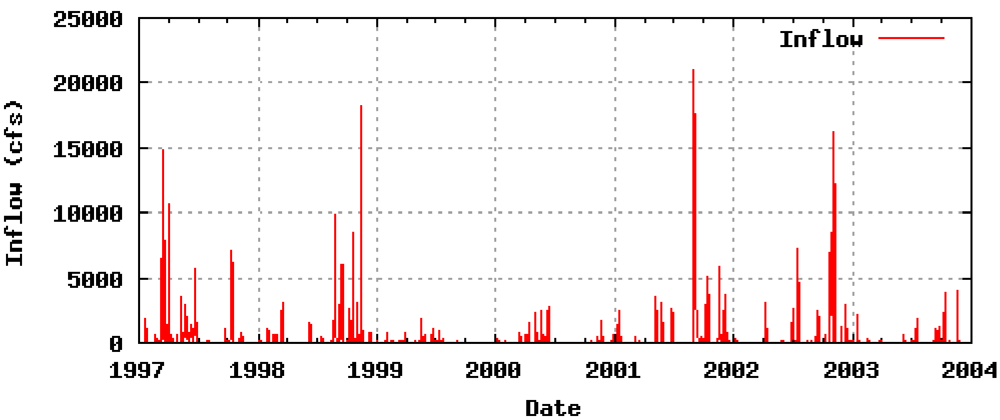


Figure 8.4.k Inflow Hydrograph for Garcitas Creek.

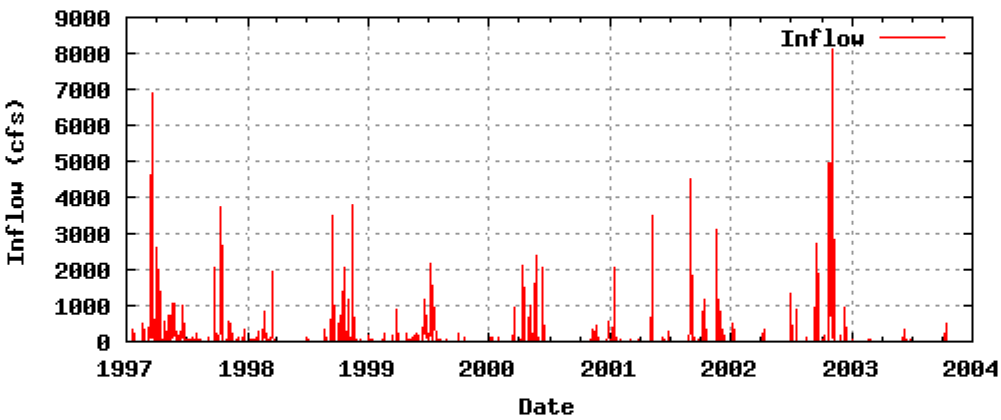


Figure 8.4.l Inflow Hydrograph for Chocolate Bayou.

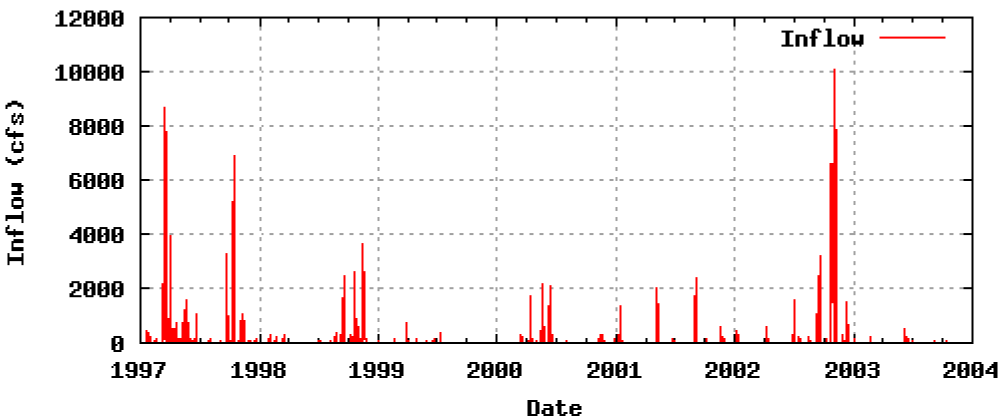


Figure 8.4.m Inflow Hydrograph for Powderhorn Lake.

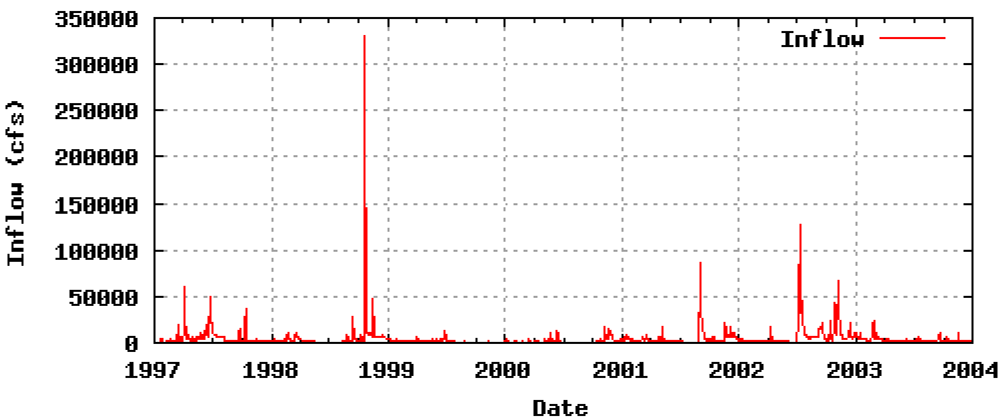


Figure 8.4.n Inflow Hydrograph for Guadalupe River.

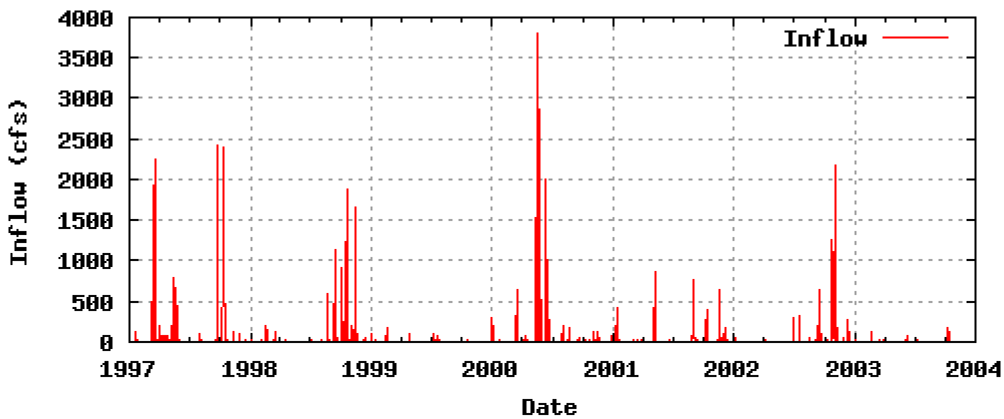


Figure 8.4.o Inflow Hydrograph for Hynes Creek.

8.2.3 Tides

Tidal elevations for Galveston Pleasure Pier were obtained from Conrad Blucher Institute[2] (Figure 8.5) and applied at the Gulf boundary in TXBLEND. Missing data was filled in using a least-squares method for computing harmonic constants (Dronkers, 1964). The data was reformatted to a bi-hourly format for use in TXBLEND. Tides in this region of the Gulf coast typically range from 3 to 4 feet, with occasional drops and surges due to passing tropical depressions and hurricanes. The time lag between the tide at Pleasure Pier and the coast off of Matagorda Bay is on the order of minutes. This was not considered significant in this study and was not incorporated into the model.

8.2.4 Meteorology

A time-varying, spatially uniform wind field (Figure 8.6) is applied in TXBLEND to compute wind stress at the water's surface. Wind speed and direction from January 1987 through November 2003 were obtained from the National Climatic Data Center for the Palacios Municipal Airport.

Rainfall and evaporation (Figure 8.6) are included in the water budget for Matagorda Bay by TXBLEND. Daily precipitation was provided by TWDB for the watershed WS15010

[2] http://lighthouse.tamucc.edu/overview/022

representing Matagorda Bay. Evaporation data was also provided by TWDB and is based on measurements of pan-evaporation.

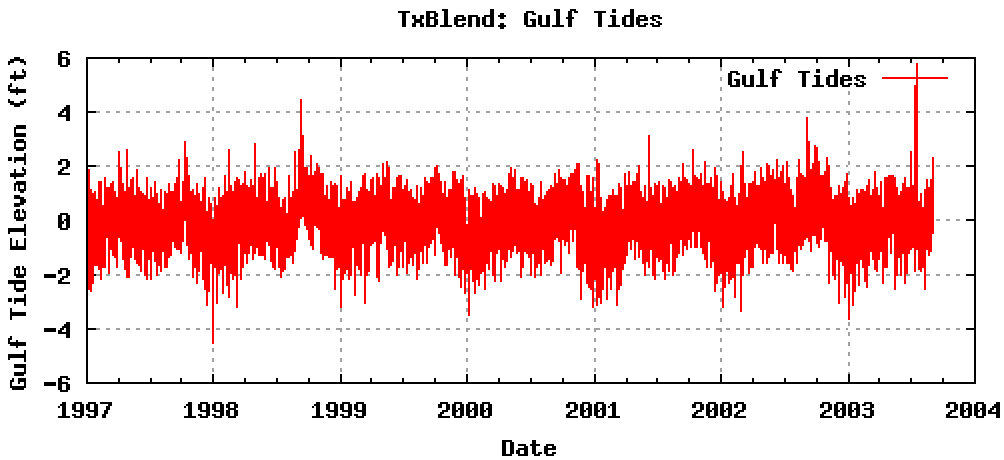


Figure 8.5 Tidal elevations, 1997 through 2003. Data obtained from Conrad Blucher Institute.

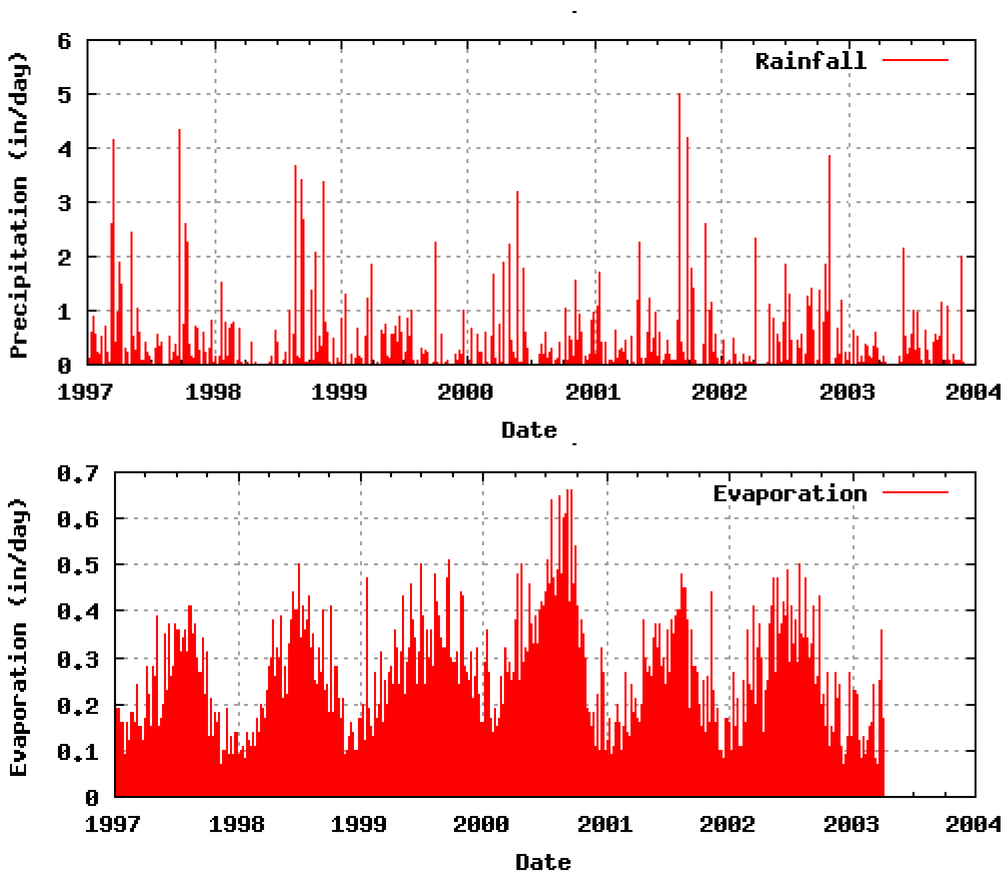


Figure 8.6 Rainfall (top) and Evaporation (bottom), 1997 through 2003. Data Provided by TWDB.

8.2.5 Gulf Boundary Salinity

A time-varying salinity boundary condition (Figure 8.7) was applied in TXBLEND at the Gulf boundary. This boundary condition was supplied by TWDB and was developed by averaging TPWD data collected offshore of the Entrance Channel and Pass Cavallo. Salinity varies significantly at this boundary, ranging from less than 24 ppt to over 37 ppt.

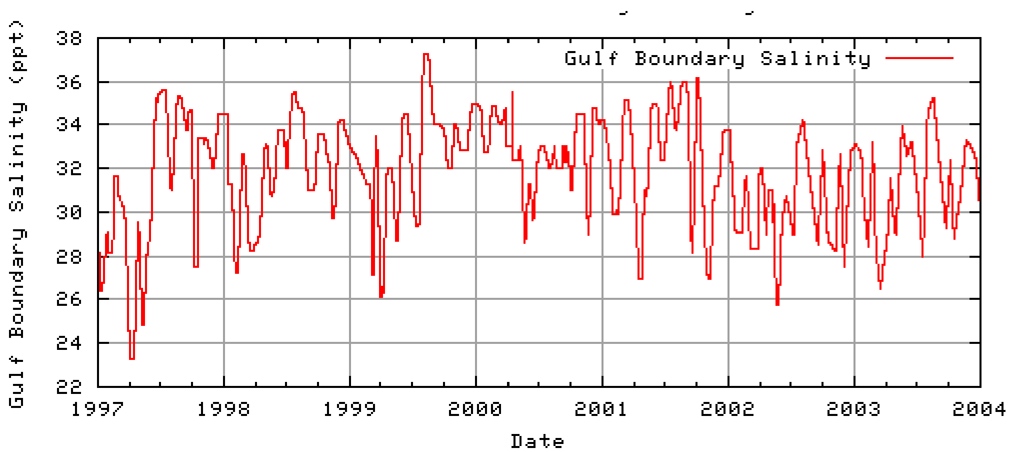


Figure 8.7 Gulf Salinity Boundary Condition, 1997 through 2003. Data provided by TWDB.

8.3 Model Calibration

Hydrodynamics in TXBLEND were calibrated by comparing computed water surface elevations and flows to data collected at eighteen sites (fourteen for flow, four for water surface elevation) in Matagorda Bay during a March 2003 field study (Figure 8.8, Table 8.1, Figures 8.9.a to 8.9.m, Figures 8.10.a to 8.10.d). Flow was measured during this study using acoustic Doppler profilers (ADCP) whereby velocity data is collected across the entire channel cross section. For the Magnolia Beach (Site 4) and Eastern Arm of Matagorda Bay (Site 6A) sites, the ADCP transects covered wide sections of the bay and were useful in monitoring movement of water into the far reaches of the bay.

Manning's n was adjusted during the calibration process and varied from 0.0211 to 0.0244 in the final calibrated model. Channel depths and widths were also adjusted at some sites within acceptable ranges. These adjustments to depths and widths were considered reasonable given the dynamic nature of channels in the system and the lack of recent bathymetric data for these sites.

Both the flow amplitude and phase match well in the calibrated model at major flow locations including the Matagorda Entrance Channel (Site 1), Pass Cavallo (Site 2A), Magnolia Beach (Site 4), the Eastern Arm of Matagorda Bay (Site 6A), and the Bypass Channel (Site 8C). Flows at the intersection of the Colorado River and GIWW do not match as well, likely because the model simulates open lock conditions, while the locks were closed during most of the field study.

Modeled water surface elevations were compared to measured elevations obtained from the Texas Coastal Ocean Observation Network (TCOON) for sites at Rawling's Bait Stand (mouth of the Bypass Channel, TCOON Site 54), Port Lavaca (Lavaca causeway, TCOON Site 33), Port O'Connor (TCOON site 57), and Seadrift, (San Antonio Bay, TCOON Site 31). Modeled elevations matched measurements well at all sites.

Transport and mixing processes were calibrated in the model using long-term salinity data collected at eleven sites (Figure 8.11) in the bay from 1997 through 2003 (8.13). This period experienced a wide range of inflows and salinity, making it desirable for calibration purposes. Also, multiple monitoring sites were available for this period, while only three sites were available prior to 1997. The model matches long-term rises and falls in observed salinity well at all points in Matagorda Bay and East Bay, but is not as successful in matching the ranges of observed high frequency variations following flood events and large salinity drops (see e.g. West Bay Tripod and Shellfish Marker B, Figures 8.12.g, and 8.12.h). Additional statistical comparisons between computed and observed salinities are presented in Appendix G.

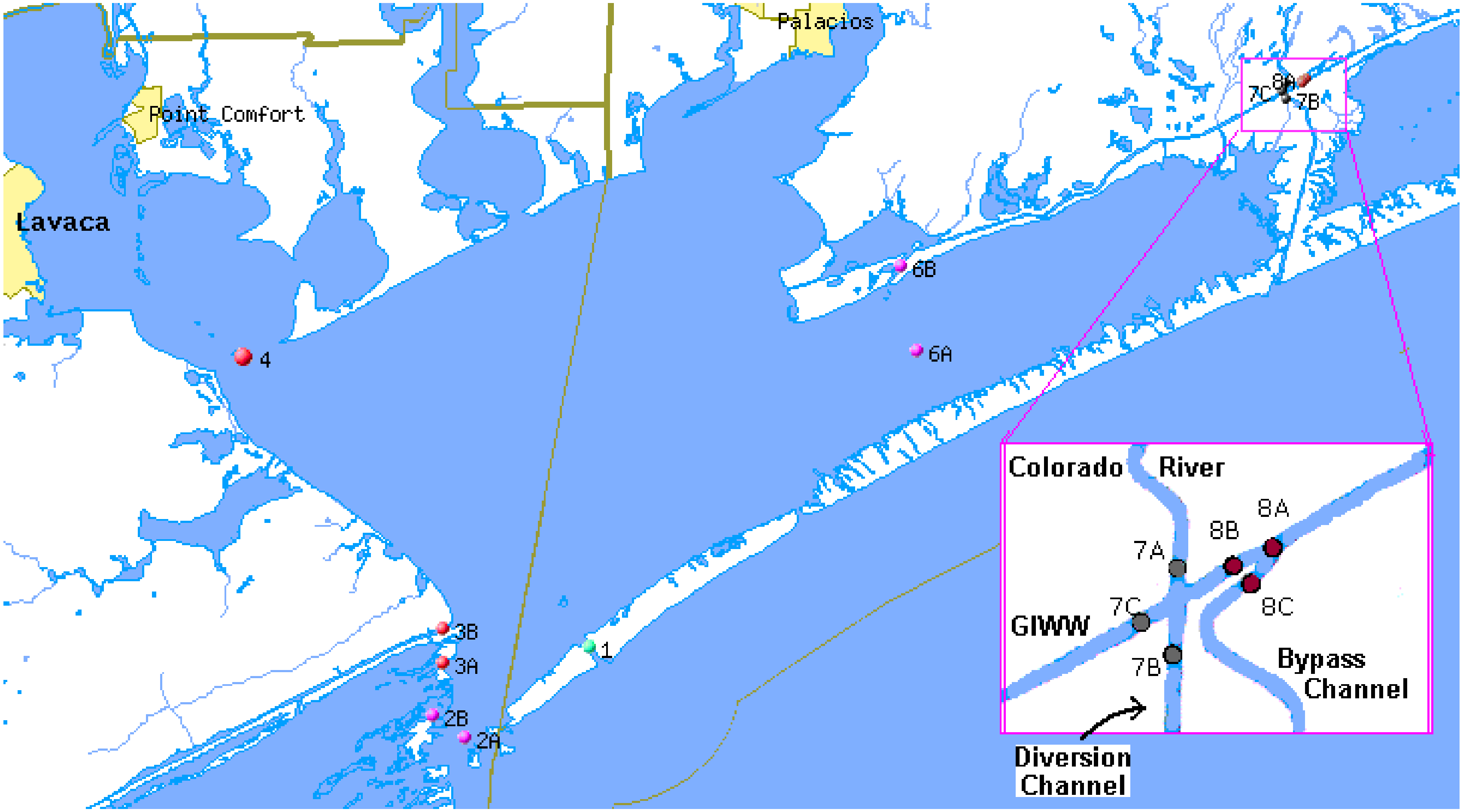


Figure 8.8 Site Map for March 2003 Field Study Measurement Locations.[3]

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[3] http://hyper20.twdb.state.tx.us/data/bays_estuaries/studies/mat03main.html

Table 8.1 Site Names and Number for March 2003 Field Study.

Site Name	Site Number
Matagorda Entrance Channel	1
Pass Cavallo	2A
Saluria Bayou	2B
Big Bayou	3A
GIWW at Port O'Connor	3B
Magnolia Beach	4
Eastern Arm of Matagorda Bay	6A
GIWW at Oyster Lake	6B
North Colorado River	7A
South Colorado River	7B
GIWW West of Locks	7C
GIWW East of Bypass Channel	8A
GIWW West of Bypass Channel	8B
Bypass Channel	8C

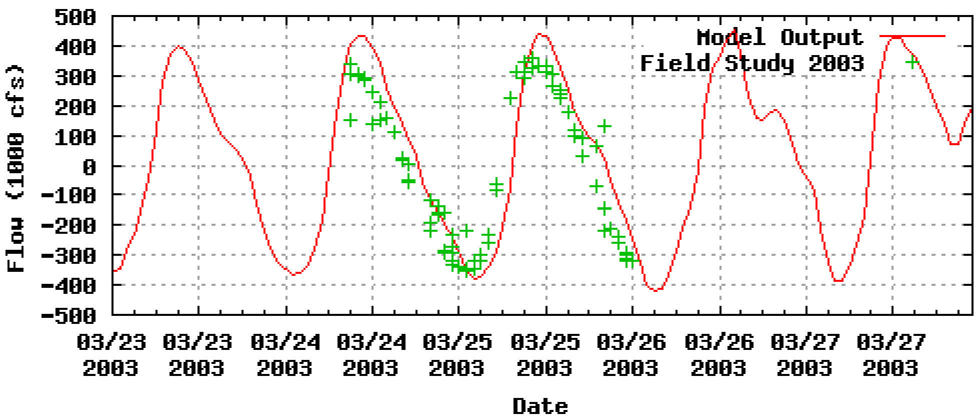


Figure 8.9.a – Measured (green crosses) and Computed (red line) Flows at Matagorda Entrance Channel (Site 1).

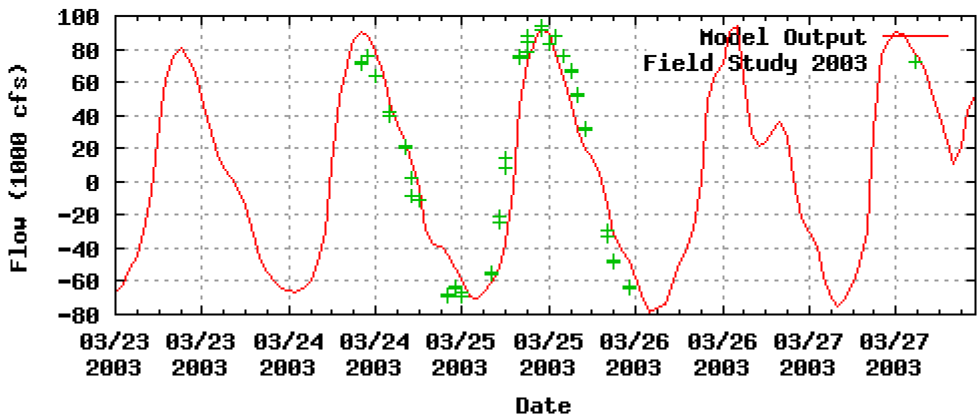


Figure 8.9.b Measured (green crosses) and Computed (red line) Flows at Pass Cavallo (Site 2A).

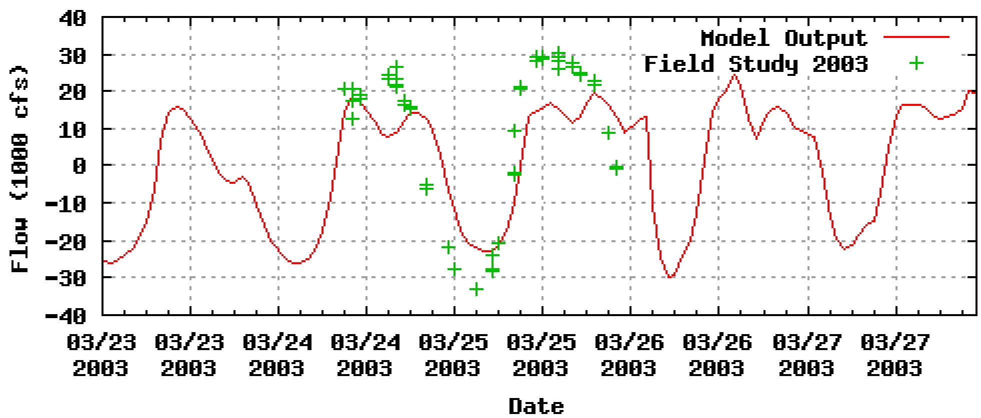


Figure 8.9.c Measured (green crosses) and Computed (red line) Flows at Saluria Bayou (Site 2B).

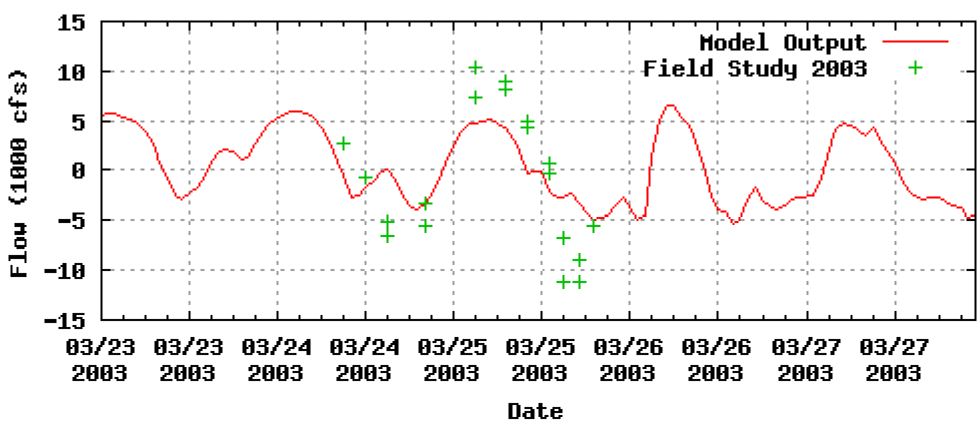


Figure 8.9.c Measured (green crosses) and Computed (red line) Flows at Big Bayou (Site 2C).

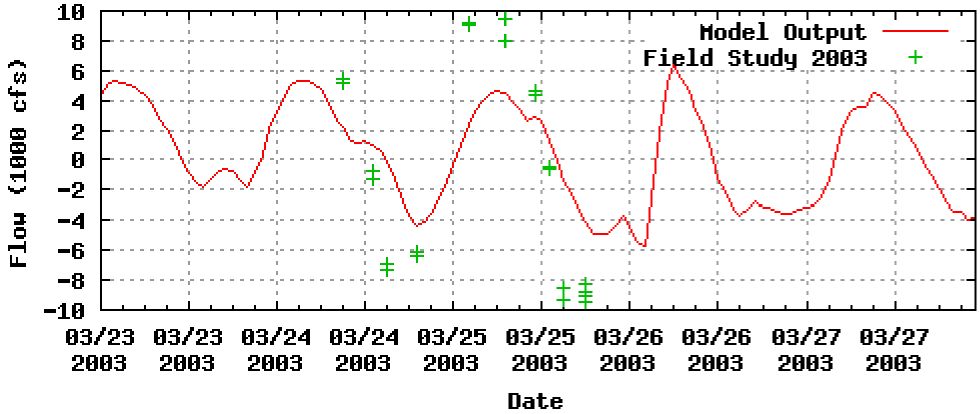


Figure 8.9.d Measured (green crosses) and Computed (red line) Flows at GIWW at Port O'Connor (Site 3B).

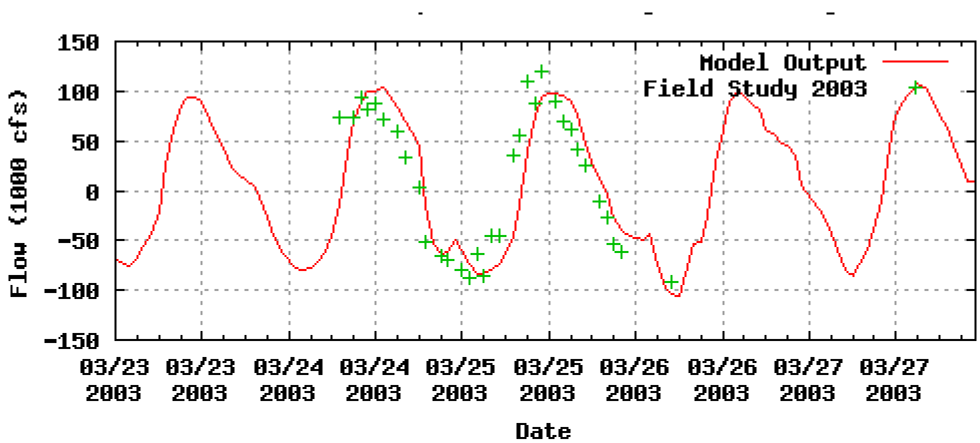


Figure 8.9.e Measured (green crosses) and Computed (red line) Flows at GIWW at Magnolia Beach (Site 4).

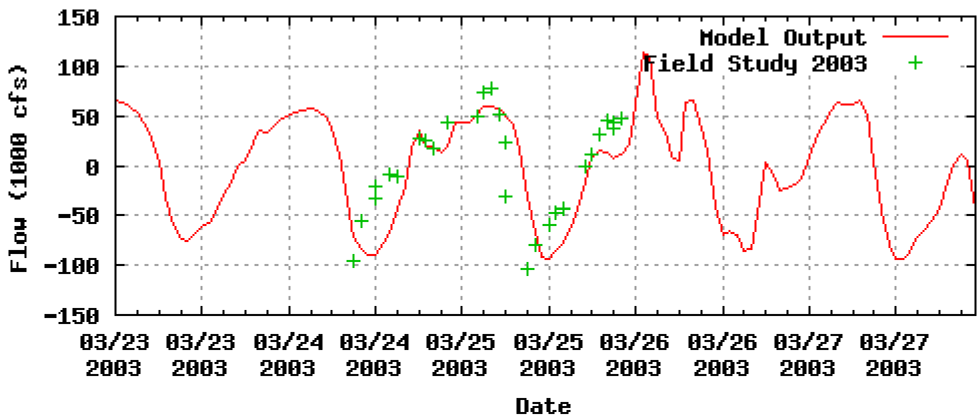


Figure 8.9.f Measured (green crosses) and Computed (red line) Flows at Eastern Arm of Matagorda Bay (Site 6A).

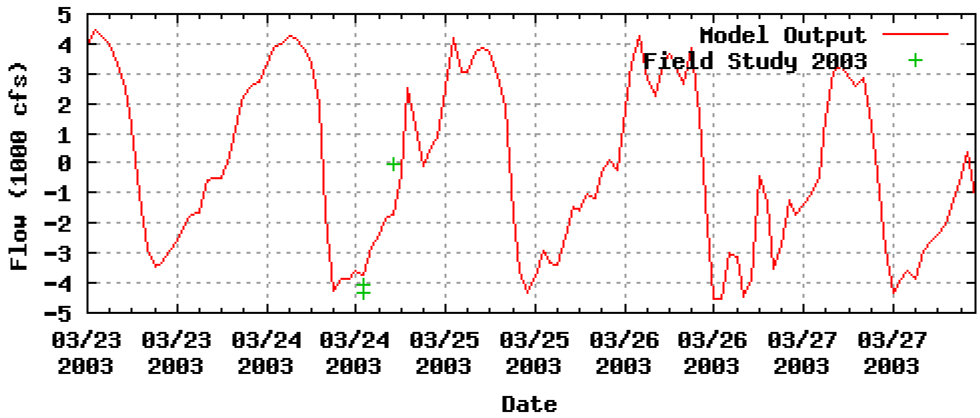


Figure 8.9.g Measured (green crosses) and Computed (red line) Flows at GIWW at Oyster Lake (Site 6B).

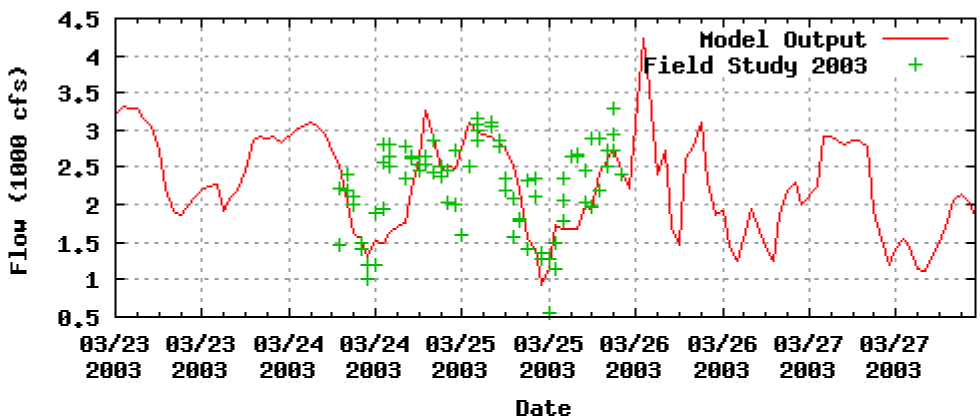


Figure 8.9.h Measured (green crosses) and Computed (red line) Flows at North Colorado River (Site 7A).

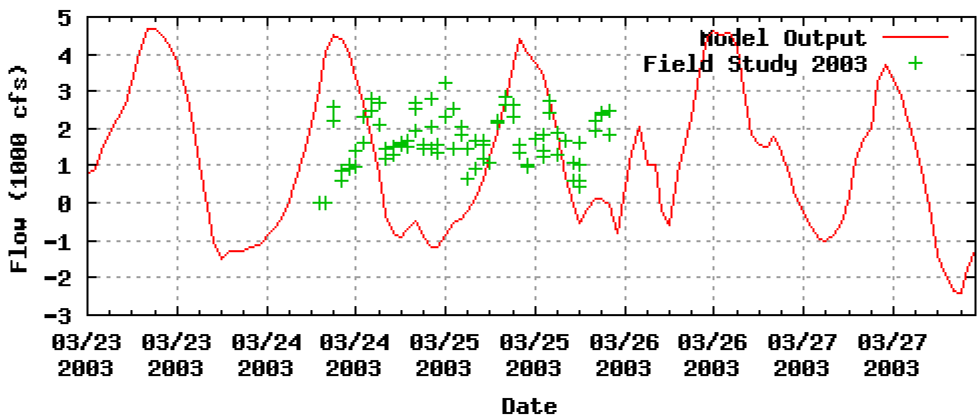


Figure 8.9.i – Measured (green crosses) and Computed (red line) Flows at South Colorado River (Site 7B).

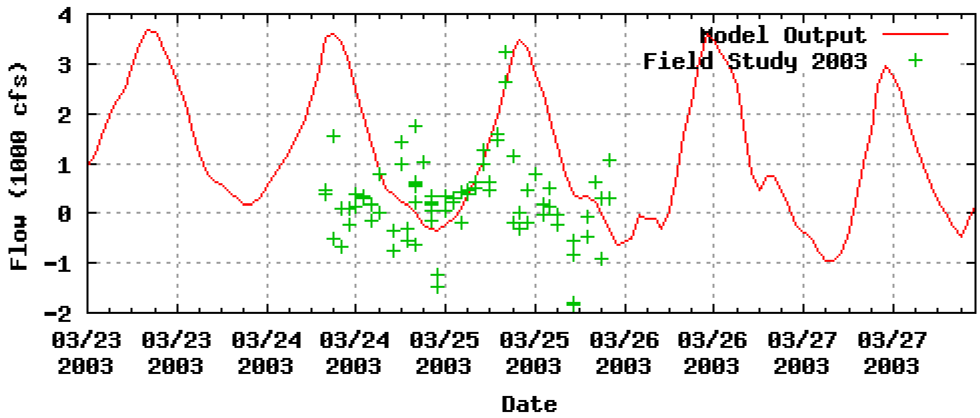


Figure 8.9.j Measured (green crosses) and Computed (red line) Flows at GIWW West of Locks (Site 7C).

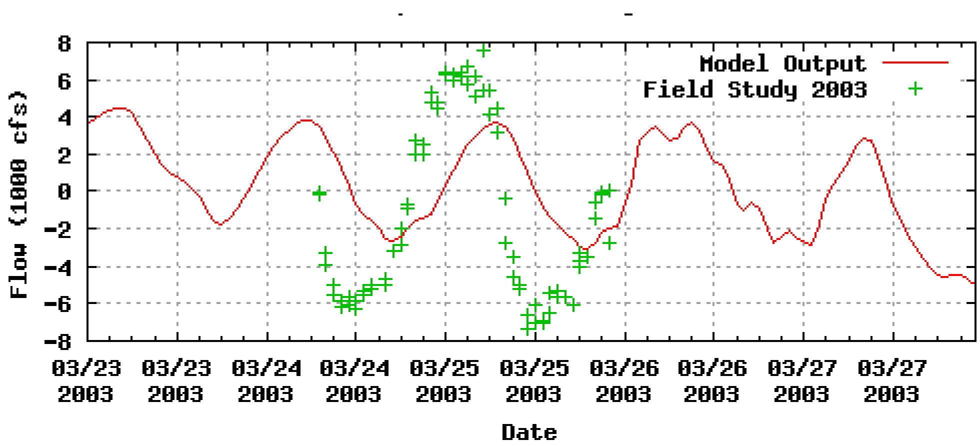


Figure 8.9.k Measured (green crosses) and Computed (red line) Flows at GIWW East of Bypass Channel (Site 8A).

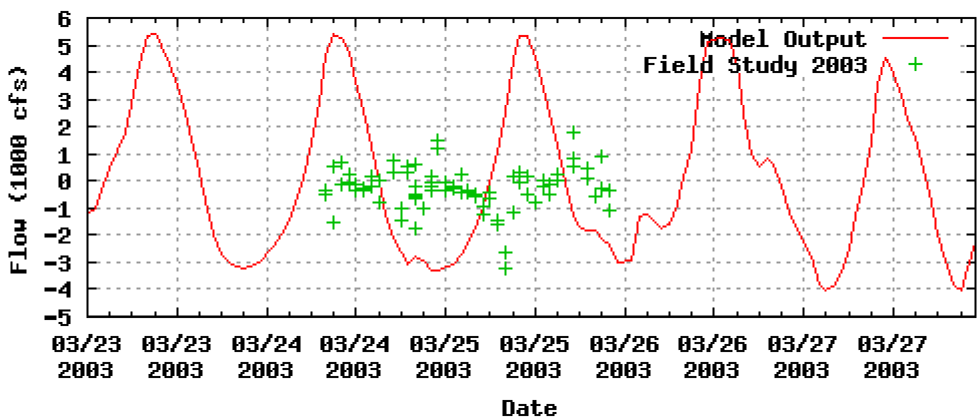


Figure 8.9.l Measured (green crosses) and Computed (red line) Flows at GIWW West of Bypass Channel (Site 8B).

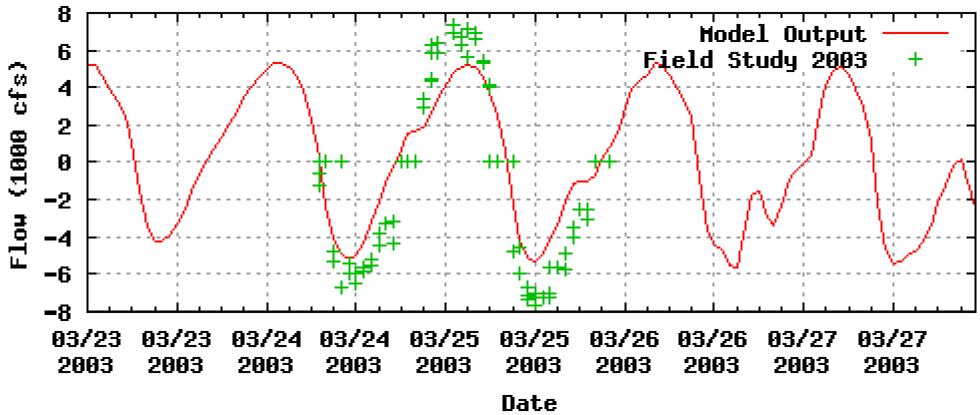


Figure 8.9.m Measured (green crosses) and Computed (red line) Flows at Bypass Channel (Site 8C).

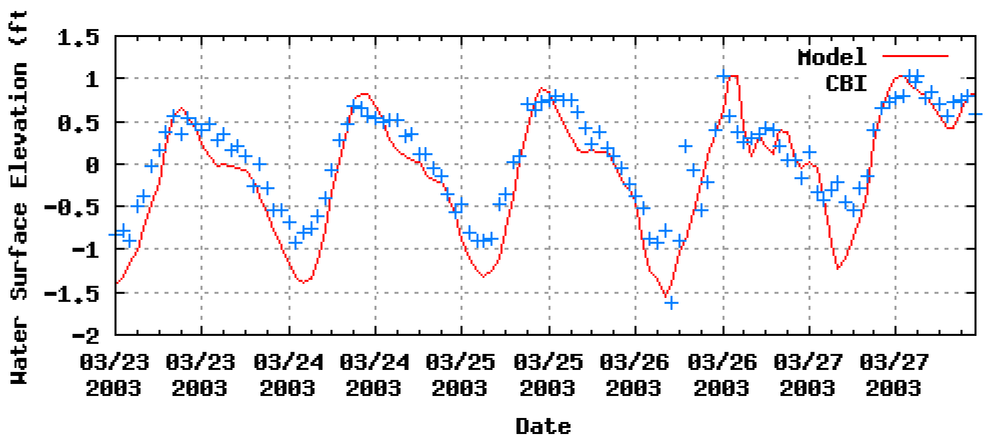


Figure 8.10.a Measured (blue crosses) and Computed (red line) Water Surface Elevation at Rawling's Bait Stand (TCOON site 54).

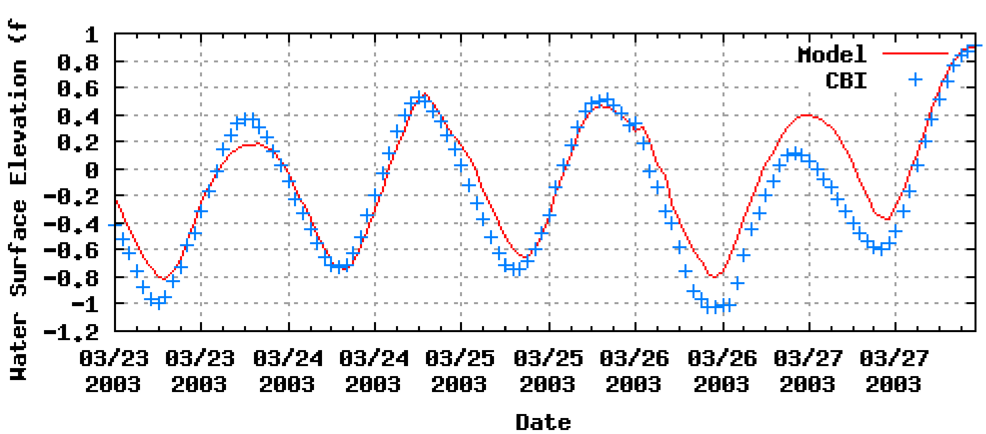
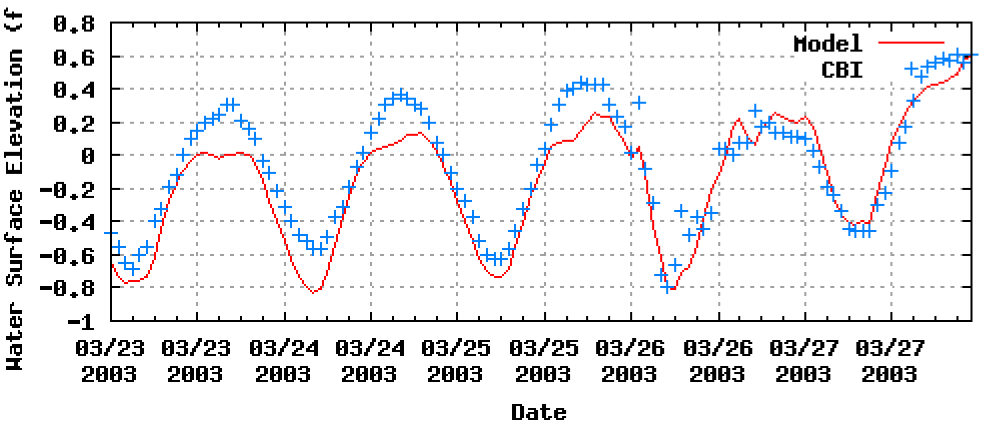
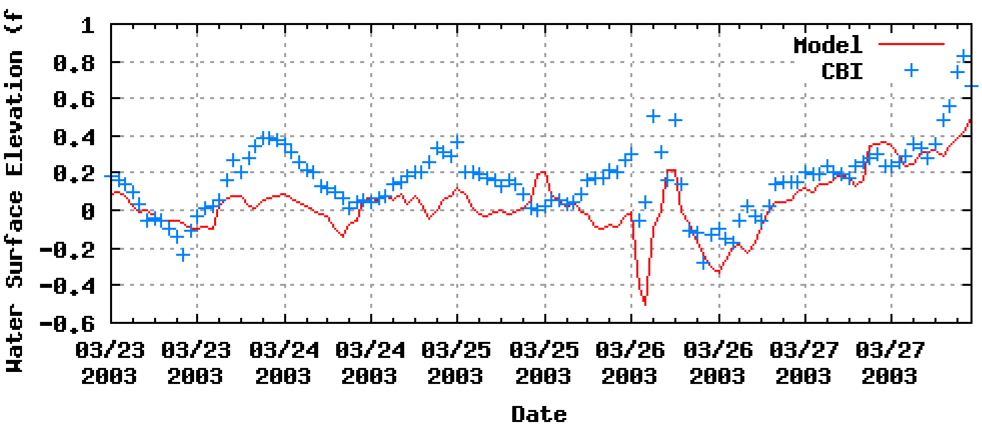


Figure 8.10.b Measured (blue crosses) and Computed (red line) Water Surface Elevation at Port Lavaca (TCOON site 33).



8.10.c Measured (blue crosses) and Computed (red line) Water Surface Elevation at Port O'Connor (TCOON site 57).



8.10.d Measured (blue crosses) and Computed (red line) Water Surface Elevation at Seadrift (TCOON site 31).

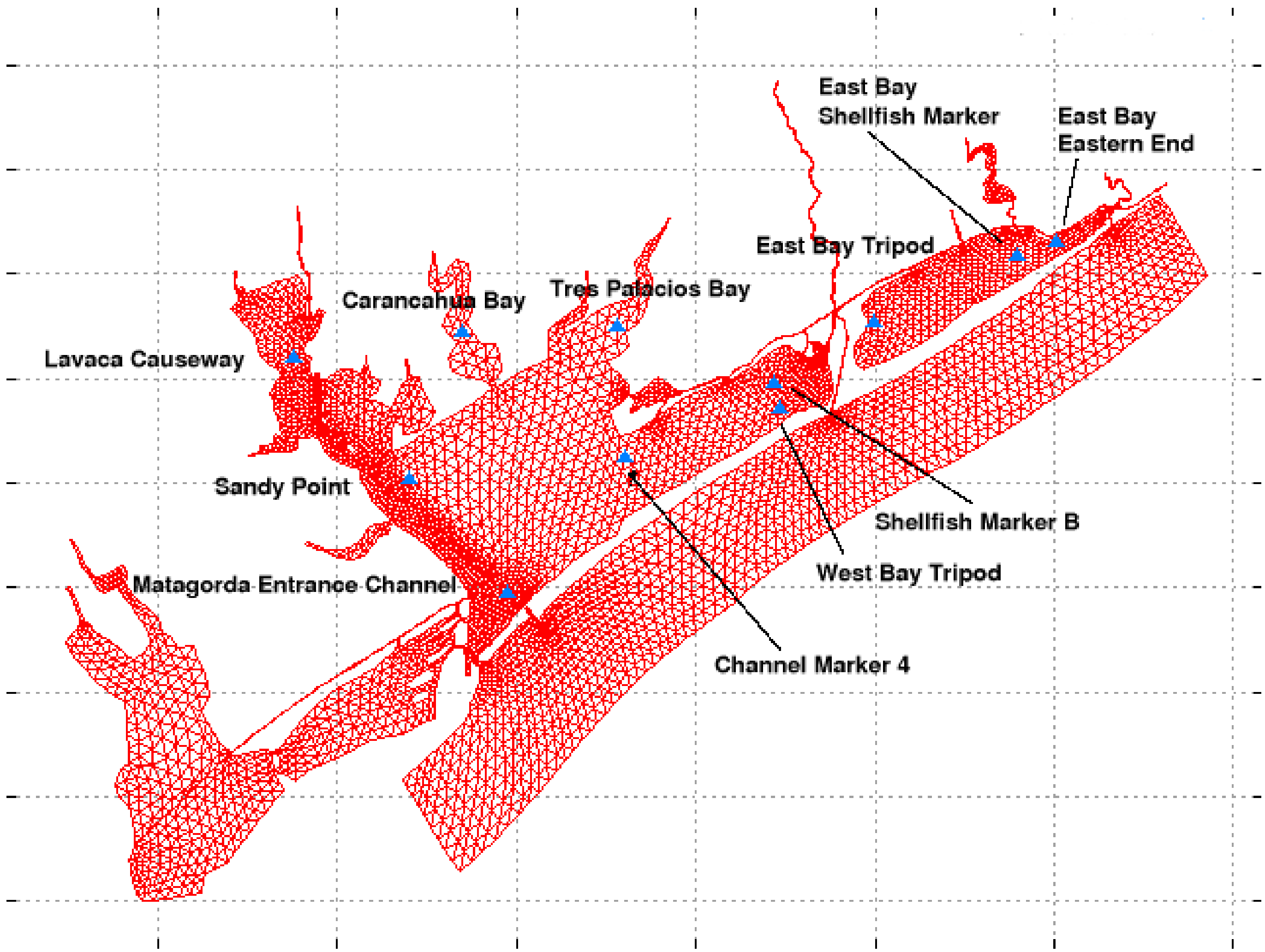


Figure 8.11 Locations of Datasonde Sites (blue triangles) Used in Calibrating TXBLEND.

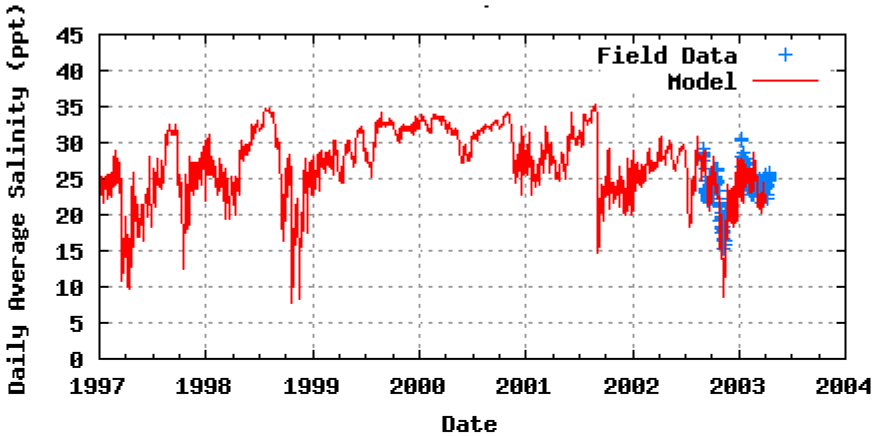


Figure 8.12.a Model (red) and Measured (blue) Daily-Average Salinity at Matagorda Entrance Channel.

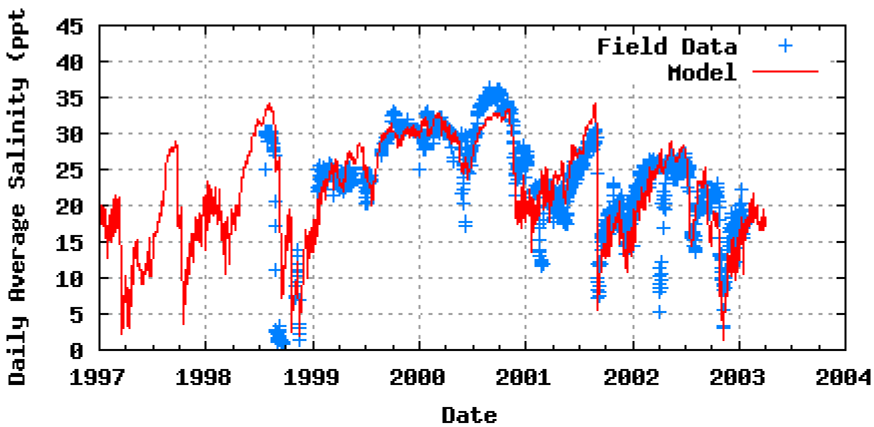


Figure 8.12.b Model (red) and Measured (blue) Daily-Average Salinity at Sandy Point.

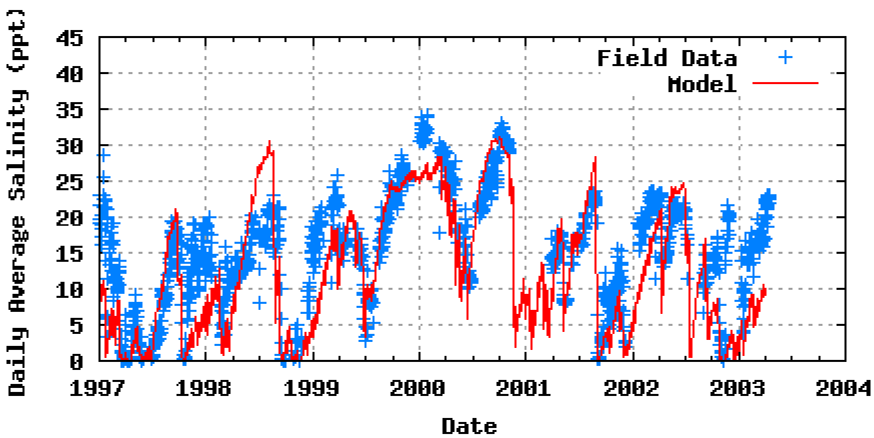


Figure 8.12.c Model (red) and Measured (blue) Daily-Average Salinity at Lavaca Causeway.

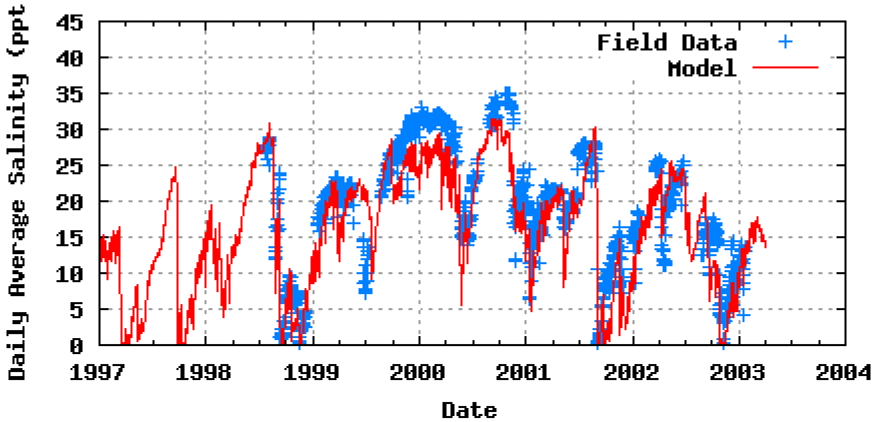


Figure 8.12.d Model (red) and Measured (blue) Daily-Average Salinity at Carancahua Bay.

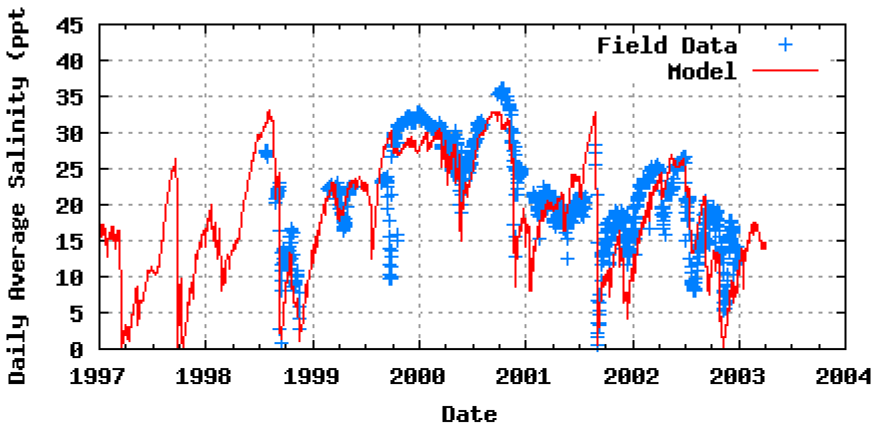


Figure 8.12.e Model (red) and Measured (blue) Salinity at Tres Palacios Bay.

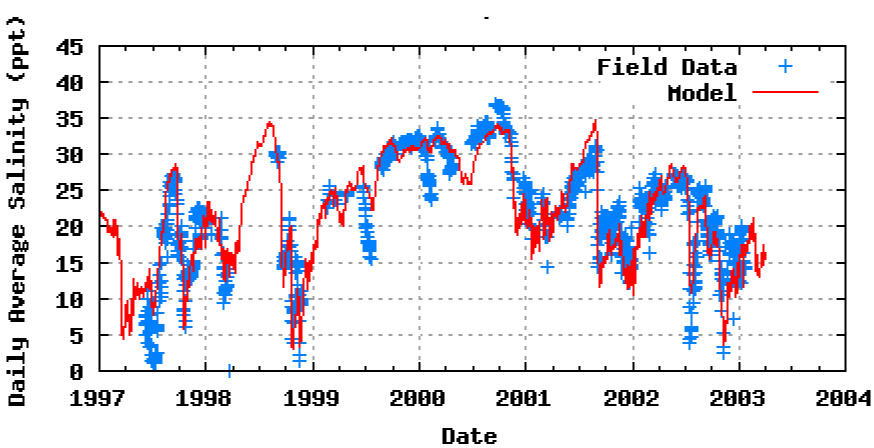


Figure 8.12.f Model (red) and Measured (blue) Daily-Average Salinity at Channel Marker 4.

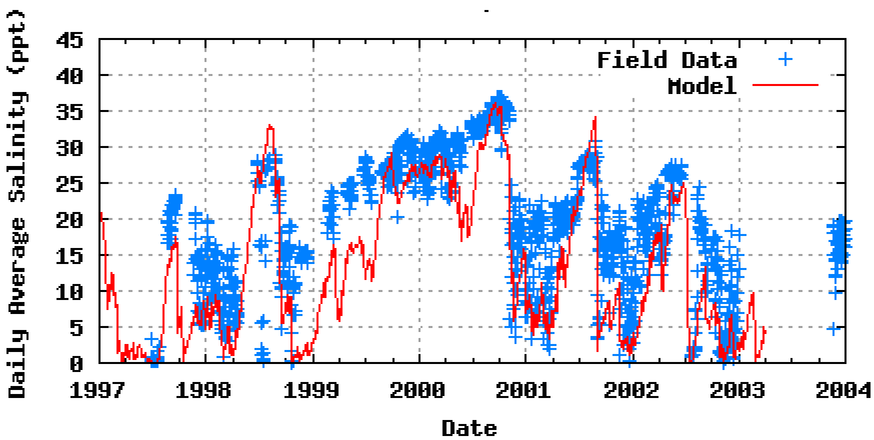


Figure 8.12.g Model (red) and Measured (blue) Daily-Average Salinity at West Bay Tripod.

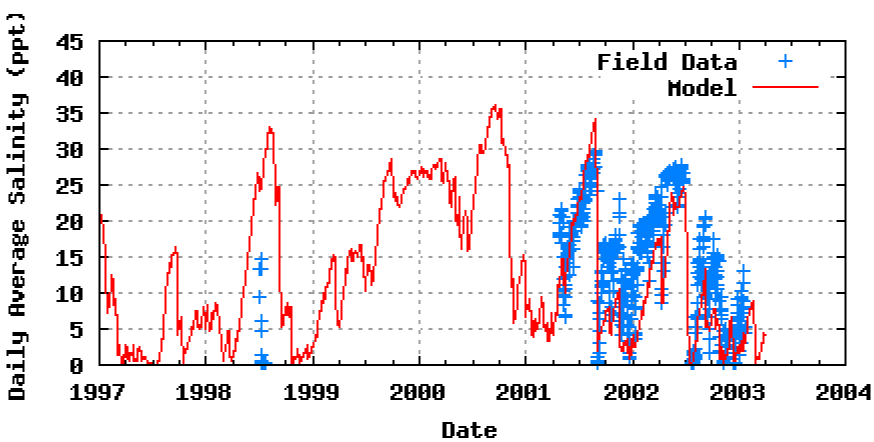


Figure 8.12.h Model (red) and Measured (blue) Daily-Average Salinity at Shellfish Marker B.

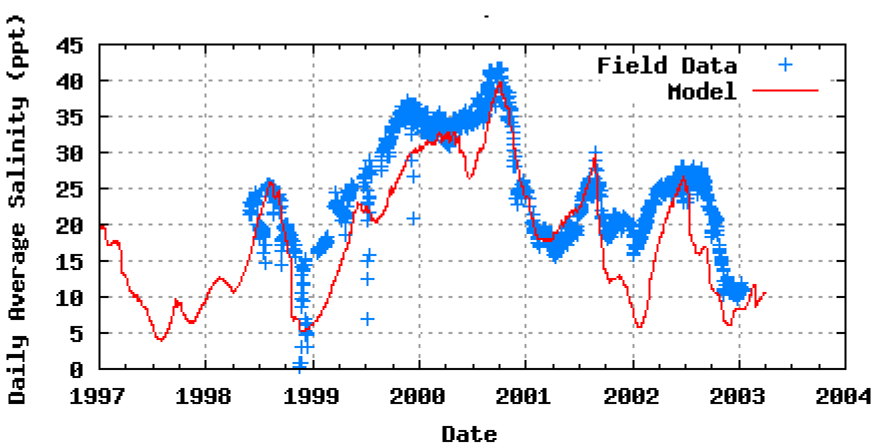


***Figure 8.12.i Model (red) and Measured (blue) Daily-Average Salinity at East Bay Tripod*.**

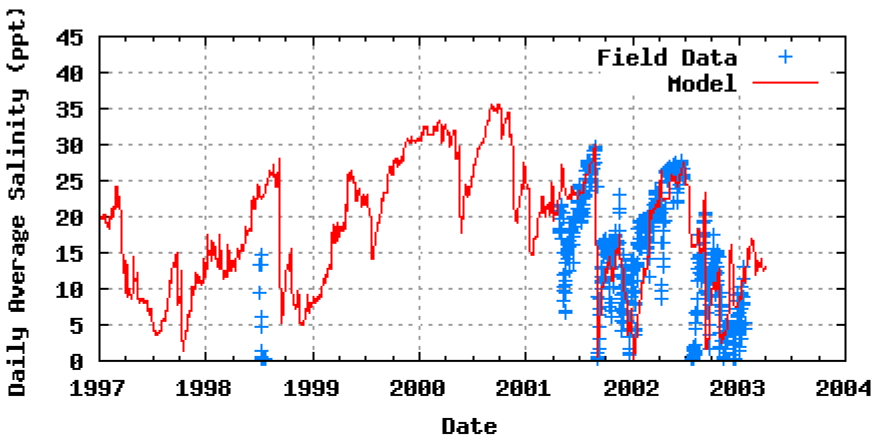


Figure 8.12.j Model (red) and Measured (blue) Daily-Average Salinity at East Bay Shellfish Marker.

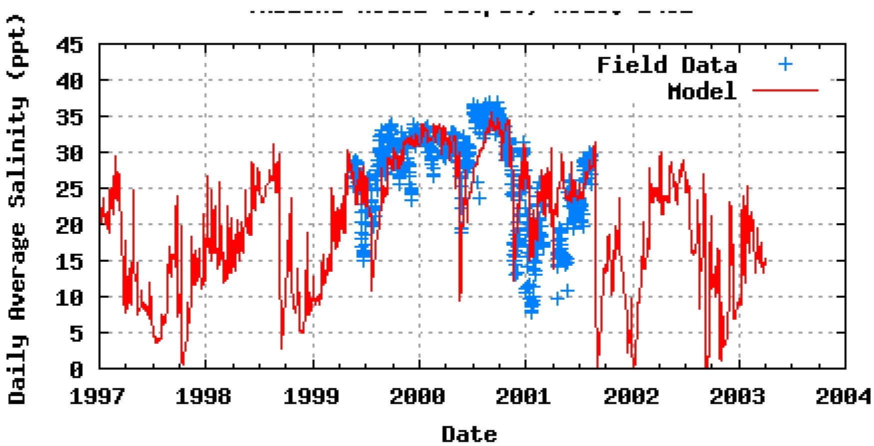


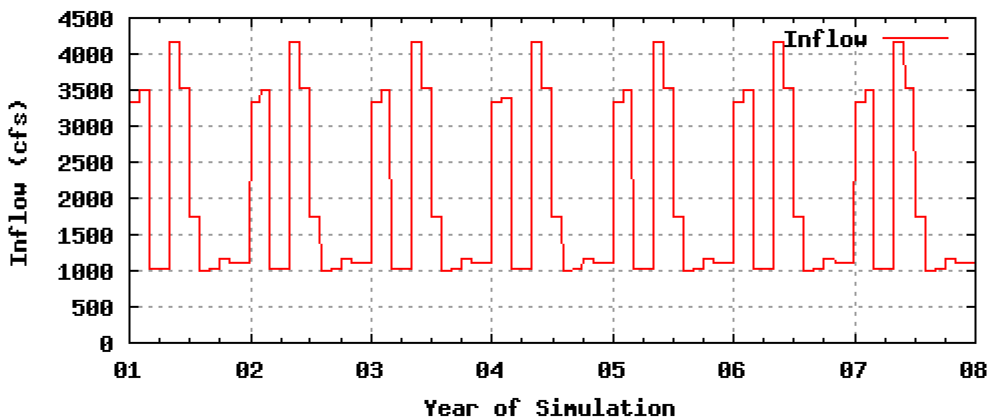
Figure 8.12.k Model (red) and Measured (blue) Daily-Average Salinity at East Bay Eastern End.

8.4 Target Flow Evaluation

The effect of releasing target flows on salinity in Matagorda Bay was evaluated with TXBLEND. Estimated Target Flows for the Colorado River and the Lavaca River, as discussed in Chapter 7, were applied as inputs to TXBLEND in a repeating fashion in a six-year simulation (Figure 8.13). Coastal basin flows used in this simulation were based on adjusted flows for the period 1997 through 2003 (Figure 8.4). During that period, annual average flow for the eight coastal basins contributing directly to Matagorda Bay was 1.09 million acre-feet/year. Target flows for the coastal basins were computed to be 729 thousand acre-feet/year (Chapter 7). For this simulation, the coastal inflows from

1997 through 2003 were reduced by multiplying by 0.729/1.09 = 0.669 in order to achieve an annual average inflow of 729 thousand acre-feet, corresponding to the Target Flow for coastal basins. The actual temporal pattern of the coastal inflows was maintained in these simulations - only the magnitudes were adjusted as described.

Tidal elevations applied in the simulation were actual tides for the period from 1997 through 2003 (Figure 8.5). Wind, precipitation, and evaporation were also based on records from 1997 through 2003 (Figure 8.6).



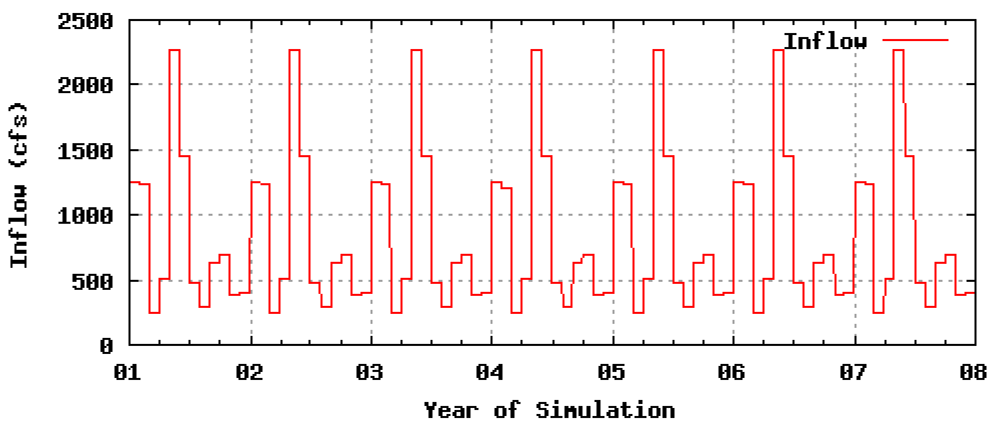


Figure 8.13 Monthly Inflows Applied in Target Flow Scenario. Colorado River (top) and Lavaca River (bottom) Flows.

Under the target flow scenario, computed salinity for the West Bay Tripod and Lavaca Causeway sites remains within the desired salinity constraints applied in TXEMP (Figure 8.14) for all but a few months, primarily during summer and fall. Salinities are highest during year 03 (third year of the evaluation) of the simulation, corresponding to a time of reduced coastal inflows. These results indicate that Target Flows generally should meet desirable salinity conditions for these sites. Specific guidelines for frequency or duration of exceedance, however, were not developed and is an area for future study.

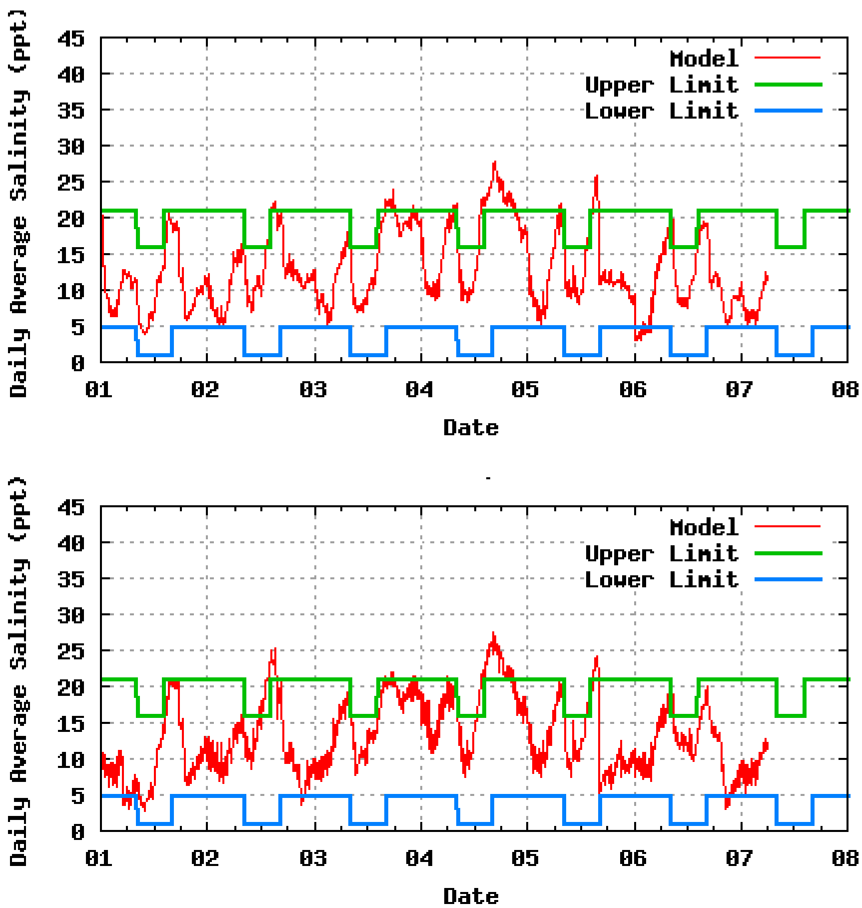


Figure 8.14. Computed Salinity (red) Compared to Target Flow Upper Salinity Constraint (green) and Lower Salinity Constraint (blue) Applied in TXEMP. Model Output for West Bay Tripod (top) and Lavaca Causeway (bottom) Sites.

8.5 Critical Flow Evaluation

Critical flows were also evaluated using TXBLEND. Flows on the Colorado River and the Lavaca River were input as constants equal to their critical flow values of 1,200 acre-feet/day (605 cfs) and 143 acre-feet/day (72 cfs), respectively (See Chapter 9).

Coastal basin flows were again adjusted in proportion to their historical ratio relative to the river basin flows in a similar fashion to adjustments made for the target flow analysis. Critical flows for the Colorado River and Lavaca River total 490.2 thousand acre-feet/year. The historical ratio of coastal basin to river basin flows applied in TXEMP, 0.361, was maintained in this simulation by adjusting coastal basin flows for the 1997 to 2003 period to average 0.361 * 490.2 = 177.0 thousand acre-feet/year. Coastal flows for the period averaged 1.09 million acre-feet/year, so for this simulation these flows were adjusted by multiplying by 0.177/1.09 = 0.162 (16.2 percent).

Tidal elevations applied in the simulation were actual tides for the period from 1997 through 2003 (Figure 8.5). Wind, precipitation, and evaporation also were based on records from 1997 through 2003 (Figure 8.6).

Although constant inflows were applied for the Colorado River and Lavaca River, computed salinities under this scenario are highly variable (Figure 8.15), indicating the strong influence of evaporation, coastal inflows, and Gulf salinity on local salinity. The periodic increase in salinity during summer months is associated with increased evaporation (Figure 8.6), and longer term trends are associated with changes in coastal inflows (Figure 8.4). These figures reinforce the idea that if constant flows are provided at volumes equal to critical flows, observed salinities at the West Bay Tripod and Lavaca Causeway will reach 25 ppt only "on average." Based on this simulation, computed daily salinities exceeded 25 ppt 32% of the time at the West Bay Tripod and 38% of the time at the Lavaca Causeway.

Reduction of the coastal flows to 16.2 percent of their original values in this simulation is significant, particularly for the years 1999 and 2000 (third and fourth years of this simulation). Coastal flows in 1999 rank at the 24th percentile of the 1941 to 2003 historical record (Table 2.2), and in 2000 rank at the 29th percentile. Reducing flows for this simulation drops them below the lowest observed from 1941 to 2003. Thus, this simulation models extremely low flows. During the most extreme conditions, salinity levels can rise significantly above 25 ppt. Attempts to limit salinity to 25 ppt or less would require consideration of and response to these additional factors.

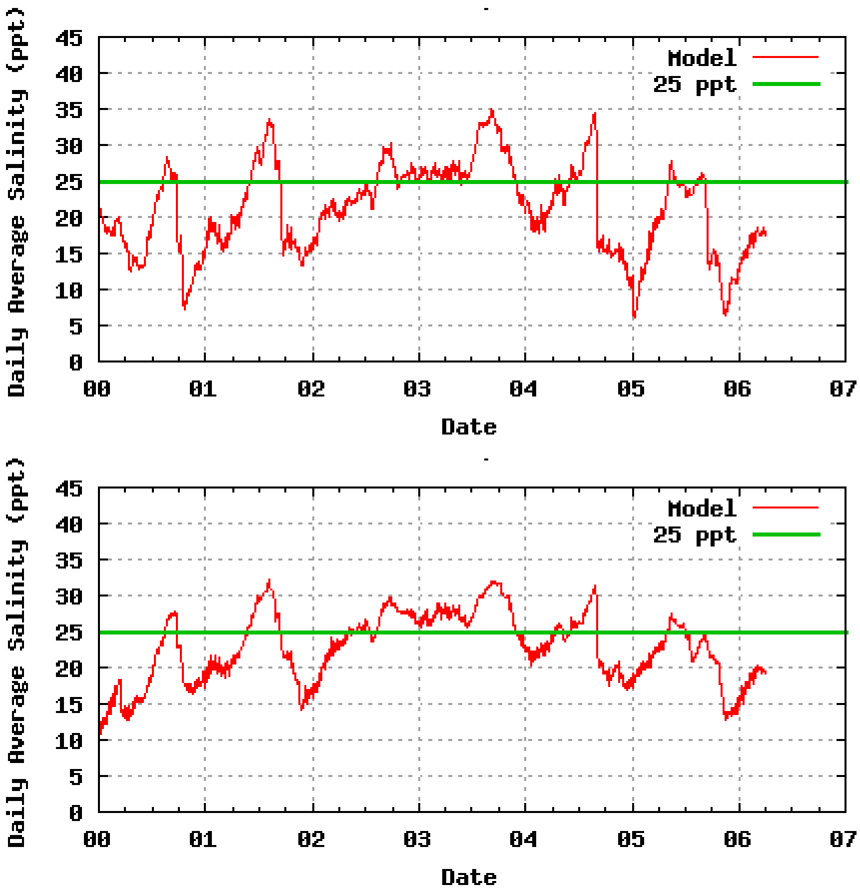


Figure 8.15 Computed Salinity (red) Compared to Critical Flow Salinity Constraint (green) of 25 ppt. Model Output for West Bay Tripod (top) and Lavaca Causeway (bottom) Sites.

8.6 Findings

The TXBLEND hydrodynamic and conservative transport model was calibrated for water surface elevation, flow and salinity with data collected in Matagorda Bay. The calibrated model was used to simulate salinity throughout the bay using target flows and critical flows developed in Chapters 7 and 9 of this report. Results for target flow simulations show that salinities remain within target salinities at the West Bay Tripod and Lavaca Causeway sites during most of the six year simulation. The critical flow simulation showed that under constant critical flow releases from the Colorado and Lavaca rivers, salinity is "on-average" 25 ppt, exceeding this level 32% of the time at the West Bay Tripod, and 38% of the time at the Lavaca Causeway under extreme low-flow conditions.

CHAPTER 9

Development of Critical Freshwater Flow Estimates

9.1 Introduction

Similar to most Texas estuaries, Matagorda Bay receives highly variable inflows due to extremes of the regional hydrological climate. Native species have adapted to survive in this highly variable environment. For example, the oyster responds to stressed environmental conditions by increasing the release of juvenile spat to improve the odds of survival.

Historically, the bay has been stressed by extreme floods and extended wet periods that have driven salinity down to near freshwater levels. For example, high flows in the summer and winter of 2004 led to salinity levels that were below 5 ppt in the eastern arm of Matagorda Bay for more than a month each. Since the construction of the Colorado River diversion, this condition is more frequently observed in the eastern arm of the bay.

Similarly extended dry periods also stress the bay, such as the one that occurred during the 1950s drought and more recently in year 2000. During 2000 the region experienced a summer of high heat, low precipitation and record evaporation. Portions of the bay reached hypersaline (> 32 ppt) conditions that summer. Productivity of some species is impacted by the severity and duration of these events. For example, TPWD staff reported a decline in white shrimp, menhaden, Atlantic croaker, mullet and oysters during this period. (Balboa, 2004).

While these stresses on the bay produce natural and perhaps even beneficial results, such as promoting oysters to release more spat, if extended over long periods of time they pose the threat of critically harming or destroying economically and ecologically important species. Therefore it has been determined prudent to identify critical flows for maintaining a finfish and shellfish sanctuary for juveniles during extended low flow periods to speed the recovery of the bay to ecologic health and economic productivity.

Critical freshwater flows from the Colorado River are particularly beneficial because TPWD has designated and posted the most eastern half of the eastern arm of Matagorda Bay, shown in Figure 9.1, as a nursery. Commercial fishing in this part of the bay is now prohibited.

Additionally, the Colorado diversion delivers freshwater flows from the Colorado basin directly into this region of the bay. From this sanctuary, it is generally expected that the finfish and shellfish species, particularly oysters, could recover and repopulate the bay when normal weather conditions return.

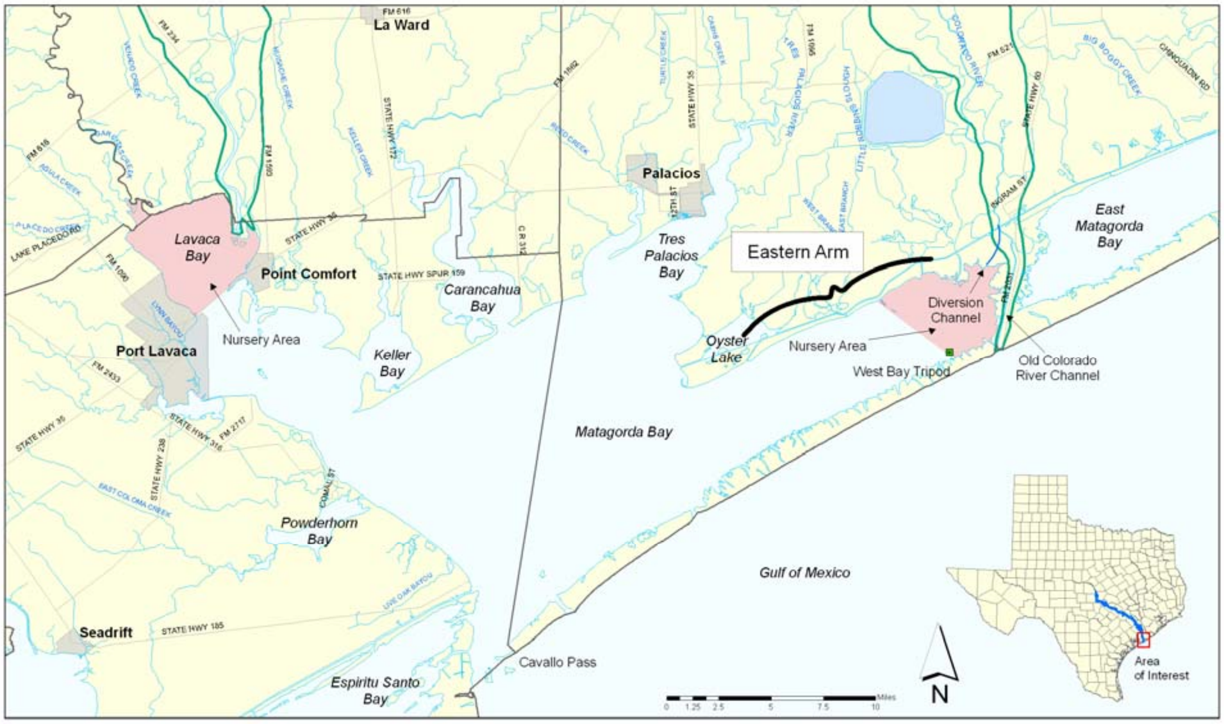


Figure 9.1 Location of Eastern Arm of Matagorda Bay and TPWD Nursery.

9.2 Establishment of Maximum Salinity Target in the Matagorda Bay Nursery

For purposes of the 1997 FINS, a desired salinity of 25 ppt was established largely through consensus as a reasonable target during extended periods of high salinity. It was agreed that this level of salinity would provide a refuge near the mouth of the river during low flow conditions. This determination was largely based on review of species tolerances. This determination was not revisited as part of this update.

In general, many estuarine species spawn in the Gulf of Mexico where salinity remains near seawater levels (above 34 ppt). Larvae then move into estuarine habitats to grow and seek refuge from predators. The information in the following table was taken from several sources including the Galveston Bay Freshwater Inflow Study and Freshwater Inflows to Texas Bays and Estuaries.

Table 9.1 Salinity Preferences and Tolerances for Estuarine Species.

Species	Preferred Salinity (ppt)[1]	Preferred Salinity (ppt)[2]	Juvenile Salinity (ppt) Tolerance [2]
White Shrimp	10 – 15	3 – 7	10-25
Brown Shrimp	10 – 20	24 – 26	10-20
Blue Crab	0 – 15	< 20	6-21
Menhaden	10 – 15	0 – 12	0-12
Atlantic Croaker	None	No info	No info
Bay Anchovy	10 – 20	No info	No info
Finfish	20 – 25	No info	No info
Oyster		10 – 24	10 - 30
Smooth Cordgrass		10 – 20	

Sources:

1. Galveston Bay Freshwater Inflow Study (TPWD, 1998).
2. Freshwater Inflows to Texas Bays and Estuaries (Longley, 1994).

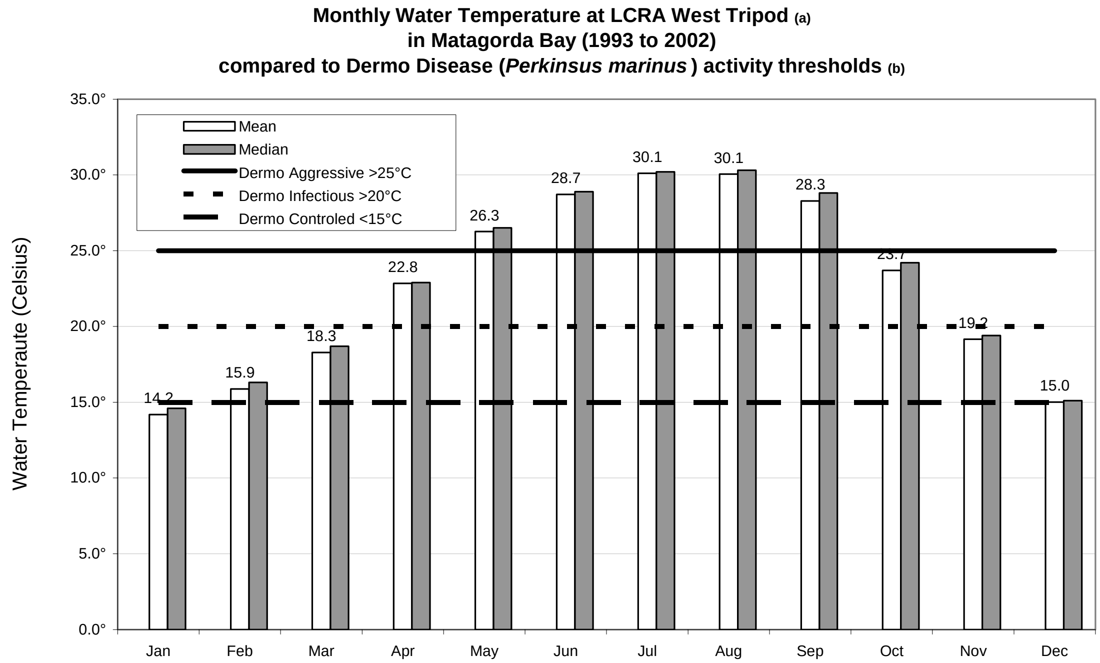
It was determined that the eastern oyster, *Crassotrea virginica*, represents a good keystone species for Matagorda Bay since it is relatively abundant and is both commercially and ecologically important. In 2001 (the latest figures available), more than 160,000 pounds of oyster valued at $370,000 were harvested from Matagorda Bay (Culbertson et al., 2004).

In addition to their direct benefit on the ecology of the bay system as filter feeders, oyster reefs provide a source of food and physical habitat for numerous other species. Furthermore, oysters represent a historically significant background condition within Matagorda Bay. Since the success of the oyster population depends on appropriate salinity conditions over immobile reef structures, salinity bounds for Matagorda Bay were set on the basis of the location of established oyster reefs (LCRA, 1997).

Oysters remain among the most ecologically important organisms in the estuarine system. In addition to their role in recycling nutrients, their shells form reefs that provide physical habitat and nursery areas for other species (Zimmerman et al, 1989). Suitable temperature and salinity ranges are both important conditions to the survival, growth and reproduction of the eastern oyster. Many investigators have attempted to define the tolerance limits and optimum ranges, but with considerable divergence in results (Shumway, 1996).

Unlike most other organisms, oysters are sessile and restricted to areas with hard substrates, such as existing oyster shell. Oysters spawn year round in Texas bays, with peak spawning in June and July, at temperatures above 20^{o}C and at salinities above 10 ppt (Hoffstetter, 1977, 1983). The larvae are free-floating for about 10 days before the final larval stage (spat) settle on hard substrate. Spat settling has been reported to be most successful at salinities from 17 ppt to 24 ppt. Once the spat have set, they remain in the same place for their adult lives. Juvenile and adults are capable of surviving a wide range of temperatures and salinities, but growth and survival is optimal with salinities fluctuating between 10 ppt and 30 ppt. Fluctuating salinities help reduce fouling and predatory organisms. Predatory gastropods, principally the oyster drill (*Thais haemostoma*), cause substantial mortality at sustained high salinities (>25 ppt).

The first oyster disease to be recognized in the United States was dermo disease, caused by *Perkinsus marinus*. This parasite is capable of killing 90 to 95% of the oysters within two to three years. Dermo can withstand a wide variety of environmental limits. The protozoan parasite develops the heaviest infections and kills most readily at salinities > 10 ppt and at temperatures >20°C (68°F), but survives at much lower salinities and temperatures (Chu and La Peyre, 1993). Thresholds of *Perkinsus marinus* activity are compared to monthly temperatures at the West Bay Tripod in Matagorda Bay in Figure 9.2.



Sources : a) LCRA Water Services, Resource Protection, monitoring data.
b) Oyster Diseases of the Chesapeake Bay, Dermo and MSX Fact Sheet, Virginia Institute of Marine Science.

Figure 9.2 Water Temperature at West Bay Tripod and Dermo Disease Activity.

B. D. King evaluated the condition of oyster populations in the eastern arm of Matagorda Bay in anticipation of the diversion of the Colorado River (King, 1989). He noted that Half Moon Reef, which was historically a highly productive reef, had high mortality of adult oysters and high incidents of predation. He noted only one successful spat set during his study in July 1987 following a flood when salinity conditions were around 10 ppt in the Colorado River the preceding month (LCRA, 1997).

Dog Island Reef, which was the largest oyster reef in Matagorda Bay, is nearly covered by the delta that is forming at the mouth of the Colorado River diversion. However, the Corps of Engineers has established three artificial reef complexes in the eastern arm of Matagorda Bay; 1) an extension of Shell Island Reef, 2) an extension of Mad Island Reef, and 3) at a point between Mad Island Reef and Half Moon Reef. These are shown in Figure 9.3.

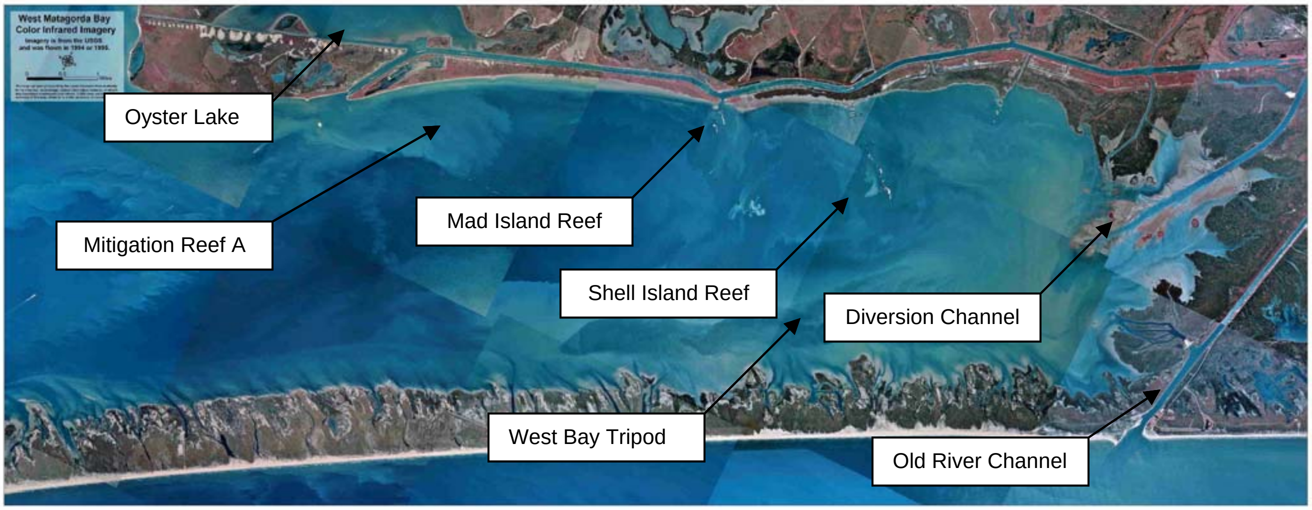


Figure 9.3 Eastern Arm of Matagorda Bay Features.

9.3 Development of Critical Flows of the Matagorda Bay East Arm Nursery

Development of critical flow equations for the bay was accomplished using multiple linear regression techniques described in Section 6.1. LCRA collected hourly salinity data from January 1993 to December 2003 at the West Bay Tripod monitoring station, although there are notable data gaps until 1998. The regression analysis was based on 62 monthly average observations. This regression analysis was not constrained by the application of TXEMP and therefore additional variables were used. Stepwise regression was performed for independent variables:

- average salinity for the prior month
- the natural log of average daily flow for each of the present month and the three prior months
- high water level in the Gulf of Mexico as measured at Galveston Pleasure Pier
- average daily precipitation
- average daily gross evaporation for each month
- average daily water temperature for each month
- mean daily wind speed

Of these variables stepwise regression found only the present month flow, prior month salinity, and present month gross evaporation to be statistically significant. Addition of the prior period salinity largely resolved autocorrelation issues. A satisfactory Durbin Watson statistic of 1.7 was achieved. The resulting equation exhibits an adjusted R^2 of 85% and a standard error of 2.9 ppt.

Equation 9.1 Monthly Salinity-Inflow Relationship for West Bay Tripod

$$Sm_i = 38.364 + 0.436 \times Sm_{i-1} - 3.818 \times LN(Qm_i) + 20.605 \times Em_i$$

where: i = month

Qm_i = Average Daily Colorado Flow for month i (acre-feet)

Sm_i = Average Monthly Salinity at for month i (ppt)

Em_i = Average daily Evaporation for month i (inches)

Performance of this equation for the period of 1992 to 2003 is shown in Figure 9.4. It shows that errors tend to be within one standard error and never more than two standard errors. Additionally during the 2000 drought the error is almost uniformly positive. It is likely that nonlinear effects were involved in this extreme event that are not entirely captured by linear regression. Future studies may be able to develop nonlinear relationships with an improved error profile over a larger range of salinity.

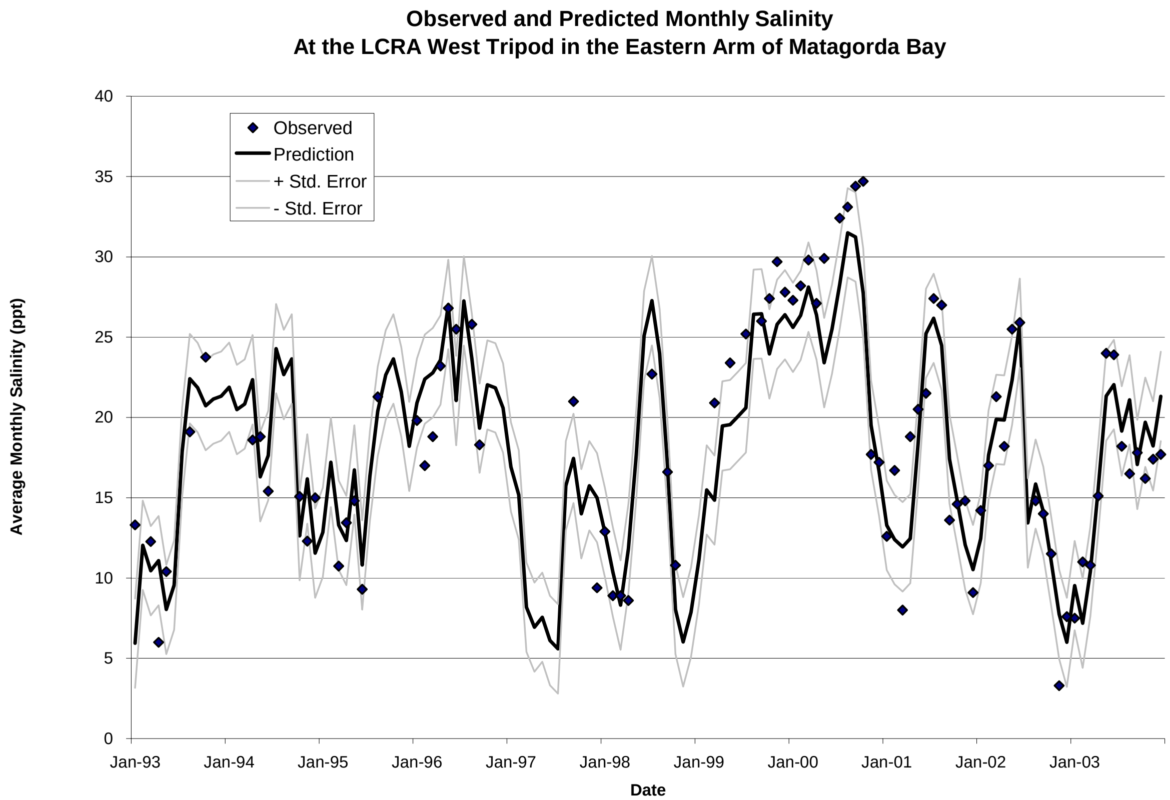


Figure 9.4 Performance of Equation 9.1.

The critical flow, Qcr, for the eastern arm of Matagorda Bay is obtained by using Equation 9.1 and assuming steady state condition, i.e. setting Sm_{i-1} and Sm_i to 25 ppt. Emi is set to the annual average of 0.136 inches/day. Solving for Qcr is shown below:

<u>Solution of Equation 9.1 for Steady State Flow to Maintain Salinity at West Bay Tripod</u>

$$Qcr = Qm_i = Qm_{i-1}$$

$$Qcr = \exp\left(\frac{Sm_i - 38.364 - 0.436 \times Sm_{i-1} + 20.65 \times Em_i}{-3.818} \right)$$

$$Qcr = \exp\left(\frac{25 - 38.364 - (0.436 \times 25) - (20.605 \times 0.1360)}{-3.818} \right)$$

Qcr = 1,200 acre-feet per day = 36,000 acre-feet per month

The equation indicates that supporting an annual average salinity of 25 ppt requires 36,000 acre-feet of inflows from the Colorado River on an average monthly basis. Salinity would still vary around this average as illustrated in Figure 8.14. Similarly the equation can be solved at plus or minus the standard error of 2.9 ppt to understand the range of uncertainty in the flow rate to achieve 25 ppt on an average monthly basis. The range of uncertainty at a 68% confidence is 23,000 to 55,000 acre-feet per month.

Alternately, Equation 9.1 can be solved for various maintenance salinities as well as relative initial salinity as illustrated in Figure 9.5.

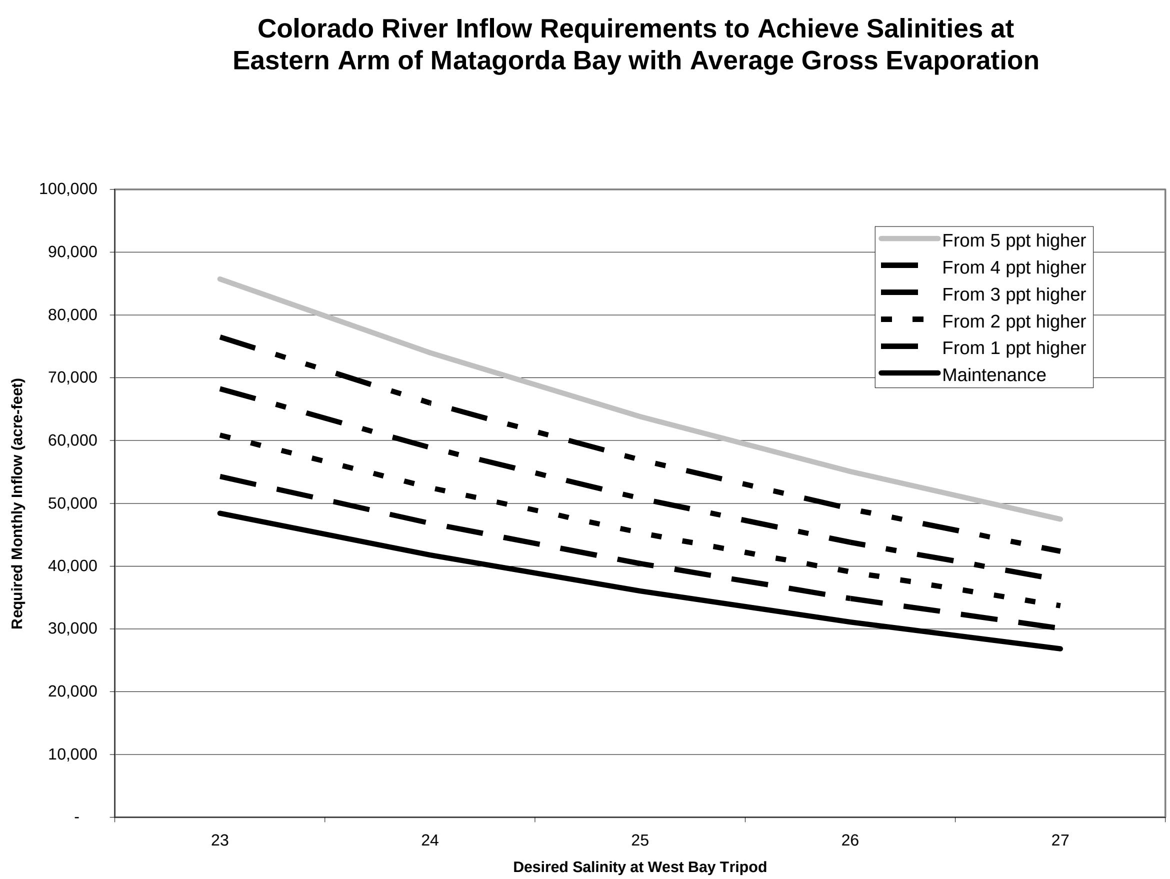


Figure 9.5 Inflow Requirements to Achieve Salinities at Eastern Arm of Matagorda Bay.

9.4 Development of Critical Flows of Lavaca Bay

Development of critical flow equations for Lavaca Bay was accomplished with multiple linear regression using techniques described in Section 9.5. Monthly salinity data from 1987 to 2003 was obtained from the TWDB. This regression analysis was not constrained by the application of TXEMP and therefore additional independent variables were investigated. Stepwise regression was performed for independent variables of:

- average salinity for the prior month
- natural log of the average daily flow for the present month and each of the prior three months
- average daily gross evaporation for the present month

Only the present month flow both prior month salinity and flow were found to be statistically significant. Addition of the prior period salinity resolved autocorrelation issues. An excellent Durbin Watson statistic of 1.94 was achieved. The resulting equation exhibits an adjusted R^2 of 82% and a standard error of 3.2 ppt.

Equation 9.2 Monthly Salinity-Inflow Relationship for Lavaca Bay

$$Sm_i = 25.7 + 0.51 \times Sm_{i-1} - 1.70 \times LN(Qm_i) - 1.04 \times LN(Qm_{i-1})$$

where: i = month
Qm_i = average daily Lavaca flow for month i (acre-feet)
Sm_i = Average monthly salinity at for month i (ppt)

The performance of this equation is shown in Figure 9.6.

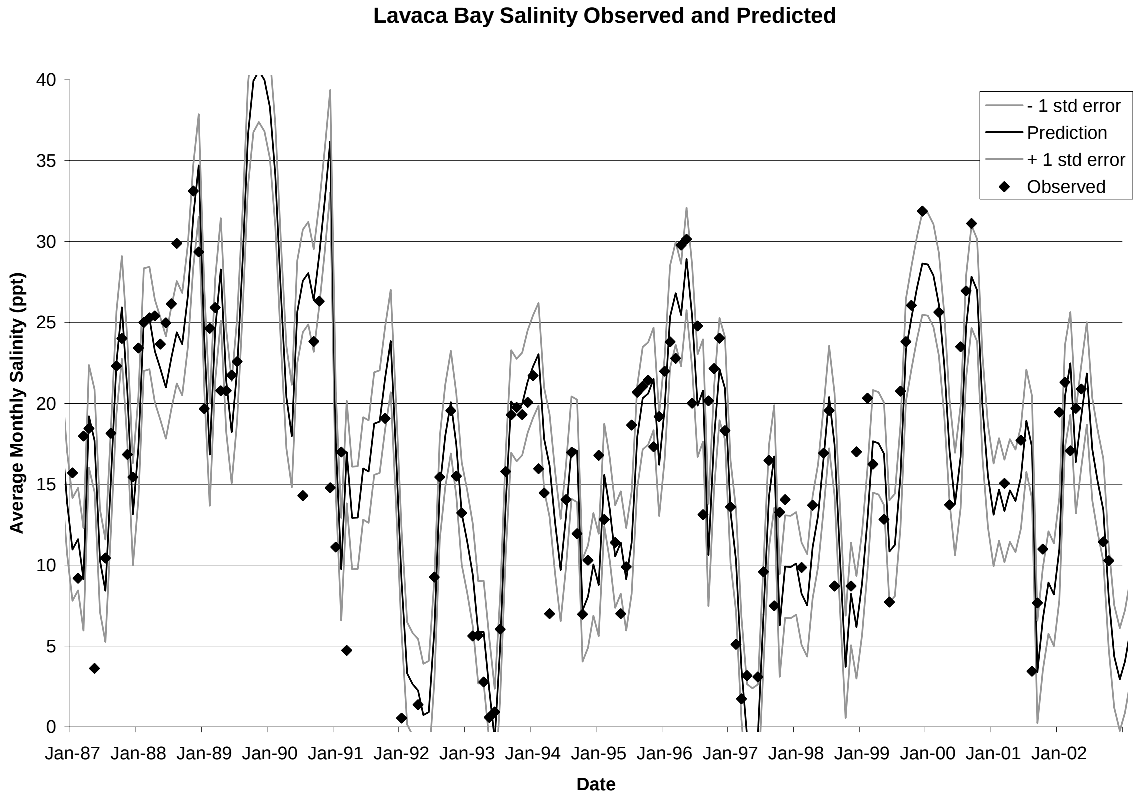


Figure 9.6 Observed and Predicted Salinity at Lavaca Bay.

Critical flow is solved using equation 9.2 by assuming steady conditions, i.e. by setting Sm_{i-1} and Sm_i to 25 ppt and setting $Qm_{i-1} = Qm_i$ then solving for Qcr as shown below.

<u>Solution to Equation 9.2 - Flow Needs to Maintain Salinity in Lavaca Bay</u>

$$Qcr = Qm_i = Qm_{i-1}$$

$$Qcr = e^{\frac{Sm_i - 25.7 - 0.51 \times Sm_{i-1}}{-2.74}}$$

$$Qcr = e^{\frac{25 - 25.7 - 0.51 \times 25}{-2.74}}$$

Qcr = 143 acft/day = 4,300 acre-feet per month

Use of this equation predicts that maintenance of 25 ppt requires 4,300 acre-feet of inflows from the Lavaca River on an average monthly basis. Similarly the equation can be solved at plus or minus the standard error of 3.2 ppt to understand the range of uncertainty in the flow rate to achieve 25 ppt on an average monthly basis. The range of uncertainty at a 67% confidence is 2,300 to 7,200 acre/feet per month.

Alternately, the equation can be solved for various maintenance salinities as well as relative initial salinity as illustrated in Figure 9.7.

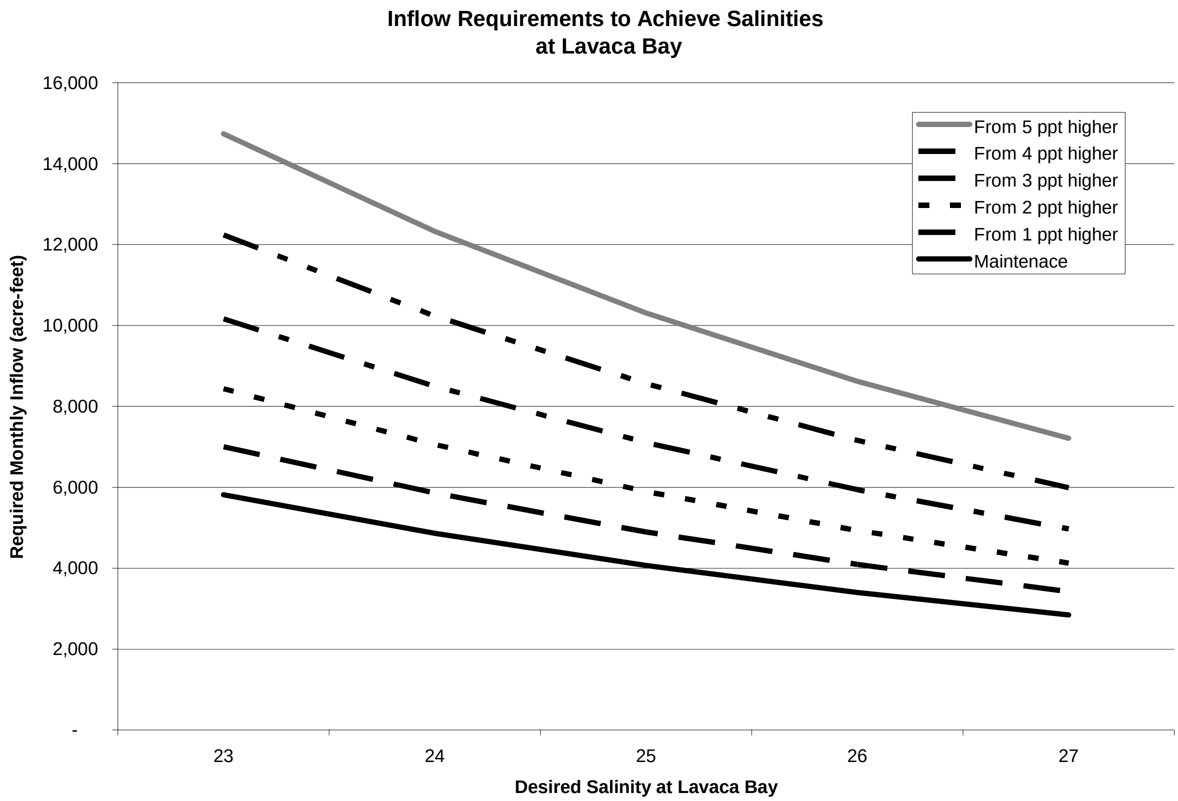


Figure 9.7 Inflow Requirements to Achieve Salinities at Lavaca Bay.

Chapter 10

Future Technology and Study Needs for Matagorda Bay

10.1 Introduction

Over the course of this three-year study, numerous technical issues were revisited or brought to light concerning insufficient data, shortcomings of analytical methods, and the potential impact of simplifying assumptions and constraints. The purpose of the current study was not to overcome all the shortcomings but rather to apply the methodology as reasonably as can be achieved with the resources available and analytical methods prescribed. In numerous areas, shortcomings identified in the 1997 study, such as the use of commercial harvest data rather than productivity data, were wholly or partially addressed. In others, such as nutrient analyses, little or no progress could be achieved.

For the benefit of future study activities, the issues identified specifically in this effort are discussed. This does not capture all of the current discussion on these methodologies that has been reported by others such as the Study Commission on Water for Environmental Flows (2004). These issues suggest significant additional data collection, analysis and research is needed to improve our understanding of the relationships between freshwater inflows and important indicators of estuarine conditions and to effectively determine the amount of inflow required to continue to maintain a healthy estuarine community.

10.2 Hydrology

- Better estimates of coastal inflows should be developed to take advantage of next generation rainfall-runoff models that incorporate NEXRAD data.

- Information should be collected on the operation of the GIWW locks.

- Data regarding irrigation return flows and diversions in the coastal areas should be revisited to more accurately account for this source of water to the bay.

- Estimates of ungaged flows may have a significant margin or error.

- Flows at the intersection of the Colorado River and Gulf Intracoastal Waterway should be measured to determine actual direct inflows to Matagorda Bay. Currently, gaged Colorado River flow at Bay City, which is upstream of the GIWW, is used to estimate freshwater inflow to the bay.

10.3 Nutrients, Sedimentation, and Primary Productivity

The current study effort identified very early that adequate additional sedimentation and nutrient data was not available to significantly improve on the limited analyses from the 1997 FINS. This is unfortunate because the lack of data was already known to be a limitation of the previous FINS effort. Instead, the contribution of this study was focused on documenting the breadth of understanding and complexities involved in determining nutrient requirements.

The recommendations previously made in the 1997 FINS (LCRA) include:

- *Additional information is needed of the nutrient concentrations and loadings per unit volume required to maintain a healthy algal population during critical periods for finfish and shellfish nourishment.*

- *Nitrogen measurements should be taken at near-shore locations in the Gulf to determine near-shore concentrations, and locations and concentrations of the bay plume water. Nitrogen measurements (DIN and TKN) should continue to be taken at sites in the bay and at critical river and creek sites. The USGS water quality monitoring site at Midfield should be re-established. TNRCC monitors should begin to collect TKN data at present stations on rivers, creeks, and in the bay. Bottom water samples should be taken at critical sites in the bay, rivers and creeks.*

- *Better estimates of ungaged flow nitrogen concentrations also need to be determined. Ungaged nitrogen concentrations could be determined by establishing monitoring sites on creeks that would be representative of the local watershed and that did not have a point source discharge located upstream of the sampling site.*

- *Nitrogen loading associated with stream bed load should be studied. This could be a significant source of nutrients for the estuary.*

- *Nitrogen dynamics in sediments of the Lavaca-Colorado Estuary should be studied to determine the storage capacity of nitrogen in the sediments, the flux of nitrogen in and out of the sediments, nitrogen fixation, denitrification, and permanent losses to the sediments. Uncertainty of the reliability of these values weakens the resolution of this analysis.*

- *A relationship between nutrients, primary productivity, and secondary productivity should be developed to better understand the impact of nutrient loading upon the fisheries. Primary productivity measurements should continue to be taken at the two bay sites influenced by the Colorado River. Additional primary productivity measurement sites should be established to measure the influences of the Lavaca River.*

- *The benthics study supported by the TWDB and the LCRA to determine the effects of freshwater inflows should continue at least through a two year dry period.*

- *Secondary productivity is measured effectively by the TPWD's ongoing fish and shellfish sampling program. The TPWD fish and shellfish monitoring program should continue.*

- *Additional data should be gathered on the development of emergent wetlands along and at the end of the USACE diversion channel into Matagorda Bay, the corresponding effect on bay productivity and overall ecological health, and the impact of freshwater inflows on the development of these wetlands.*

10.4 Salinity and Salinity-Inflow Relationships

- Further explore the TPWD Coastal Fisheries data. The TPWD Coastal Fisheries data provides a content rich and spatially diverse data set. It appears that considerably more can be learned about the bay through spatial analysis such as GIS. This study did not investigate the data extensively; however Chapter 4 introduces the potential of the data analysis. Further analyses could identify seasonal, regional norms and efficiencies in utilizing freshwater by tertiary bay.

- Investigate relationships to coastal inflows. For the development of statistical salinity relationship, this study only explicitly examined freshwater contributions from the Lavaca and the Colorado Rivers. Contributions from coastal inflows are therefore inherently assumed to be either highly correlated to the river flows and have identical influence on salinity, or uncorrelated to river flows and accounted for in the model error. However, it could be instructive to explicitly examine freshwater contributions from coastal basins in the salinity relationships. This may produce relationships with better predictive ability as well as provide insight into the relative influence of coastal inflows on salinity as compared to river flows. It may also be necessary to investigate regional relationships from secondary bays to obtain statistically significant relationships.

- Explore potential for use of additional salinity monitoring station located in the Eastern Arm of Matagorda Bay. It was reviewed as part of this study but the period of record was short and no utility for it was found so there was no use for it in this study. However with additional data collection and the use of coastal flows, future investigations at this station may prove useful.

- Continue data collection for out-of-set relationship validations. Verifying a statistical relationships predictive ability using an independent data set (out-of-set) is a widely accepted performance test. For the purposes of this study, the entire data set (in-set) was used to develop the equations due to the short history since the diversion project and the desire to include a wide range of extremes. However, additional data collection will provide a new data set to use in testing the relationships developed in this study and hopefully a long enough period to enable future efforts to utilize a secondary dataset for out-of-set testing.

- The relationships used in TXEMP for this study include multiple monthly flows. It is instructive that the significance of the multiple months remained even after advanced regression methods reduced the effects of autocorrelation. This results in a predictive equation that is not highly responsive to inflows in the current month. While this captures the system behavior most of the time which is appropriate for TXEMP, it does not capture the physical observation of salinity dilution during extreme high flow periods. Shorter periods of analysis would be needed to capture this system response. Daily salinity linear relationships were attempted but the effort was abandoned due to poor predictive ability. Further investigation with non-linear or longer periods may be more successful at capturing this response.

- The role of coastal inflows on maintaining nursery conditions was not fully explored. In the development of the regression equations in Chapters 9 and 3, coastal inflows were not explicitly considered. To the extent they are random they would be included in the error term, but to the extent that they are correlated to the river flows they would be accounted for in the coefficient on the independent variable. In a managed system such as during a drought the flows may be less correlated due to management actives. This introduces a source of unknown error, hopefully small, in use of the regression equation for this purpose. A more robust method of exploring this effect would be in more detailed equations or use of TXBLEND for critical flow analyses.

10.5 Biological Productivity

- The Colorado River diversion project was intended to create additional marsh habitat for the purpose of increasing species abundance. The amount of marsh habitat created since the diversion should be quantified.

- The National Marine Fisheries Service (NMFS) has extensively collected biological data in the Galveston Bay to develop nekton habitat models. The models utilize environmental factors (marsh habitat, salinity, temperature, etc.) to estimate species density in a particular habitat. Moreover, these models are predictive and potentially useful to managers seeking to optimize productivity. Future research should seek to apply these types of models in Matagorda Bay. Such models could help refine inflow needs of various regions within the bay.

- A conceptual model of the productivity-inflow relationships should be developed and refined. Models for each species or species with similar traits may be required.

- Smaller tertiary bays provide important habitat. Thus, coastal inflows into these areas should be considered in the productivity-inflow relationships in future studies.

- Productivity-inflow relationships were used to relate productivity directly to river inflows without explicit consideration of salinity, habitat, or spatial distribution; however preliminary analysis shows that the relationships are much more complex. More explicit consideration of these factors should be considered.

- Preliminary analysis suggests that the productivity-inflow relationship may be better explained using quadratic or higher order regressions, particularly over a wide range of flows. This analysis should be expanded to determine its usefulness in further inflow needs studies as well as investigate the inclusion of additional variables.

- Optimization models need to be updated to utilize more complex fisheries equations.

- The spatial variation in the relationship of inflows to productivity should be investigated. The biology data set is spatial, however this study lumped the data bay wide as required by the State Methodology. Important regional factors may have been lost due to this approach which disaggregating will hopefully reveal.

- Evaluation of the impact of the diversion on productivity was not a primary focus of this study. Yet, preliminary analyses suggest that an in depth analysis could produce useful information on trends, the influence of flood flows, and influence of droughts. This investigation would benefit from additional post diversion data as well as more robust statistical analysis methods.

- Additional long-term biological and chemical data (temperature, dissolved oxygen, salinity, pH) is needed to augment the TPWD Coastal Fisheries Data. Targeted fixed station biological monitoring in the Colorado River diversion and in several tertiary bays, coupled with chemical data, would provide tremendous insight into species utilization and response to various inflow regimes.

- Additional data on nutrient, sediment and salinity requirements and preferences of marsh plant species would be useful to future studies.

10.6 Target Flow Methods

- Additional salinity locations should be included in future TXEMP evaluations to more adequately constrain a salinity gradient across the bay. This is contingent on establishing acceptable salinity constraints for the new locations.

- Use of location-specific inflow-productivity relationships should be used rather than a single bay-wide relationship in TXEMP.

- Practical use of information provided by probabilistic constraints on salinity and productivity should be further explored, or abandoned to simplify the analysis if no practical application of this information is found.

- For Lavaca Bay, use of hydrology following construction of Lake Texana should be considered for setting constraints.

- Current model uses juvenile abundance as a measure of productivity. Guidelines on when this or other life-stages are most appropriate for the analysis should be established.

- Management objectives for Lavaca and Colorado river flow ratio constraints should be reviewed.

- Role of TXBLEND in the validation process should be more clearly defined.

- Development of hydrological inputs used in TXBLEND analysis (Target flows, Critical flows) should be more clearly defined.

- Criteria for exceedance of salinity constraints should be established, i.e. the accepted number, frequency or length of time that a salinity constraint can or cannot be violated should be established.

- A new hydrodynamic and water quality (non-conservative transport) model of the bay is being developed during the LCRA-SAWS Water Project study period. The results of this new model should be compared with the performance of TXBLEND. Use of other models with improved numerical methods, non-conservative transport, and three-dimensionality should be evaluated for future studies.

10.7 Critical Flow Methods

- Further investigate piecewise and non-linear predictive relationships between salinity and inflow. In both this study and the prior study, the linear relationship for predicting salinity exhibits larger error at high and low salinities. This observation was made in the prior study and, while less prominent, is still a factor in this study. Process changes in the physical system in a non-steady state manner during these extreme conditions could explain why this occurs with a linear equation. For example, these process changes may be the effect of a flow restriction due to sedimentation at low flows that is not an impediment at higher flows. Some investigation was made in this study to develop piecewise relationships by flow, salinity, and season. However no improvement in predictability was found over the single linear equation. Additional analysis may be more successful particularly as additional data is obtained in the extreme salinity conditions.

- Opportunities to enhance productivity by diverting flow to other habitats needs to be investigated. This work is currently being conducted by the LCRA-SAWS Water Project.

- Effect of exceeding 25 ppt criterion on survival over short (days), intermediate (months), and long (years) periods of time needs to be investigated.

- It would be useful to understand and quantify the beneficial and detrimental effects to the eastern oyster of different durations of extreme salinities. Also the recovery duration for various stress levels to oysters is uncertain. This type of information is notably not addressed in the research literature cited for this study.

10.8 Intermediate Flow Investigations

- Given that hydrological conditions are least often at Critical or Target conditions, management of flows during the more frequently occurring intermediate hydrological conditions needs to be emphasized. Use of TXEMP results for those flow conditions should be evaluated.

10.9 East Matagorda Bay

- The 1997 FINS suggested that a separate inflow study of East Matagorda Bay should be conducted. The TWDB has initiated a Freshwater Inflow Needs Study for East Matagorda Bay. In addition, the LSWP will include an evaluation of East Matagorda Bay during the six year study period (2004-2010) and should address the needs listed in the 1997 FINS.

10.10 General Methodology / Management Objectives

- Define more clear management objective and purpose for environmental flows and inflow needs studies.

- Determine the types of information required by water planning operations models of environmental flows.

- Determine how information provided by inflow needs studies can best be used or implemented.

- Determine whether the optimization approach is best suited to meet management, planning and operations objectives.

10.11 Summary

The current study effort has updated the 1997 FINS within reasonable conformance to the State Methodology. However, significant opportunity exists to refine the science and methodologies while also expanding the data collection efforts within the bay. Opportunity also exists to better relate inflows to biological health and to identify the range of validity and uncertainly in the freshwater inflow needs estimates for more informed consideration of bay needs in the process of balancing limited resources of freshwater.

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Appendix A
Study Agreement

MEMORANDUM OF AGREEMENT
AMONG THE LOWER COLORADO RIVER AUTHORITY
TEXAS PARKS AND WILDLIFE DEPARTMENT
TEXAS WATER DEVELOPMENT BOARD AND
TEXAS NATURAL RESOURCE CONSERVATION COMMISSION

WHEREAS, the Lower Colorado River Authority ("LCRA") is a conservation and reclamation district created by the State of Texas with statutory responsibility for control and management of the waters of the Lower Colorado River watershed; and

WHEREAS, the Texas Parks and Wildlife Department ("TPWD") is the state agency with primary responsibility for protecting fish and wildlife resources in the State of Texas; and

WHEREAS, the Texas Water Development Board ("TWDB") is the state agency with primary responsibility to plan and finance the water resource needs of Texas; and

WHEREAS, the Texas Natural Resource Conservation Commission ("TNRCC") is the state agency given primary responsibility for implementing the constitution and laws of the state related to water; and

WHEREAS, the bays and estuaries of Texas are vital economic and natural resources for all citizens of Texas, and freshwater inflows are critical to providing nutrients, sediments, and proper salinity balances to preserve and maintain the sound environment of the bays and estuaries; and

WHEREAS, the Lavaca-Colorado Estuary is a major estuary on the Texas Gulf Coast, ranking third in the state in surface area, and the Colorado River is the most important source of freshwater inflows to the Lavaca-Colorado Estuary; and

WHERAS, establishing the freshwater inflow needs from the Colorado River is vital to the LCRA's management of its water rights in the Colorado River Basin for all beneficial purposes; and

WHEREAS, pursuant to a Memorandum of Agreement dated October 20, 1993 ("1997 Freshwater Inflow Needs Study"), LCRA, TPWD, TWDB, and TNRCC cooperated to develop estimates of the freshwater inflow needs of the Lavaca-Colorado Estuary from the Colorado River, which estimates were then incorporated into LCRA's <u>Water Management Plan</u>; and

WHEREAS, LCRA, TPWD, TWDB, and TNRCC agree that the freshwater inflow needs estimates developed in the 1997 Freshwater Inflow Needs Study should be updated; and

WHEREAS, TWDB and TPWD are mandated by §16.058 of the Texas Water Code to study the ecology of the bays and estuaries and evaluate the needs for freshwater inflows; and

WHEREAS, TNRCC and TPWD are mandated by §11.1491 of the Texas Water Code to review studies prepared under §16.058, to determine inflow conditions necessary for the bays and estuaries; and

WHEREAS, TWDB is authorized by §6.190 of the Texas Water Code to enter into this agreement; and

WHERAS, TNRCC is authorized by §5.229 of the Texas Water Code to enter into this agreement; and

WHEREAS, TPWD is authorized by § 11.0171 of the Texas Parks & Wildlife Code to enter into this agreement; and

WHEREAS, LCRA is authorized by the Lower Colorado River Act of 1934, Ch. 74, Acts of the 64th Legislature, R. S., 1979, as amended; and

WHEREAS, consistent with Texas law and public policy, LCRA, TNRCC, TWDB, and TPWD mutually desire to protect and maintain a proper ecological environment and the health of related living marine resources in the Lavaca-Colorado Estuary.

NOW, THEREFORE, in consideration of the following promises, covenants, conditions, and the mutual benefits to accrue to the parties to this Agreement, the parties, desiring to cooperate in providing functions and services, agree as follows:

I. RESPONSIBILITIES OF EACH PARTY

A. Lower Colorado River Authority

1. LCRA agrees to adapt or modify existing methods and apply those methods to compute updated freshwater inflow needs for the Lavaca-Colorado Estuary by performing the tasks set forth in the Scope of Work in Attachment A, which is attached hereto and incorporated as if fully set forth herein (hereinafter referred to as the "study"). Completion of the study is contingent on the timely technical assistance to LCRA from the other participating parties. This assistance includes, but is not limited to, the transfer of technical information and procedures and advice on their usage to fulfill the purposes of this Agreement.

2. Project management responsibility for the study shall rest solely with LCRA. LCRA shall appoint an individual to serve as the Project Manager and Chair of the Advisory Committee for this Agreement.

3. LCRA agrees to make available to all parties to this Agreement all data, computer models, and information developed by LCRA in the study at any time upon reasonable written notice. At the completion of the study, LCRA will provide all data developed by LCRA to the Texas Natural Resources Information System in a computer-compatible format. Nothing herein shall be construed as limiting the LCRA's use, control, or ownership of any of the data developed in performing the study.

4. LCRA may solicit funding from the parties to this Agreement and from other sources to complete the study.

5. LCRA agrees to prepare a report on the methodology, data and results of the computation of updated freshwater inflow needs of the Lavaca-Colorado Estuary. LCRA shall consider any modifications to the draft of the final report recommended by any member of the Advisory Committee. If any party to this Agreement disagrees with any statements in the draft study

report, LCRA is obligated to include a rebuttal statement in the final report. There will be no recommendations in the draft or final study report regarding adoption of freshwater inflow needs presented unless all parties are in unanimous agreement. LCRA shall furnish all parties to this Agreement five (5) copies of the final report. The other parties in this Agreement reserve the right to take exception to any or all of the final report.

6. To the extent parties consider it appropriate based on the findings of the study, LCRA agrees to initiate a process for amending the Water Management Plan within six (6) months of completion of the study.

7. The LCRA will participate in updating the TWDB intensive inflow study of the estuary to collect tidal, flow, depth, and water quality data reflecting the new channel modifications at the Colorado River Delta. In cooperation with TWDB and TPWD, LCRA will use this information to revise and recalibrate the TWDB TXBLEND.G hydrodynamic model of the estuary to account for the new geomorphology

B. <u>Texas Water Development Board</u>

1. TWDB shall assist in the transfer of technical information and procedures to LCRA pertinent to the evaluation of the needs for freshwater inflows to the Lavaca-Colorado Estuary. TWDB shall advise LCRA in using such information and procedures to fulfill the purposes of this Agreement.

2. TWDB shall appoint an agency representative to serve on the Advisory Committee for this Agreement. This individual shall also act as the contact person for facilitating the transfer of technical information between TWDB and LCRA.

3. TWDB shall make available to all parties in this Agreement any existing data and analyses completed by TWDB related to freshwater inflow needs of Matagorda Bay and associated bays. These data and analyses shall be provided by July 1, 2002. TWDB will conduct and TPWD, TNRCC and LCRA will assist in updating gauged and ungauged inflows into Matagorda Bay as well as with the intensive inflow study and updating bathymetric survey.

4. TWDB shall make available to all parties in this Agreement any data and analyses collected or performed concerning the productivity of the Colorado-Lavaca Estuary, including but not limited to fisheries, shellfish, waterfowl, and other aquatic species (including plants).

5. TWDB shall assist LCRA in identifying data needs concerning the impacts of the Lavaca River on the Colorado-Lavaca Estuary

6. With assistance from TPWD, TNRCC and LCRA the TWDB will update the intensive inflow study of the estuary by collecting tidal, flow, depth, and water quality data reflecting the new channel modifications at the Colorado River Delta. The TWDB will assist LCRA in revising and re-calibrating the TXBLEND.G hydrodynamic model of the estuary to account for the new geomorphology. The TWDB will also assist with revisions to and execution of TXEMP model.

C. <u>Texas Parks and Wildlife Department</u>

1. TPWD shall assist in the transfer of technical information and procedures to LCRA pertinent to the evaluation of the needs for freshwater inflows to the Lavaca-Colorado Estuary. TPWD

shall advise LCRA in using such information and procedures to fulfill the purposes of this Agreement.

2. TPWD shall appoint an agency representative to serve on the Advisory Committee for this Agreement. This individual shall also act as the contact person for facilitating the transfer of technical information between TPWD and LCRA.

3. TPWD shall make available to all parties in this Agreement any data and analyses collected or performed concerning the productivity of the Colorado-Lavaca Estuary, including but not limited to fisheries, shellfish, waterfowl, and other aquatic species (including plants). These data and analyses shall be provided by July 1, 2002.

4. TPWD shall assist LCRA in identifying data needs concerning the impacts of the Lavaca River on the Colorado-Lavaca Estuary.

5. The TPWD will participate in updating the TWDB intensive inflow study of the estuary to collect tidal, flow, depth, and water quality data reflecting the new channel modifications at the Colorado River Delta. The TPWD will assist LCRA in revising and re-calibrating the TXBLEND.G hydrodynamic model of the estuary to account for the new geomorphology. The TPWD will also assist with revisions to and execution of TXEMP model

D. Texas Natural Resource Conservation Commission

1. TNRCC shall assist in the transfer of technical information and procedures to LCRA pertinent to the evaluation of the needs for freshwater inflows to the Lavaca-Colorado Estuary. TNRCC shall advise LCRA in using such information and procedures to fulfill the purposes of this Agreement.

2. TNRCC shall appoint an agency representative to serve on the Advisory Committee for this Agreement. This individual shall also act as the contact person for facilitating the transfer of technical information between TNRCC and LCRA.

3. The TNRCC will participate in updating the TWDB intensive inflow study of the estuary to collect tidal, flow, depth, and water quality data reflecting the new channel modifications at the Colorado River Delta. The TNRCC will assist LCRA in revising and re-calibrating the TXBLEND.G hydrodynamic model of the estuary to account for the new geomorphology.

II. ADVISORY COMMITTEE

A. Membership

The Advisory Committee shall consist of one representative from each participating party to this Agreement and the Lavaca-Navidad River Authority ("LNRA") should that agency choose to participate. LCRA shall appoint an individual to serve as Chair of the Advisory Committee for this Agreement.

B. Duties

The purpose of the Advisory Committee is to: (1) review study scope, schedule and technical methods; (2) facilitate inter-agency communication and cooperation; (3) formulate alternative estuarine inflow management objectives required for the analyses; and (4) evaluate results of the analyses and make consensus recommendations on freshwater inflows and estuarine inflow management alternatives. The Committee shall be chaired by LCRA and shall meet quarterly at times and places chosen by the Advisory Committee. LCRA shall provide the Committee quarterly written status reports. LCRA shall provide draft reports to the Committee on each of the three major tasks identified in Appendix A according to the approximate dates shown in Figure 2. These reports will include the methodology, data and results of these tasks. The Committee members shall have a minimum sixty (60) day review period to review, comment, and make recommendations for changes. LCRA shall provide copies to the Committee of the draft final report on the methodology, data and results of the computation of updated freshwater inflow needs of the Lavaca-Colorado Estuary. The Committee members shall have a minimum sixty (60) day review period to review, comment, and make recommendations for changes. LCRA will review the comments and recommendations with the Committee to attempt to resolve any differences.

III. GENERAL CONDITIONS

A. Final Report

The final report under the terms of this Agreement is not intended to replace the reporting requirements on the TWDB and TPWD under §11.1491 of the Texas Water Code. The results from the studies conducted under this Agreement may be used by TWDB and TPWD to fulfill the obligations under §11.1491.

B. Term of Agreement

The term of this Agreement shall be from April 1, 2002 until December 31, 2004.

C. Ability to Perform

Should any party's ability to perform its obligation under this Agreement depend upon the appropriation of funds or budget approval of funds from any governing body for the term of this Agreement and the funds are not appropriated or budget is not approved, upon written notice by the affected party to all other parties, this Agreement, or part thereof not funded, shall be terminated.

D. Notice of Termination

Any party may terminate its participation in this Agreement upon thirty (30) days written notice to the other parties for any reason or for no reason.

E. Contractors and Subcontractors

Any use by any party of contractors or subcontractors in the performance of this Agreement shall be by unanimous consent of all parties.

F. Cooperation of Parties

1. It is the intention of the parties that the details of providing the services in support of this Agreement shall be worked out, in good faith, by the parties.

2. All parties shall continue their planned data collection programs in the Lavaca-Colorado Estuary during the duration of this Agreement. All data collected to complete this Agreement shall be shared among the participating parties.

G. Notices

Any notices required by this Agreement to be in writing shall be addressed to the respective party as follows:

Texas Natural Resource Conservation Commission
Attn. Mr. Doyle Mosier
P.O. Box 13087
Austin, Texas 78711

Texas Water Development Board
Attn. Mr. Gary Powell
1700 North Congress Ave.
P.O. Box 13231
Austin, Texas 78711-3231

Texas Parks and Wildlife Department
Attn. Ms. Cindy Loeffler
3000 S. IH 35, Suite 320
Austin, Texas 78704

Lower Colorado River Authority
Attn. Dr. Jobaid Kabir
P.O. Box 220
Austin, Texas 78767-0220

H. Effective Date of Agreement

This Agreement is effective upon execution below by all parties. By signing this Agreement, the signatories acknowledge that they are acting under proper authority form their governing bodies.

Texas Natural Resource Conservation Commission

By: [signature]

Title: Executive Director

Date: 9/4/02

Texas Water Development Board

By: [signature]

Title: Executive Administrator

Date: 3/4/02

Texas Parks and Wildlife Department

By: [signature]

Title: Interim Executive Director

Date: 1/25/02

Lower Colorado River Authority

By: [signature]

Title: Executive Manager, River Services

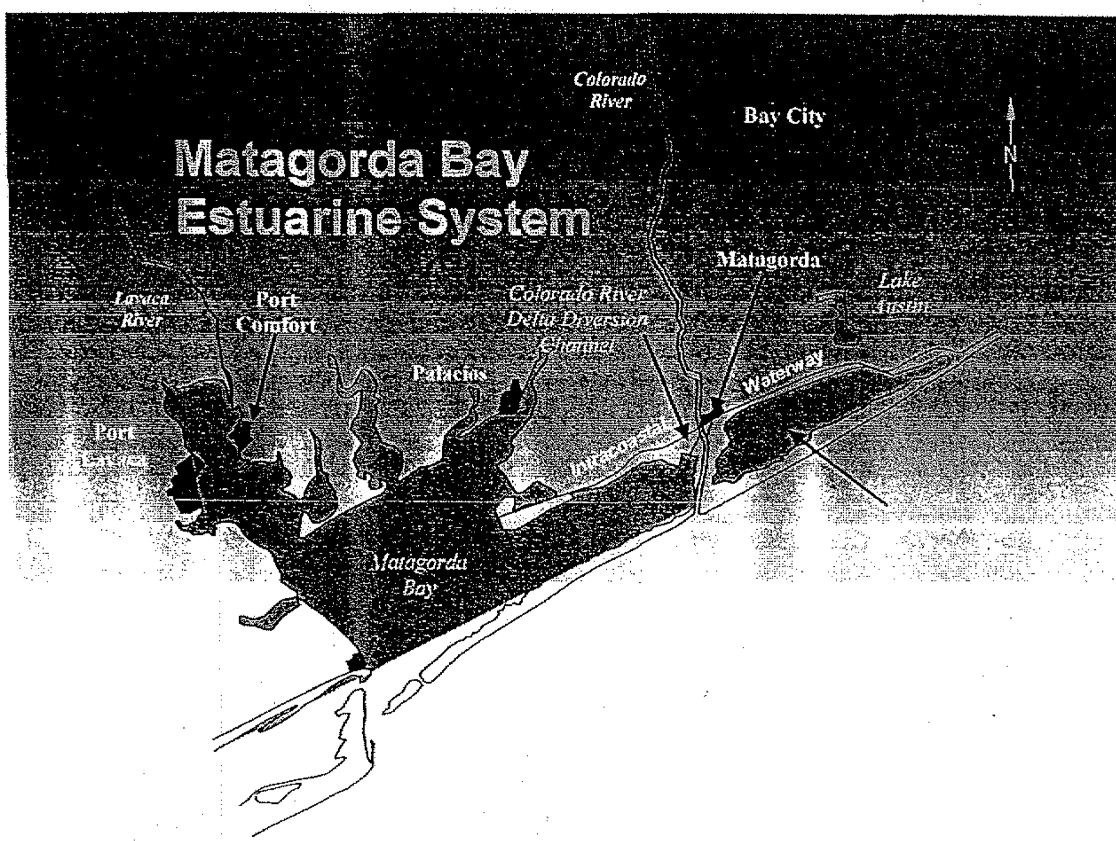
Date: 9/9/02

ATTACHMENT A

SCOPE OF WORK

INTRODUCTION

This study will be a comprehensive assessment of the need for freshwater inflows to maintain and enhance the natural ecology of the Lavaca-Colorado Estuary (Figure 1). Emphasis will be on the estuary west of the Colorado River in determining freshwater inflows from the Colorado and Lavaca Rivers and coastal basins. This assessment will use existing data and analyses from the Lower Colorado River Authority (LCRA), Texas Water Development Board (TWDB), and Texas Parks and Wildlife Department (TPWD), in combination with additional data collected and evaluated by LCRA during the course of this study. The inflow needs will be computed separately for each of the Lavaca and Colorado Rivers and un-gauged coastal areas except where the commingling of the impacts prohibits treating them in isolation. The freshwater inflow needs will be computed for a variety of alternative estuarine inflow management options. This study will be closely coordinated with the activities of the LCRA Water Resource Protection Program.



PROJECT TASKS

There are three major technical tasks in this project. These involve assessing the biological, chemical and hydrologic interrelations in the estuary. All three major tasks will include assessment of existing data and data needs. A detailed schedule is attached hereto at Figure 2.

Task 1: Technical Studies

1. **Hydrology:** LCRA will evaluate historical freshwater inflows to the estuary. This task will update, as necessary, the inflow estimates developed during the 1997 Freshwater Inflows Needs Study. In addition, LCRA will participate in updating the TWDB intensive inflow study of the estuary to collect tidal, flow, depth, and water quality data reflecting the new channel modifications at the Colorado River Delta. In cooperation with TWDB and TPWD, LCRA will use this information to revise and recalibrate the TWDB TXBLEND.G hydrodynamic model of the estuary to account for the new geomorphology.

2. **Water Quality:** LCRA will continue to monitor salinity and other water quality field parameters in the river at Bay City and at two points in the eastern arm of Matagorda Bay on a continuous basis. The LCRA will also assess the need for additional points in the bay for monitoring salinity and other water quality parameters. In the same part of the river and estuary, LCRA will conduct periodic sampling of nutrients, sediments and other water quality parameters. Data from these ongoing activities will be used in the analysis. TPWD routinely collects water quality date for the bay. TWDB and TPWD will supply data collected by respective agencies for the remainder of the estuary. LCRA, in concert with TWDB, will develop a nutrient balance for the estuary. LCRA will develop quantitative relationships between inflows salinity, nutrients and sedimentation for Colorado and Lavaca Rivers. LCRA will also evaluate sediment inflow needs from the Colorado River Basin. TWDB, in cooperation with LNRA and TPWD, will determine the sediment inflow needs from the Lavaca River Basin. In cooperation with TWDB and TPWD, LCRA will revise and recalibrate the TWDB TXBLEND.G salinity transport model of the estuary to account for modifications to the Colorado River Delta, as described under Task 2 below.

3. **Biology:** LCRA will use existing data, including any additional data provided by TPWD and TWDB, on freshwater inflows, salinity, harvest effort and other factors to revise, as necessary, estimates of fish productivity and viability developed in the 1997 Freshwater Inflow Needs Study. Adult and juvenile fin and shellfish salinity preferences and tolerance ranges will be revised and updated.

4. **Management Decision Model: LCRA** will re-evaluate the inter-actions between inflows and estuarine conditions. In cooperation with TWDB and TPWD, LCRA will modify, as necessary, the TWDB Estuarine Mathematical Programming (TXEMP)_Model to fit conditions in the estuary, which will then be used to execute the TXBLEND.G model, as described under Task 2 below.

Task 2. Computation of Freshwater Inflow Needs

LCRA, in conjunction with the Advisory Committee, will formulate a variety of estuarine inflow management alternatives. For each of these alternatives, LCRA staff will use the Estuarine Mathematical Programming Model (TXEMP) and associated models (TXBLEND.G), as revised under Task 1, or alternative methods if deemed appropriate, to compute monthly and seasonal freshwater inflow needs from both the Colorado and Lavaca River Basins. The Advisory Committee may select a range of estuarine inflow management alternatives to meet the freshwater inflow needs identified. The first alternative to be evaluated will be selected jointly by the LCRA, TNRCC, TWDB and TPWD.

Task 3. Review and Revision to Final Report

LCRA shall prepare a draft final report on the computation of inflow needs. There will be no recommendations in the draft or final study report regarding adoption of freshwater inflow needs presented unless all parties are in unanimous agreement. The Advisory Committee shall have 60 days to review the draft report and provide LCRA with comments and recommended changes. LCRA shall consider comments and suggested changes and may revise the final report as appropriate. If any party to this Agreement disagrees with any statements in the draft study report, LCRA is obligated to include a rebuttal statement in the final report. LCRA shall prepare and publish the final study report. The participating agencies reserve the right to publish their own findings and conclusions.

DELIVERABLE WORK PRODUCTS

1. Quarterly status reports
2. Draft and final reports on four subtasks of Task 1 and on Task 2
3. Draft and final technical report

PROJECT SCHEDULE

The estimated time for project completion is 36 months with the study to be initiated by April 1, 2002.

The time schedule for each major task is identified in Figure 2. The major milestones in the project are noted as follows.

Program initiation:	April 1, 2002
Quarterly status reports:	A quarterly progress report will be prepared every three months starting July 1, 2002.
Draft final report:	October 1, 2004
Final report:	December 31, 2004

TWDB Contract No. 2004-MOA-032

STATE OF TEXAS
TRAVIS COUNTY

Texas Water Development Board

and

Lower Colorado River Authority
Texas Parks and Wildlife Department
Texas Commission on Environmental Quality

AMENDMENT NO. 1

This Contract and Agreement fully executed on September 9, 2002, is hereby amended as follows:

1. Article III, B. Term of the Agreement is modified to read:

   "The term of this Agreement shall be from April 1, 2002 until June 30, 2005."

2. All other terms and conditions of Board Contract No. 2004-MOA-032 shall remain in effect.

IN WITNESS WHEREOF the parties hereto cause this Contract and Agreement to be duly executed in multiple.

TEXAS WATER DEVELOPMENT BOARD

By: [signature]
William F. Mullican, III
Deputy Executive Administrator

Date: 9/17/04

LOWER COLORADO RIVER AUTHORITY

By: [signature]
Joseph J. Beal
General Manager

LCRA LEGAL

Date:

TEXAS COMMISSION ON ENVIRONMENTAL QUALITY

By: [signature]
Glenn Shankle
Executive Director

Date: 10·8·2004

TEXAS PARKS & WILDLIFE DEPARTMENT

By:
Robert L. Cook
Executive Director

Date:

FILE COPY

Appendix B
Dataset Summary

APPENDIX B

Dataset Summary

Maragorda Bay Salinity Data:

LCRA currently maintains eight continuous monitoring sites (Table B.1), including four height of tide gage sites, throughout the Matagorda Bay system. Multi-probe water quality instruments record hourly measurements for salinity, dissolved oxygen, pH, height of tide and temperature. Average daily salinity is calculated for each monitoring station.

Table B.1. LCRA Bay Monitoring Locations

Site Description	Period of Record	Latitude (Deg. decimal deg.)	Longitude (Deg. decimal deg.)	Height of Tide
West Bay Tripod	6/93 to present	28 5960	96 0396	Yes
West Bay Marker #4	6/93 to present	28 5620	96 2159	-
Palacios Marker #44	6/98 to present	28 6737	96 2320	Yes
Carancahua Bay	6/98 to present	28 6724	96 3998	-
Sandy Point	6/98 to present	28 5465	96 4649	Yes
East Bay Tripod	6/98 to present	28 6721	95 9326	Yes
East Bay Shellfish	6/98 to present	28 7233	95 7667	-
West Bay Shellfish #B	4/02 to present	28 3714	96 0301	-

Lavaca Bay Salinity Data:

The TWDB has maintained a program for the automated collection of water quality data in Texas estuaries since the fall of 1986. The purpose of this water quality monitoring effort is primarily to support calibration of estuary circulation and salinity simulation models and for development of inflow-salinity relationships for the estuaries. The program meets that need by providing high-frequency data (most measurements every 60 or 90 minutes), so that the pattern of salinity changes with changing river flow or meteorological events is accurately traced.

Data are collected by multi-probe, battery-powered, self-contained electronic instruments which can be programmed to collect and record a number of water quality parameters on a set sampling frequency. In addition to salinity, TWDB Datasondes are equipped to measure temperature, conductivity, dissolved oxygen and water level. Some sondes record pH, and turbidity as well.

Datasondes were deployed in the fall of 1986 in Corpus Christi, Nueces, Aransas, Mesquite, San Antonio, Lavaca, Matagorda, Galveston, and Trinity bays. After September, 1989 some new sites were established and old sites abandoned. Station locations were determined in part by the need for salinity data near the heads and mouths of major estuaries for purposes of salinity modeling. Locations were also determined by ease of access and availability of anchoring structures, in compromise with ideal locations.

The datasets and period of record used for the salinity analysis include:

- Colorado River basin Critical Flow Equation January 1993 to December 2002, LCRA West Bay Tripod
- Colorado River basin TXEMP equation, August 1993 to December 2003, LCRA West Bay Tripod
- Lavaca River basin Critical Flow and TXEMP Equation - February 1987 to March 2003, TWDB data

Biology Data:

1978 -2002 TPWD Coastal Fisheries Data was used for both pre- and post-diversion project comparisons. Equations were developed with the post diversion period sub-set, 1993 - 2002, by relating annual abundance to river inflows. Some data years were not used for the analysis for some species. Table B.2 lists the coastal fisheries data used for each species by year.

Table B.2. Coastal Fisheries Data Used in Analysis (individuals/acre)

Year	Blue Crab	Brown Shrimp	White Shrimp	Gulf Menhaden	Striped Mullet	Red Drum	Oysters (number/dredge)
1992			257.02				
1993	20.50		234.00			4.83	4.89
1994	38.33		204.83	165.28	24.89	3.33	8.95
1995	25.44		242.83	287.11	11.00	3.22	13.51
1996	15.39	110.83	181.94	593.56	13.06	7.94	19.66
1997	25.11			918.83	28.39	7.72	16.70
1998	19.28	150.44	188.56	379.89	13.56	3.17	15.08
1999	13.94	192.44		159.72	7.44	5.11	19.14
2000	17.72	179.28	77.33	28.67	9.33	1.67	19.92
2001	14.39	141.89	137.72	1676.17	42.17	4.28	
2002	15.56	99.78		97.56	14.11	4.44	

Appendix C
Species Abundance Maps

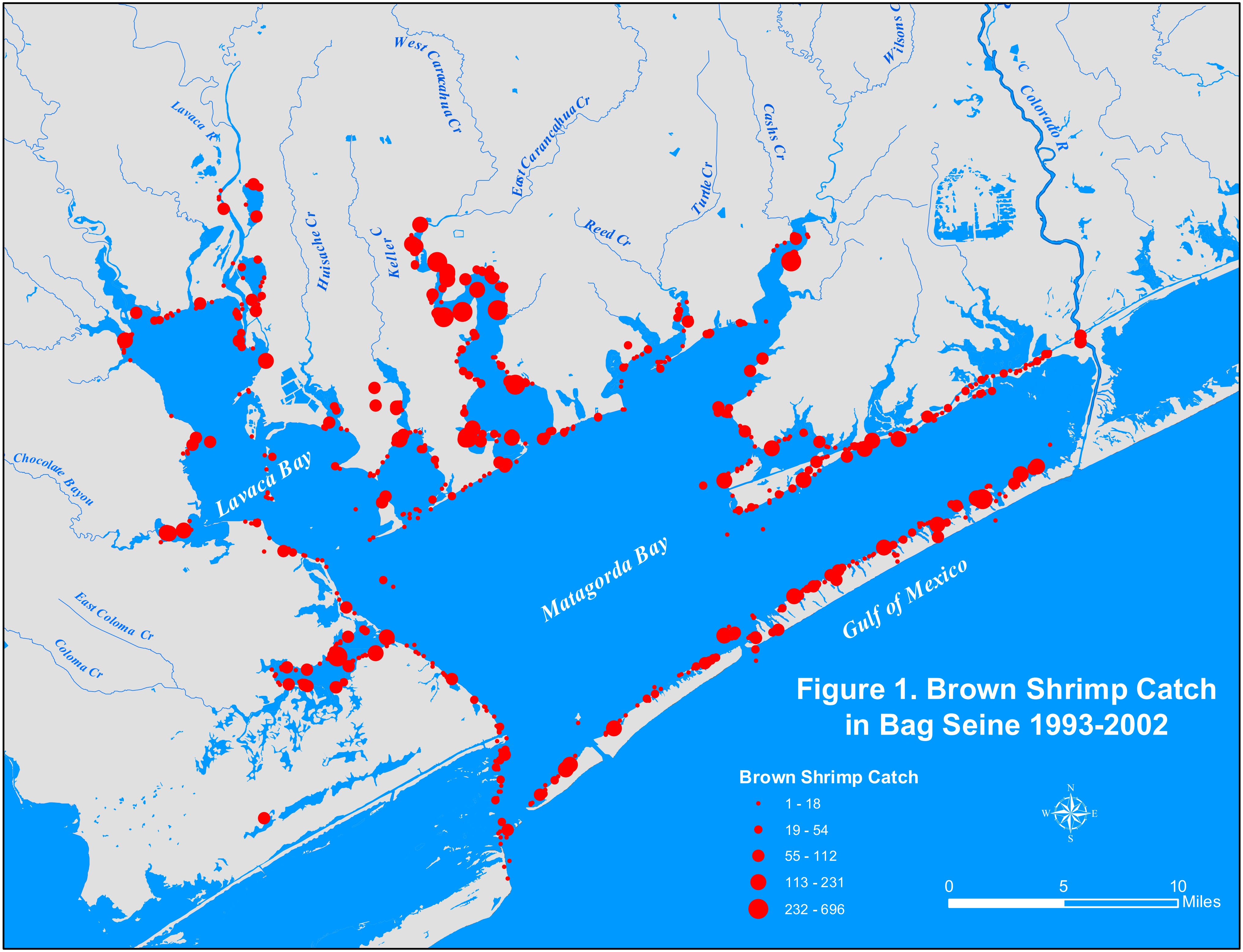


Figure 1. Brown Shrimp Catch in Bag Seine 1993-2002

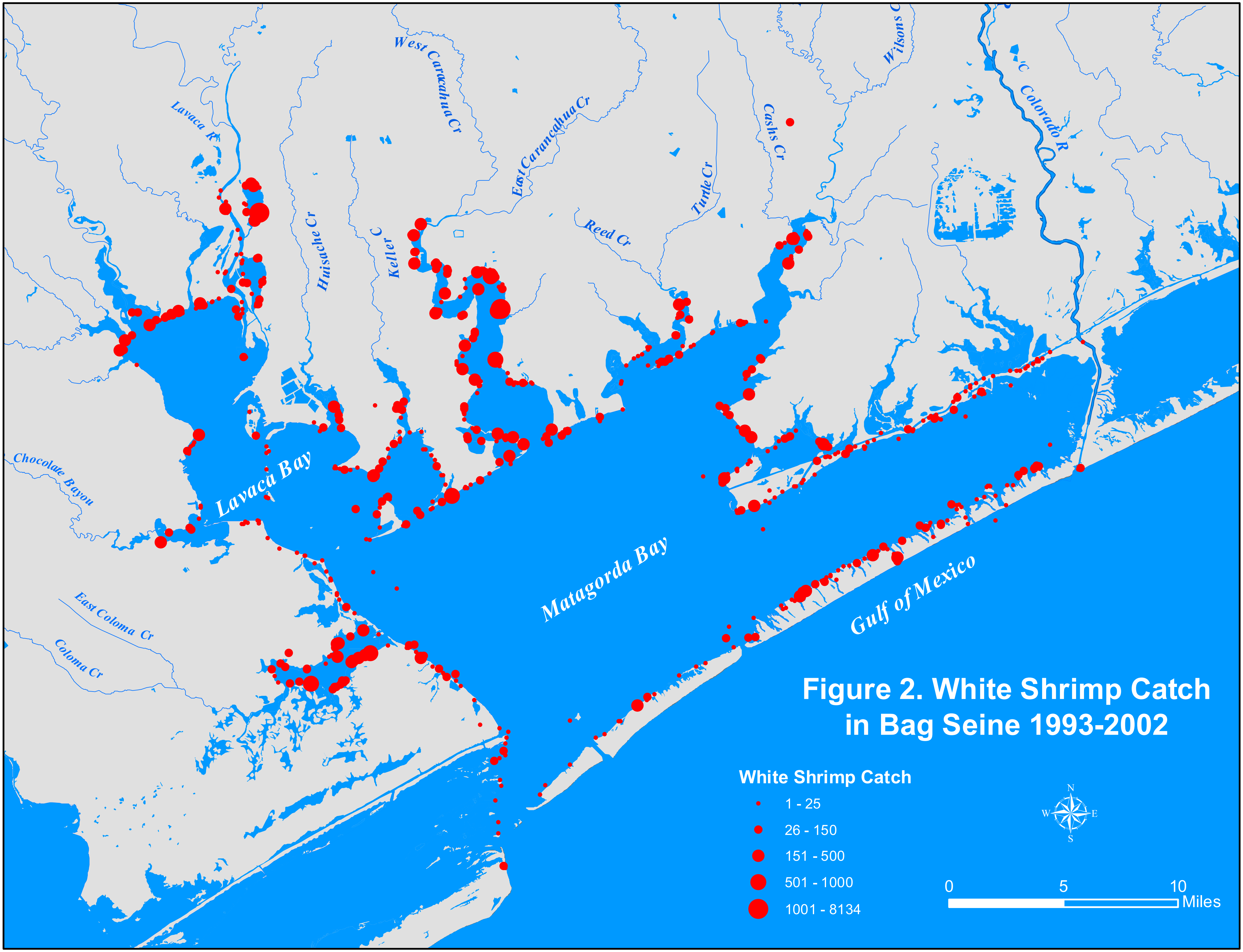


Figure 2. White Shrimp Catch in Bag Seine 1993-2002

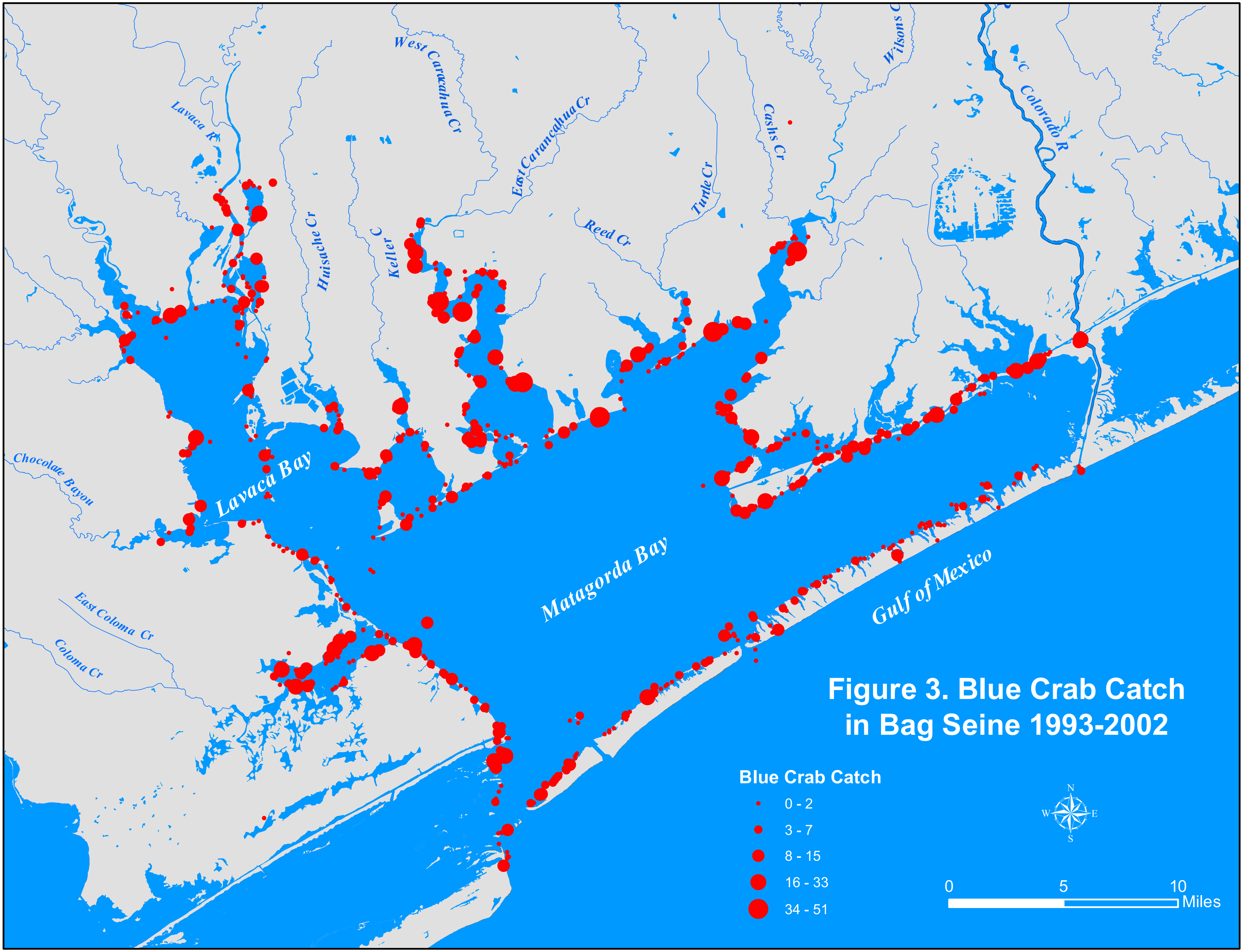


Figure 3. Blue Crab Catch in Bag Seine 1993-2002

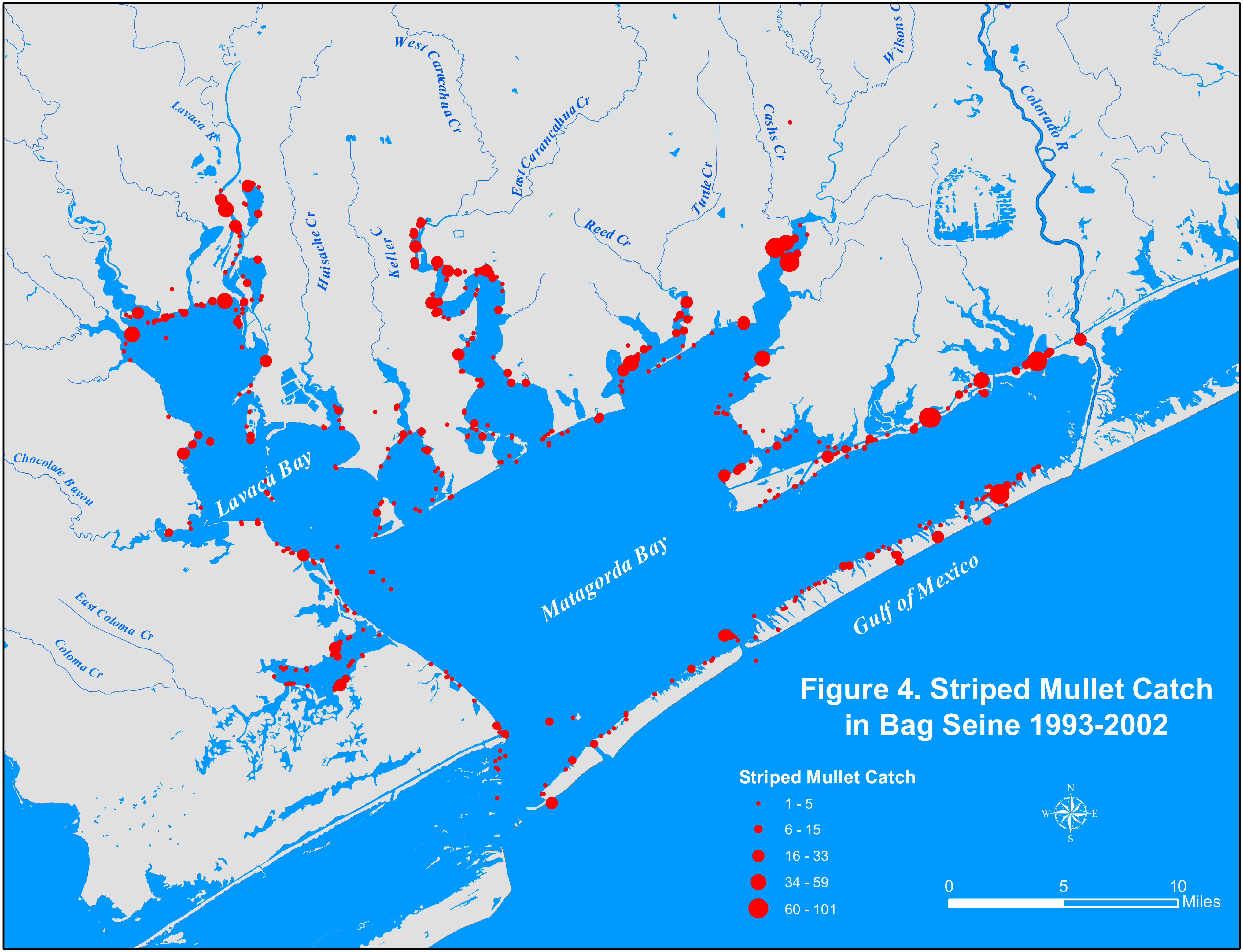


Figure 4. Striped Mullet Catch in Bag Seine 1993-2002

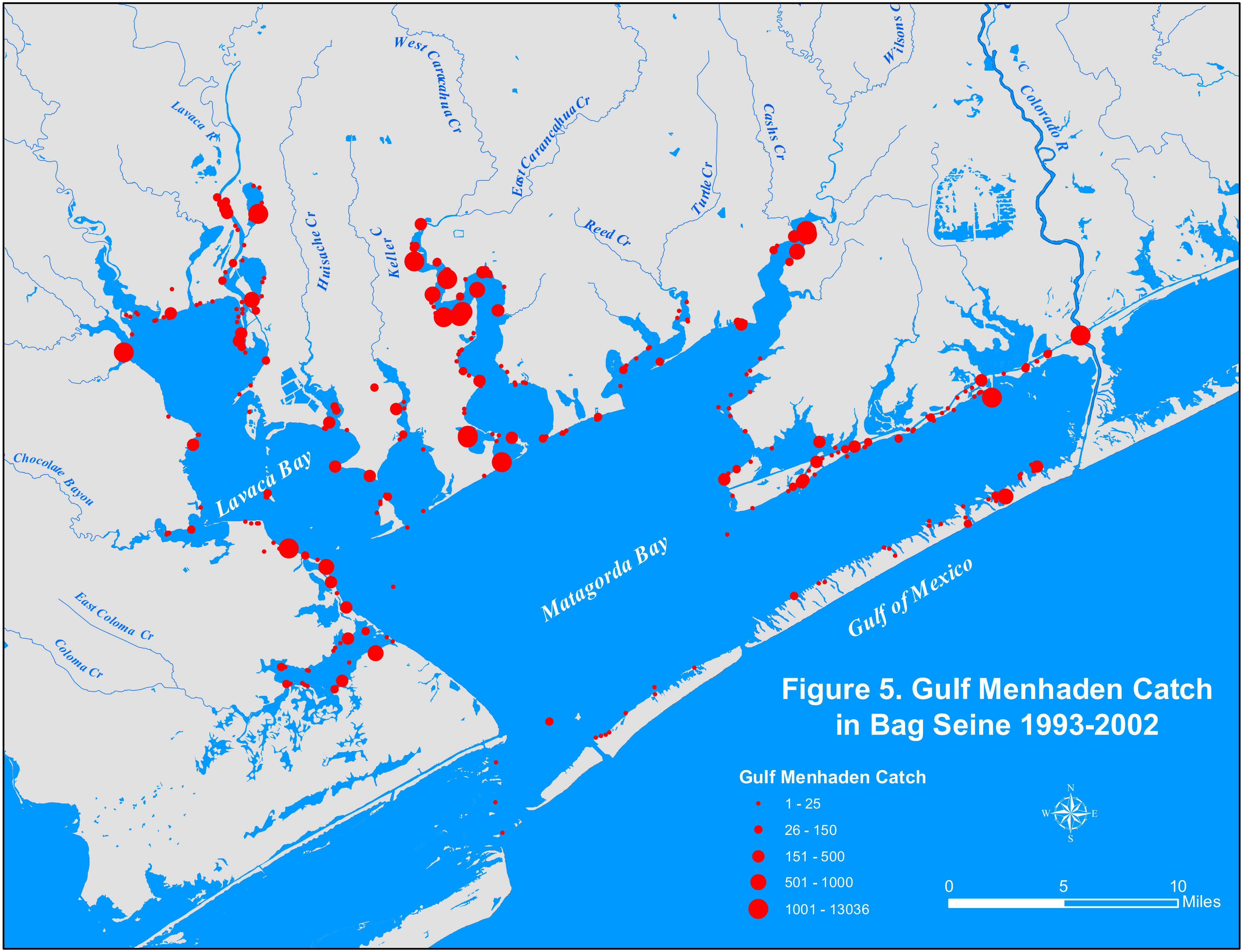


Figure 5. Gulf Menhaden Catch in Bag Seine 1993-2002

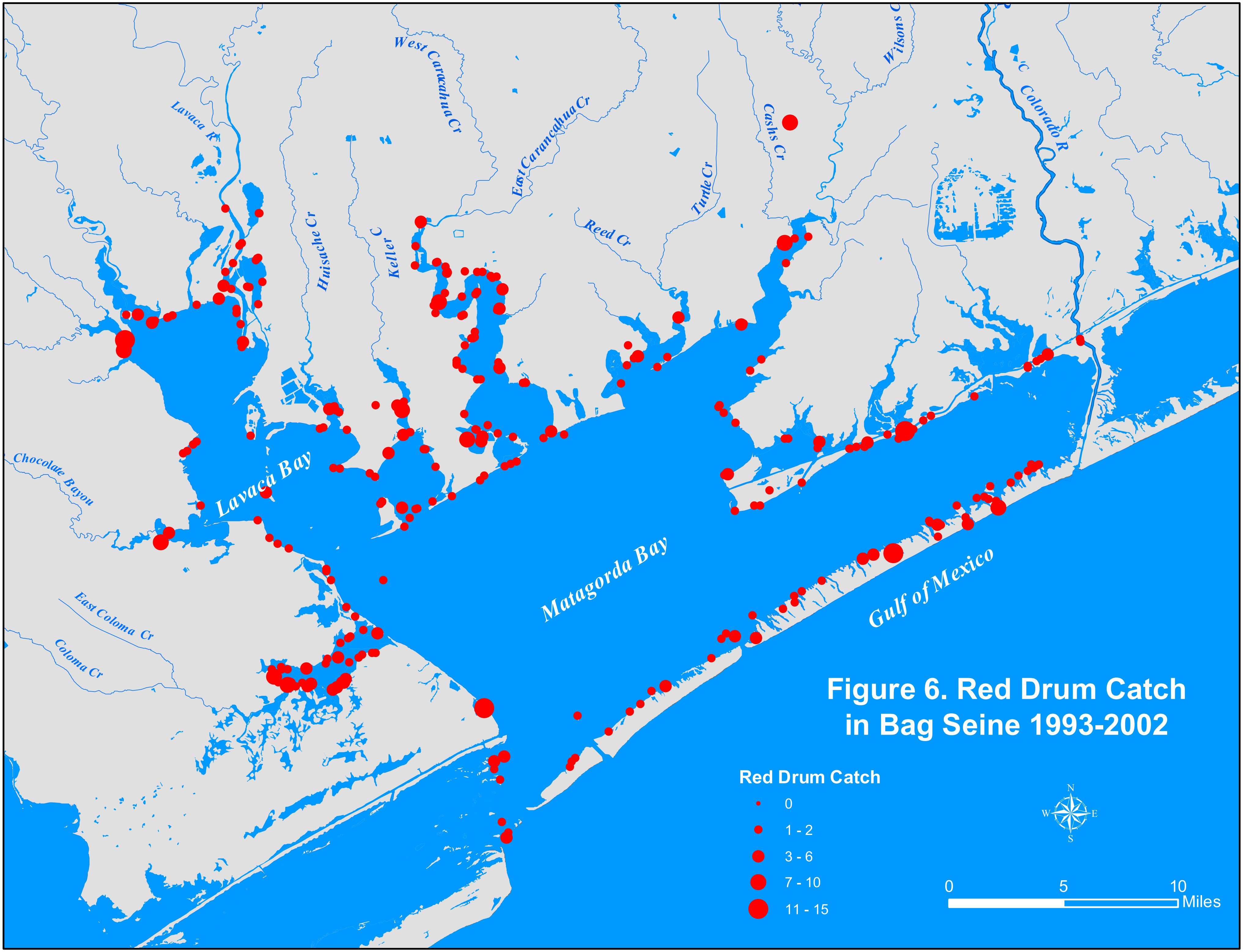


Figure 6. Red Drum Catch in Bag Seine 1993-2002

Appendix D
Salinity Regression Analysis

StatTools (Core Analysis Pack)

Analysis: Regression
Performed By: Ron Anderson
Date: Thursday, April 01, 2004
Updating: Static

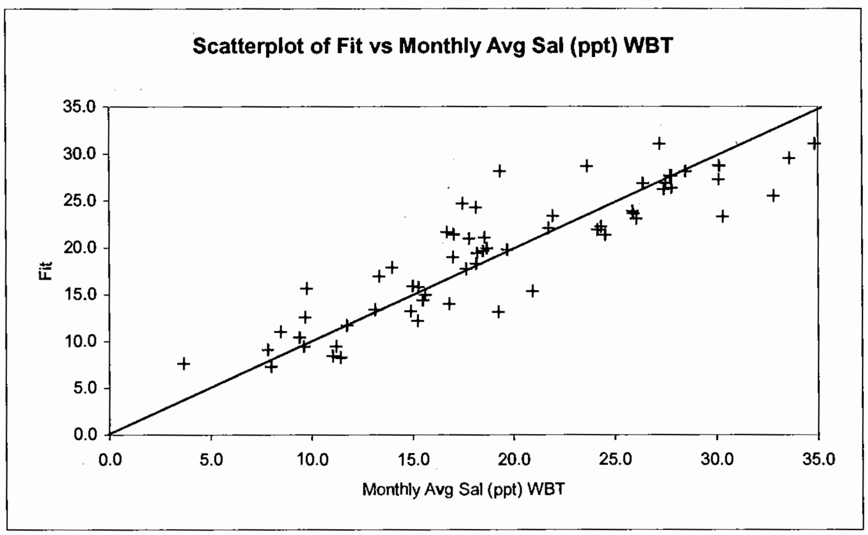
Summary	Multiple R	R-Square	Adjusted R-Square	StErr of Estimate	Durbin Watson
	0.891	0.794	0.7832	3.527	1.4500

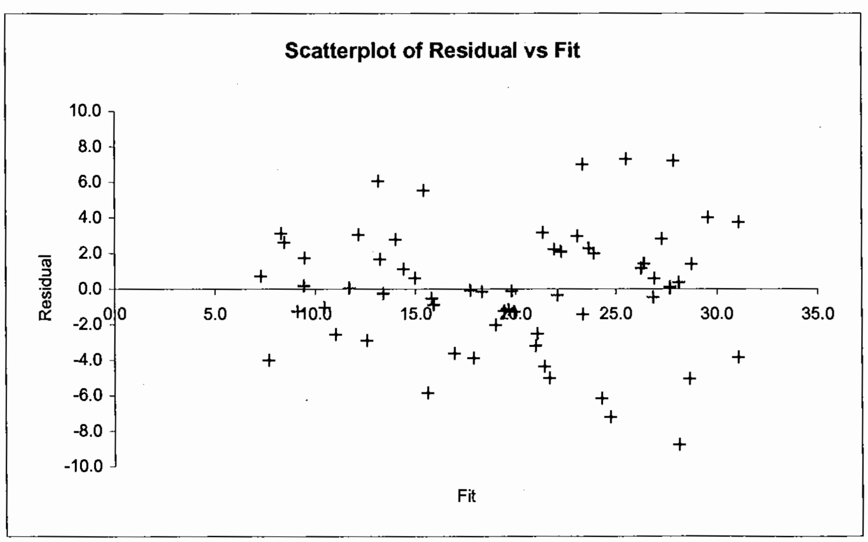
ANOVA Table	Degrees of Freedom	Sum of Squares	Mean of Squares	F-Ratio	p-Value
Explained	3	2778.2	926.1	74.434	< 0.0001
Unexplained	58	721.6	12.4		

Regression Table	Coefficient	Standard Error	t-Value	p-Value	Lower Limit	Upper Limit
Constant	106.618	6.128	17.399	< 0.0001	94.352	118.885
LN(Qm1)	-4.125	0.604	-6.827	< 0.0001	-5.335	-2.916
LN(Qm2)	-2.050	0.744	-2.753	0.0079	-3.540	-0.559
LN(Qm3)	-1.531	0.589	-2.598	0.0119	-2.711	-0.352

Step Information	Multiple R	R-Square	Adjusted R-Square	StErr of Estimate	Entry Number
LN(Qm1)	0.8204	0.6730	0.6676	4.367	1
LN(Qm2)	0.8774	0.7698	0.7620	3.695	2
LN(Qm3)	0.8910	0.7938	0.7832	3.527	3

LN(Qm4) had a t-value of less than .3





10:48 Thursday, April 22, 2004 16

The ARIMA Procedure

Maximum Likelihood Estimation

Parameter	Estimate	Standard Error	t Value	Approx Pr > |t|	Lag	Variable	Shift
MU	108.93249	8.64139	12.61	<.0001	0	SAL	0
AR1,1	0.43929	0.13146	3.34	0.0008	1	SAL	0
NUM1	-3.84131	0.53625	-7.16	<.0001	0	LQm	0
NUM2	-2.65652	0.53931	-4.93	<.0001	0	LQm_1	0
NUM3	-1.33709	0.53676	-2.49	0.0127	0	LQm_2	0

Constant Estimate	61.07972
Variance Estimate	9.316634
Std Error Estimate	3.052316
AIC	273.6555
SBC	283.507
Number of Residuals	53

Correlations of Parameter Estimates

Variable	Parameter	SAL MU	SAL AR1,1	LQm NUM1	LQm_1 NUM2	LQm_2 NUM3
SAL	MU	1.000	-0.093	-0.492	-0.436	-0.488
SAL	AR1,1	-0.093	1.000	0.100	0.010	0.018
LQm	NUM1	-0.492	0.100	1.000	-0.187	-0.111
LQm_1	NUM2	-0.436	0.010	-0.187	1.000	-0.193
LQm_2	NUM3	-0.488	0.018	-0.111	-0.193	1.000

Autocorrelation Check of Residuals

To Lag	Chi-Square	DF	Pr > ChiSq	Autocorrelations					
6	4.92	5	0.4254	-0.071	0.163	0.050	0.053	-0.211	0.039
12	13.38	11	0.2695	0.156	-0.102	0.140	-0.065	0.166	-0.196
18	14.83	17	0.6079	0.038	-0.044	-0.006	-0.072	0.059	-0.078
24	19.43	23	0.6762	-0.045	0.023	-0.056	0.075	-0.062	0.178

StatTools (Core Analysis Pack)

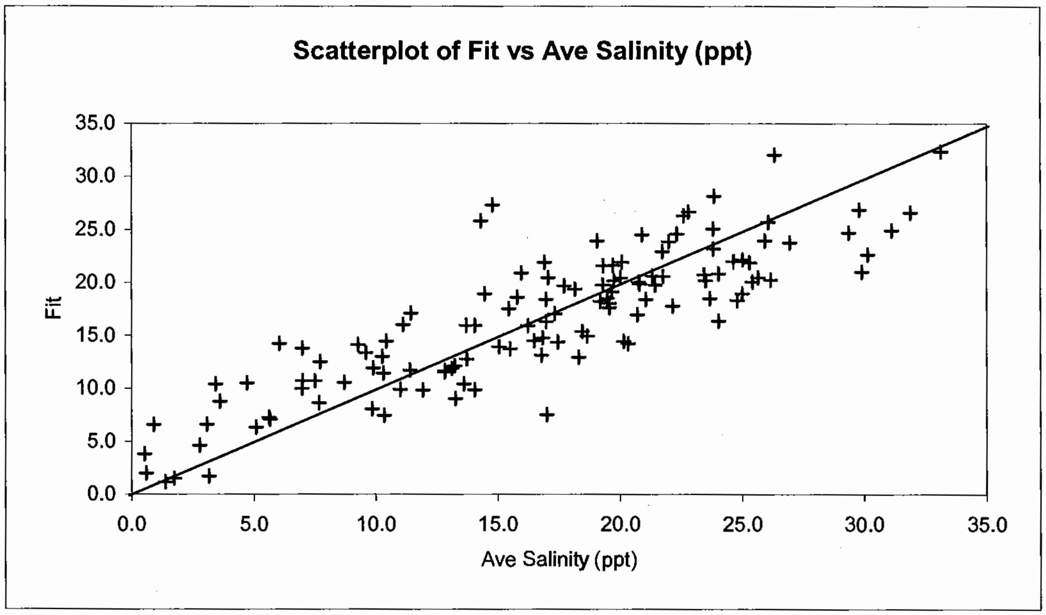
Analysis: Regression
Performed By: Ron Anderson
Date: Wednesday, March 24, 2004
Updating: Static

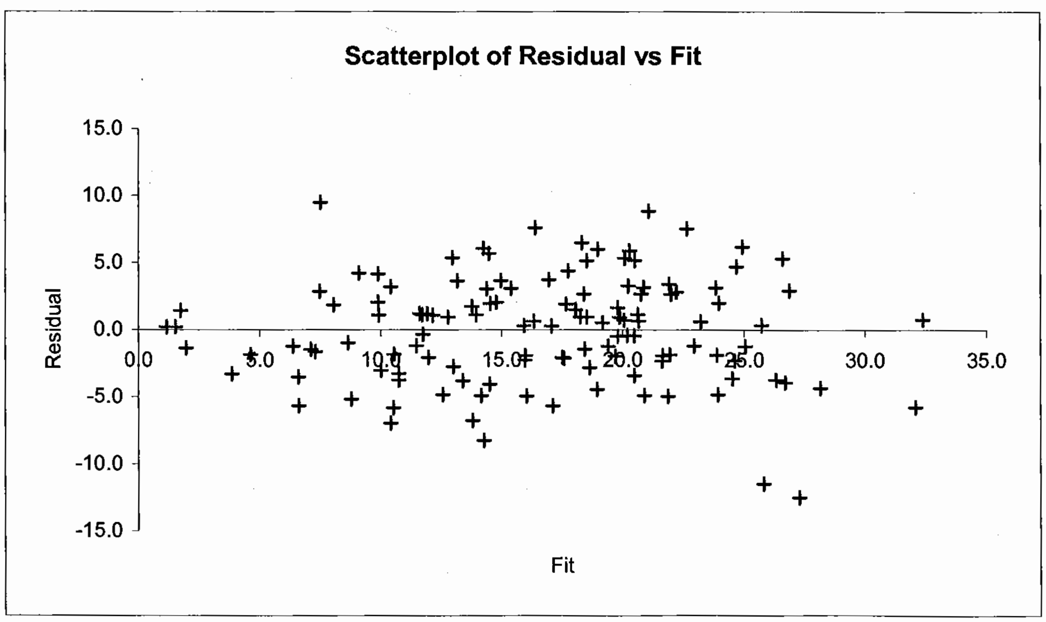
LAVACA SALINITY REGRESSION

Summary	Multiple R	R-Square	Adjusted R-Square	StErr of Estimate	Durbin Watson
	0.8551	0.7311	0.7222	4.0245	1.3342

ANOVA Table	Degrees of Freedom	Sum of Squares	Mean of Squares	F-Ratio	p-Value
Explained	4	5285.6324	1321.4081	81.5846	< 0.0001
Unexplained	120	1943.6131	16.1968		

Regression Table	Coefficient	Standard Error	t-Value	p-Value	Lower Limit	Upper Limit
Constant	64.7772	2.8358	22.8426	< 0.0001	59.162	70.392
LNQm2)	-1.7722	0.2526	-7.0166	< 0.0001	-2.272	-1.272
LN(Qm1)	-1.7431	0.2224	-7.8367	< 0.0001	-2.183	-1.303
LN(Qm4)	-0.7740	0.2187	-3.5385	0.0006	-1.207	-0.341
LN(Qm3)	-0.6386	0.2418	-2.6413	0.0094	-1.117	-0.160





The ARIMA Procedure

Maximum Likelihood Estimation

Parameter	Estimate	Standard Error	t Value	Approx Pr > |t|	Lag	Variable	Shift
MU	67.10222	4.26406	15.74	<.0001	0	Sal	0
AR1,1	0.48832	0.09932	4.92	<.0001	1	Sal	0
NUM1	-1.68509	0.23955	-7.03	<.0001	0	lnQ	0
NUM2	-2.02093	0.24659	-8.20	<.0001	0	lnQ_1	0
NUM3	-0.83264	0.24861	-3.35	0.0008	0	lnQ_2	0
NUM4	-0.59384	0.23855	-2.49	0.0128	0	lnQ_3	0

Constant Estimate	34.33486
Variance Estimate	10.1779
Std Error Estimate	3.190283
AIC	454.8098
SBC	469.6053
Number of Residuals	87

Correlations of Parameter Estimates

Variable	Parameter	Sal MU	Sal AR1,1	lnQ NUM1	lnQ_1 NUM2	lnQ_2 NUM3	lnQ_3 NUM4
Sal	MU	1.000	0.033	-0.505	-0.396	-0.318	-0.465
Sal	AR1,1	0.033	1.000	-0.069	-0.068	-0.004	0.096
lnQ	NUM1	-0.505	-0.069	1.000	-0.176	-0.038	0.098
lnQ_1	NUM2	-0.396	-0.068	-0.176	1.000	-0.161	0.008
lnQ_2	NUM3	-0.318	-0.004	-0.038	-0.161	1.000	-0.277
lnQ_3	NUM4	-0.465	0.096	0.098	0.008	-0.277	1.000

Autocorrelation Check of Residuals

To Lag	Chi-Square	DF	Pr > ChiSq	Autocorrelations					
6	7.50	5	0.1859	-0.051	0.115	-0.043	-0.153	0.198	0.003
12	17.62	11	0.0909	0.185	-0.060	0.052	0.185	-0.114	0.116
18	27.16	17	0.0557	-0.148	0.045	0.167	-0.025	0.143	-0.123
24	36.41	23	0.0374	0.104	-0.066	0.174	-0.053	-0.054	0.163

Autocorrelation Plot of Residuals

```
Lag   Covariance   Correlation   -1 9 8 7 6 5 4 3 2 1 0 1 2 3 4 5 6 7 8 9 1   Std Error

  0    10.177905       1.00000   |                    |********************|          0
  1    -0.522065       -.05129   |                .  *|   .                |   0.107211
  2     1.168725       0.11483   |                .   |** .                |   0.107493
  3    -0.442540       -.04348   |                .  *|   .                |   0.108894
  4    -1.561171       -.15339   |                .***|   .                |   0.109093
  5     2.012918       0.19777   |                .   |****                |   0.111545
  6     0.026665       0.00262   |               .    |    .               |   0.115505
  7     1.884159       0.18512   |               .    |****.               |   0.115506
  8    -0.607411       -.05968   |               .   *|    .               |   0.118867
  9     0.527871       0.05186   |               .    |*   .               |   0.119211
 10     1.886428       0.18535   |               .    |****.               |   0.119470
 11    -1.162633       -.11423   |               .  **|    .               |   0.122731
 12     1.184240       0.11635   |               .    |**  .               |   0.123947
```

Inverse Autocorrelations

```
Lag   Correlation   -1 9 8 7 6 5 4 3 2 1 0 1 2 3 4 5 6 7 8 9 1

  1      -0.00162   |                .   |   .                |
  2      -0.18674   |                ****|   .                |
  3       0.07648   |                .   |** .                |
  4       0.21414   |                .   |****                |
  5      -0.12082   |                . **|   .                |
  6      -0.17668   |                ****|   .                |
  7      -0.07258   |                .  *|   .                |
  8       0.11685   |                .   |** .                |
  9      -0.09691   |                . **|   .                |
 10      -0.17790   |                ****|   .                |
 11       0.08613   |                .   |** .                |
 12       0.01018   |                .   |   .                |
```

Partial Autocorrelations

```
Lag   Correlation   -1 9 8 7 6 5 4 3 2 1 0 1 2 3 4 5 6 7 8 9 1

  1      -0.05129   |                .  *|   .                |
  2       0.11249   |                .   |** .                |
  3      -0.03299   |                .  *|   .                |
  4      -0.17246   |                .***|   .                |
```

```
 5      0.20108   |              .    |****             |
 6      0.05732   |              .    |*    .           |
 7      0.13009   |              .    |***.             |
 8     -0.07067   |              .   *|    .           |
 9      0.08295   |              .    |**  .           |
10      0.21370   |              .    |****             |
11     -0.10239   |              .  **|    .           |
12     -0.01215   |              .    |    .           |
```

Model for variable Sal

Estimated Intercept 67.10222

Autoregressive Factors

Factor 1: 1 - 0.48832 B**(1)

Input Number 1

Input Variable	lnQ
Overall Regression Factor	-1.68509

Input Number 2

Input Variable	lnQ_1
Overall Regression Factor	-2.02093

Input Number 3

Input Variable	lnQ_2
Overall Regression Factor	-0.83264

Input Number 4

Input Variable	lnQ_3
Overall Regression Factor	-0.59384

The AUTOREG Procedure

Maximum Likelihood Estimates

SSE	824.414799	DFE	81
MSE	10.17796	Root MSE	3.19029
SBC	469.605303	AIC	454.809854
Regress R-Square	0.6901	Total R-Square	0.8534
Durbin-Watson	2.0443		

Variable	DF	Estimate	Standard Error	t Value	Approx Pr > |t|
Intercept	1	67.1085	4.2694	15.72	<.0001
lnQ	1	-1.6851	0.2399	-7.02	<.0001
lnQ_1	1	-2.0211	0.2470	-8.18	<.0001
lnQ_2	1	-0.8329	0.2490	-3.34	0.0013
lnQ_3	1	-0.5940	0.2389	-2.49	0.0150
AR1	1	-0.4880	0.0995	-4.90	<.0001

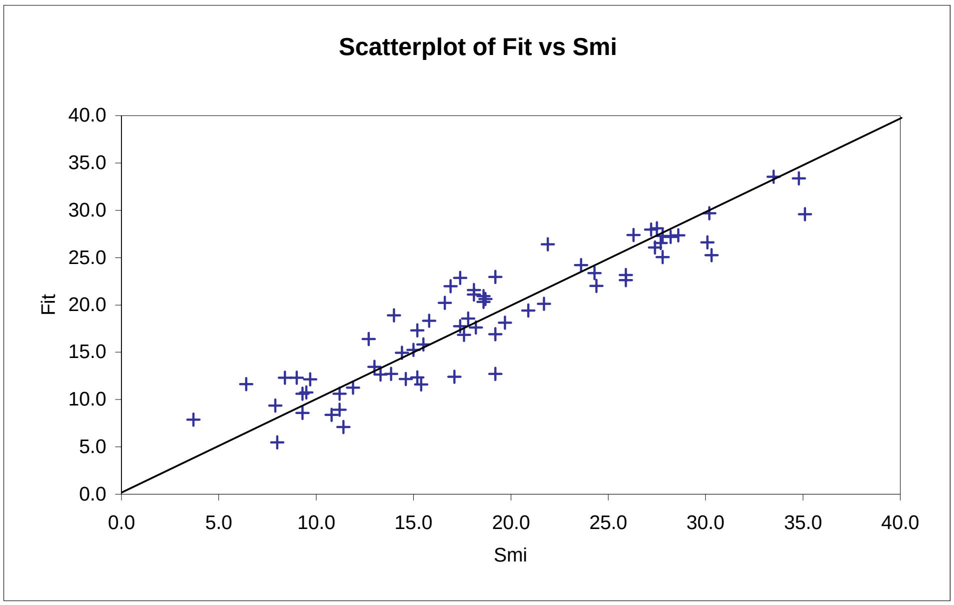
StatTools (Core Analysis Pack)

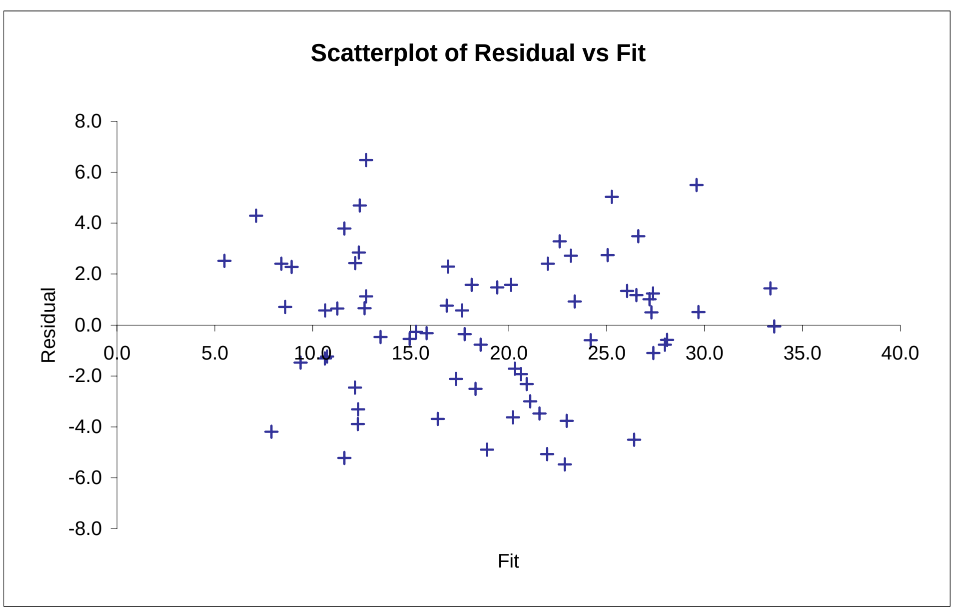
Analysis: Regression Equation 9.1 Monthly Salinity Inflow Relationship for West Tripod
Performed By: Ron Anderson
Date: Thursday, May 27, 2004
Updating: Static

Summary	**Multiple R**	**R-Square**	**Adjusted R-Square**	**StErr of Estimate**	**Durbin Watson**
	0.93	0.86	0.85	2.86	1.73

ANOVA Table	**Degrees of Freedom**	**Sum of Squares**	**Mean of Squares**	**F-Ratio**	**p-Value**
Explained	3	3241.97	1080.66	131.96	< 0.0001
Unexplained	64	524.12	8.19		

Regression Table	**Coefficient**	**Standard Error**	**t-Value**	**p-Value**	**Lower Limit**	**Upper Limit**
Constant	38.364	4.351	8.8175	< 0.0001	29.672	47.056
smi-1	0.436	0.061	7.1398	< 0.0001	0.314	0.558
LNQmi	-3.818	0.425	-8.9920	< 0.0001	-4.666	-2.970
Emi	20.605	8.496	2.4252	0.0181	3.632	37.579





StatTools (Core Analysis Pack)

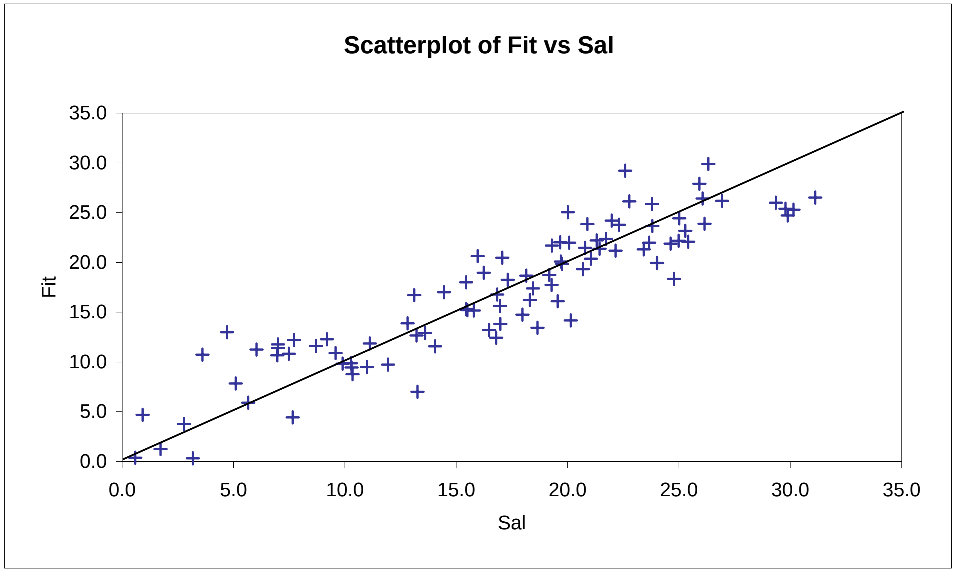
Analysis: Regression Equation 9.2 Lavaca Bay Critical Equation
Performed By: Ron Anderson
Date: Monday, June 28, 2004
Updating: Static

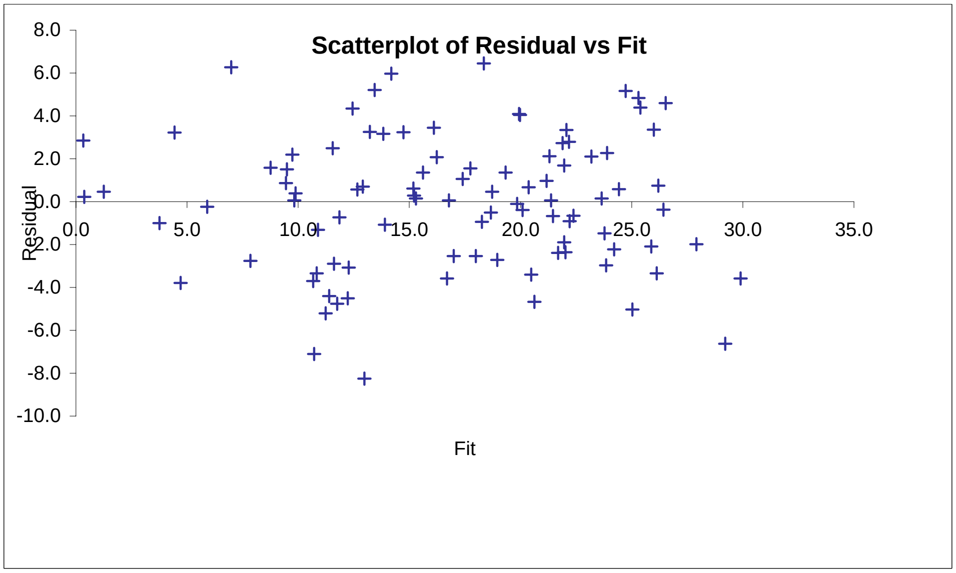
Summary	Multiple R	R-Square	Adjusted R-Square	StErr of Estimate	Durbin Watson
	0.9097	0.8275	0.8218	3.17	1.9430

ANOVA Table	Degrees of Freedom	Sum of Squares	Mean of Squares	F-Ratio	p-Value
Explained	3	4384.1	1461.4	145.5261	< 0.0001
Unexplained	91	913.8	10.0		

Regression Table	Coefficient	Standard Error	t-Value	p-Value	Lower Limit	Upper Limit
Constant	25.738	2.330	11.0447	< 0.0001	21.11	30.37
Sal-1	0.515	0.057	9.0604	< 0.0001	0.40	0.63
LN(Qm1)	-1.701	0.207	-8.2184	< 0.0001	-2.11	-1.29
LNQm2)	-1.040	0.260	-3.9991	0.0001	-1.56	-0.52

Step Information	Multiple R	R-Square	Adjusted R-Square	StErr of Estimate	Entry Number
Sal-1	0.7578	0.5742	0.5696	4.925	1
LN(Qm1)	0.8929	0.7972	0.7928	3.417	2
LNQm2)	0.9097	0.8275	0.8218	3.169	3





Appendix E
TXEMP Input Files

Appendix E – TXEMP Input Files

The three input files – input, inphvt.dat, and inpsal.dat - used by TXEMP in the Target Flow model run are listed below:

****
input
****
Matagorda Estuarine System*** using Colorado Gaged inflows, 70'th %ile
simple reg. eqns; tpwd data; SalP=50%%
RATUNG ratio of annual ungaged flow to sum of Lavaca & Colo. (coastal/river basin ratio)
0.361 - 1941-2003 ratio
UGMFACT(i) i=1,12, monthly factors to distribute annual ungaged flow
.051, .061, .058, .070, .117, .110, .091, .043, .147, .138, .065, .049 - 1941-2003
RATIOLC(i) i=1,7, ratio of (ave. seasonal Lavaca)/(ave. seasonal Col.) gaged, 1941-2003
.377, .391, .469, .287, .670, .375, .434, six seasons + annual
RSEASLC(i) i=1,7, ratio of (std of seasonal Lav)/(std of seasonal Col.) gaged,1941-2003
.326, .508, .408, .290, 1.019, .503, .399, six seasons + annual
RATSPD, RATSPS *** factors for spread of annual & seasonal lav.to col. inflows
0.5,.1, 2.0,.9, !Adj std dev for ratio of Lav to Col ann. seasonal flows
BLVARC(M), BUVARC(M), M=1,12, bounds on monthly flows in sal eqn., 1000 ac-ft, 1987-2003
0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, BLVARC
1043.,1043.,1043.,1043.,1043.,1043.,1043.,1043.,1043.,1043.,1043.,1043., BUVARC
2.2, 3.5, 3.3, 3.7, 5.9, 4.8, 4.6, 2.0, 4.9, 1.7, 1.5, 1.9 ! BLVAR(M),M= 1,12 Lav R Lwr Bnds on mo flows: LOWEST 10%, 1000 ac-ft, 1941-2003
77.0, 68.9, 43.7, 85.0, 139.4, 86.0, 29.2, 18.3, 50.6, 58.1, 53.4, 57.9 !BUVAR(M),M= 1,12 Lav R Upr Bnds on mo flws: 70'th %ile, , 1941-2003
30.6, 26.8, 22.3, 22.9, 28.4, 22.0, 20.0, 17.3, 25.3, 33.1, 26.2, 23.8! BLVAR(M),M=14,25 Col R Lwr Bnds on mo flws: LWST 10%, 1941-2003
208.9, 197.6, 231.7, 221.7, 255.4, 210.5, 120.1, 68.7, 133.8, 154.2, 162.5, 166.2 !BUVAR(M),M=14,25 Col R Upr Bnds: 70'th %ile, 1941-2003
SFLWLB(K), SFLWUB(K), K=1,6 Seasonal (bi-monthly) Flow Bounds: 1000 acre-ft, 1941-2003
60.6, 50.8, 76.9, 47.1, 68.5, 56.8 !Lower Total Flow Bounds for productivity eqns
667.6, 2624.7, 2064.0, 1048.1, 2503.2, 1774.8 Upper Total Flow Bounds for productivity eqns
Productivity Target as % of mean productivity
0.8 ! (HARVSTM(I),I=1,9),TARHVFT annual harvest means, target
Productivity Probability Levels
.50, .50, .50, .50, .50, .50, .50, .50, .50 ! HARPRB(I),I=1,9 productivity reliability
Salinity Probability Levels
0.50, 0.50! SALPRB(L),L=1,NLOCS salinity constraint probability for lavaca and eastern Matagord bay

** Nutrient LB and UB (annual inflow to estuary)
1710., 3600.   ! XLBNUT, XUBNUT   Lower and Upper Bounds on Nutrient (Nitrogen Remaining in million grams)
****GRG2 parameters !
0.,0.0001   ! defaul(1),FPNEWT
0.,0.0001   ! defaul(2),FPINIT
0.,0.00001   ! defaul(3),FPSTOP
0.,0.0001   ! defaul(4),FPSPIV
0.,0.0   ! defaul(5),PPH1EP
1.,10   ! defaul(6),NNSTOP
0.,10   ! defaul(7),IITLIM
1.,080   ! defaul(8),LLMSER
1.,6   ! defaul(9),IIPR
0.,0   ! defaul(10),IIPN4
0.,0   ! defaul(11),IIPN5
0.,0   ! defaul(12),IIPN6
0.,0   ! defaul(13),IIPER
0.,0   ! defaul(14),IIDUMP
1.,0   ! defaul(15),IIQUAD
1.,0   ! defaul(16),LDERIV
1.,0   ! defaul(17),MMODCG
1.   ! defaul(18)
1, ! IOPTN problem specification 1=maxH;2=minH;3=maxQ;4=minQ;5=maxSalP;6=maxHarP
**SpeciesID:
1, 1, 1, 1, 1, 1, 1, 1, 1   ! IOBJCT(I),I=1,9 Set to 1 if species is to be included in the sum of hrvst eqn
3600   ! SUMQLB Lower bound on annual inflow
3650   ! SUMQUB Upper Bound on annual inflow
** initial solution and weighting scheme
0. ! SOLN Set to 0. to generate initial montly flow soln; 1. to read in
131., 147., 280., 307., 272., 278., 215., 106., 178., 198., 152., 136., ! X(M),M=1,12 INITIAL MONTHLY INFLOWS
0.10   ! WT1 initial weight
1.00   ! WT9 limit of weight range
0.1   ! WTINC increment to weighting factor
** confidence interval
0.70   ! SIGSAL significance level FOR SALINITY RANGE
0.80   ! SIGFSH significance level FOR PRODUCTIVITY RANGE

************End of Input*********

```
*************************
inphvt.dat
*************************
7 2004 RIVER
brownshrimp
6 2
 22.070 0.080
0 3
5.49432
    0.91154   -0.00383
   -0.00383    0.00002
whiteshrimp
8 2
 8.579 0.154
0 4
5.36046
    1.15420   -0.00775
   -0.00775    0.00006
menhaden
9 3
 -39.533 45.435 -28.331
0 11 35
22.42180
    4.86309   -0.73053   -0.13581
   -0.73053    0.20754   -0.06707
   -0.13581   -0.06707    0.08509
reddrum
10 4
 0.387 0.113 0.085 -0.168
0 14 15 16
0.14331
    5.10209   -0.49787    0.01034   -0.42248
   -0.49787    0.13679   -0.03857    0.00317
    0.01034   -0.03857    0.12343   -0.09269
   -0.42248    0.00317   -0.09269    0.16288
stripedmullet
9 3
 0.451 0.658 -0.484
0 11 35
```

```
0.41755
    4.86309   -0.73053   -0.13581
   -0.73053    0.20754   -0.06707
   -0.13581   -0.06707    0.08509
bluecrab
10 4
 -1.966 -0.378 0.666 0.380
0 12 13 15
0.52962
    7.22187    0.03950   -0.71561   -0.52707
    0.03950    0.13493   -0.09618   -0.04326
   -0.71561   -0.09618    0.16388    0.05201
   -0.52707   -0.04326    0.05201    0.07936
oyster
8 3
 18.367 -0.008 0.018
0 3 4
4.05893
    0.26254   -0.00016   -0.00007
   -0.00016    0.00000    0.00000
   -0.00007    0.00000    0.00000
****** End of regression eqns ******
HVSTLB(I) ,  HVSTUB(I) ,  HARVSTM(I),    COST(I)  ! NAME
25.72, 100.0, 37.57, 1.0, brownshrimp - increased upper constraint
11.78, 100.0, 29.02, 1.0, whiteshrimp - increased upper constraint
2.42, 141.38, 40.36, 1.0, menhaden
0.18, 0.85, 0.49, 1.0, reddrum
0.48, 2.72, 1.17, 1.0, stripedmullet
1.37, 3.77, 2.02, 1.0, bluecrab
5.28, 21.49, 15.90, 1.0, oyster

*************************
inpsal.dat
*************************
2 2004 TOTAL
W_Tripod
62 4
 53.375 -4.118 -2.056 -1.531
0 11 12 13
3.52333
    0.46828   -0.04846   -0.00243   -0.05231
   -0.04846    0.02935   -0.02300    0.00428
```

```
   -0.00243   -0.02300    0.04455   -0.02040
   -0.05231    0.00428   -0.02040    0.02792
UpperLav
126 5
 30.745 -1.760 -1.762 -0.628 -0.774
0 1 2 3 4
4.01425
    0.05064   -0.00497   -0.00227   -0.00259   -0.00488
   -0.00497    0.00301   -0.00151    0.00000    0.00016
   -0.00227   -0.00151    0.00392   -0.00135   -0.00014
   -0.00259    0.00000   -0.00135    0.00359   -0.00136
   -0.00488    0.00016   -0.00014   -0.00136    0.00295
c**end of input data
Eastern Matagorda Bay Salinity Lower Bounds
5., 5.,  5.,  5.,  1.,  1.,  1.,  1.,  5.,  5.,  5.,  5.
Eastern Matagorda Bay Salinity Upper Bounds - increase to 16-21
21., 21., 21., 21., 16., 16., 16., 21., 21., 21., 21., 21.
Upper Lavaca Bay Salinity Lower Bounds
5.,  5.,  5.,  5.,  1.,  1.,  1.,  1.,  5.,  5.,  5., 5.
Upper Lavaca Bay Salinity Upper Bounds  - increase to 16-21
21., 21., 21., 21., 16., 16., 16., 21., 21., 21., 21., 21.
```

Appendix F
TXEMP Sensitivity

Appendix F

Sensitivity of Productivity to Constraints in TXEMP

Introduction

This appendix describes four applications of the TXEMP optimization model for evaluating inflows to Matagorda Bay. The first is the solution of a constrained optimization problem that represents application of the State Methodology. The second is the solution of a loosely constrained optimization problem that looks at changes in productivity if flow and salinity constraints are simultaneously relaxed. The third is a sensitivity analysis in which salinity constraints are maintained while flow constraints are relaxed. The fourth is a sensitivity analysis in which flow constraints are maintained while salinity constraints are relaxed. A comparison of results is provided as a conclusion.

1) Constrained Optimization - Application of the State Methodology

The management objective of the State Methodology for determination of freshwater inflow needs is to maintain bay productivity near historical levels for certain key species found in the bay. These levels are maintained in the optimization model by enforcing productivity constraints on the solution. Additional management objectives call for constraining the solution to flows that are considered feasible from a water supply perspective. Finally, constraints on salinity are also applied to act as a safeguard to ensure that species salinity preferences are achieved. Application of the State Methodology answers the question of how best to provide (optimize) flows to the bay on a monthly basis so as to meet the productivity objectives while being constrained by flow and salinity requirements. This is referred to here as the constrained optimization problem.

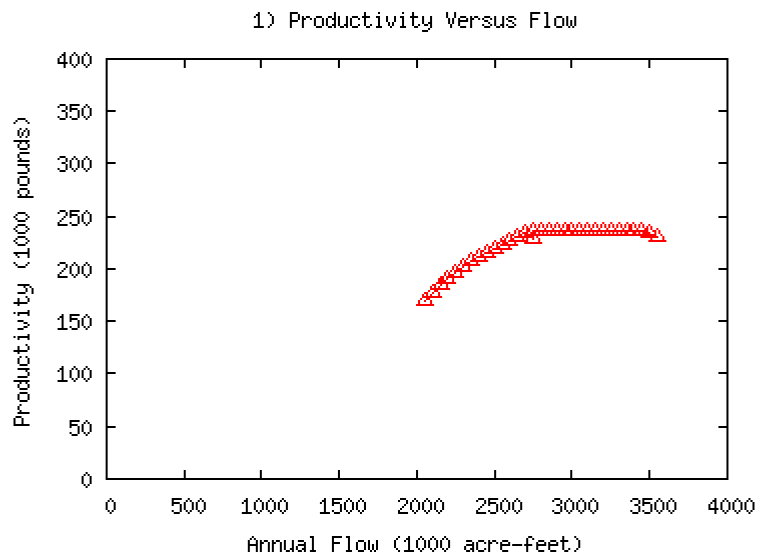


Figure F.1 Constrained productivity response curve.

The solution to the constrained optimization problem for Matagorda Bay is provided in Figure F.1. The curve shown represents bay productivity versus total inflow to the bay, where total inflow is defined as the sum of Colorado River, Lavaca River, and coastal basin flows. Flow constraints in this run were set at the 70'th percentile monthly flow. Upper salinity constraints were set at 16 ppt during May, June, and July, and 21 ppt for all other months. Maximum productivity of 236 thousand pounds occurs for total inflows between 2.75 and 3.50 million acre-ft/year.

Each of the points on the productivity response curve represents a solution to the constrained optimization problem. The approach used to decide which flow to use as a management goal, or “Target Flow”, in the 1997 study was to select the flow below which productivity began to rapidly decrease. Following that same approach, the “Target Flow” for the current solution occurs at an annual flow of 2.75 million acre-feet. The Colorado River contribution to this flow is 1.43 million acre-feet/year, and the Lavaca River contribution is 0.593 million acre-ft/year. Annual flow volumes are distributed on a monthly basis for the Colorado and Lavaca Rivers as shown in Figure F.2. In that figure, the optimal solution is shown in blue, and the upper and lower flow constraints are shown in red and green, respectively. Upper flow constraints limit the solution in January, February, May, June, July, and August. Flow peaks in January, February, and May through August (Figure F.2, Table F.1) reflect the model's attempt to maximize productivity for menhaden, brown shrimp, and white shrimp, which have large positive terms in their combined productivity equations for these months (Table F.2). The minimum in March-April flows is in response to the negative term in the blue crab equation for those months.

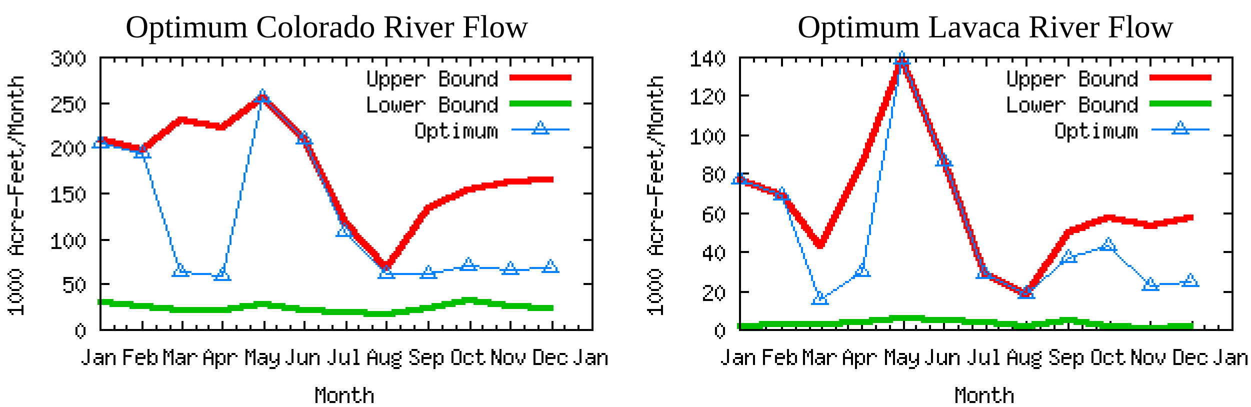


Figure F.2 Optimum monthly Colorado River and Lavaca River flows for the constrained optimization problem. Optimum solution is shown in blue, upper constraint is in red, and lower constraint is in green.

Salinities corresponding to the optimum monthly flows are shown in Figure F.3. Upper and lower constraints are shown in Figure F.3 in red and green, respectively. Salinity at the West Bay Tripod constrains the solution in April, May, and September through December. No salinity constraints are hit for the Lavaca Bay Causeway site.

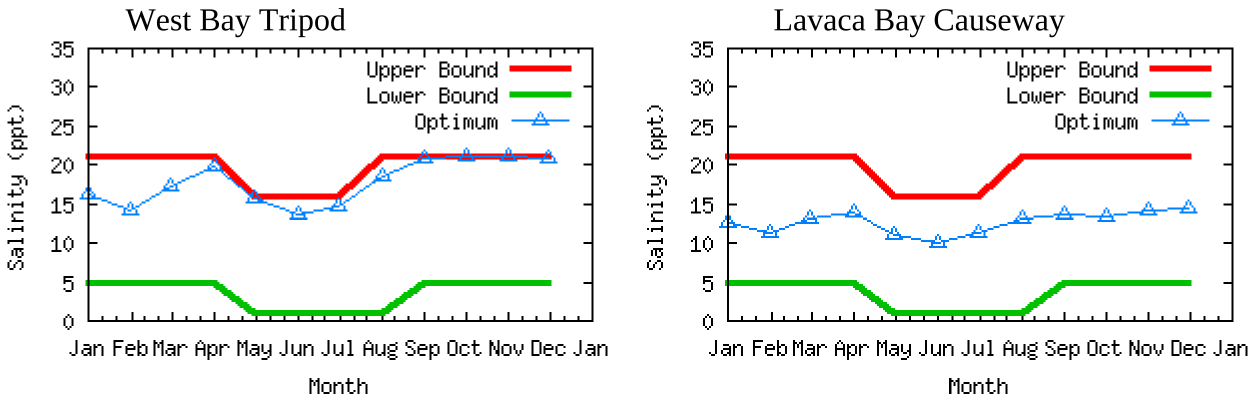


Figure F.3 Salinity corresponding to optimum flow solutions (Figure F.2) for the constrained optimization problem. Optimum salinity is shown in blue, upper constraint is in red, and lower constraint is in green.

Table F.1 Monthly optimal flows for Colorado River, Lavaca River, and coastal basins for the constrained optimization problem.

MONTHLY INFLOWS
(1000 ACRE-FEET)

MONTH	COLORADO	LAVACA	OTHER BASINS	TOTAL MONTHLY INFLOW
1	205.6	77.0	37.2	319.8
2	194.5	68.9	44.5	307.9
3	63.2	15.6	42.3	121.1
4	60.4	30.3	51.1	141.8
5	255.4	139.4	85.3	480.1
6	210.5	86.0	80.2	376.7
7	108.4	29.2	66.4	204.0
8	62.0	18.3	31.4	111.7
9	61.9	37.3	107.2	206.5
10	71.3	42.9	100.7	214.9
11	66.5	23.0	47.4	136.9
12	68.0	24.9	35.7	128.7
TOTAL	1427.8	592.8	729.4	2750.0
(PERCENT)	51.9	21.6	26.5	

Table F.2 Productivity equations for brown shrimp, white shrimp menhaden, red drum, striped mullet, blue crab, and oyster for the constrained optimization problem. Productivity is in thousands of pounds. Monthly flows are in thousands of acre-feet. LN is natural log of flow. Lag refers to prior year's flow.

```
Pbrownshr =  22.070 +  0.080 *    (Qmay+Qjun)

Pwhiteshr =   8.579 +  0.154 *    (Qjul+Qaug)

Pmenhaden = -39.533 + 45.435 *  LN(Qjan+Qfeb)
                    - 28.331 * {LN(Qsep+Qoct)}lag

Preddrum  =   0.387 +  0.113 *  LN(Qjul+Qaug)
                    +  0.085 *  LN(Qsep+Qoct)
                    -  0.168 *  LN(Qnov+Qdec)

Pstripedm =   0.451 +  0.658 *  LN(Qjan+Qfeb)
                    -  0.484 * {LN(Qsep+Qoct)}lag

Pbluecrab =  -1.966 -  0.378 *  LN(Qmar+Qapr)
                    +  0.666 *  LN(Qmay+Qjun)
                    +  0.380 *  LN(Qsep+Qoct)

Poyster   =  18.367 -  0.008 *    (Qmay+Qjun)
                    +  0.018 *    (Qjul+Qaug)
```

2) Loosely Constrained Optimization

The State Methodology provides "Target" flow recommendations based on the constrained optimization problem. That "optimum" set of monthly flows is distinct from optimal flows that would occur if the problem were more loosely constrained, i.e. by increasing upper flow and salinity constraints while maintaining other constraints related to productivity and flow. (The problem would be somewhat meaningless without a minimum set of constraints.) The loosely constrained optimum has generally not been investigated because it was considered infeasible from the perspective of water supply management (in the case of open flow constraints) or biologically undesirable (in the case of open salinity constraints). There has, however, been interest in investigating the loosely constrained problem since this provides a glimpse of potential, although from a management perspective unrealistic, optimum bay productivity. This problem is referred to here as the loosely constrained optimization problem.

The solution to the loosely constrained optimization problem is presented in Figure F.4. In this problem, upper flow constraints were set to the maximum observed monthly flow (100'th percentile), and salinity constraints were set to 17 ppt in May, June, July and to 22 ppt in the remaining months. Constraints were left in place for lower flow, lower salinity, Lavaca/Colorado flow ratios, and species productivity targets, and species abundance ratios. Maximum productivity in this case is 331 thousand pounds for total annual flows of 3.60 million acre-feet/year.

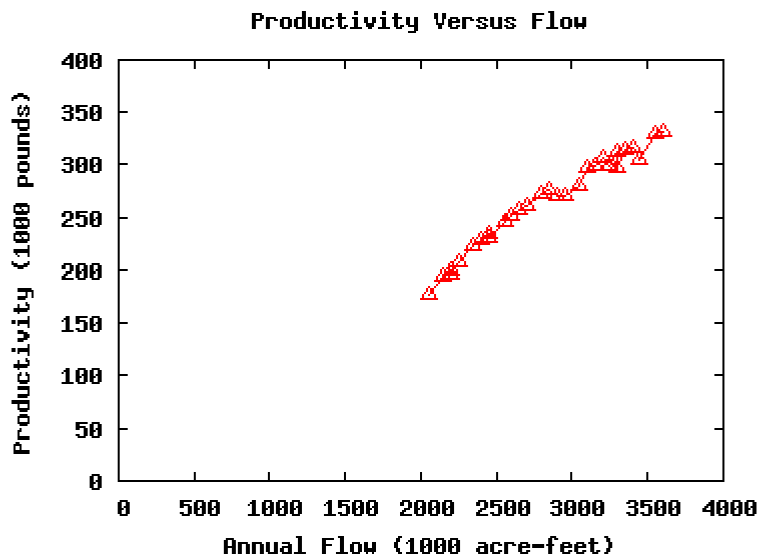


Figure F.4 Productivity response curve for the loosely constrained optimization problem. Upper flow constraint set to maximum monthly flow. Upper salinity constraint set to 17 ppt from May to July, 22 ppt in remaining months.

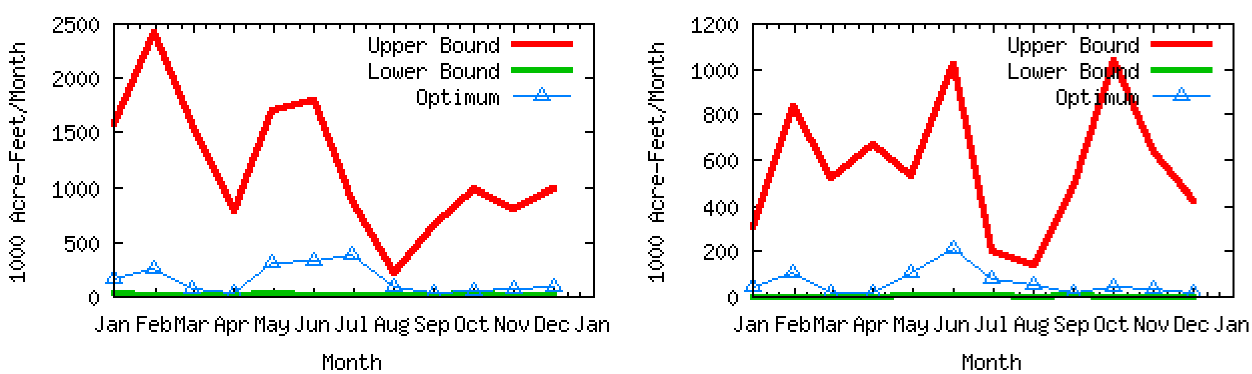


Figure F.5 Optimum monthly Colorado River (left) and Lavaca River (right) flows for the loosely constrained optimization problem. Optimum solution is shown in blue, upper constraint is in red, and lower constraint is in green.

The Colorado River contribution to the total annual flow is 1.893 million acre-feet/year, and the Lavaca River contribution is 0.752 million acre-feet/year. The monthly flow distributions corresponding to these annual flows are presented in Figure F.5. Upper flow constraints are well above the optimum solution and clearly play no role in restricting the solution. Peaks in January, February, and May through July are driven primarily by the significant positive terms in the productivity equations (Table F.2). Salinities corresponding to the monthly flows are shown in Figure 6. Only the April-May and October –November salinity constraints for the West Bay Tripod limit the solution. The April-May peak in salinity is driven by the negative coefficient for the March-April term in the blue crab equation. The model tries to minimize flows for those months, leading to increased salinities in April-May. The October-November peak is drive by the negative September-October coefficient for menhaden following the same logic. The constraint on the ratio of monthly flows between the Lavaca River and the Colorado River prevents Lavaca River flows from decreasing any further during March-April and September-October.

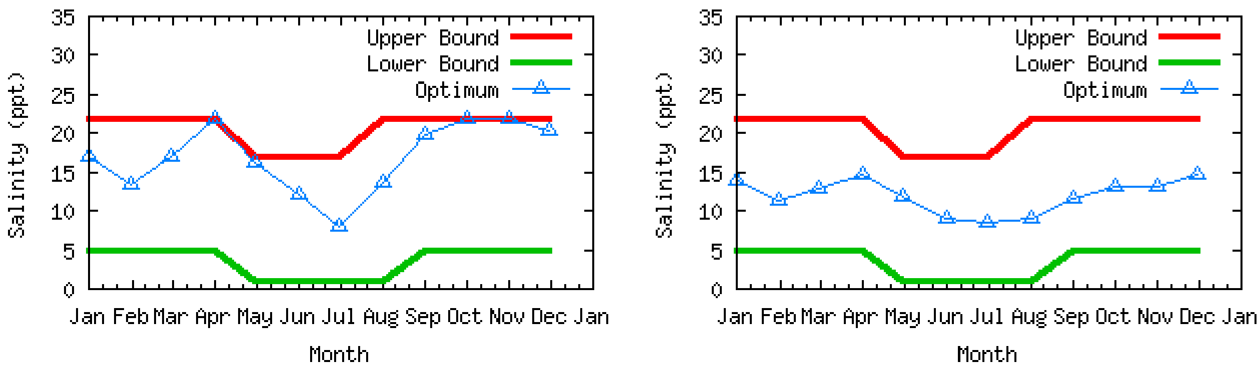


Figure F.6 Salinity corresponding to optimum flow solutions (Figure F.5) for the loosely constrained optimization problem. Optimum salinity is shown in blue, upper constraint is in red, and lower constraint is in green. West Bay Tripod (left), Lavaca Causeway (right).

Table F.3 Monthly optimal flows for Colorado River, Lavaca River, and coastal basins for the loosely constrained optimization problem.

	MONTHLY INFLOWS (1000 ACRE-FEET)			
MONTH	COLORADO	LAVACA	OTHER BASINS	TOTAL MONTHLY INFLOW
1	162.3	40.5	48.7	251.5
2	248.5	109.3	58.2	416.1
3	64.8	15.8	55.4	136.0
4	32.6	20.3	66.8	119.8
5	318.3	108.4	111.7	538.5
6	337.0	210.3	105.0	652.4
7	385.5	78.5	86.9	550.9
8	93.8	55.1	41.1	190.0
9	40.0	19.1	140.4	199.4
10	59.7	40.9	131.8	232.4
11	67.1	32.1	62.1	161.3
12	83.4	21.5	46.8	151.7
TOTAL	1893.2	751.9	954.9	3600.0
(PERCENT)	52.6	20.9	26.5	

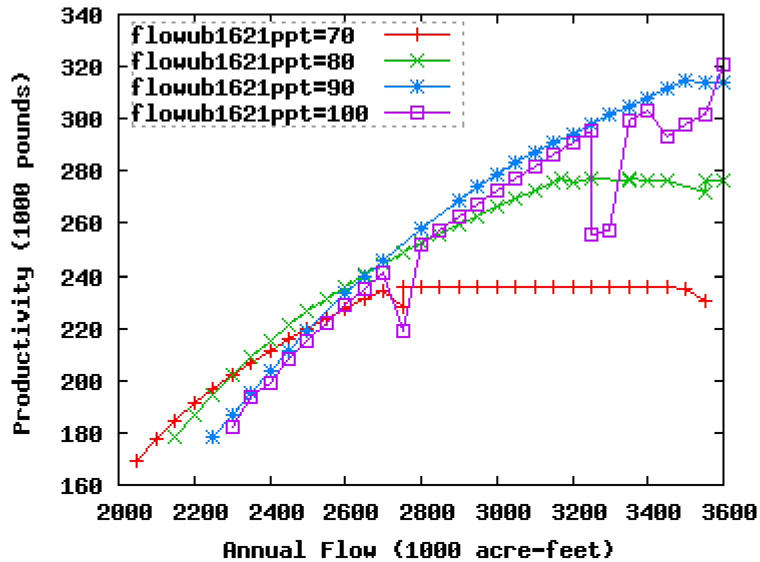


Figure F.7 Salinity-constrained sensitivity analysis. Upper monthly flow constraint range from 70'th percentile (red) flow to 100'th percentile (maximum observed) flow (purple).

3) Salinity-Constrained Sensitivity Analysis

The effect on productivity of varying the upper flow constraint was investigated in this series of runs. In this problem, the upper salinity constraint was set to 16 ppt in May, June, and July, and to 21 ppt in the remaining months. The upper flow constraint was set to the 70'th, 80'th, 90'th, and 100'th percentile (maximum observed) monthly flow in separate runs to generate a series of productivity response curves (Figure F.7).

Maximum productivity occurs for the 90'th and 100'th percentile curves at above 300 thousand pounds for total inflows of 3.50 million acre-feet/year. Significant reduction in productivity occurs as flows are reduced to the 80'th percentile constraint (276 thousand pounds, 3.15 million acre-feet/year) and the 70'th percentile constraint (236 thousand pounds, 2.75 million acre-feet/year). Increased productivity for ever larger upper flow constraints is accomplished in the optimization model by distributing larger flows to those months with positive coefficients in their productivity equations.

4) Flow-Constrained Sensitivity Analysis

The effect on productivity of varying upper salinity constraints was investigated in this series of runs. In this problem, the upper monthly flow constraints were fixed at the 70'th percentile flows. The upper salinity flow constraint was increased in 0.5 ppt increments from 15 ppt to 17 ppt in May, June, and July, and from 20 ppt to 22 ppt in the remaining months. Five curves representing these varying constraints are presented in Figure 8.

Maximum productivity increases slightly as the salinity constraints are increased. Using 15 ppt and 20 ppt constraints, productivity is 229 thousand pounds at a total flow of 2.850 million acre-ft/year. With the 17 ppt and 22 ppt constraints, productivity increases slightly to 241 thousand pounds for a flow of 2.616 million acre-ft/year. A small increase in productivity is achieved with lesser amounts of water by allowing flow reductions for those months that have negative coefficients in the productivity equations (Table F.2).

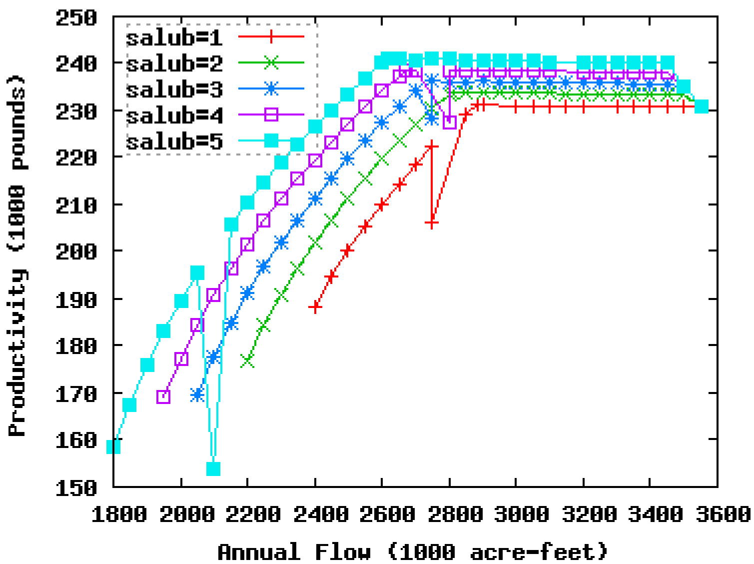


Figure F.8 Flow constrained sensitivity analysis. Salinity constraints for salub=1 – 15 ppt in May, June, and July, 20 ppt for all other months; salub=2 – 15.5 ppt and 20.5 ppt; salub=3 – 16.0 ppt and 21.0 ppt. salub=4 - 16.5 ppt and 21.5 ppt; salub=5 – 17 ppt and 22 ppt.

Comparison of Results

The above sensitivity analyses were extended to include more combinations of inflow and salinity constraints. Results from these runs are summarized in Table F.4 for productivity, Table F.5 for total flow, Table F.6 for Colorado River flow, and Table F.7 for Lavaca River flow. The productivity response to both relaxed flow and salinity constraints is displayed graphically in Figure F. 9. Changes in the salinity constraint (labeled delta (Upper Salinity Constraint)(ppt) on the figure) are represented as increases above the 15 ppt in May, June, and July and 21 ppt in other months. So, 0 ppt on this axis represents the 15 ppt-21 ppt constraint, 1 ppt on the axis represents the 16 ppt-22 ppt constraint, and so on. Figure F.9 shows that by relaxing upper flow and salinity constraints, the optimization model is provided a greater range of flexibility in distributing monthly flows, and productivity can be made to increase. Mild increases in productivity are indicated with relaxed salinity constraints, and even greater increases are indicated with relaxed flow constraints.

Although productivity is predicted to increase with relaxed salinity and flow constraints, these should be considered carefully. From the perspective of water availability, flows are limited and generally cannot be supplied in either volume or timing as is assumed by the optimization model. Flows that have historically occurred infrequently will not likely be provided at higher frequencies in the future. From the ecological perspective, species are salinity tolerant within ranges represented by the salinity constraints. The bounds of these constraints are not sharp, but there are limits beyond which productivity will suffer. The productivity equations have no means of directly capturing the species response to salinity, so in a sense the salinity constraints act as a safeguard to ensure ecologically meaningful solutions. The constrained optimization problem described at the beginning of this section represents an example of moderately relaxed constraints and is suitable as a target flow recommendation.

Table F.4 Productivity with relaxed upper flow and upper salinity constraints.

	Productivity (thousand pounds) Flow Constraint %'ile			
Salinity Constraints (ppt)	70	80	90	100
15, 20	229	274	307	305
16, 21	236	277	315	321
17, 22	241	280	308	331
18, 23	246	283	324	336
19, 24	250	286	326	340
20, 25	255	289	327	345
21, 26	260	289	329	340
22, 27	262	289	329	329
23, 28	262	290	329	316

Table F.5 Total optimal inflow with relaxed upper flow and upper salinity constraints.

	Total Flow (million acre-feet) Flow Constraint %'ile			
Salinity Constraints (ppt)	70	80	90	100
15, 20	2.850	3.400	3.600	3.600
16, 21	2.750	3.173	3.500	3.600
17, 22	2.616	3.050	3.200	3.600
18, 23	2.533	3.000	3.300	3.500
19, 24	2.461	2.850	3.200	3.450
20, 25	2.399	2.750	3.150	3.400
21, 26	2.345	2.700	3.089	3.250
22, 27	2.307	2.700	3.066	3.300
23, 28	2.300	2.670	3.049	3.000

Table F.6 Optimal Colorado River inflow with relaxed upper flow and upper salinity constraints.

Salinity Constraints (ppt)	Colorado Flow (million acre-feet) Flow Constraint %'ile 70	80	90	100
15, 20	1.486	1.757	1.896	1.899
16, 21	1.428	1.665	1.837	1.884
17, 22	1.359	1.587	1.685	1.893
18, 23	1.317	1.564	1.725	1.841
19, 24	1.281	1.502	1.675	1.810
20, 25	1.250	1.437	1.647	1.802
21, 26	1.223	1.410	1.633	1.703
22, 27	1.203	1.420	1.597	1.729
23, 28	1.197	1.400	1.588	1.560

Table F.7 Optimal Lavaca River inflow with relaxed upper flow and upper salinity constraints.

Salinity Constraints (ppt)	Lavaca Flow (million acre-feet) Flow Constraint %'ile 70	80	90	100
15, 20	0.608	0.742	0.749	0.746
16, 21	0.593	0.666	0.735	0.761
17, 22	0.563	0.654	0.666	0.752
18, 23	0.544	0.640	0.700	0.731
19, 24	0.527	0.592	0.676	0.724
20, 25	0.513	0.584	0.668	0.696
21, 26	0.500	0.574	0.637	0.685
22, 27	0.492	0.564	0.656	0.696
23, 28	0.492	0.562	0.653	0.644

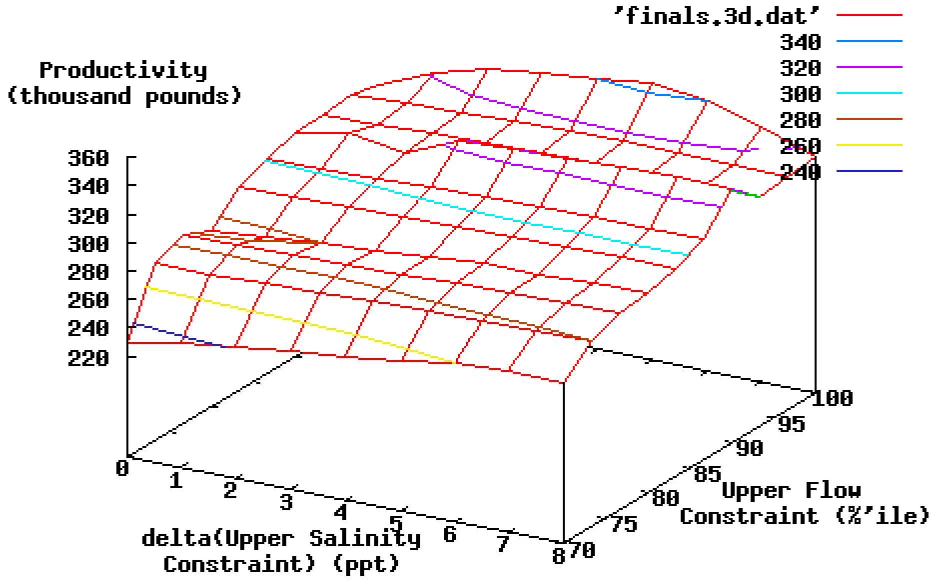


Figure F.9 Productivity for increased flow and salinity constraints. Salinity constraint change (delta(Upper Salinity Constraint)) represents as increment above 15 ppt for May, June, and July, and 20 ppt for all other months. Flow constraint represents monthly flow percentile. Constrained optimization problem represented by delta(Upper Salinity Constraint) = 0 ppt, Upper Flow Constraint = 70'th percentile

Appendix G
Statistical Comparisons of TXBLEND Output to Measured Data

Appendix G

Statistical Comparisons of TXBLEND Output to Measured Data

Statistical comparisons between salinities computed with the TXBLEND model and measured salinities are presented in this Appendix. Model outputs were provided for eleven sites in Matagorda Bay at which salinity was monitored (Figure 8.10). The comparisons below are for daily average salinity. Table 1 provides several statistical comparisons between the measured and model salinities, including the mean error, mean absolute error, root mean square error, and linear correlation coefficient. Cross plots showing modeled versus measured daily average salinity for each site are provided in Figure G.1 through Figure G.11, and correspond to the time series of the same data presented in Figure 8.11.a through Figure 8.11.k.

Table G.1 - Statistical Measures Comparing Modeled and Measured Daily Average Salinity.

Site	**Mean Error (ppt)**	**Mean Absolute Error (ppt)**	**RMS Error (ppt)**	**Linear Correlation Coefficient, r^2**
1492 - Matagorda Entrance Channel	-2.53	3.32	5.93	0.186
2449 - Sandy Point	0.02	2.98	4.36	0.641
4944 - Lavaca Causeway	-2.32	4.58	5.90	0.659
3022 - Carancahua Bay	-2.33	3.47	4.21	0.835
2791 - Tres Palacios Bay	-1.84	3.76	4.70	0.701
2235 - Channel Marker 4	-0.00	2.46	3.14	0.842
3445 - West Bay Tripod	-4.64	5.62	7.12	0.734
3672 - Shellfish Marker B	-3.96	6.12	8.04	0.441
4969 - East Bay Tripod	-4.00	4.80	5.90	0.750
2971 - East Bay Shellfish Marker	0.01	5.36	7.58	0.322
2491 - East Bay Eastern End	-0.07	3.78	4.97	0.434

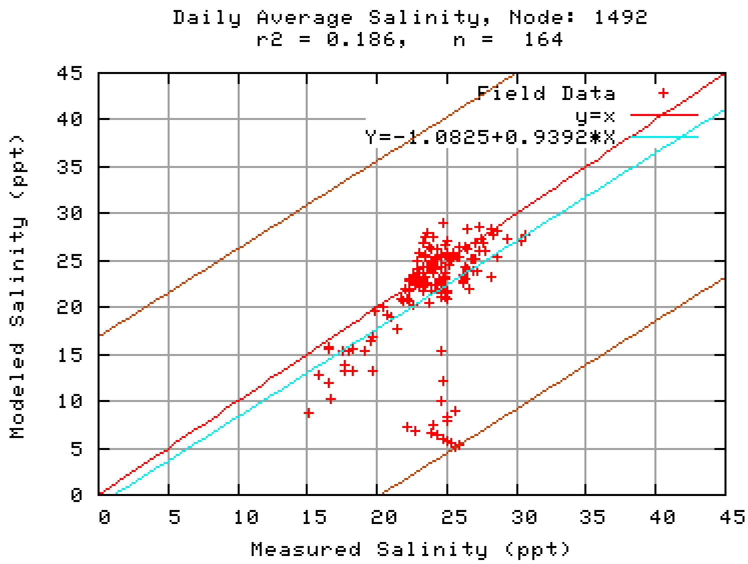


Figure G.1 Model Versus Measured Daily-Average Salinity at Matagorda Entrance Channel.

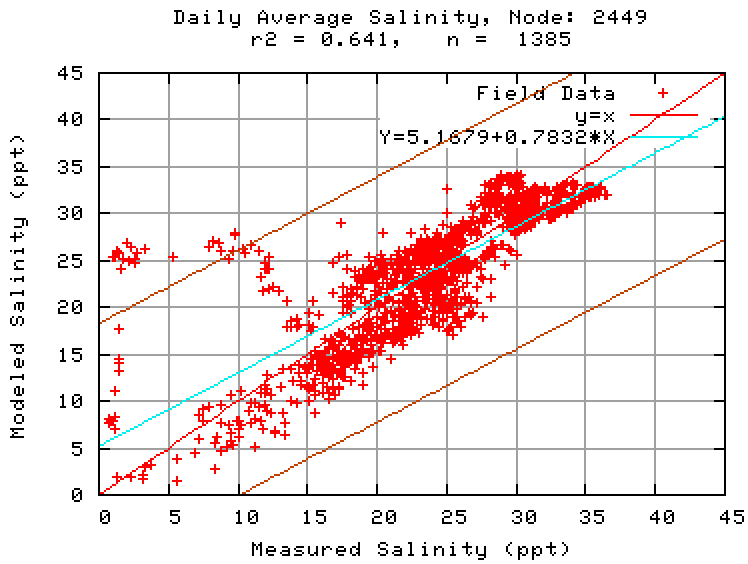


Figure G.2 Model Versus Measured Daily-Average Salinity at Sandy Point.

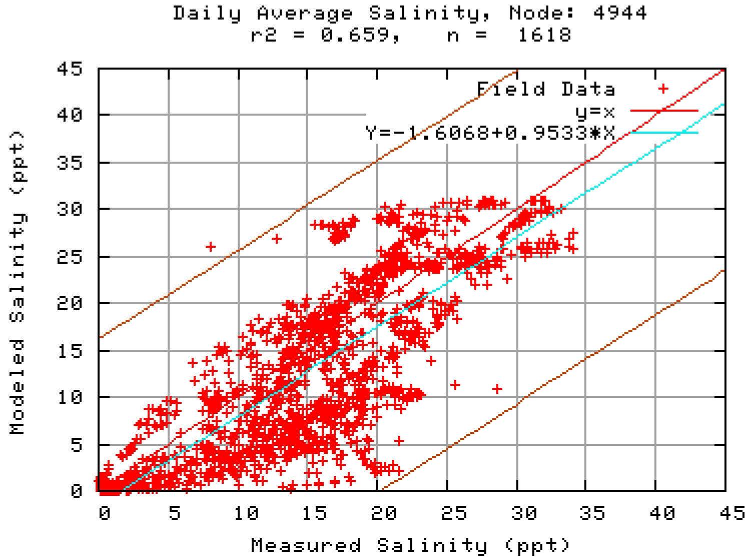


Figure G.3 Model Versus Measured Daily-Average Salinity at Lavaca Causeway.

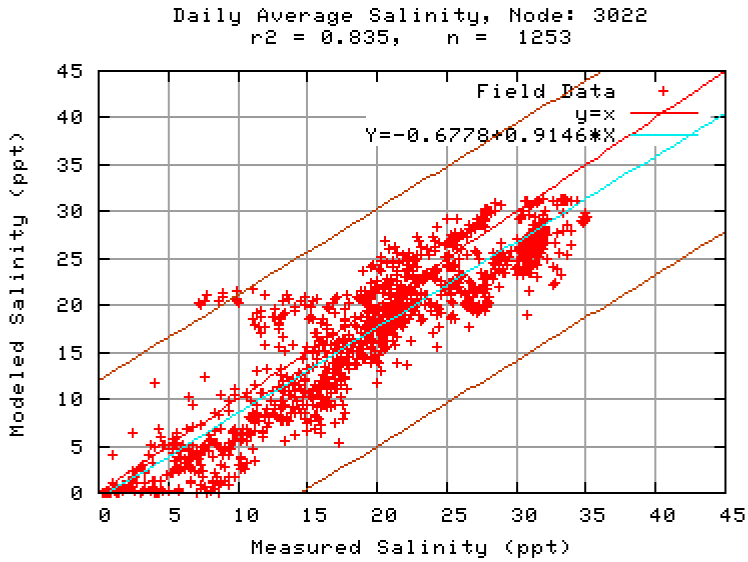


Figure G.4 Model Versus Measured Daily-Average Salinity at Carancahua Bay.

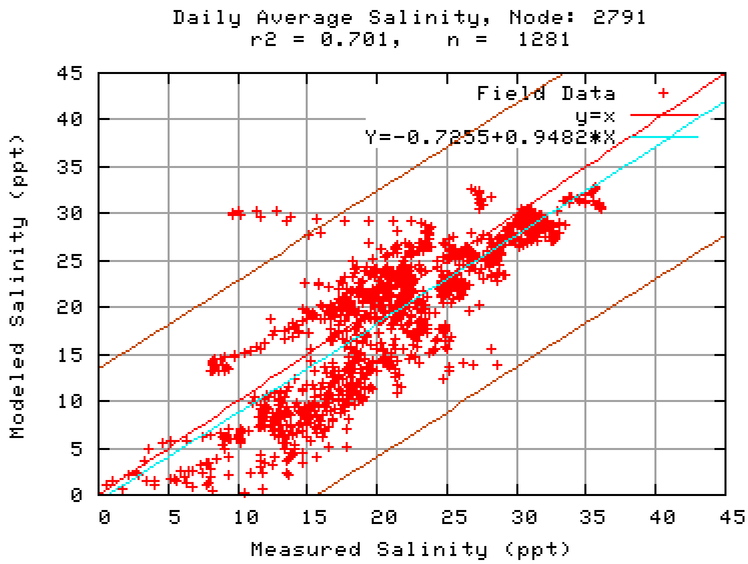


Figure G.5 Model Versus Measured Daily-Average Salinity at Tres Palacios Bay.

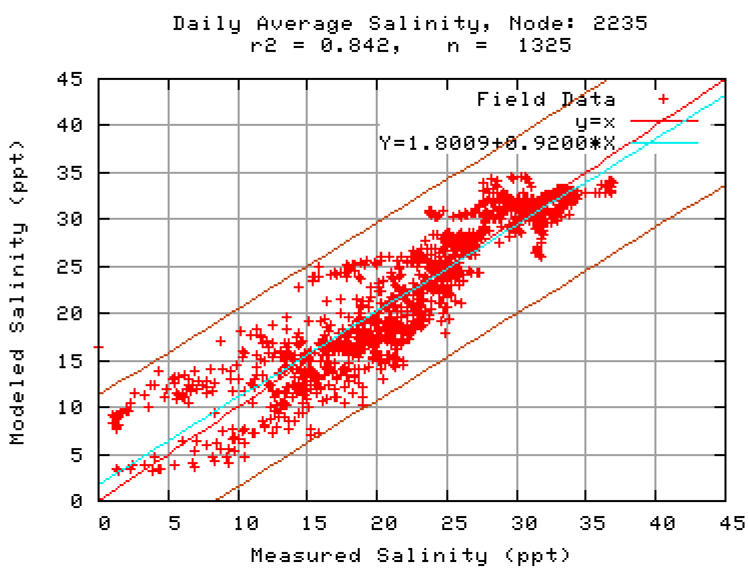


Figure G.6 Model Versus Measured Daily-Average Salinity at Channel Marker 4.

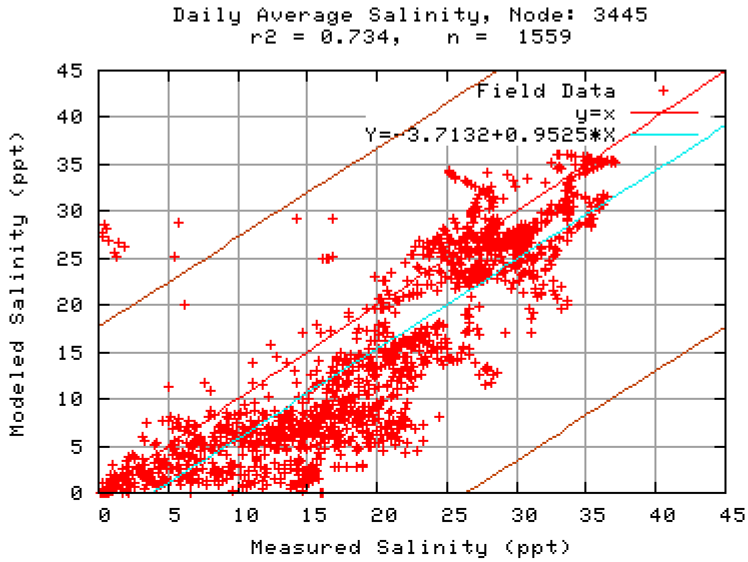


Figure G.7 Model Versus Measured Daily-Average Salinity at West Bay Tripod.

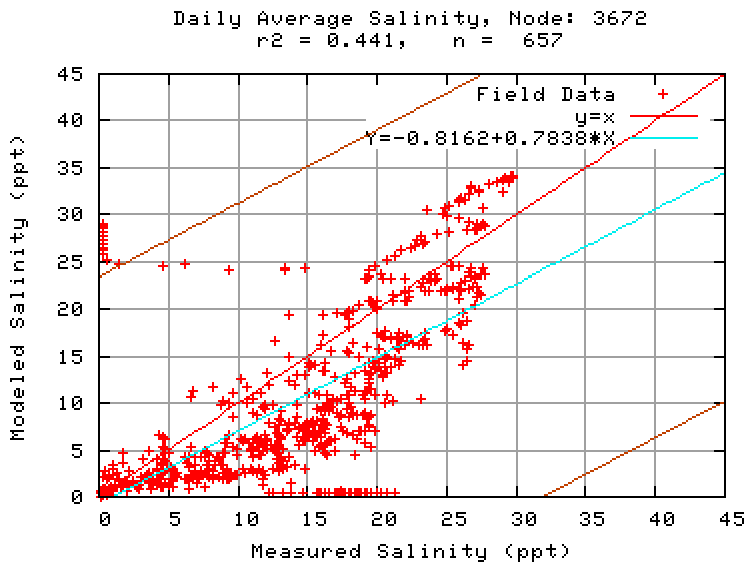


Figure G.8 Model Versus Measured Daily-Average Salinity at Shellfish Marker B.

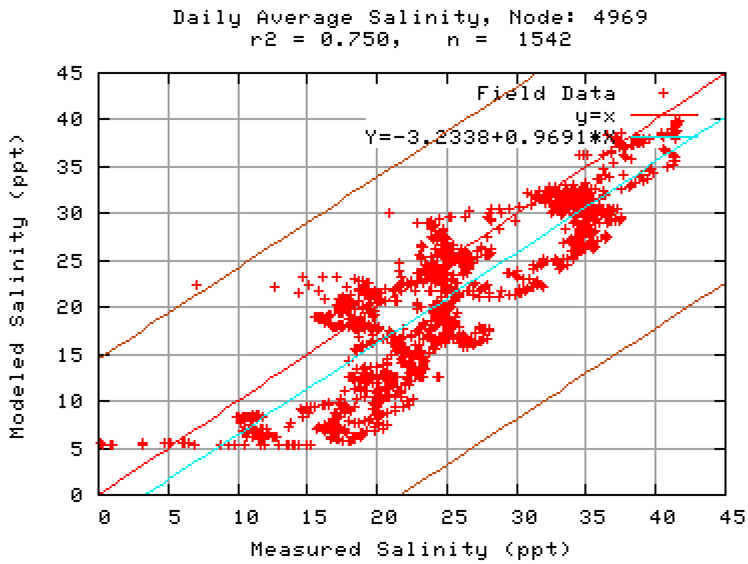


Figure G.9 Model Versus Measured Daily-Average Salinity at East Bay Tripod.

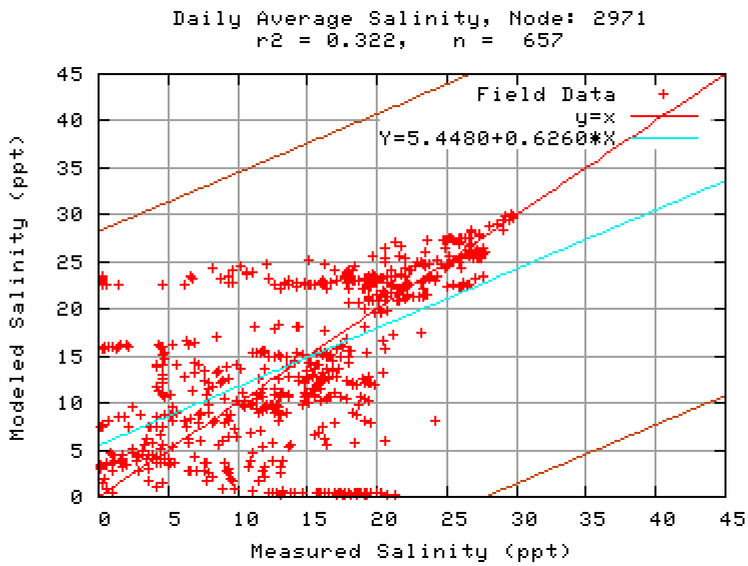


Figure G.10 Model Versus Measured Daily-Average Salinity at East Bay Shellfish Marker.

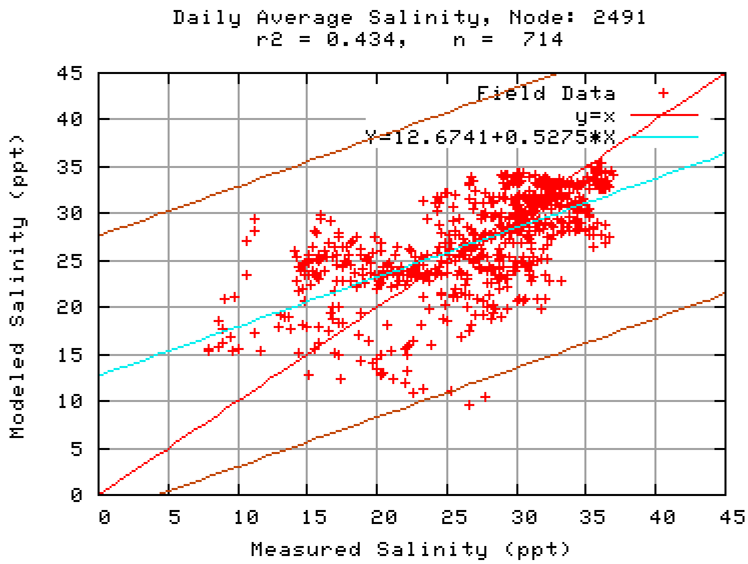


Figure G.11 Model Versus Measured Daily-Average Salinity at East Bay Eastern End.

ACRONYMS

ADCP -	Acoustic Doppler Current Profiler
DIN -	Dissolved Inorganic Nitrogen
ERDC -	Engineers Research and Development Center
FINS -	Freshwater Inflow Needs Study
GIS -	Geographical Information Systems
GIWW -	Gulf Intracoastal Waterway
LCRA -	Lower Colorado River Authority
LNRA -	Lavaca – Navidad River Authority
LWSP -	Lower Colorado River Authority/San Antonio Water System Water Project
MOA -	Memorandum of Understanding
NEXRAD -	Next Generation Weather Radar
NMFS -	National Marine Fisheries Service
NOAA -	National Oceanic and Atmospheric Administration
SAC -	Science Advisory Committee
SAWS -	San Antonio Water System
STP -	South Texas Project
TCEQ -	Texas Commission on Environmental Quality
TCOON -	Texas Coastal Ocean Observation Network
TDWR -	Texas Department of Water Resources
TKN -	Total Kjeldahl Nitrogen
TN -	Total Nitrogen
TNRCC -	Texas Natural Resources Conservation Commission

TP -	Total Phosphorus
TPWD -	Texas Parks and Wildlife Department
TWDB -	Texas Water Development Board
TXEMP -	Texas Estuarine Mathematical Programming Model
USACE -	United States Army Corps of Engineers
USFWS -	United States Fish and Wildlife Service
USGS -	United States Geological Survey
WES -	Waterways Experiment Station
WMP-	Water Management Plan

GLOSSARY

Acre-foot - An acre-foot of water equals 325,851 gallons of water or 43,560 cubic feet of water and is a common unit of measurement for larger volumes of water.

Beneficial inflows - Freshwater inflows providing for a salinity, nutrient, and sediment loading regime adequate to maintain an ecologically sound environment in the receiving bay and estuary that is necessary for the maintenance of productivity of economically important and ecologically characteristic sport or commercial fish and shellfish species and estuarine life upon which such fish and shellfish are dependent.

Coastal inflow - The difference between the total surface inflow and the river basin inflows in this study

Critical freshwater inflows needs - The amount of freshwater inflows needed to provide a fishery sanctuary habitat at specific locations in Matagorda Bay defined as 25 ppt or an annual average. This inflow level is used in water management during drier periods or drought from which finfish or shellfish species are expected to recover and repopulate the bay when more normal weather conditions return.

River basin inflows - The amount of surface water entering Matagorda Bay from the Lavaca River basin and Colorado River. For the Lavaca River basin, the amount is the sum of streamflow from the Lavaca River measured by a gage near Edna and streamflow from the Navidad River measured as outflow from Lake Texana but does not include any contribution from the portion of the Lavaca River basin downstream of these measurement locations. For the Colorado River basin for the period prior to June 1990, the amount is based on a method developed by TDWR in 1978. For the Colorado River basin for the period beginning in June 1990, the amount is streamflow measured at the Bay City gage minus diversions by the South Texas Project but does not include any contribution from the portion of the Colorado River basin downstream of the measurement location.

Streamflow - The amount of surface water passing a measurement location. For the Lavaca River basin the measurement locations are a gage near Edna and outlet from Lake Texana. For the Colorado River the measurement location is a gage at the Bay City

Target freshwater inflow needs - The amount, timing, and location of freshwater inflows needed to optimize selected estuarine species productivity. This inflow level is used in water management for above average years where there are sufficient inflows to maximize biological productivity.

Target species - Economically important and ecologically characteristic sport or commercial fish and shellfish species and estuarine life upon which such fish and shellfish are dependent used in this study as indicator species of overall bay health and productivity. These species include gulf menhaden, striped mullet, red drum, blue crab, white shrimp, and oysters.

Total surface inflow - The estimated amount of surface water entering Matagorda Bay from all watersheds. It does not include either precipitation directly on Matagorda Bay or evaporation directly from Matagorda Bay

TXBLEND - A hydrodynamic and conservative transport model developed by the Texas Water Development Board specific to water bodies such as lakes or bays that seek to predict the movement of water quality characteristics such as salinity through the water body. The TXBLEND model is used in this study to verify that the freshwater inflow regime results identified by the TXEMP model and meeting all constraints will provide the desired salinity regime through the Matagorda Bay system.

TXEMP - The Texas Estuarine Mathematical Programming model is a general optimization model developed by the Texas Water Development Board designed to find a minimum and maximum function (e.g. biological productivity) that satisfies constraints that are imposed (hydrology, salinity, biological). TXEMP results are bounded by the constraints.