FRESHWATER INFLOW RECOMMENDATION FOR THE SABINE LAKE ESTUARY OF TEXAS AND LOUISIANA

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EXECUTIVE SUMMARY

Freshwater inflows are integral to the proper functioning of Texas bays and estuaries. These inflows provide a key source of nutrients and sediments, and also create the salinity gradient within the bay system, which is the defining characteristic of an estuary. Texas Parks and Wildlife Department (TPWD) and the Texas Water Development Board (TWDB) have been charged by the Texas Legislature with determining the freshwater inflows that provide suitable salinity, nutrient and sediment loading regimes (i.e., support a sound estuarine environment) for Texas bays. This report presents the results of the freshwater inflow analysis for the Sabine Lake system.

The TWDB modeled the relationship between freshwater inflow, salinity and fisheries for Sabine Lake. Model results utilizing historical data indicated that a range of annual freshwater inflows between 7.1 and 11.6 million acre-feet with a defined seasonal distribution sustained the estuarine environment. Within the range of annual freshwater inflows considered, model results estimated that an annual inflow of 9.6 million acre-feet would support optimal fish abundance. The analysis in the present report evaluates whether the inflow and salinity output generated by TWDB's optimization and hydrological models translates into biologically suitable and appropriate conditions for Sabine Lake. The present analysis compares the effects of annual inflows of 7.1 versus 9.6 million acre-feet and assumes the appropriate seasonal delivery of these inflows as presented herein. A comparison of salinities predicted for these two target inflows at three key locations in the upper, mid, and lower reaches of Sabine Lake indicated that the higher inflow would better maintain salinities within specified boundaries. TPWD analysis of six target fisheries species showed that three (Gulf menhaden, *Brevoortia patronus*; spot, *Leiostomus xanthurus*; and blue crab, *Callinectes sapidus*) exhibited significant preferences for certain salinity zones based on 15 years of Coastal Fisheries data (1986-2000) collected within the Sabine Lake system. In this instance, peak salinity zones predicted for the lower inflow level appeared to more closely match those from Coastal Fisheries data for these three species. In contrast, an analysis of local wetlands based on resident plant species salinity preferences indicated that the higher inflow amount was clearly better at supporting continued wetland plant growth and productivity, and hence the long term survival of these wetlands and their nursery function for fisheries species within the Sabine Lake system. The higher target inflow is also nearly equal to the amount estimated necessary to provide a sufficient level of nutrient loading to the system (10.3 million acre-feet). Thus, the above analyses indicate that an annual inflow of 9.6 million acre-feet with a defined seasonal distribution will best create biologically suitable salinity and nutrient regimes for critical fish, shellfish and wetland plants in Sabine Lake.

SECTION 1. INTRODUCTION

Freshwater inflows have long been known to play a key role in the functioning of Texas bays and estuaries. Indeed, estuaries are defined as the places where fresh and salt water meet and mix, and thus require freshwater inflows in order to exist (Chabreck 1988). The importance of freshwater to Texas bays and estuaries has been recognized by the Texas Legislature. The 69th session of the Texas Legislature directed Texas Parks and Wildlife Department (TPWD) and the Texas Water Development Board (TWDB) to "establish and maintain on a continuous basis a bay and estuary data collection and evaluation program and conduct studies and analyses to determine bay conditions necessary to support a sound ecological environment" (TEXAS WATER CODE 16.058(a)). This report describes the results of these analyses for the Sabine-Neches or Sabine Lake estuary.

Freshwater inflows provide for both the physical and biological needs of estuaries. Inflows carry sediment and organic material which help to build and maintain the various landforms characteristic of these systems (Alber 2002). These landforms include the associated river delta, wetlands, bay bottom, shorelines, beaches, and islands or barrier islands which may comprise the bay system. Without the contribution of these sediments, coastal areas would eventually disappear due to the effects of subsidence, sea level rise, and/or erosion which all constantly operate in coastal environments (Chabreck 1988, Boesch et al. 1994).

Furthermore, inflows provide nutrients to the system which perform a dual role in Texas bays and estuaries. They maintain the above landforms by supporting the various plant communities which help build, protect, and anchor these areas from wind and wave erosion, while at the same time forming the basis of a food web for the bay system. If not used by plants, these nutrients may enter the food web through direct consumption by microorganisms, which utilize these nutrients in their internal biological processes. These microorganisms in turn provide food for larger organisms such as oysters, juvenile fish, and shellfish, which serve as food for larger organisms.

The salinity gradient created by freshwater inflows performs an equally important role in the functioning of these ecosystems. It allows for the establishment of a diversity of wetland plant communities having different salinity tolerances throughout the bay system. Typically, along the upper Texas coast, wetland communities grade from freshwater swamps to marshes, which give way to intermediate and then brackish marshes. Finally, in the most saline zones, salt marshes occur along the bay edges and landward sides of barrier islands. Similar gradations in submerged aquatic vegetation or seagrasses may also occur. These coastal wetland systems are considered some of the most productive habitats in the world (Mitsch and Gosselink 1993).

These various wetlands and their associated salinity gradients play an irreplaceable role as habitat for many species of fish and wildlife. Numerous species of resident and migratory mammals, birds, reptiles, and amphibians rely on these areas for their survival. Furthermore, many species of bay and Gulf fish and shellfish require these protected low salinity zones as nursery habitat. Many of these species are of great economic or recreational value, and all are of great ecological value.

Freshwater inflows are highly variable in nature. Annual inflows can vary greatly depending on local and regional meteorological events such as cold fronts, tropical storms, hurricanes, and drought. In addition, freshwater inflows to estuaries vary seasonally. Certain months typically have higher inflows than others, with the greatest flows generally occurring in winter and spring and lows occurring later in the summer and fall along the upper Texas coast. However, there is a minimal inflow level below which proper functioning of the ecosystem will break down. If inflows are insufficient to support the historic sediment, nutrient, and biological requirements of the system, serious ecological changes and damage will occur (Kowalewski et al. 2000).

The freshwater inflow determination process was developed by TPWD and TWDB in order to estimate the appropriate volume and timing of freshwater inflows needed to protect and manage for the characteristic productivity, abundance, and species composition of each Texas bay and estuary. A detailed account of the procedures followed in conducting these freshwater inflow studies is found in *Freshwater inflows to Texas bays and estuaries: Ecological relationships and methods for determination of needs* by Longley (1994) and in Powell et al. (2002) and will not be outlined here. These documents describe the modeling method TWDB employs to estimate the recommended freshwater inflows for an estuary. The former report also explains the method TPWD uses to determine if recommended inflows will maintain the current ecological functioning of the system.

The State of Texas has studied complex environmental flow issues for several decades. During this time the scientific methodology has continuously evolved and improved. To fully address bay and estuary environmental flow issues while considering related environmental and water supply issues, this foundation of work must continue to evolve and be improved. This is especially important in the unique and complex Sabine Lake system. The Sabine Lake Estuary is significantly different from other estuaries in the State: it is the smallest of the seven major Texas estuaries (at approximately 60,000 surface acres) yet it receives by far the most annual freshwater inflow. This water-rich system is partially in Texas and partially in Louisiana, and there is much interest and concern for the estuary in both states. Scientific study, water management strategy implementation, and regulatory permitting must recognize the unique climatic, hydrologic, and aquatic environment of this system, considering both human and environmental needs.

The current report will present the range of inflows, calculated by the TWDB model, which satisfy all the hydrology, sediment, nutrient, salinity, and fisheries catch constraints applied to the model for the Sabine Lake estuary, as well as the results of the process employed by TPWD to determine whether modeled flows support local ecosystem functioning. Any variations to the method presented by Longley (1994) in the construction or application of the inflow model used by the TWDB are presented in the appendix of this report.

The range of inflows provided by TWDB includes MinQ, MaxQ, and MaxC flows. MinQ is the minimum inflow that meets the salinity and biological constraints of the model. Its counterpart, MaxQ, is the maximum inflow which satisfies all the salinity and biological constraints of the model. MaxC inflow lies between MinQ and MaxQ. It maximizes fisheries productivity within the range of possible inflows considered. The present analysis focuses on a comparison of MinQ and MaxC inflows.

Previous freshwater inflow studies derived a MaxH inflow rather than a MaxC. These studies used commercial harvest data to create the fisheries constraint for TWDB's Estuarine Mathematical Programming or Optimization Model (TxEMP). However, for the Sabine Lake system, TWDB utilized bag seine catch data collected by TPWD from 1986-1999 (14 years) in calculating the model. These data have the value of focusing on the young (i.e., larval or juvenile forms) of the target fisheries species which tend to show a more direct response to the effects of freshwater inflows relative to adults. In addition, the use of bag seine data addresses many of the purported shortcomings of harvest data, including the contention that harvest landings can be unduly influenced by effort (see appendix).

The objective of this report is to establish whether the volume and timing of inflows resulting from TWDB simulations will create a biologically suitable salinity and nutrient regime in the Sabine Lake ecosystem. This report presents the methods and results of the analysis used by TPWD to conduct this assessment, and identifies the inflow which TPWD determined to be most appropriate for achieving the above objective. Based on these considerations, MaxC was chosen as the recommended inflow. MaxC inflow was better than MinQ at creating salinity gradients similar to those found in TPWD monitoring data for Sabine Lake. Furthermore, MaxC should better maintain the current diversity of local wetlands and hence associated fisheries species which rely on these wetlands for their reproduction and survival. However, this inflow recommendation is made with the understanding that the system will periodically experience flood and drought conditions, and the recommendations provided herein do not provide guidance for managing freshwater inflows during these drought periods. The natural occurrence of flood and drought conditions, rather than adversely affecting the productivity of the system, are actually an integral part of maintaining the system's productivity. The inflow recommendation herein is made assuming that floods/droughts will continue to occur on a natural schedule, and that these floods and droughts will not be artificially decreased or prolonged, respectively, by human activities related to water management.

Relative to other major Texas estuaries, biological data for the Sabine Lake system has been collected for a shorter period of time. Much of the existing data was not collected for the purpose of studying environmental flows. New cooperative data collection programs should be initiated. TWDB's methodology and TPWD's verification process provide a pattern of inflows determined mainly by constraints. As stated earlier, it does not address one of the most important concerns related to the management of environmental inflows to Texas estuaries – maintenance of ecological health during critical low flow periods. Wetland habitat protection during those low flow periods is of key importance in the Sabine Lake ecosystem. Unfortunately, these wetlands have been adversely impacted by over 100 years of human activities in the estuary, including the dredging of the Sabine-Neches Waterway, the Sabine Pass Ship Channel, the Intracoastal Waterway, and secondary channels for logging and oil and gas exploration. All of which have contributed to a general increase in water salinities throughout the system. Most of these modifications will not be reversed due to economic priorities and national security concerns, and successful protection or restoration of those wetlands now may require more than just maintenance of freshwater inflows.

The ultimate success of accomplishing the common goal of maintaining a sound ecological environment in Sabine Lake, while providing for human needs, will require an inclusive stakeholder process comprised of Texas and Louisiana interests and rigorous scientific review. TPWD is committed to proceeding forward in this collaborative effort to evaluate the environmental inflow needs of the Sabine Lake Estuary, with the publication of this report marking one step in that process.

SECTION 2. ANALYTICAL PROTOCOL AND MODEL OUTPUT

All decisions regarding the freshwater inflow recommendation process must rely on sound and accurate data and tested analytical techniques. A flow chart of the process followed by TWDB in conducting their modeling effort is presented in Figure 1 with more details in the appendix. A list of the constraints considered, the source of the data used to shape these constraints, and the order in which the models are run is shown. The process developed by TPWD to determine that modeled freshwater inflows maintain historic salinity gradients and productivity levels is diagrammed in Figure 2. It should be noted from Figure 2 that actual development of specific freshwater inflow management options is a separate process not included in this report.

2.1 TxEMP Model Results

TWDB utilizes the Estuarine Mathematical Programming or Optimization Model (TxEMP) to identify the range of inflows that produce biologically suitable salinity regimes. This is the program which incorporates the salinity-inflow, sediment, nutrient, and fisheries productivity constraints mentioned above and is explained in detail in the appendix. Unlike past reports for the Colorado-Lavaca (Matagorda) (Martin et al. 1997), Guadalupe (Pulich et al. 1998), Trinity-San Jacinto (Galveston) (Lee et al. 2001), and Nueces (Corpus Christi) estuaries (Pulich et al. 2002), the fisheries constraints used for the Sabine Lake model were calculated exclusively using bag seine data collected by the Coastal Fisheries Division of TPWD as part of their marine resources monitoring program, rather than commercial harvest data (the Colorado-Lavaca Estuary study used a combination of bag seine and commercial harvest data).

The hydrologic record considered by TWDB in determining the annual, bi-monthly and monthly inflow boundaries for their model were obtained from the historic flows into the Sabine Lake system measured from 1941-1999. Also, for purposes of constraining the model, the Sabine Lake system was separated into three salinity zones, which roughly correspond to upper, middle and lower portions of the lake. The upper and lower salinity values applied to these three zones should be considered as a preferred salinity range for the indigenous wetlands and target fisheries species, rather than as limits to the optimal salinity range.

The range of acceptable inflows is first determined by calculating the minimum (MinQ) and maximum (MaxQ) monthly flows which satisfy all the model constraints previously mentioned. For Sabine Lake, the MinQ value was 7.11 million acre-ft/yr. MaxQ equaled 11.62 million acre-ft/yr. Second, MaxC was derived by allowing TxEMP to solve for the inflow which maximized fisheries productivity while remaining within the range of upper and lower monthly inflow boundaries determined from the above MinQ and MaxQ calculations. MaxC corresponds to an inflow of 9.60 million acre-ft/yr. Additional inflow values were calculated at intervals in order to create a performance curve (Figure 3). It should be mentioned that the results of the present study also agree well with an earlier study conducted by the Texas Department of Water Resources (now the TWDB) in 1981 which found that an inflow of 8.78 million acre-ft/yr would provide a "subsistence" flow that would "satisfy the basic salinity gradient and marsh inundation needs" of this estuary (TDWR 1981).

One key point that should not be overlooked in discussing the calculation of MinQ and MaxC is that TxEMP not only calculates the appropriate inflow volume necessary on an annual basis to maintain an ecologically sound environment, but its output also allows for the calculation of monthly inflow values. TxEMP calculates bi-monthly (also called seasonal) inflow values (e.g., January-February, March-April, etc.). These bi-monthly inflow estimates are separated into two monthly values based on the relative proportion of inflow the system historically received over each two month period (Table 1 and Figure 4). In the end, the monthly distribution of inflows corresponded fairly well to the historical monthly inflow pattern characteristic of the Sabine Lake system. The monthly inflow values, rather than the annual one, are the most meaningful in maintaining an ecologically sound environment because it is not only the volume but the timing of inflow which is key to the natural functioning of the estuary (Alber 2002).

Table 1. Median monthly inflow values from 1941 to 1999, and estimated monthly inflow values for MinQ, MaxC and MaxQ from TxEMP for the Sabine Lake system. Data are acre-feet.

Month	Median	MinQ	MaxC	MaxQ
January	1246401	624000	1246400	1246400
February	1539183	832500	1539200	1539200
March	1866980	998000	1565780	1867000
April	1355311	778600	1136640	1355300
May	1348014	691900	691900	1348000
June	845150	478700	478700	845200
July	547342	424400	547300	547300
August	466500	361700	466500	466500
September	488455	574600	574600	574600
October	342305	537900	537900	537900
November	374432	237600	237550	378100
December	899712	574100	574130	913800
TOTAL	11319785	7114000	9596600	11619300

2.2 TxBLEND Model Results

The TxBLEND model , a "high-resolution hydrodynamic and conservative mass transport model" capable of simulating bay circulation conditions in 2 or 3 dimensions (Powell et al. 2002), was used to predict bay salinity regimes under two different climatic scenarios. MinQ and MaxC seasonal and annual inflows calculated by TxEMP were used as input into TxBLEND as well as annual meteorological and tidal measurements for specific years (see below). To simulate a wet year, meteorological and tidal data from 1991 were input into the TxBLEND model. To simulate a dry year, meteorological and tidal data from 1996 were input into TxBLEND. Thus, TxBLEND simulated the effects that MinQ and MaxC inflows to Sabine Lake would have on salinities when climatic (wind, precipitation, evaporation) and tidal conditions mimicked those measured during a known wet (1991) and dry (1996) year.

The entire TxBLEND model for Sabine Lake was composed of 2341 nodes or modeling points for which salinities were calculated every 2 hours for a period of a year. Salinity output from TxBLEND model runs were output into 2 formats:

1. Monthly average salinities for each node making up the entire Sabine Lake system.
2. Daily average salinities calculated for a period of 1 year (365 days) for 1 location (i.e., node) in the upper, middle and lower portions of Sabine Lake (i.e., 3 locations/nodes total).

SECTION 3. BIOLOGICAL RESPONSES TO HISTORICAL FRESHWATER INFLOWS

In order to determine the efficacy of modeled inflows at maintaining biologically suitable conditions in the Sabine Lake system, results of TWDB's models were compared with actual physical and biological data collected by TPWD as an independent "reality check". Freshwater inflows or inflow-mediated factors such as salinity, and nutrient and sediment inputs are known to influence the health and survival of estuarine flora and fauna (Adam 1990, Mitsch and Gosselink 1993, Guillory 2000, Meng et al. 2002, Mueller and Marsh 2002). Thus, measurements of physical parameters and fisheries catch data collected by TPWD since 1986 in the Sabine Lake system should reflect the effects of variations in inflow experienced by the system during this time period. Because bag seine data were used to create the fisheries constraints in TxEMP, it was inappropriate to also use them to check the model. Therefore, physical and biological data from trawl samples collected by TPWD were used to assess the results of the TWDB model. These data consist of measurements of salinity, dissolved oxygen, temperature, and catch from trawl samples taken within the Sabine Lake system on a monthly basis at randomly chosen sampling locations. Actual numbers of individuals caught in the 10 minute trawl samples were converted into catch per hour values for the analysis. These values are alternatively referred to as catch per unit effort or CPUE values. Likewise, the location of various types of wetlands within the system was considered in the assessment process. Their location should provide a good indication of long term inflow/salinity patterns. Comparing their locations with the salinity profiles created from model output will provide another means of testing the suitability of the recommended inflows.

TWDB estimated the inflow necessary to maintain historic nutrient loading levels to Sabine Lake, but no estimate was provided for sediment loading needs. Sediment data are available for the system following the construction of the Toledo Bend Reservoir but none exist prior to its construction (see appendix), so an estimate of the inflows necessary to provide for sediment needs in the system could not be definitively made. Even so, salinity, nutrient, and sediment responses to freshwater inflow are well established, and each parameter is directly or indirectly linked to the others (Mitsch and Gosselink 1993, Longley 1994, Alber 2002). However, a spatial analysis of nutrients and sediments could not be done because these parameters were not included in TxBLEND analysis or Coastal Fisheries sampling.

3.1 Time Series Analysis of Salinities at Critical Bay Sites

A time series analysis was performed on the daily average salinities predicted by TxBLEND for three selected sites (i.e., model nodes) within the Sabine Lake system (Figure 5). These three sites were chosen based on guidance from the TPWD Coastal Fisheries Ecosystem Leader for Sabine Lake as representing areas of key importance for fisheries within the ecosystem. The time series analysis was performed to determine the effects inflow, as measured by salinity, would have on the flora and fauna at these specific sites. Mean daily salinities predicted by TxBLEND for the MinQ and MaxC inflow scenarios were then compared with the corresponding salinity bounds (Table 2) set for each portion of Sabine Lake to determine the number of days when predicted salinities exceeded their respective boundary conditions under the two inflow conditions. These time series scenarios were further refined to investigate the effects MinQ and MaxC inflows would have if meteorological (i.e., local daily winds, direct precipitation, and evaporation) and tidal conditions were set to mimic those measured during an historic wet year (1991) and dry year (1996).

The salinity bounds used for this portion of the analysis were those used for TxEMP. A more detailed description of how these boundary salinities were determined can be found in the appendix.

Overall, results indicated that MinQ and MaxC inflows kept salinities within the upper and lower salinity bounds set for Sabine Lake most of the time; however, MaxC was more effective at keeping salinities below the upper boundary than was MinQ (Figures 6 and 7). Salinities predicted from MinQ inflows during the wet year (1991) at the upper lake site (i.e., node) were within the corresponding salinity boundaries 92% of the time (7 days above upper bound in January and 21 in December), while for the dry year (1996) salinities stayed within boundary conditions 91% of the time (31 days above upper bound in December). MaxC inflows met salinity boundary constraints 95% of the time during the wet year (19 days above upper bound in December), while results were

Table 2. Upper and lower salinity bounds used in TxEMP for the Sabine Lake system. Upper, mid and lower lake salinities were those applied to upper, mid and lower lake nodes for time series analysis (see text). Salinity concentrations are ppt.

	Upper Lake		Mid Lake		Lower Lake	
Month	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound
January	0	10	1	10	2	20
February	0	10	1	10	2	20
March	0	10	1	10	2	20
April	0	10	1	10	2	20
May	0	10	1	10	2	20
June	0	10	1	15	2	20
July	0	10	1	15	2	20
August	2	10	2	15	5	20
September	2	15	2	15	5	20
October	2	15	2	15	5	20
November	2	15	2	15	5	20
December	2	10	2	15	2	20

the same as those for MinQ during the dry year in the upper lake. Mid-lake salinities were within boundaries 91% of the time in response to MinQ inflows during the wet year (31 days above upper bound in January) and 97% of the time during the dry year (10 days above upper bound in January). MaxC inflows were predicted to maintain mid-lake salinities within boundary conditions 99% of the time during the wet year (5 days above upper bound during January), and 99% of the time during the dry year (4 days below lower bound during March). Lower lake salinities were within boundaries 99% of the time with MinQ inflows during the wet year (2 days above upper boundary in November and 1 day in December) and 97% of the time during the dry year (2 days above upper boundary in January, 6 in November, and 4 in December). MaxC inflows were predicted to maintain salinities within boundary conditions for the lower lake 98% of the time during a wet year (2 days below lower bound in March and 1 day in April; 2 days above upper bound in November and 1 day in December), while staying within the boundaries 92% of the time during the dry year (3 days below lower boundary in February, 9 days in March, and 7 days in April; and 6 days above upper boundary in November and 4 days in December).

MaxC inflows appear to maintain salinities below upper salinity boundaries throughout Sabine Lake better than MinQ. From an ecological standpoint, the instances where salinities fell below the lower boundary condition are of lesser concern, because low salinities create less of a stress than higher salinities on non-mobile, wetland plants. The greater number of exceedances of the upper salinity boundary during the wet year vs. the dry year is likely explained by differences in meteorological and tidal conditions unique to January of the wet year (1991) versus the dry year (1996). These data show that salinities are generally lower during wet years than dry years and that more freshwater inflow (MaxC) maintains lower bay salinities than less inflow (MinQ).

3.2 Relationship Between Fisheries Species Spatial Distribution and Salinity Zones

To examine fisheries responses to historical inflows, eight target species were used as indicators. These species were: Atlantic croaker (*Micropogonias undulatus*), Gulf menhaden (*Brevoortia patronus*), spot (*Leiostomus xanthurus*), spotted seatrout (*Cynoscion nebulosus*), red drum (*Sciaenops ocellatus*), white shrimp (*Litopenaeus setiferus*), blue crab (*Callinectes sapidus*), and brown shrimp (*Farfantepenaeus aztecus*). They represent a spectrum of responses to salinity with certain species known to prefer lower salinities and others to prefer higher ones.

Of these, two species were removed from the TPWD analysis due to low catch rates. Red drum was removed because only 0.6% of all trawl samples (N=2568 trawls) recorded a catch for this species. Likewise, spotted seatrout was removed from the analysis because only 3% of trawl samples recorded a catch for this species. The frequency of catch for the remainder of the species ranged from 17-76% of trawl samples.

The analysis of the relationship between fisheries spatial distributions and salinity zones follows the method used in the freshwater inflow report for the Guadalupe estuary (Pulich et al. 1998). Basically, TPWD fisheries catch data were pooled over the 15-year collection period to calculate a mean abundance (i.e., CPUE) value for each month for each species. The season of maximum abundance was determined for each of the six species analyzed. This period corresponded with the months where mean catch rates were greater than the annual mean catch rate for each species. The seasons of abundance for target species used in the TPWD analysis were: Atlantic croaker, March through October; Gulf menhaden, March through June; spot, May through November; white shrimp, July through December; blue crab, February through July; and brown shrimp, May through July. Spatial abundance values were calculated for each species at each Coastal Fisheries sampling grid station for the corresponding season of abundance. In other words, a grid of catch values across the bay was created from the 15 years of fisheries data for each species. Similarly, physical data collected for the 15 years of sampling was pooled and used to create salinity profiles for Sabine Lake during the corresponding season of abundance for each species using the kriging function in ArcGIS. The salinity profile utilized 3 parts per thousand (ppt) increments to delimit the different salinity zones (e.g., 0-3 ppt, 3-6 ppt, etc.) unlike previous reports which used 5 ppt salinity intervals. Because the salinity range in the Sabine Lake system is much smaller than that for all other Texas bays and estuaries, a smaller interval was necessary to more precisely present the salinity gradient in this system.

Spatial abundance values were overlaid on the corresponding salinity profile for each species to display species spatial distributions relative to Sabine Lake salinity profiles during the corresponding seasons of abundance (Figures 8-13). Figures 8-13 show the relative abundance of each species within each salinity zone present in Sabine Lake during its corresponding season of abundance. The salinity patterns within Sabine Lake are different for each species because of the difference in the timing of each species' season of abundance. Abundance values (CPUE's) and associated salinities were extracted from these maps to test whether each species exhibited a statistically significant zone of peak abundance. Data were analyzed using analysis of variance. The results of these statistical tests are shown in Table 3 and discussed in detail below. All abundance data were $\log_{10}+1$ transformed prior to statistical analysis. Log transformations were performed to improve the homogeneity of variance. In order to log transform the data, a value of one was added to each catch record due to the presence of zero catches in the dataset. Also, for a given species, any salinity zone where fewer than three trawl samples were collected was removed from statistical analysis, since a true mean and variance value could not be calculated for statistical tests. However, simple statistics such as means were still calculated for these zones for use in figures and for discussion purposes. Finally, any catch value with a studentized residual $\geq \pm 3$ was removed from statistical analysis.

Table 3. Peak density zones for target species in the Sabine Lake system.

Species	Peak Density Zone (ppt)
Atlantic croaker	None Detected
Gulf menhaden	3-6
Spot	6-12
White shrimp	None Detected
Blue crab	0-3
Brown shrimp	None Detected

Atlantic croaker (Figure 8): An estuarine dependent species (Pattillo et al. 1997), croaker were caught throughout the year in the Sabine Lake System, but were most abundant from March through October. Mean CPUE ranged from 70.50 in the 0-3 ppt salinity zone to 94.15 in the 9-12 ppt salinity zone. Only two trawl samples were collected in the 0-3 ppt salinity range during the 15 years of sampling, and one value in the 9-12 ppt salinity zone had a studentized residual <-3, so these were removed from the statistical analysis (see above). Although croaker were most abundant in the 9-12 ppt range, this apparent preference did not prove to be statistically significant (p=0.9). An earlier freshwater inflow study of the Trinity-San Jacinto estuary (Lee et al. 2001) found no peak zone of abundance for this species, as well. However, a study of the Guadalupe estuary (Pulich et al. 1998) found a peak zone in the 5-20 ppt salinity range. The lack of a significant peak zone of abundance for this species in the Sabine Lake system may be explained by the relatively low salinities typical of this system year round. Research in Texas and Louisiana found that juveniles of this species are most abundant in salinities ≤15 ppt and adults were found to be most abundant in 15-20 ppt waters in Mississippi (Pattillo et al. 1997). Salinities throughout the Sabine Lake system were ≤15 ppt during croaker's season of abundance. Because these salinities were all in the range of those preferred by juveniles and all below those preferred by adults, this may have prevented any significant statistical pattern from emerging in terms of a zone of salinity preference for this species.

Gulf menhaden (Figure 9): Menhaden were also caught throughout the year in the Sabine Lake system, but the season of greatest abundance for this species was from March to June. Mean CPUE for this species ranged from 3.64 in the 0-3 ppt zone to 7.75 in the 3-6 ppt zone. Unlike croaker, menhaden did show a significant (p=0.008) preference for the 3-6 ppt salinity zone. The Guadalupe estuary freshwater inflow study found two zones of peak abundance in the 5-10 and 15-20 ppt salinity ranges for this species (Pulich et al. 1998). In the Trinity-San Jacinto estuary, menhaden showed a peak abundance in the 10-15 ppt salinity zone (Lee et al. 2001). Adults of this species have been reported to prefer relatively high salinities in the range of 20 ppt or above (Pattillo et al. 1997) which would seem to conflict with results presented for the Sabine Lake system. However, closer investigation of the average lengths of individuals (mean length ± SE = 70.9 ± 2.6 mm) collected in the trawl samples revealed this gear type was primarily capturing juveniles of the species. Juveniles occupy a wider range of salinities than those preferred by adults, generally occurring in salinities from 5-30 ppt (Pattillo et al. 1997).

Thus, results presented here fall within the range of those found previously for this species.

Spot (Figure 10): Spot were present in the Sabine Lake system throughout the year, with their greatest abundance occurring from May to November. The season of abundance for spot represented a problem in terms of defining its duration, because there were two separate periods where catch rates were above the mean annual rate, separated by 2 months (July and August) where catch rates fell below the annual mean. In order to have a single period of peak abundance, these intervening months were included in the season of abundance for spot. A single, zero catch in the 0-3 ppt salinity range and a value with a studentized residual of >3 in the 12-15 ppt salinity range were removed prior to statistical analysis. Spot showed a significant preference for salinities between 6 and 12 ppt in the Sabine Lake system (p=0.003). Previous inflow reports have not included spot among the suite of eight species studied for their analyses. However, this species has been shown to be euryhaline in its salinity preference, being found across a wide range of salinities (Pattillo et al. 1997), though one study found large numbers occurring in the 15-30 ppt range (Warren and Sutter 1982).

White shrimp (Figure 11): White shrimp were found in the Sabine Lake system year round, but were most abundant from July to December. Mean CPUE ranged from 41.51 to 114.27 individuals caught per hour in the various salinity zones, but a zone of peak abundance was not detected for this species (p=0.12). Conversely, previous results for the Guadalupe estuary indicated white shrimp were at peak abundance in the 5-10 ppt salinity zone (Pulich et al. 1998) and at the 10-15 ppt salinity zone in the Trinity-San Jacinto estuary (Lee et al. 2001). Like spot, this species is considered euryhaline, being found throughout the spectrum of possible salinities present in Texas estuarine environments (Pattillo et al. 1997). Analysis of the average lengths of individuals caught (mean length ± SE = 85.8 ± 0.8 mm) indicated that trawl samples were collecting juveniles of this species, which are between 25 and 140 mm in length (Pattillo et al. 1997). Although this life stage usually prefers salinities of < 10 ppt, juveniles have been found in salinities ranging from 0.3 to 41.3 ppt (Pattillo et al. 1997). Therefore, it appears that some factor(s) other than salinity, such as the extensive wetland complexes found on the eastern and southwestern shores of Sabine Lake, may have been operating to disperse white shrimp across a broader expanse of the Sabine Lake system.

Blue crab (Figure 12): Blue crabs were numerous throughout the year in the Sabine Lake system, but abundances were greatest between February and July. A single observation collected in the 9-12 ppt salinity range during the 15 years of sampling was removed prior to statistical analysis. Mean CPUE ranged from 19.73 to 55.94 individuals caught per hour in the various salinity zones, but blue crabs showed a clear and highly significant ($p<0.000$) preference for the lowest salinity range (0-3 ppt). In fact, catch rates in this zone were twice those found in any other salinity zone studied for this species. The peak abundance zone was similar to that found in the Trinity-San Jacinto estuary (0-15 ppt) (Lee et al. 2001) and slightly lower than the one seen in the Guadalupe estuary (5-15 ppt) for this species (Pulich et al. 1998). Analysis of carapace widths (mean width ± SE = 110.6 ± 1.9 mm) indicate that trawl samples were primarily sampling juvenile or sub-adult blue crabs (Pattillo et al. 1997). These life stages have been reported to typically inhabit lower salinity waters ranging from 2-21 ppt (Pattillo et al. 1997); therefore, results presented here are at least somewhat similar to those previously reported in other studies.

Brown shrimp (Figure 13): Brown shrimp were most abundant from May through July of each year, although individuals were caught throughout the year. Mean CPUE ranged from 12.0 to 519.75 individuals caught per hour; however, the high value in this range was the only sample ever taken in the 9-12 ppt salinity zone, so it was removed prior to conducting statistical analysis of the data. Statistical analysis did not reveal a significant trend ($p=0.14$). The Guadalupe estuary freshwater inflow study found a significant zone of abundance in the 10-20 ppt range (Pulich et al. 1998), and the same peak zone was detected in the Trinity-San Jacinto estuary (Lee et al. 2001). Size class analysis of individuals showed that trawl samples in Sabine Lake were primarily capturing juveniles (mean length ± SE = 83.4 ± 1.1 mm) (Pattillo et al. 1997). Previous studies report that juveniles prefer a salinity range between 10 and 20 ppt (Pattillo et al.

1997). The absence of this salinity zone during brown shrimp's season of peak abundance in Sabine Lake may help explain why catch rates from Coastal Fisheries data for this species are lower here compared to other bays along the Texas coast. This species likely distributed itself throughout the bay system based on other factors.

3.3 Comparison of Species Peak Density Zones with Predicted Salinities Created by MinQ and MaxC Inflows

Recommended inflows calculated by TxEMP (i.e., MinQ and MaxC) were input into TxBLEND to predict monthly salinities across the Sabine Lake area. TxBLEND calculated average monthly salinity values for 2341 locations (or nodes) within the Sabine Lake system. These results were then spatially analyzed using geographic information system (GIS) to calculate the size of each salinity zone in terms of percent bay area. The sizes of the salinity zones predicted from MinQ and MaxC inflows could then be compared with those from TPWD data for each species that had a significant peak zone of abundance (Gulf menhaden, spot and blue crab) during its season of abundance (Table 4). This procedure is used to determine if MinQ and/or MaxC inflows will provide similarly sized peak zones in the bay relative to the ones found from TPWD data. Two example maps are included for visualization purposes, using the data for blue crab to represent salinity conditions during the spring (Figure 14) and white shrimp to represent salinity conditions during the fall (Figure 15). Salinity values predicted for MaxC by TxBLEND for each of the 2341 nodes during the dry year and wet year were averaged together after determining that salinity gradients created by the model were very similar under these two climatic conditions. Results for MinQ were also similar for wet and dry periods, so salinities predicted for these two years were pooled for this target inflow, as well. In other words, only one MinQ and one MaxC result is presented, rather than two for each target inflow (e.g., one for MaxC during the wet year and another for the dry year) and serve as a representation of "typical" conditions. Also, much of the Salt Bayou wetland complex in the southwestern portion of the region is not included in these maps because TxBLEND did not model this part of the Sabine Lake system.

The salinity zones predicted from MinQ and MaxC inflows were compared with those from TPWD data for each species with a significant peak zone of abundance (Gulf menhaden, spot and blue crab). MinQ appeared to more closely approximate the size of the peak zone of abundance for each of the three species relative to the corresponding zone observed in Coastal Fisheries data (Table 4). This appears due to increased freshening of the bay system during spring-summer by MaxC inflows relative to MinQ flows (Figure 14). The peak zone of abundance for blue crab (0-3 ppt) increased in size relative to TPWD's observed data with MaxC inflows, but these inflows decreased the size of the zone of peak abundance for menhaden (3-6 ppt). Conversely, the overall sizes of the peak zones of abundance predicted for spot (6-12 ppt) by MaxC and MinQ inflows were similar to the one from Coastal Fisheries data (though the size of peak zone predicted for MinQ inflows was closer). This similarity is likely because MaxC and MinQ target inflows are closer to observed median inflows to Sabine Lake during these months (summer/fall) of the year (Figure 4). Thus, MinQ inflows did appear to more closely match the size of the peak zone of abundance from TPWD data for these three species. However, it is also true that for two of these same three species, MaxC inflows either had a positive (increased size of peak zone of abundance for blue crab) or similar effect (spot) relative to MinQ inflows.

Table 4. Sizes of peak zones of abundance for Gulf menhaden, spot, and blue crab under observed, MinQ, and MaxC freshwater inflows.

Species	Salinity at Peak Density Zone (ppt)	Season of Abundance (months)	Observed Bay Area (%)	MinQ Bay Area (%)	MaxC Bay Area (%)
Gulf menhaden	3-6	Mar-Jun	78	74	19
Spot	6-12	May-Nov	87	86	73
Blue crab	0-3	Feb-Jul	5	2	33

3.4 Comparison of Wetland Locations with Salinities Predicted by MinQ and MaxC Inflows

The salinity distribution in the Sabine Lake system predicted by TxBLEND for MinQ and MaxC inflows was also compared with the locations of local wetlands. Wetland plant species composition was used to classify the various wetlands of the Sabine Lake system into different salinity types. The wetland types found on the Louisiana side of Sabine Lake were classified by Chabreck and Linscombe (1997). Wetlands on the Texas side were classified by TPWD Wildlife Division - Region IV, upper coast biologists: James Sutherlin, Michael Rezsutek and Amos Cooper based on the wetland plant-salinity type classification scheme provided in Chabreck and Linscombe (1997). Salinity zonation during the months of January, April, July, and November are presented with associated Sabine Lake area wetlands to consider the potential impact of seasonal variation in salinities (Figures 16-19). These months were determined to be good representatives of seasonal and annual salinity conditions and/or extremes in the system after a review of monthly and seasonal salinities predicted by TxBLEND for the upper, mid, and lower bay nodes (see Section 3.1 above). For reasons already stated in Section 3.3, TxBLEND salinity results presented for MinQ and MaxC are pooled over their respective wet and dry year runs.

Unlike the results from the fisheries analysis in Section 3.3 above, MaxC inflows were clearly better (versus MinQ) at creating beneficial salinity conditions within the Sabine Lake system for surrounding wetlands. Sabine Lake was historically much fresher than at present, so fresh in fact, that the upper reaches of the lake supported a stand of bald cypress trees (*Taxodium distichum*) (TPWD and USFWS 1990). The objective of this analysis is not to recommend inflows which re-create those conditions, but it is important to understand the ecological history of this system when considering present conditions. The majority of Sabine Lake is now surrounded by intermediate to brackish wetlands, which tolerate a range of soil salinities between 0.5-3.5 ppt and 3.5-10 ppt, respectively (Stutzenbaker 1999). TPWD's goal is to recommend the inflow condition that is most likely to maintain the ecological health of the system within the boundaries established for the recommendation by TxEMP output (i.e., MinQ and

MaxQ). As stated earlier, this recommendation is also made assuming that floods and droughts will continue to occur on a natural schedule and not be artificially decreased or prolonged, respectively, by human activities.

Historic salinity conditions heavily influenced the plant species composition and soils which presently exist in the surrounding wetlands of the Sabine Lake system. Soils in wetlands along the periphery of much of Sabine Lake have a relatively high organic content (TPWD and USFWS 1990, USDA 1993), which is typical of freshwater dominated wetlands (Nyman et al. 1990, DeLaune et al. 1992). These organic soils are highly erodible (USDA 1993). Over time, increasing salinities in the Sabine Lake system have had a negative effect on the wetland plant community and its associated soils. Increased salinities have reduced wetland plant species diversity and productivity with only the more salt tolerant species still present in the remaining wetlands (TPWD and USFWS 1990, USDA 1993). Many of these plants show signs of salinity and flooding stress (Good et al. 1982, Broome et al. 1995, Howard and Mendelssohn 1999) such as reduced, shallow rhizospheres and reduced aboveground production (N. Kuhn, unpublished observations). Salinity is also acting on these organic soils directly as a dispersing agent causing their dissolution (USDA 1993). Maintaining the wetland plant community is key to maintaining the wetland soils, because their roots bind the soil together and protect it from erosion. Furthermore, the wetland plant community is the primary contributor of sediment in the form of organic material (above and belowground biomass) to these wetlands (Nyman et al. 1990, USDA 1993, Reed 1995). Thus, an increase in plant productivity normally translates into an increased rate of soil accretion in these wetlands.

Wetland losses in this area are also due to natural and human induced subsidence and sea level rise (Ratzlaff 1980, White et al. 1987, White and Tremblay 1995, White and Morton 1997) which result in increased flooding of local wetlands. This further stresses indigenous plants by reducing soil aeration (Mendelssohn et al. 1981) and promoting biogeochemical activities in the soil that result in the chemical or bacterial production of plant toxins (Gambrell and Patrick Jr. 1978, Havill et al. 1985, Bradley and Dunn 1989, Koch and Mendelssohn 1989). Obviously, increased flooding also translates into more saltwater intrusion into these wetland areas and increased susceptibility of wetland soils to erosion. However, reduced salinities result in increased plant productivity, helping these wetlands offset the relative drop in elevation due to subsidence and/or sea level rise through increased rates of plant production and subsequent organic soil aggradation. Thus, wetland plants represent the keystone to maintaining the overall ecological and biological integrity of the Sabine Lake system's wetlands and soils. Restoration projects have been undertaken in Louisiana and Texas to stave off the effects increased salinity and flooding are having on wetlands in the Sabine Lake system (TPWD and USFWS 1990, LCWCRTF 2002), but more work still needs to be done to insure that these areas are protected.

Lower salinity conditions predicted for MaxC inflows during winter (January), spring (April), and summer (July) months will relieve plant salinity stress and promote wetland plant growth and associated organic soil formation processes which will in turn reduce flooding stress on these plants, relative to conditions created by MinQ inflows. MinQ and MaxC salinities are similar during the fall (November), but this is because monthly inflow recommendations for September, October and November are the same for both target flows (see Table 1). Regardless, MaxC is superior to MinQ in providing favorable conditions for local wetland plants and soils when the year is considered as a whole.

In addition, salinity regimes predicted for MaxC inflows appear to more closely match the monthly salinity profiles from Coastal Fisheries data overall. Results predicted for MaxC inflows during January and July are clearly more similar to observed conditions than are the results for MinQ. Salinities predicted for MinQ and MaxC inflows are similar in November for the reason already stated above. Salinities predicted for MaxC during April are somewhat lower than those observed in Coastal Fisheries data, but considering these lower salinities occur during the growing season, the benefit to local wetlands will likely outweigh any adverse impact that might occur from reducing the size of a particular fisheries species' zone of peak abundance. Because these wetlands form the basis of the nursery function provided by estuaries (Rozas and Zimmerman 2000, Beck et al. 2003), insuring their long term survival should help insure the long term survival of the fisheries (and wildlife) resources that rely upon them.

3.5 Nutrient Loading Requirements of the Sabine Lake System

MaxC inflows appear best at meeting the nutrient loading requirements of the system. As mentioned earlier, no direct measurements of nutrient levels in waters of the Sabine Lake system are made during Coastal Fisheries sampling. However, TWDB does estimate the amount of freshwater inflow necessary to provide for historic levels of nutrient loading to the bay system (Longley 1994, Powell et al. 2002). The estimated inflow necessary to meet historic nutrient loading levels in the Sabine Lake system is 10.3 million acre-feet (see appendix for details). MaxC inflows closely approximate this estimate (9.60 million acre-feet) and are recommended as the target inflow to meet the nutrient loading needs of the Sabine Lake system.

Sufficient nutrient loading is necessary to maintain the biological productivity of the system. Microorganisms require these nutrients for their internal biological processes, and these microorganisms provide the food source for larger organisms such as oysters, juvenile fish, and shellfish. The oysters, juvenile fish, and shellfish in turn provide a food source for larger predators. In addition, sufficient nutrient availability supports plant growth in the face of salinity stress, thus insuring that wetland plants are able to remain productive and fulfill their roles as habitat, food, soil stabilizers, and producers of new material for continued organic soil aggradation. Thus, these nutrients form the foundation of the food web acting through the plants and microorganisms that absorb or consume them, and they also support the habitats integral to the functioning of this ecosystem.

SECTION 4. FUTURE CONDITIONS

This report would be incomplete without some discussion of a significant change being proposed for the Sabine Lake system. Currently there is a proposal to deepen (and widen) the Sabine-Neches Waterway (SNWW) from its present depth of 40 feet to a depth of 48 feet. Historically, Sabine Pass had a depth of 5 to 6 feet (USDA 1993). Most, if not all, of the increase in salinities that has occurred within the Sabine Lake system can be attributed to this channel being progressively enlarged over time, allowing more saline Gulf water enter the system. Efforts are being made to reduce the impacts that increased salinities are expected to have on the ecological resources of the system through the beneficial use of dredge material. However, a recent report by the Louisiana Department of Natural Resources suggests that the only true fix to this problem may be the installation of a system of navigable gates or locks at the mouth of the SNWW (LCWCRTF 2002). Thus, it appears highly likely that salinities will further increase within this system. This information lends further support for recommending MaxC inflows for the Sabine Lake system in an effort to maintain current conditions.

SECTION 5. TARGET INFLOW RECOMMENDATION

Based on the results of the preceding analyses, TPWD finds that MaxC inflow (9.6 million acre-feet) will create biologically suitable salinity and nutrient regimes in the Sabine Lake system. Although, inflows between MinQ and MaxC meet all model constraints, TPWD's recommendation is based on the following results from the analysis:

1. Time series analysis of predicted salinities at three sites located in the upper, mid and lower parts of Sabine Lake showed that although both MinQ and MaxC inflows maintained salinities within the respective upper and lower salinity boundaries at these locations fairly well, MaxC was better at keeping salinities below the upper boundary than MinQ, especially during a wet year.

2. MinQ inflows create peak zones of abundance similar in size to those derived from Coastal Fisheries data for the three species exhibiting a significant peak zone of abundance (Gulf menhaden, spot and blue crab). However, the peak zone of abundance for two of these same three species showed a positive or similar response (relative to MinQ) to MaxC inflows, as well.

3. MaxC inflows are predicted to create seasonal salinity conditions that are much more advantageous for wetland plant growth. Lower salinities will promote the growth and production of intermediate and brackish marsh plants which dominate the periphery of Sabine Lake. This increase in plant production will also increase soil organic matter input which will alleviate flooding stress and help insure the long term integrity of these wetland systems. Long term protection of the wetland resources in the Sabine Lake system will in turn insure the long term protection of the fisheries resource, which depends on these wetlands for nursery habitat.

4. MaxC closely approximates the inflow amount needed to provide for sufficient nutrient loading to the system as estimated by TWDB. These nutrients play a key role in supporting the bay system's food web and in supporting plant related processes that protect wetlands in the Sabine Lake system.

This recommendation is made with the full realization that the methodology will continually require refinement as new data become available. Other initiatives are currently underway to collect additional data that can provide information for water management needs for the future. This study represents one facet of that ongoing research and only addresses the narrower subject of presenting the freshwater inflow that will provide for the long term sustainability of the natural ecosystems of the Sabine Lake system using the best data currently available. TPWD is committed to participating in future analysis of freshwater inflow needs for the Sabine Lake ecosystem with other partners.

SECTION 6. REFERENCES

Adam, P. 1990. Saltmarsh Ecology. Cambridge University Press, Boston, MA.

Alber, M. 2002. A conceptual model of estuarine freshwater inflow management. Estuaries **25**:1246-1261.

Beck, M. W., K. L. Heck, K. W. Able, D. L. Childers, D. B. Eggleston, B. M. Gillanders, B. S. Halpern, C. G. Hays, K. Hoshino, T. J. Minello, R. J. Orth, P. F. Sheridan, and M. P. Weinstein. 2003. The role of nearshore ecosystems as fish and shellfish nurseries. Issues in Ecology Report Number 11, Ecological Society of America.

Boesch, D. F., M. N. Josselyn, A. J. Mehta, J. T. Morris, W. K. Nuttle, C. A. Simenstad, and D. J. P. Swift. 1994. Scientific assessment of coastal wetland loss, restoration and management in Louisiana. Journal of Coastal Research, Special Issue Number 20, Lawrence, KS.

Bradley, P. M., and E. L. Dunn. 1989. Effects of sulfide on the growth of three salt marsh halophytes of the Southeastern United States. American Journal of Botany **76**:1707-1713.

Broome, S. W., I. A. Mendelssohn, and K. L. McKee. 1995. Relative growth of *Spartina patens* (AIT.) MUHL. and *Scirpus olneyi* Gray occurring in a mixed stand as affected by salinity and flooding depth. Wetlands **15**:20-30.

Chabreck, R. A. 1988. Coastal Marshes: Ecology and Wildlife Management. University of Minnesota Press, Minneapolis, MN.

Chabreck, R. H., and G. Linscombe. 1997. Vegetative type map of Louisiana coastal marshes. *in*. US Geological Survey and Louisiana Department of Wildlife and Fisheries, Baton Rouge, LA.

DeLaune, R. D., W. H. Patrick Jr., and C. J. Smith. 1992. Marsh aggradation and sediment distribution along rapidly submerging Louisiana Gulf Coast. Environmental Geology and Water Sciences **20**:57-64.

Gambrell, R. P., and W. H. Patrick Jr. 1978. Chemical and microbiological properties of anaerobic soils and sediments. Pages 375-423 *in* D. D. Hook and R. M. M. Crawford, editors. Plant life in anaerobic environments. Ann Arbor Scientific Publishing, Inc., Ann Arbor, MI.

Good, R. E., N. F. Good, and B. R. Frasco. 1982. A review of primary production and decomposition dynamics of the belowground marsh component. Pages 139-157 *in* V. S. Kennedy, editor. Estuarine Comparisons. Academic Press, New York, NY.

Guillory, V. 2000. Relationship of blue crab abundance to river discharge and salinity. Pages 213-220 *in* Annual Conference of the Southeastern Association of Fish and Wildlife Agencies.

Havill, D. C., A. Ingold, and J. Pearson. 1985. Sulphide tolerance in coastal halophytes. Vegetatio **62**:279-285.

Howard, R. J., and I. A. Mendelssohn. 1999. Salinity as a constraint on growth of oligohaline marsh macrophytes. I. Species variation in stress tolerance. American Journal of Botany **86**:785-794.

Koch, M. S., and I. A. Mendelssohn. 1989. Sulphide as a soil phytotoxin: Differential responses in two marsh species. Journal of Ecology **77**:565-578.

Kowalewski, M., G. E. A. Serrano, K. W. Flessa, and G. A. Goodfriend. 2000. Dead delta's former productivity: Two trillion shells at the mouth of the Colorado River. Geology **28**:1059-1062.

LCWCRTF (Louisiana Coastal Wetlands Conservation and Restoration Task Force). 2002. Hydrologic Investigation of the Louisiana Chenier Plain. Louisiana Department of Natural Resources, Coastal Restoration Division, Baton Rouge, LA.

Lee, W. Y., D. Buzan, P. Eldridge, and W. M. Pulich. 2001. Freshwater Inflow Recommendation for the Trinity-San Jacinto Estuary of Texas. Texas Parks and Wildlife Department, Austin, TX.

Longley, W. L., editor. 1994. Freshwater inflows to Texas bays and estuaries: Ecological relationships and methods for determination of needs. Texas Water Development Board and Texas Parks and Wildlife Department, Austin, TX.

Martin, Q., D. Mosier, J. Patek, and C. Gorham-Test. 1997. Freshwater inflow needs of the Matagorda Bay system. Lower Colorado River Authority, Austin, TX.

Mendelssohn, I. A., K. L. McKee, and W. H. Patrick Jr. 1981. Oxygen deficiency in *Spartina alterniflora* roots: Metabolic adaptation to anoxia. Science **214**:439-441.

Meng, L., C. D. Orphanides, and J. C. Powell. 2002. Use of a fish index to assess habitat quality in Narragansett Bay, Rhode Island. Transactions of the American Fisheries Society **131**:731-742.

Mitsch, W. J., and J. G. Gosselink. 1993. Wetlands, 2nd edition. Van Nostrand Reinhold, New York, NY.

Mueller, G. A., and P. C. Marsh. 2002. Lost, a desert river and its native fishes: A historical perspective of the lower Colorado river. USGS/BRD/ITR-2002-0010, United States Geological Survey.

Nyman, J. A., R. D. DeLaune, and W. H. Patrick Jr. 1990. Wetland soil formation in the rapidly subsiding Mississippi river deltaic plain: Mineral and organic matter relationships. Estuarine, Coastal and Shelf Science **31**:57-69.

Pattillo, M. E., T. E. Czapla, D. M. Nelson, and M. E. Monaco. 1997. Distribution and abundance of fishes and invertebrates in Gulf of Mexico estuaries, Volume II: Species life history summaries. ELMR Report Number 11, NOAA/NOS Strategic Environmental Assessments Division, Silver Springs, MD.

Powell, G. L., J. Matsumoto, and D. A. Brock. 2002. Methods for determining minimum freshwater inflow needs of Texas bays and estuaries. Estuaries **25**:1262-1274.

Pulich, W. M., W. Y. Lee, C. L. Loeffler, P. Eldridge, J. Hinson, M. Minto, and D. German. 1998. Freshwater Inflow Recommendation for the Guadalupe Estuary of Texas. Coastal Studies Technical Report No. 98-1, Texas Parks and Wildlife Department, Austin, TX.

Pulich, W. M., J. Tolan, W. Y. Lee, and W. Alvis. 2002. Freshwater Inflow Recommendation for the Nueces Estuary. Texas Parks and Wildlife Department, Austin, TX.

Ratzlaff, K. W. 1980. Land-surface subsidence in the Texas coastal region. Open File Report 80-969, US Department of Interior Geological Survey, Austin, TX.

Reed, D. J. 1995. The response of coastal marshes to sea-level rise: Survival or submergence? Earth Surface Processes and Landforms **20**:39-48.

Rozas, L. P., and R. J. Zimmerman. 2000. Small-scale patterns of nekton use among marsh and adjacent shallow nonvegetated areas of the Galveston Bay Estuary, Texas (USA). Marine Ecology Progress Series **193**:217-239.

Stutzenbaker, C. D. 1999. Aquatic and Wetland Plants of the Western Gulf Coast. Texas Parks and Wildlife Press, Austin, TX.

TDWR. 1981. Sabine-Neches Estuary: A study of the influence of freshwater inflows. LP-116, Texas Department of Water Resources, Austin, TX.

TPWD, and USFWS. 1990. Salt Bayou Project: Joint water management concept plan for Sea Rim State Park, McFaddin National Wildlife Refuge, and Murphree Wildlife Management Area, A wetland habitat restoration and management project, Gulf Coast Joint Venture, North American Waterfowl Management Plan. 7-M-639-03/30/90, Texas Parks and Wildlife Department and U. S. Fish and Wildlife Service.

USDA. 1993. Calcasieu-Sabine cooperative river basin study. U. S. Department of Agriculture, Natural Resources Conservation Service, Alexandria, LA.

Warren, J. R., and F. S. Sutter. 1982. Industrial bottomfish monitoring and assessment. Pages 1-69 *In*: McIlwain, T. D., Fishery monitoring and assessment completion report, Chapter II – Section 1. Project Number 2-2996-R, Gulf Coast Research Laboratory, Ocean Springs, MS

White, W. A., T. R. Calnan, R. A. Morton, R. S. Kimble, T. G. Littleton, J. H. McGowen, and H. S. Nance. 1987. Submerged lands of Texas, Beaumont-Port Arthur area: Sediments, geochemistry, benthic macroinvertebrates, and associated wetlands. Bureau of Economic Geology at the University of Texas, Austin, TX.

White, W. A., and R. A. Morton. 1997. Wetland losses related to fault movement and hydrocarbon production, southeastern Texas coast. Journal of Coastal Research **13**:1305-1320.

White, W. A., and T. A. Tremblay. 1995. Submergence of wetlands as a result of human-induced subsidence and faulting along the upper Texas Gulf Coast. Journal of Coastal Research **11**:788-807.

Figure 1

Determining Freshwater Inflows for a Healthy Estuary

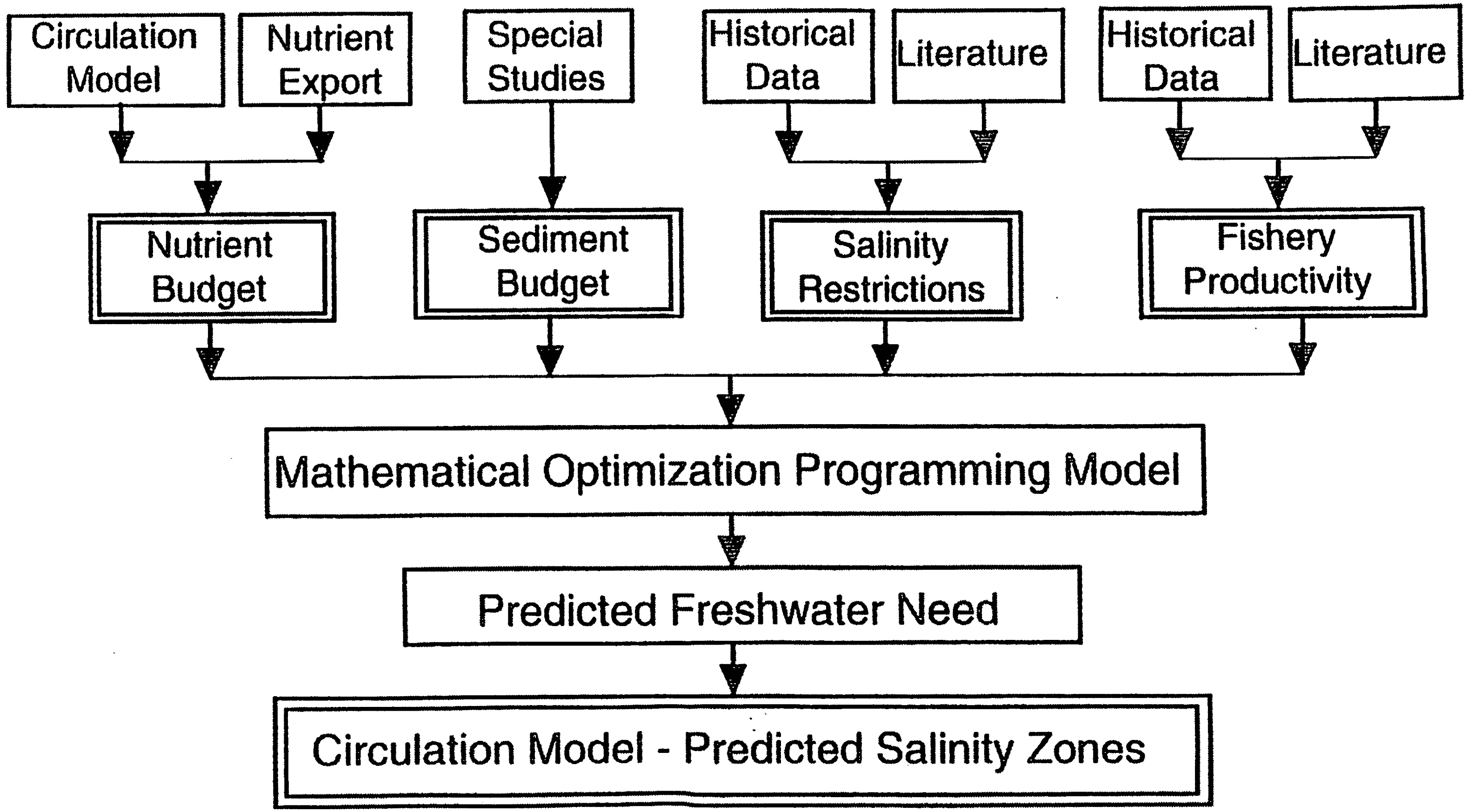


Figure 2

Recommending Freshwater Inflows for a Healthy Estuary

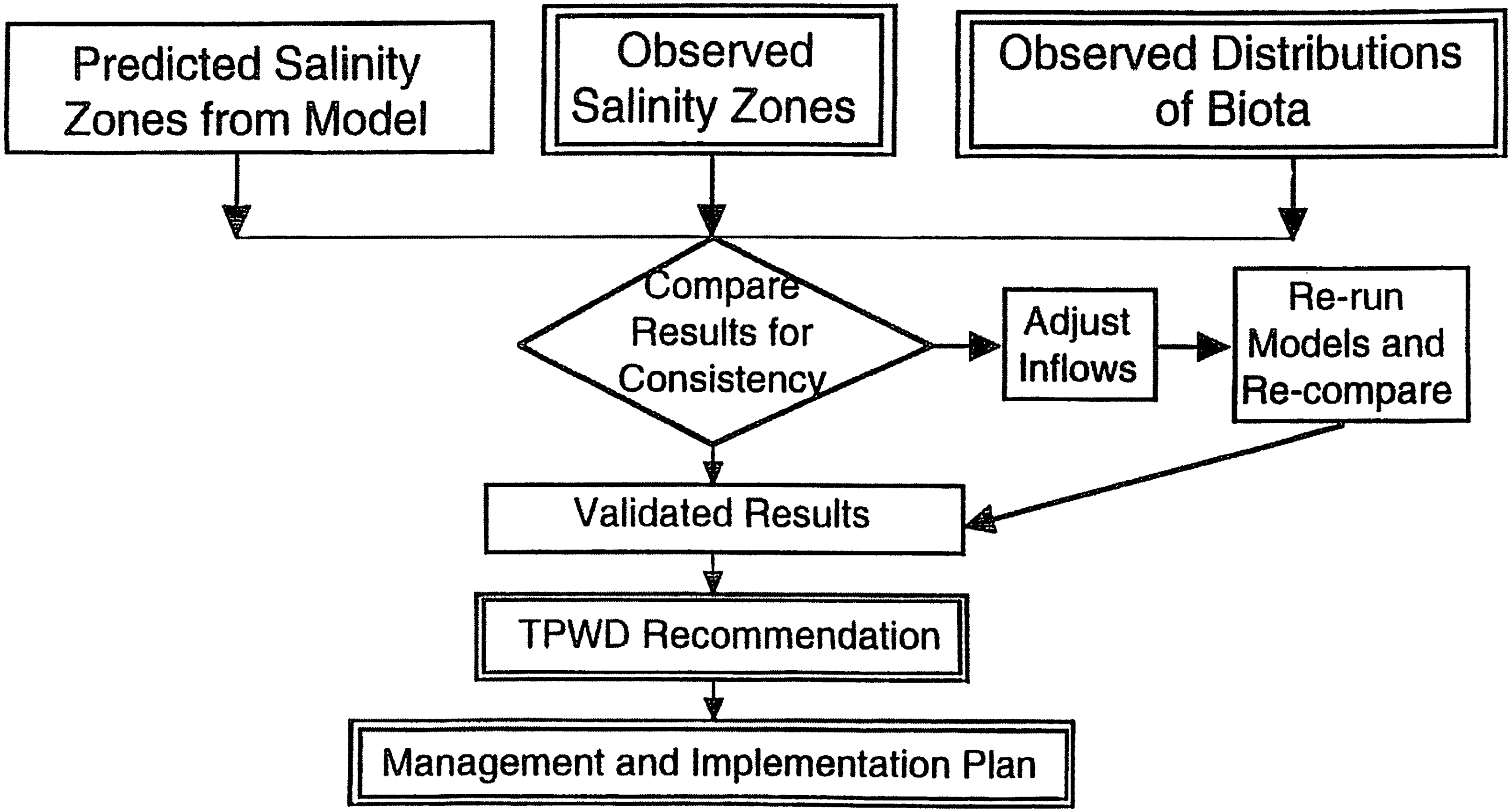
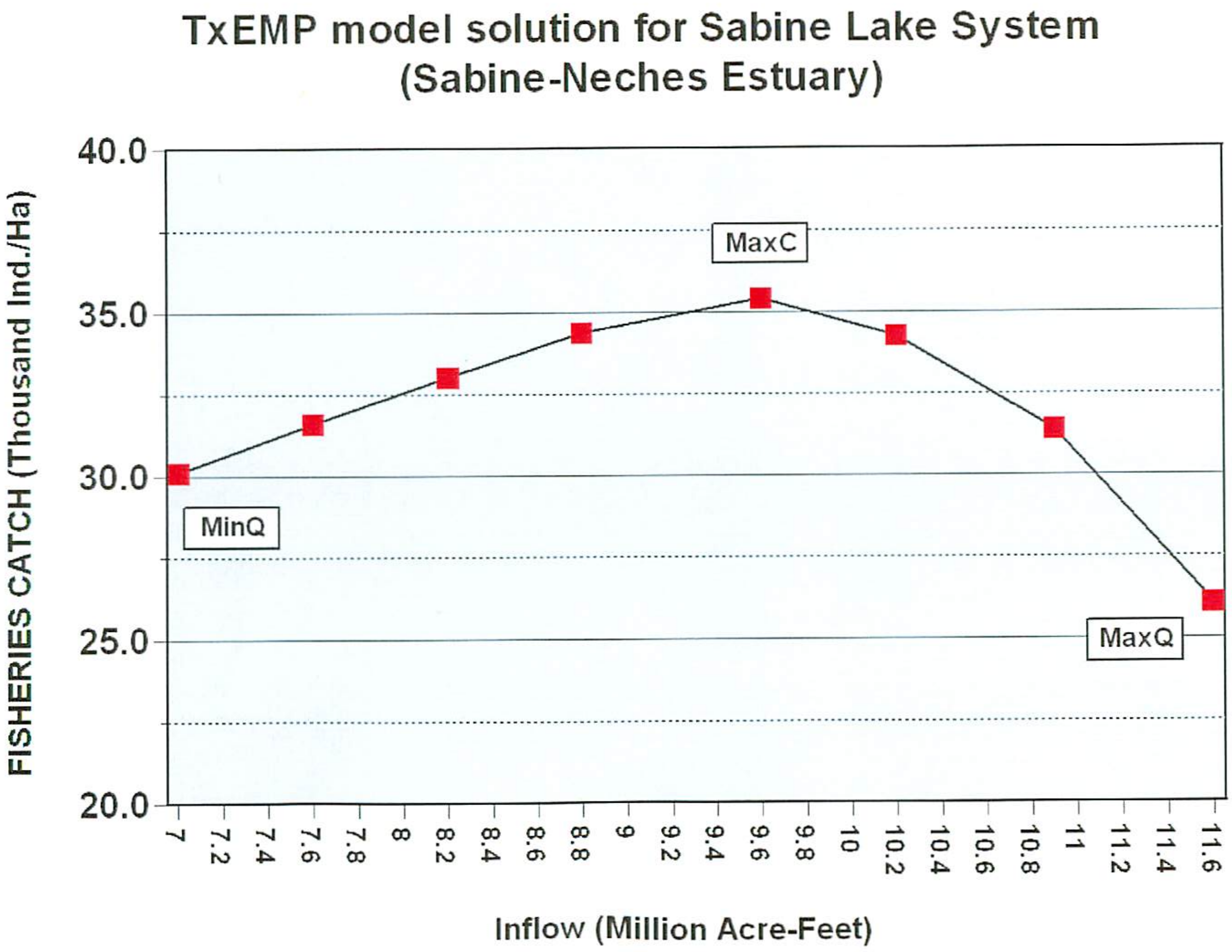
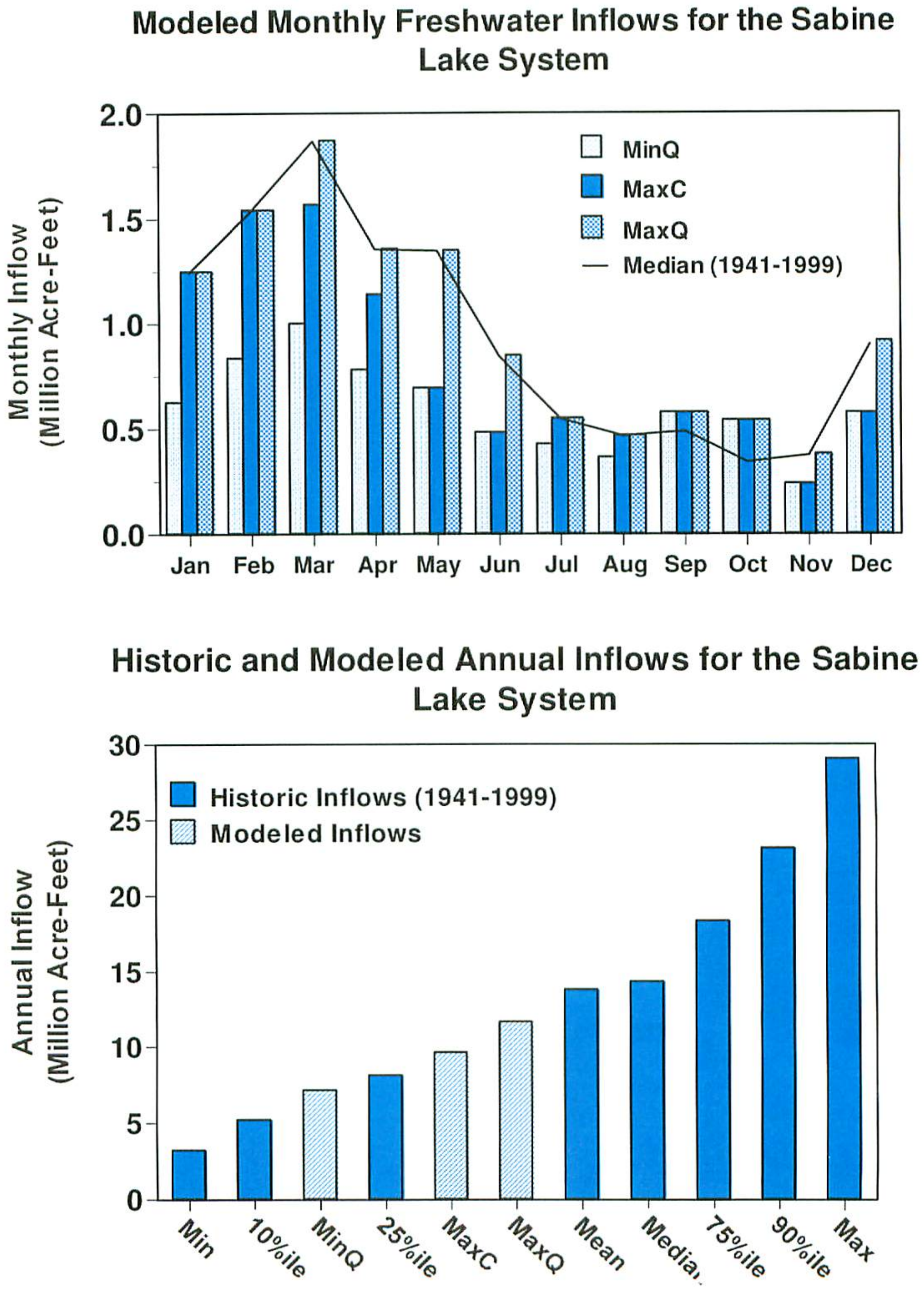


Figure 3



TxEMP model solution for Sabine Lake System
(Sabine-Neches Estuary)


Modeled Monthly Freshwater Inflows for the Sabine Lake System

Historic and Modeled Annual Inflows for the Sabine Lake System

Figure 4. Monthly inflow distribution for MinQ, MaxC, and MaxQ relative to historic monthly median inflows, and a comparison of modeled annual inflow estimates with historic annual inflows.

Study Site Locations for Salinity Time Series Analysis

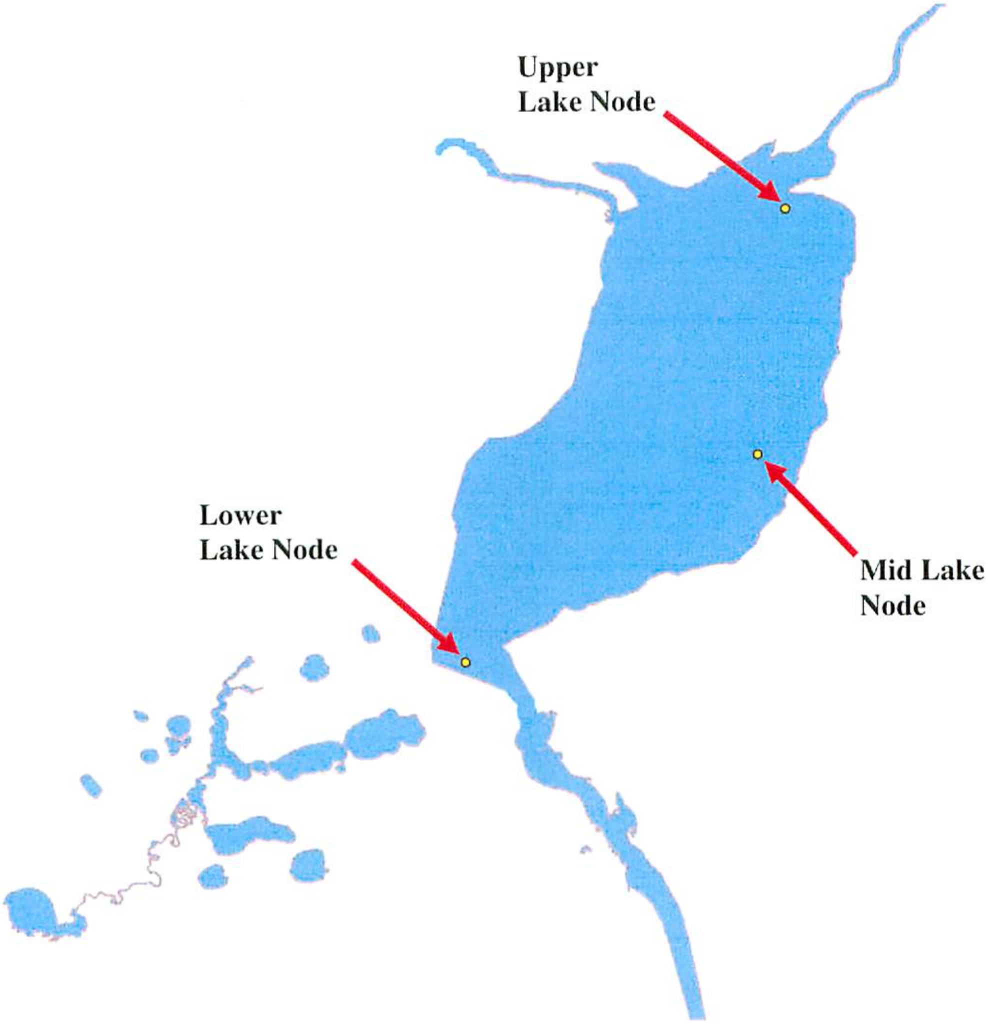


Figure 5. Location of study sites (i.e., model nodes) in the Sabine Lake system used for time series analysis of salinities predicted by TxBLEND (see text).

Predicted Wet Year Salinities in Sabine Lake

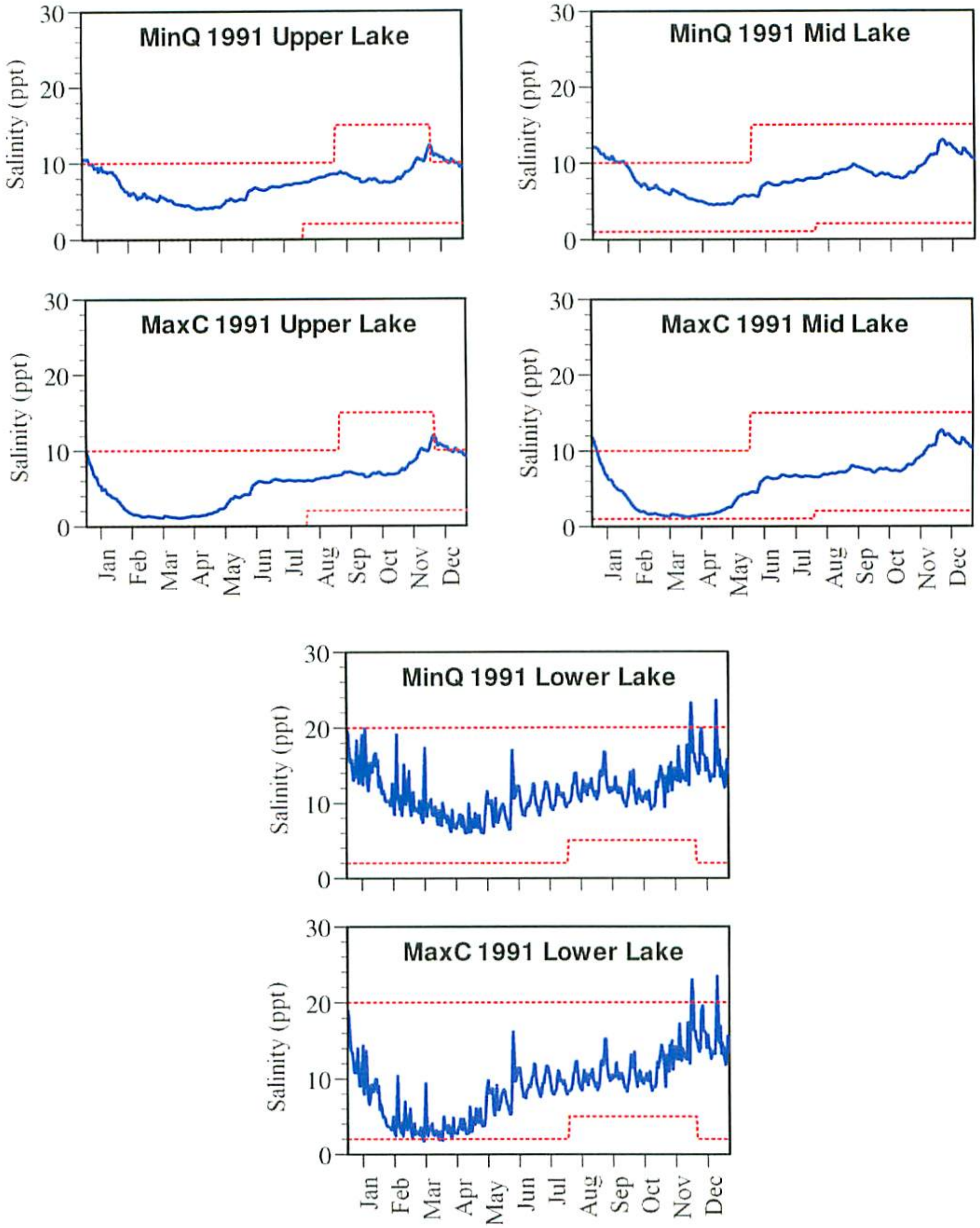
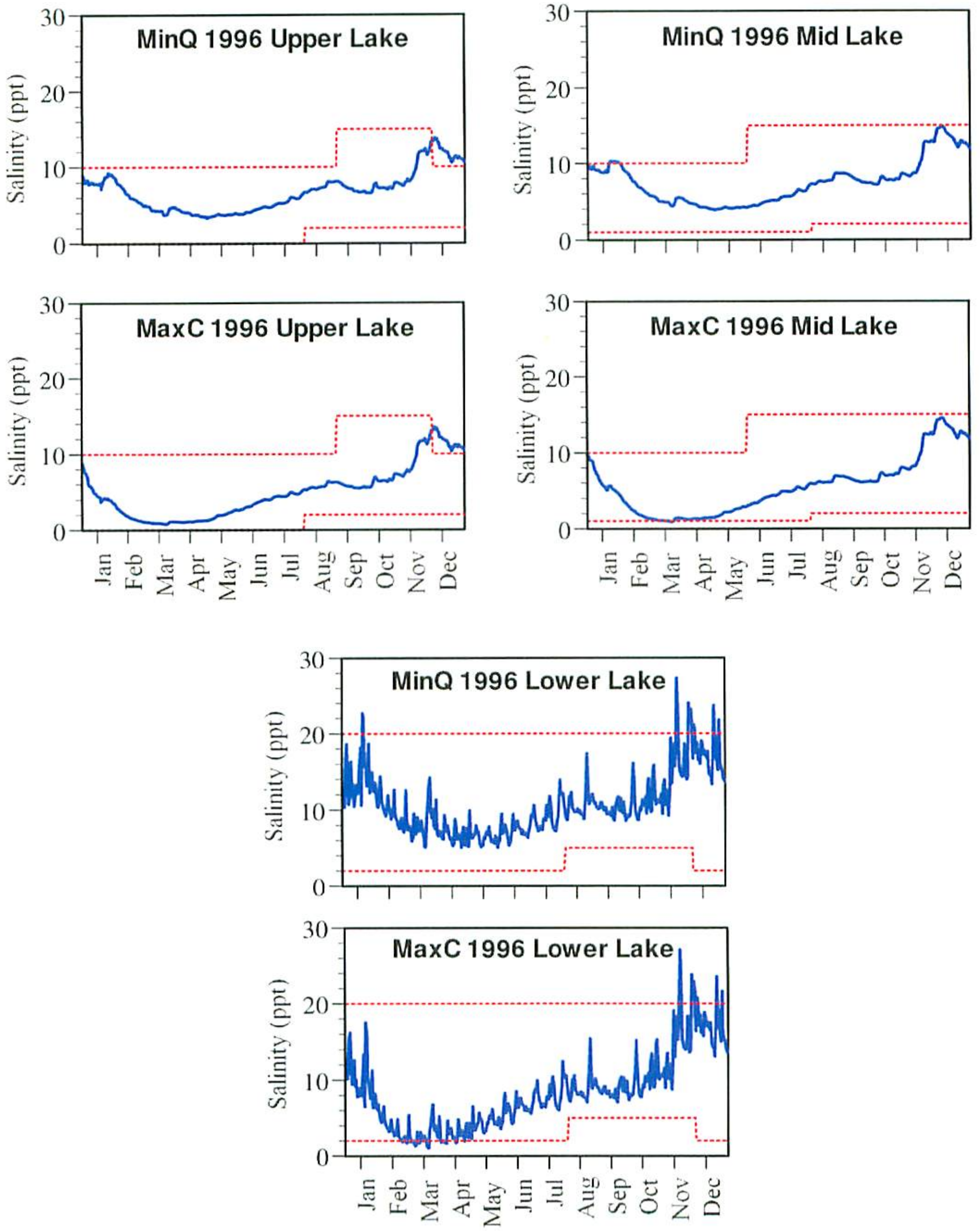


Figure 6. Salinities predicted for MinQ and MaxC by TxBLEND (solid blue line) at the upper, mid and lower lake nodes (see text) for Sabine Lake during a wet year (1991) with associated upper and lower salinity bounds (dashed red line).

Predicted Dry Year Salinities in Sabine Lake


MinQ 1996 Upper Lake

MinQ 1996 Mid Lake

MaxC 1996 Upper Lake

MaxC 1996 Mid Lake

MinQ 1996 Lower Lake

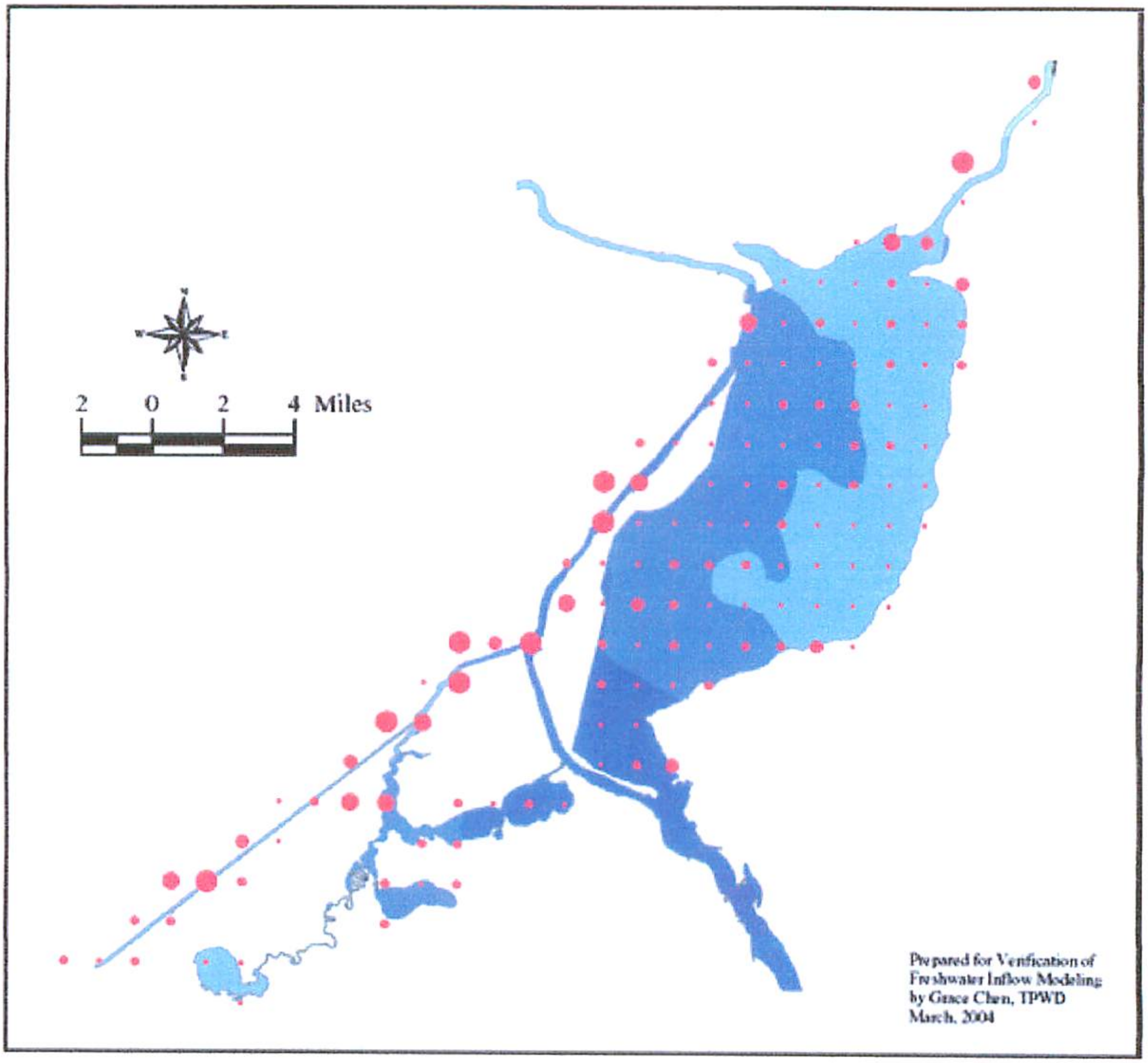
MaxC 1996 Lower Lake

Figure 7. Salinities predicted for MinQ and MaxC by TxBLEND (solid blue line) at the upper, mid and lower lake nodes (see text) for Sabine Lake during a dry year (1996) with associated upper and lower salinity bounds (dashed red lines).

Figure 8

Spatial Distribution of Atlantic Croaker in the Sabine Lake System

Trawl -- March through October



Salinity Zones

	Salinity (ppt)	% Bay Area	Mean CPUE	% Abundance
▨	0.00 - 3	0.46	70.50	0.41
▨	3.01 - 6	42.14	78.66	41.37
▨	6.01 - 9	40.89	73.69	40.16
▨	9.01 - 12	15.37	94.15	18.07
▨	12.01 - 15	1.14	0.00	0.00
▨	> 15.01	0.00	0.00	0.00

Species Abundance

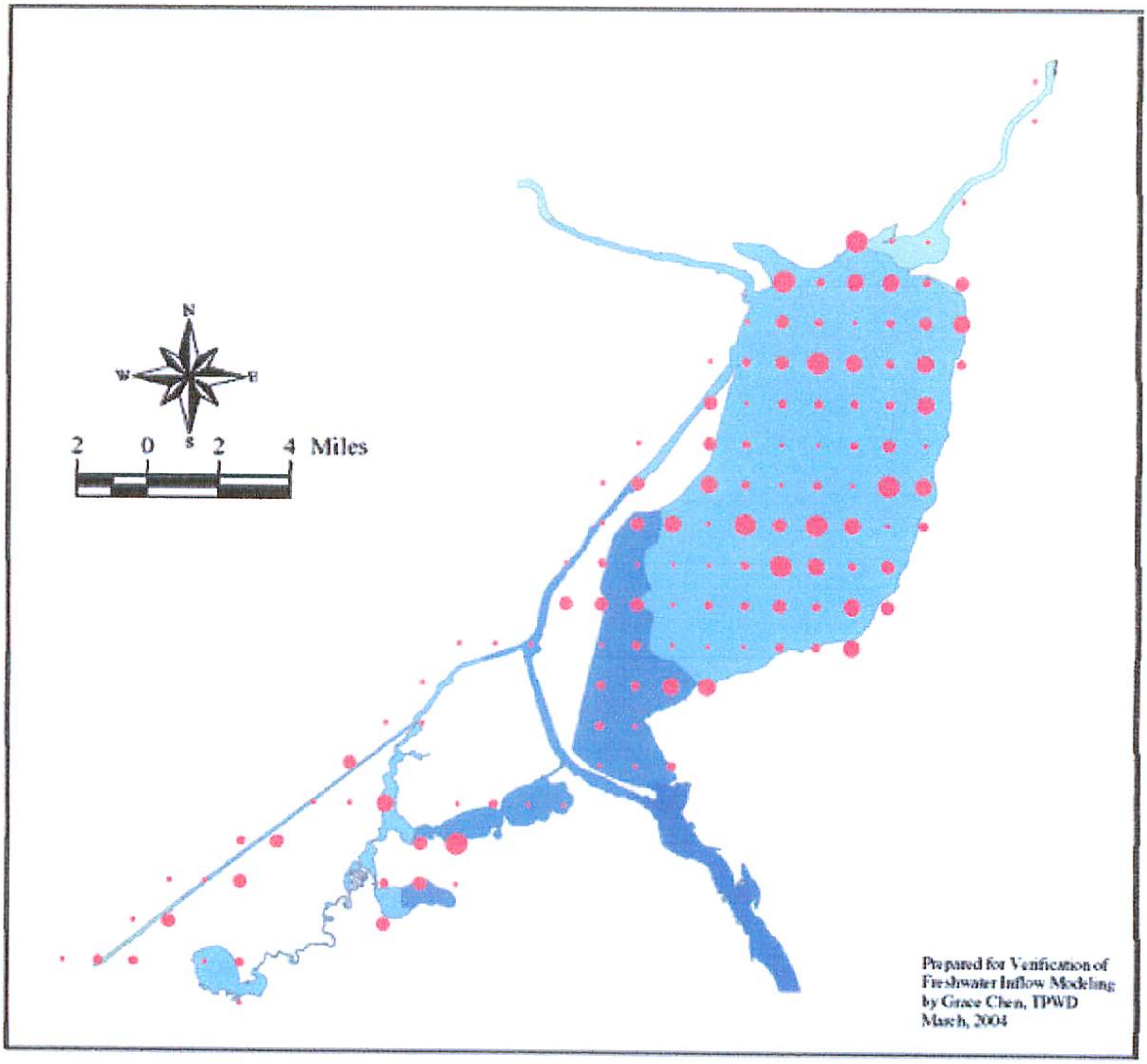
CPUE (Catch per Hour)

·	3.00 - 50.61
•	50.62 - 92.00
•	92.01 - 154.00
●	154.01 - 256.00
●	256.01 - 370.00

Figure 9

Spatial Distribution of Gulf Menhaden in the Sabine Lake System

Trawl -- March through June



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Freshwater Inflow Modeling
by Grace Chen, TPWD
March, 2004

Salinity Zones

	Salinity (ppt)	% Bay Area	Mean CPUE	% Abundance
🟦	0.00 - 3	3.37	3.64	1.86
🟦	3.01 - 6	73.36	7.75	86.32
🟦	6.01 - 9	18.62	4.18	11.82
🟦	9.01 - 12	4.64	0.00	0.00
🟦	12.01 - 15	0.00	0.00	0.00
🟦	> 15.01	0.00	0.00	0.00

Species Abundance

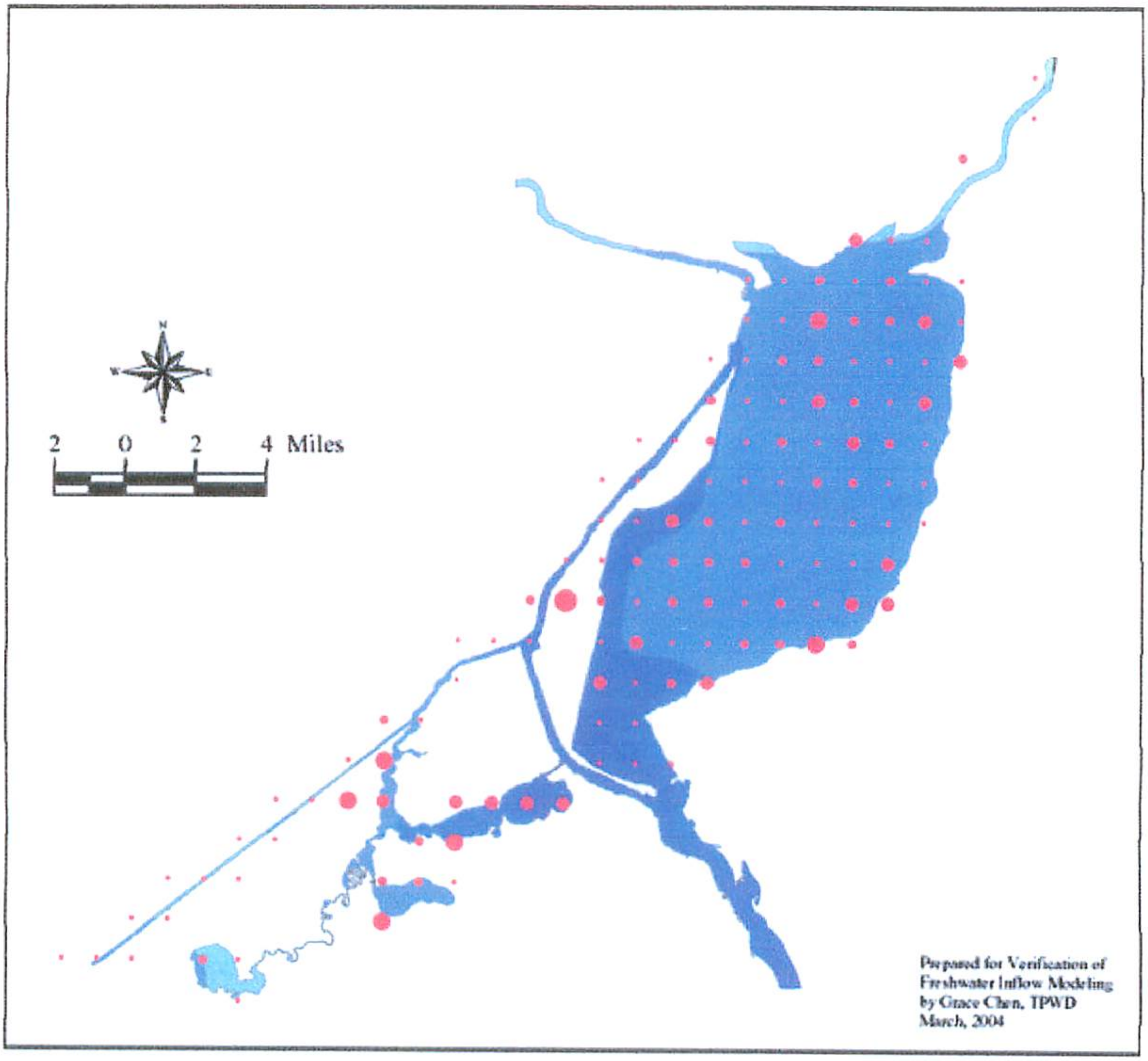
CPUE (Catch per Hour)

·	0.00 - 1.50
•	1.51 - 5.25
●	5.26 - 11.14
●	11.15 - 25.50
⬤	25.51 - 49.00

Figure 10

Spatial Distribution of Spot in the Sabine Lake System

Trawl -- May through November



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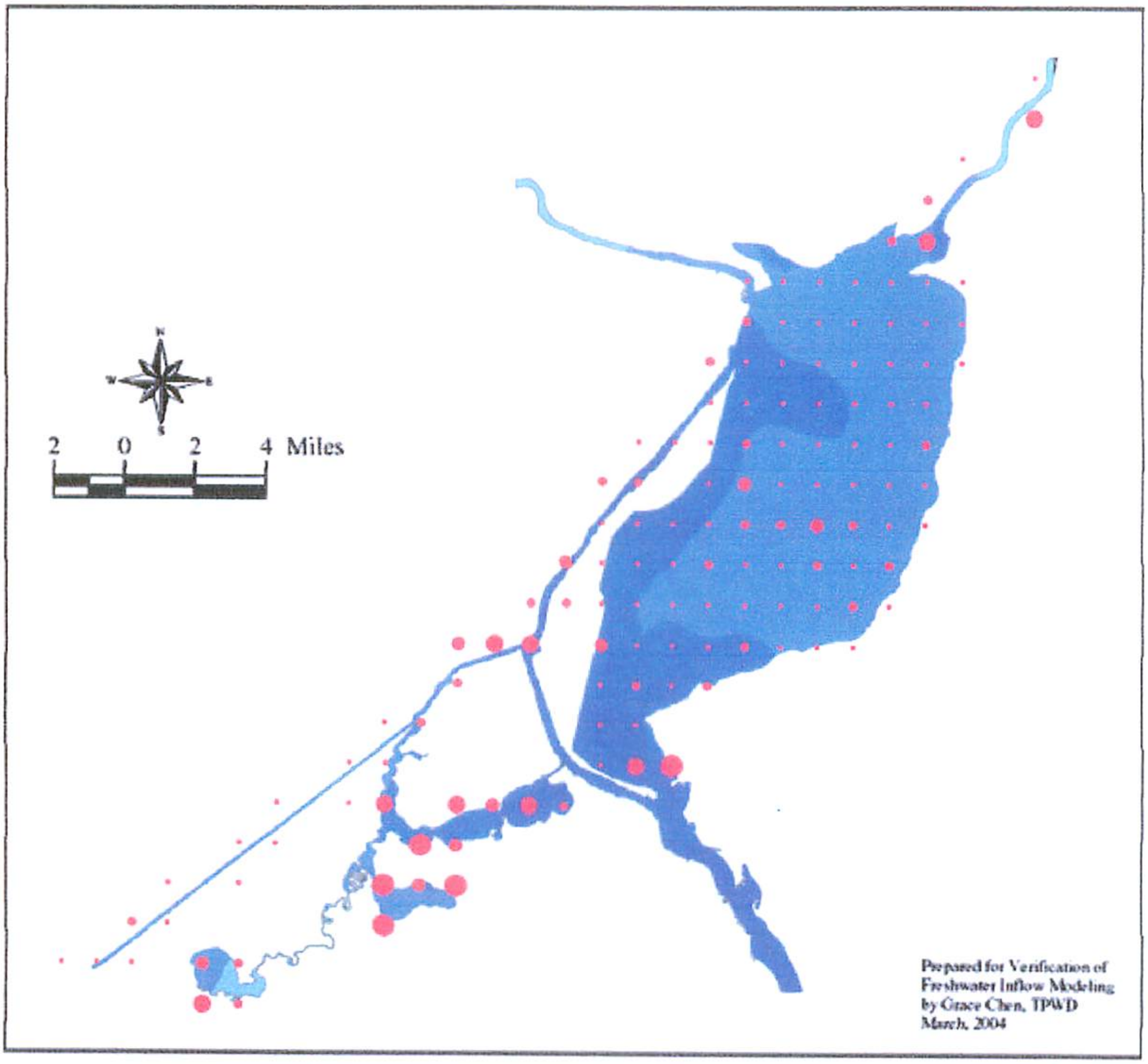
Salinity Zones				
	Salinity (ppt)	% Bay Area	Mean CPUE	% Abundance
▨	0.00 - 3	0.13	0.00	0.00
▨	3.01 - 6	4.12	8.32	1.42
▨	6.01 - 9	72.01	22.06	65.98
▨	9.01 - 12	13.63	24.07	13.62
▨	12.01 - 15	10.12	45.17	18.98
▨	> 15.01	0.00	0.00	0.00

Species Abundance	
CPUE (Catch per Hour)	
·	0.00 - 12.00
•	12.01 - 33.00
•	33.01 - 72.00
●	72.01 - 163.50
●	163.51 - 423.00

Figure 11

Spatial Distribution of White Shrimp in the Sabine Lake System

Trawl -- July through December



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Salinity Zones

Salinity (ppt)	% Bay Area	Mean CPUE	% Abundance
🟦 0.00 - 3	0.00	0.00	0.00
🟦 3.01 - 6	2.14	83.60	2.88
🟦 6.01 - 9	58.66	41.51	39.17
🟦 9.01 - 12	26.12	91.00	38.23
🟦 12.01 - 15	8.73	114.27	16.04
🟦 > 15.01	4.34	52.74	3.69

Species Abundance

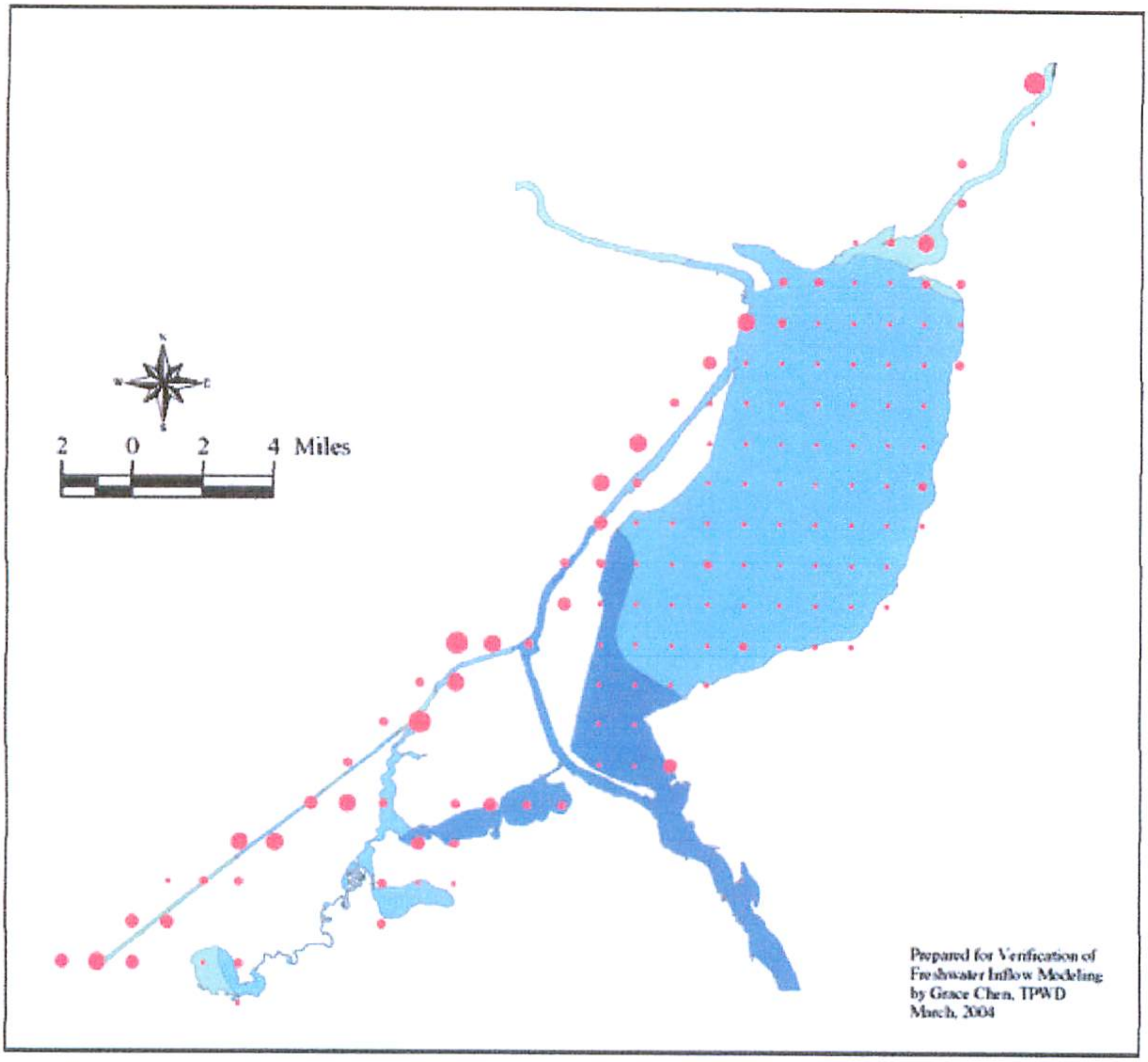
CPUE (Catch per Hour)

●	0.00 - 34.15
●	34.16 - 102.00
●	102.01 - 179.40
●	179.41 - 319.20
●	319.21 - 535.00

Figure 12

Spatial Distribution of Blue Crab in the Sabine Lake System

Trawl -- February through July



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Salinity Zones

	Salinity (ppt)	% Bay Area	Mean CPUE	% Abundance
▨	0.00 - 3	5.66	55.94	14.39
▨	3.01 - 6	75.72	19.73	67.88
▨	6.01 - 9	18.47	20.96	17.59
▨	9.01 - 12	0.14	22.00	0.14
▨	12.01 - 15	0.00	0.00	0.00
▨	> 15.01	0.00	0.00	0.00

Species Abundance

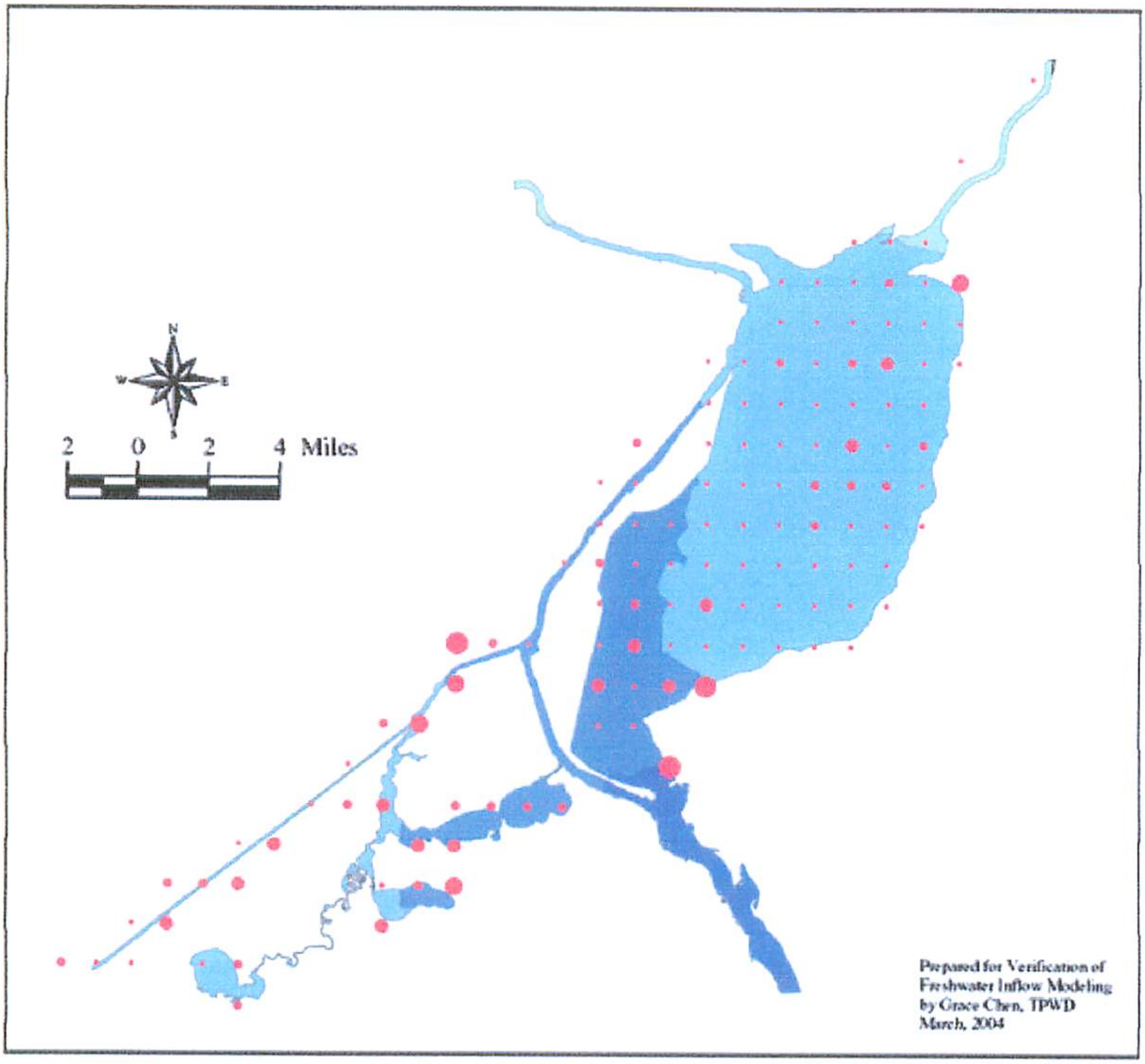
CPUE (Catch per Hour)

•	0.00 - 12.67
•	12.68 - 34.80
●	34.81 - 72.00
●	72.01 - 162.00
●	162.01 - 301.50

Figure 13

Spatial Distribution of Brown Shrimp in the Sabine Lake System

Trawl -- May through July



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March, 2004

Salinity Zones

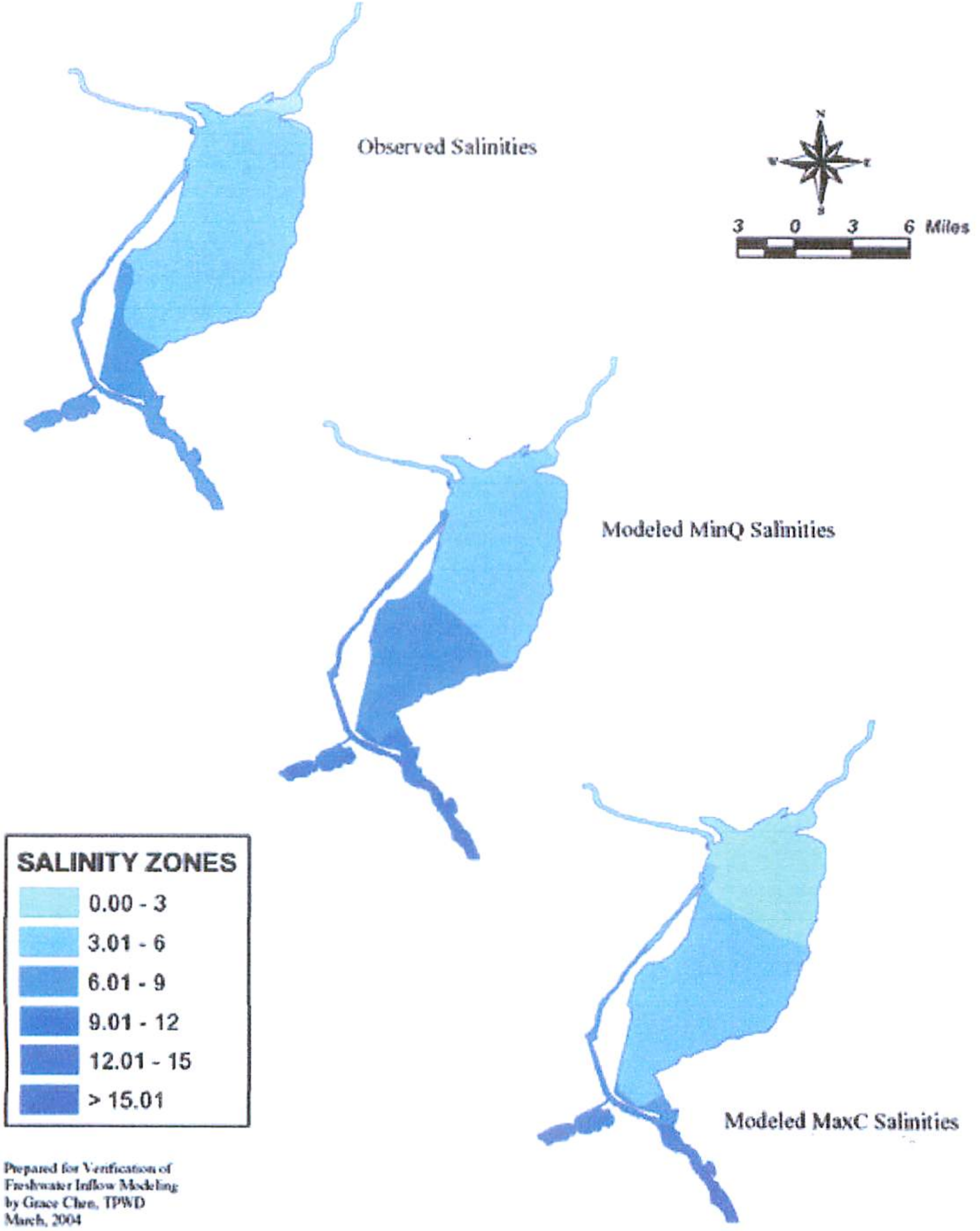
	Salinity (ppt)	% Bay Area	Mean CPUE	% Abundance
▨	0.00 - 3	2.05	12.00	0.39
▨	3.01 - 6	71.12	29.90	33.62
▨	6.01 - 9	21.33	61.72	20.82
▨	9.01 - 12	5.50	519.75	45.17
▨	12.01 - 15	0.00	0.00	0.00
▨	> 15.01	0.00	0.00	0.00

Species Abundance

CPUE (Catch per Hour)

●	0.00 - 18.00
●	18.01 - 51.00
●	51.01 - 96.00
●	96.01 - 378.00
●	378.01 - 634.00

Figure 14



Observed vs. Modeled MinQ and MaxC Salinity Gradients

Blue Crab -- February through July

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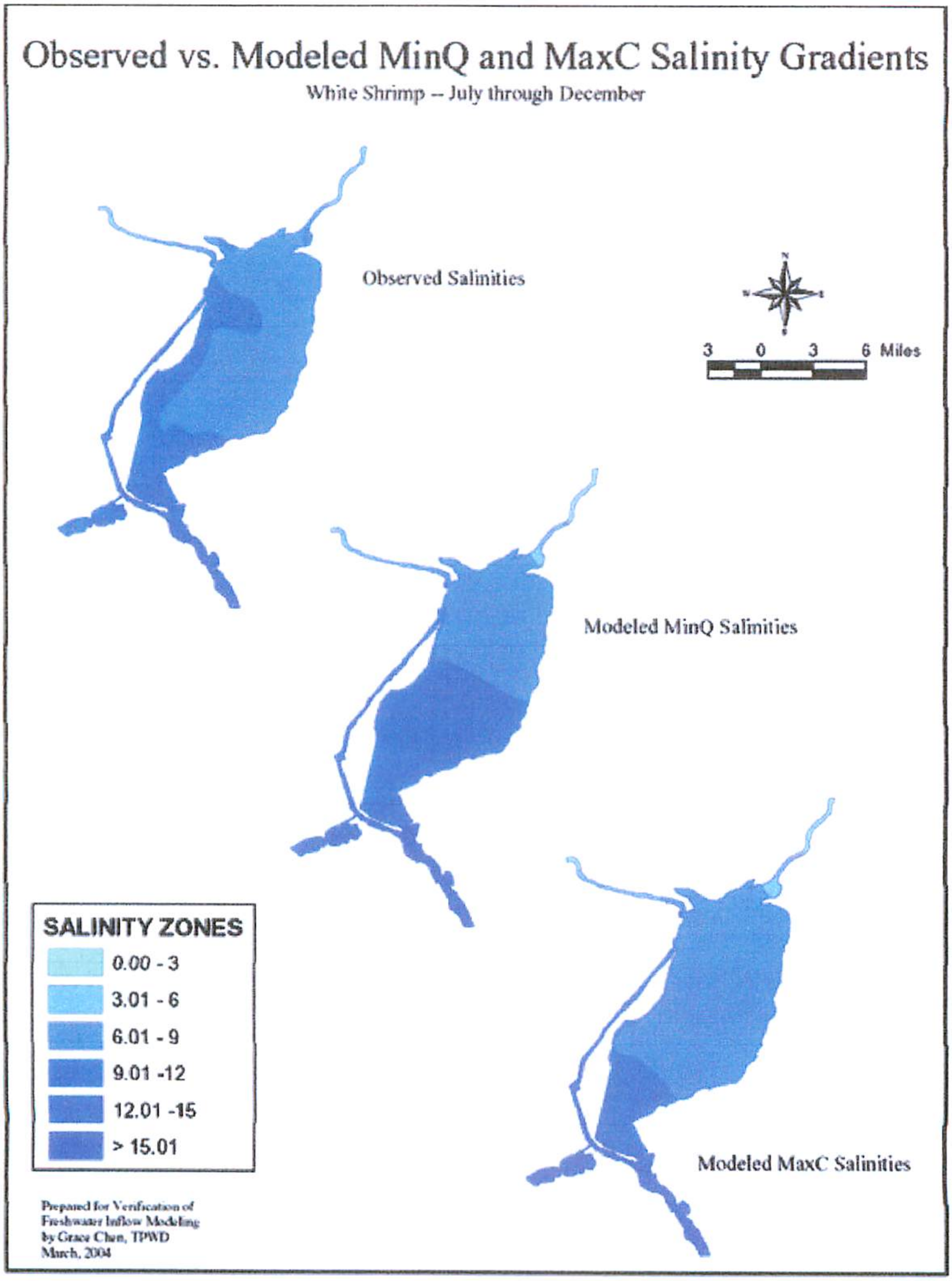
March, 2004

Figure 15



Observed vs. Modeled MinQ and MaxC Salinity Gradients

White Shrimp -- July through December

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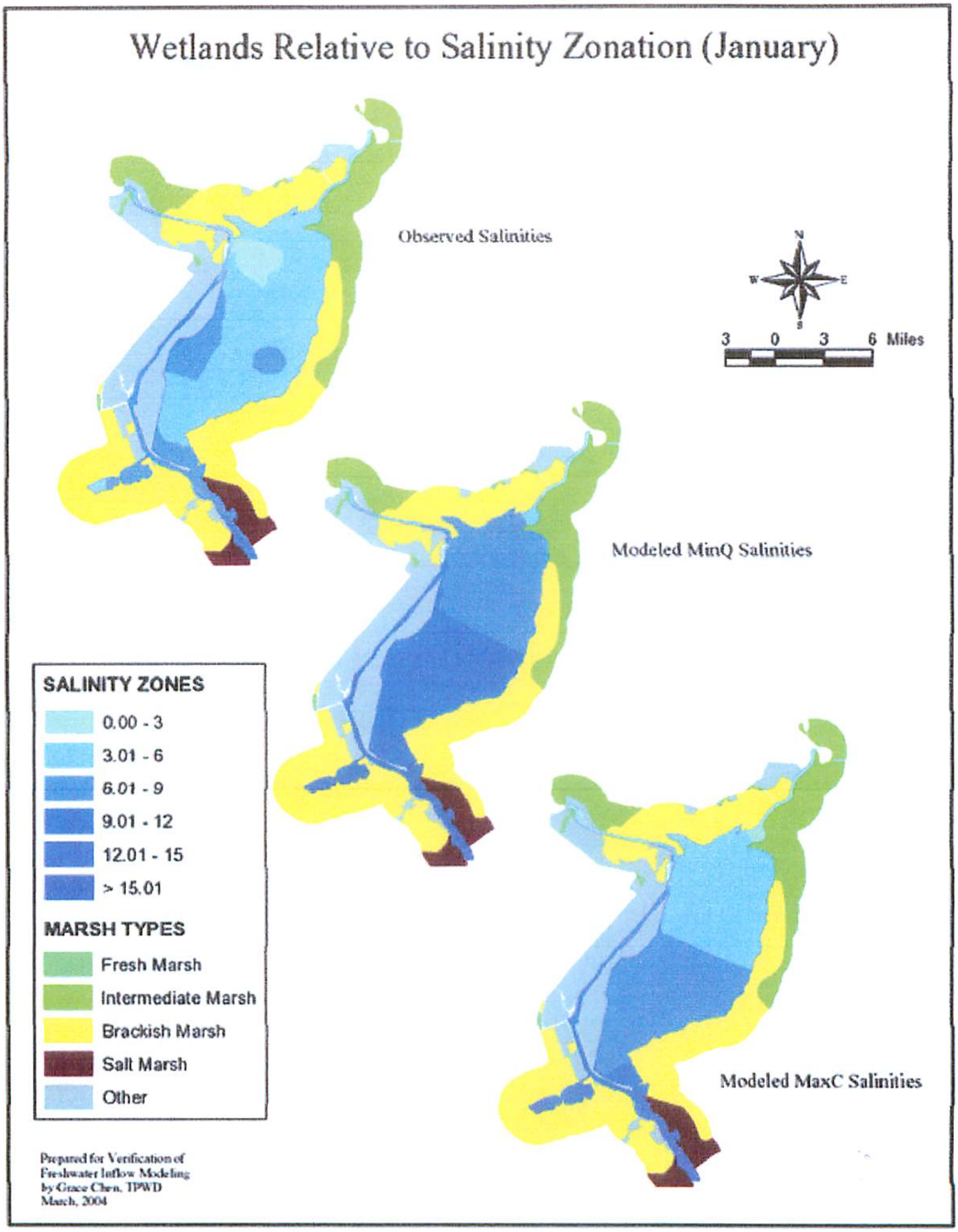
by Grace Chen, TPWD
March, 2004

Figure 16



Wetlands Relative to Salinity Zonation (January)

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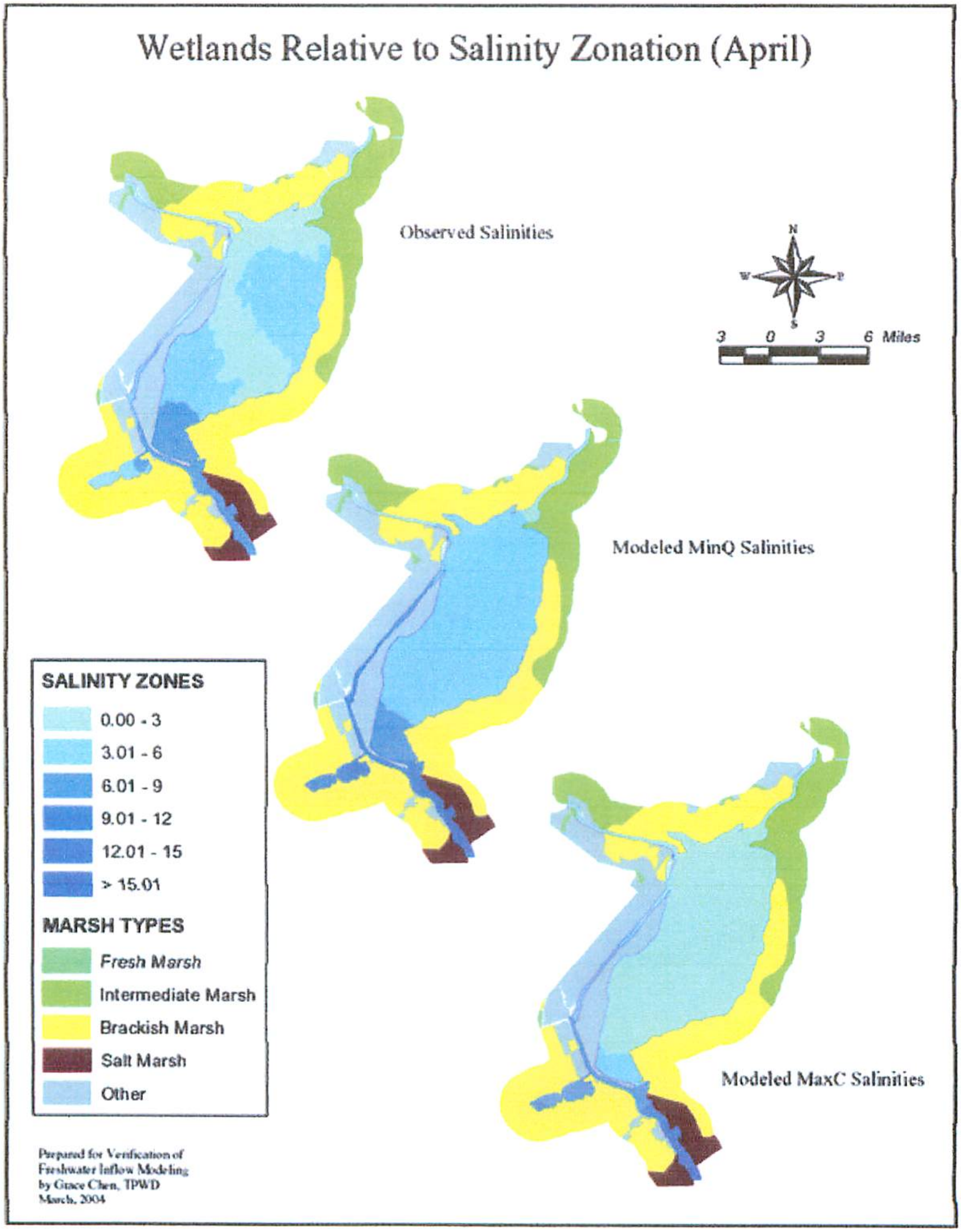
by Grace Chen, TPWD
March, 2004

Figure 17



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March, 2004

Figure 18

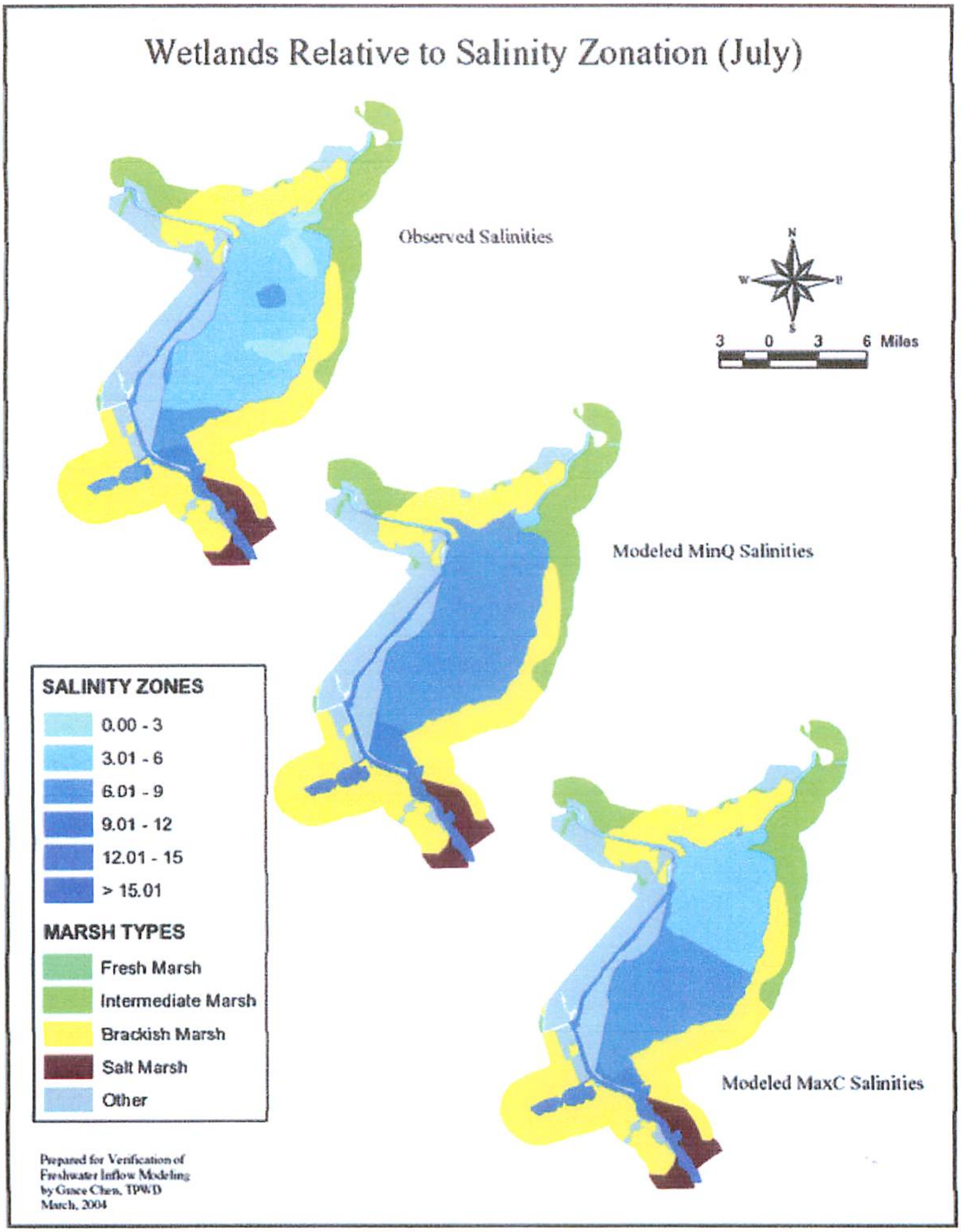

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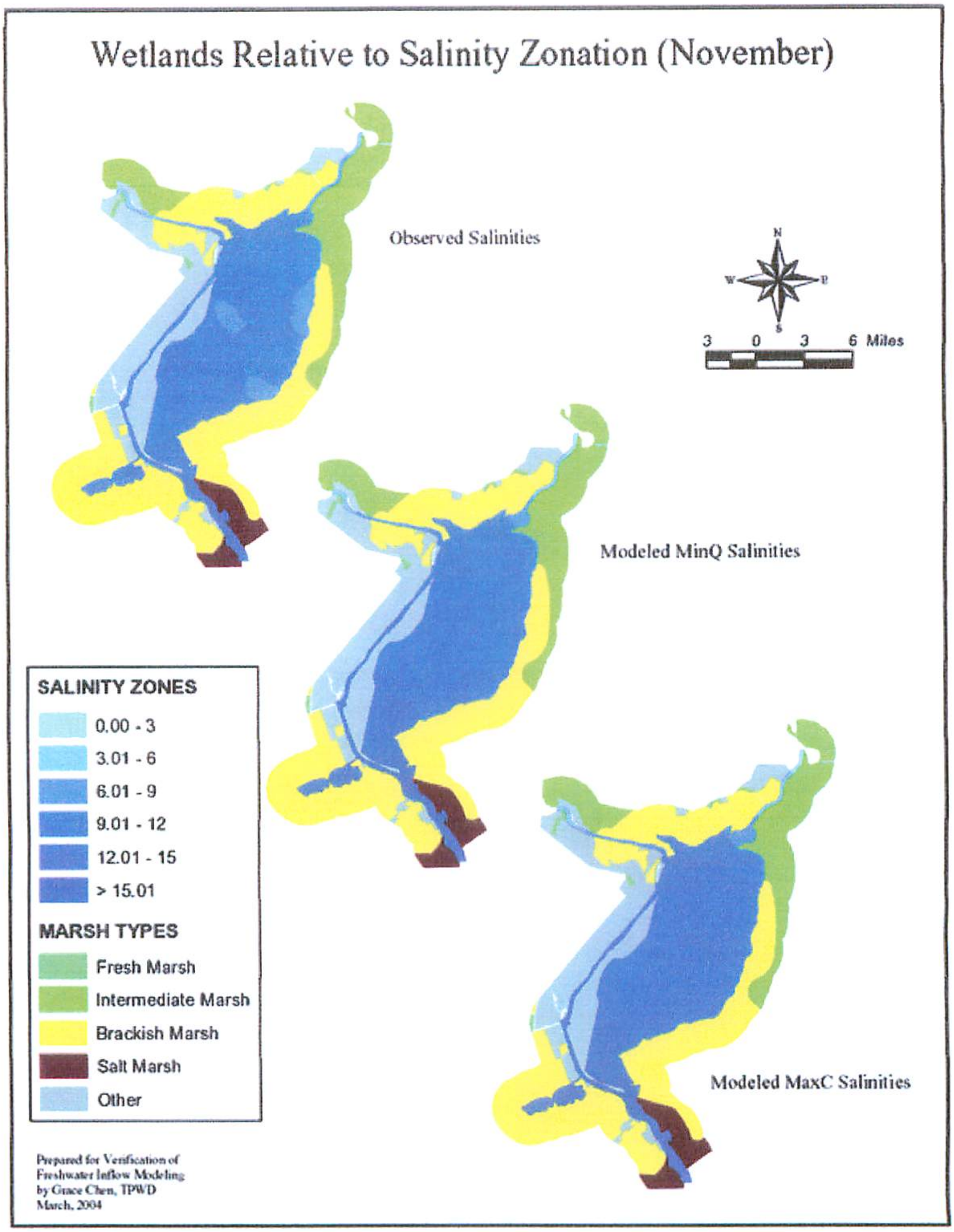
Figure 19



Wetlands Relative to Salinity Zonation (November)

Prepared for Verification of
Freshwater Inflow Modeling
by Grace Chen, TPWD
March, 2004

APPENDIX

Values and Constraints for the TxEMP Model Used in the Freshwater Inflow Analysis of the Sabine Lake Estuary

Technical Memorandum

By

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Performed in Cooperation with
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Coastal Fisheries Division
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February 10, 2005

Values and Constraints for the TxEMP Model Used in the Freshwater Inflow Analysis of the Sabine Lake Estuary

EXECUTIVE SUMMARY

The Texas Estuarine Mathematical Programming (TxEMP) model was developed to estimate the amount of freshwater inflow needed to maintain economically productive and ecologically healthy estuaries. It was developed in response to legislative mandates described in the Texas Water Code 11.147(a), 11.147(b), and 16.058(a). Execution of TxEMP is the culmination of a cooperative effort between the Texas Water Development Board (TWDB) and the Texas Parks and Wildlife Department (TPWD), with the Texas Commission on Environmental Quality (TCEQ) providing additional expertise.

TxEMP accounts for biological needs and ecological requirements by incorporating regression equations linking historical salinity data with current and preceding monthly inflows. TxEMP also accounts for biological productivity by incorporating regression equations linking historical catch data with corresponding bi-monthly inflows. Eight species were considered: blue crab, brown shrimp, white shrimp, red drum, speckled trout, menhaden, spot, and croaker. Historical freshwater inflow data were determined based on standard TWDB hydrology methods, and gaged flow stations on rivers and creeks flowing into the Sabine Lake Estuary. Execution of TxEMP yielded minimum inflow (MinQ) of 7.11×10^6 acre-ft/yr, maximum inflow (MaxQ) of 11.62×10^6 acre-ft/yr, and maximum total catch (MaxC) at inflow of 9.60×10^6 acre-ft/yr. It is the consensus of the Bays and Estuaries teams from both the TWDB and TPWD that inflow recommendations between MinQ and MaxQ satisfy all constraints and produce biologically feasible results.

ACKNOWLEDGEMENTS

The following present and former TWDB staff also contributed substantially to the work represented in this report: Bill Longley, Roger Wolff, Barney Austin, Greg Malstaff, Ruben Solis, Zhenwen Jia, Gary Powell. Various components in the following analyses were developed through a process including discussion with the TPWD project staff, including Wen Lee, Warren Pulich, Dave Buzan, Cindy Loeffler, Dan Moulton, Grace Chen, and Nathan Kuhn. Doyle Mosier and John Botros of the Texas Commission on Environmental Quality (TCEQ) also provided input.

INTRODUCTION

Values and constraints for the TxEMP mathematical programming model were developed for salinity conditions in the estuary, historical fish catch, freshwater inflows, ratios of species catch, nutrient loading, sediment loading, salinity-inflow equations, and catch-inflow equations. All values and constraints were based on historical data collected in the estuary, or in the rivers flowing to the estuary. Methods for determining values and constraints (Matsumoto et al. 1994) were consistent with the requirements in TEXAS WATER CODE 11.147, for maintenance of beneficial inflows to sustain fish and shellfish productivity, and the estuarine life on which they depend. Use of values and constraints in the TxEMP mathematical programming model generally follows the procedures described in sections 8.1 and 8.2 of Longley (1994). The general methodology is also described in Powell, et al. (2002).

SALINITY

Salinity zones

Salinity-based constraints for TxEMP were defined for three sites selected to represent the longitudinal salinity gradient from the river inflow points to the sea: Upper Sabine Lake, Mid Sabine Lake, and Lower Sabine Lake. These are areas defined by latitude-longitude "windows", which include sites with a substantial amount of salinity data (Table 1).

Table 1: Definition of salinity zones in Sabine Lake and salinity statistics for each zone.

Location of data collection sites for named areas in Sabine Lake			
Data Source	Upper Sabine Lake	Mid Sabine Lake	Lower Sabine Lake
TWDB CDS	Line-site 244-2, 244-3, 244-4	Line-site 274-2,274-3	Lines 293,300
TCEQ	13302		13300
TDH		SAB8, SAB13	SAB2, SAB4
TPWD	29-56-00, 29-58-30 93-46-00, 93-50-00	29-52-00,29-54-30 93-49-00,93-51-30	29-46-30,29-50-00 93-54-00,93-55-30
TWDB Datasonde	"Upsab"		"Losab"

Salinity Zone	Median	Mean	Std. Dev.	Range	N
Upper Sabine Lake	5.07	5.72	4.878	0.0 - 17.0	463
Mid Sabine Lake	4.0	5.27	4.878	0.0 - 19.0	244
Lower Sabine Lake	8.45	8.89	6.79	0.0 - 30.08	353

Data

Salinity data were obtained from the Texas Water Development Board (TWDB) Coastal Data System and Bay and Estuary Datasonde programs, Texas Parks and Wildlife Department (TPWD) Fishery Monitoring Program, Texas Commission on Environmental Quality (TCEQ) Statewide Monitoring Network, and Texas Department of Health (TDH) Seafood Safety Monitoring Program. Salinity data were available for years 1968-1999 and reported as psu (practical salinity units, equivalent to parts per thousand, ppt). All data before May, 1990 and some later data were grab-sample measurements made during site visits at various times throughout the year. Beginning in May 1990, ambient water quality data were also collected *in situ* with automated, recording instruments (Hydrolab Datasondes) through a series of monthly deployments. Datasondes recorded sensor readings every 1 to 2 hours while deployed.

Descriptive statistics for salinity data were used to establish upper and lower salinity bounds. These statistics were based on data for the entire period of record from 1968-1999. Data from all agencies were summarized into daily averages, a set for each program. Data from recording instruments were separately summarized into daily averages and sub-sampled via a semi-random algorithm (Press et al. 1986). Sub-samples were selected with an average interval between readings roughly equivalent to the average interval (~28 days) between readings obtained from combined non-continuous monitoring programs. This sample of the record was combined with data from the other monitoring programs, the data were sorted, and daily averages computed. The sub-sampling method was used in this case because it is a simple approach, and avoids bias associated with combining two datasets, where one is more densely sampled than the other. It also avoids the artificial reduction of natural variation that can occur with averaging.

Salinity data used to compute salinity-inflow relationships were handled differently from that used to establish salinity bounds (above). The period of record was limited to 1977-1997. Salinity data were averaged daily and summarized into one average for each of a series of non-overlapping, seven-day bins. Because non-continuous data were combined with the full record of continuous automated data, a weighted regression was used. Weighting is another means of limiting bias associated with combining datasets where one dataset has a greater number of records per time period than the other. Weighting was used in this case so that all of the data could be used in regression. The weight assigned to each bin salinity was N (normalized), the number of samples within that bin.

Salinity bounds

Salinity bounds were selected based primarily on salinity frequency distributions and biotic limits. Frequency distributions of salinity measurements for each month were examined for each zone to provide information about historical monthly ranges of salinity. The 25th and 75th percentiles were of greatest interest because salinity values in this interval represent half of all measurements, and fall in the mid-range salinity values for the zone. Biotic salinity limits from scientific literature and reports for major estuarine plant and animal species, compiled in tables 5.2.2 and 6.7.3 of Longley (1994), were used in the evaluation. With this information, the salinity bounds for the analysis were selected by TWDB and TPWD staff, and are presented in Tables 2, 3, and 4, below. In all cases, upper salinity bounds were set at or above the 75th percentile of the historical salinity distribution. In most cases, lower bounds were set below the 25th percentile of the historical salinity distribution.

Table 2: Salinity bounds (ppt) for the Upper Sabine Lake salinity zone.

Month	Lower Bound	Upper Bound
January	0	10
February	0	10
March	0	10
April	0	10
May	0	10
June	0	10
July	0	10
August	2	10
September	2	15
October	2	15
November	2	15
December	2	10

Table 3: Salinity bounds (ppt) for the Mid Sabine Lake salinity zone.

Month	Lower Bound	Upper Bound
January	1	10
February	1	10
March	1	10
April	1	10
May	1	10
June	1	15
July	1	15
August	2	15
September	2	15
October	2	15
November	2	15
December	2	15

Table 4: Salinity bounds (ppt) for the Lower Sabine Lake salinity zone.

Month	Lower Bound	Upper Bound
January	2	20
February	2	20
March	2	20
April	2	20
May	2	20
June	2	20
July	2	20
August	5	20
September	5	20
October	5	20
November	5	20
December	2	20

Salinity chance constraint bounds

The salinity chance constraint is the minimum probability that the calculated salinity will satisfy the lower salinity bound or the minimum probability that the calculated salinity will also satisfy the upper salinity bound. For TxEMP analysis, the salinity chance constraints for the lower and upper salinity bounds were set to 50% at all sites.

CATCH DATA

In past inflow analyses, the ecological integrity and economic productivity of the estuary has been incorporated in TxEMP through the use of equations relating fishery harvest to bimonthly inflows. In the present analysis, bag seine monitoring "catch" data (individuals/ha.) were used instead of harvest landings (lbs/yr). The primary reason for this change is that fishing effort appeared to unduly influence harvest landings in the Sabine Lake Estuary. In addition, a bag-seine catch basis was used successfully for the Upper and Lower Laguna Madre analyses, and a 14-year record of bag seine data was available for the Sabine Lake.

Bag seine catch data were obtained from Texas Parks and Wildlife Department (TPWD) for the period of 1986-1999. Species used in analysis were blue crab, brown shrimp, white shrimp, red drum, speckled trout, croaker, spot, and menhaden.

Catch targets and historical values

Harvest targets were defined for most species as 75% of mean historic monitoring data. The harvest target for each species is the value for which TxEMP must maintain a specific probability of achieving. This probability is defined by the harvest chance constraint, and is usually 50%.

Table 5: Mean, minimum, maximum and target values for species catch (individuals/ha.).

Species	N	Mean	Min.	Max.	Target
Brown Shrimp	14	3761	169	13678	2772
Blue Crab	13	587	280	1003	440
Croaker	13	2193	950	4280	1645
Menhaden	13	11136	860	33087	8352
Red Drum	14	166	56	728	124
Spotted Seatrout	13	39	17	81	29
Spot	14	619	60	2220	449
White Shrimp	12	6272	3697	9882	4704

Catch chance constraint bounds

The catch chance constraint is the minimum probability that the calculated catch equals or exceeds the catch target. For TxEMP analysis, the catch chance constraint was set to 50%. Although setting chance constraints higher than 50% may theoretically produce a more statistically reliable solution, it also has the undesirable effect of reducing the range of feasible inflows, and requiring more inflow in the final solution.

INFLOWS

Data

The inflow bounds in the analysis represent statistical measures of the combined flow, also called surface inflow, of all runoff from the land to the estuary for the period 1941 to 1999. Combined flow is the sum of gaged and ungaged flow. Gaged flow is the measured flow at the last U.S. Geological Survey (USGS) stream gage on a river or creek that flows toward the estuary. USGS gages in the Sabine Lake area used to determine inflows were: Sabine River at Ruliff (id# 8030500), Cow Bayou at Mauriceville (id# 8031000), Neches River at Evadale (id# 8041000), Pine Island Bayou at Sour Lake (id# 8041700), and Village Creek at Kountze (id# 8041500).

Ungaged flow is the water reaching the estuary whose source is below the farthest downstream flow gage, or from an ungaged catchment area (i.e., water is not measured by the gages). Ungaged flow consists of three hydrologic components: modeled runoff from land areas below the farthest downstream gage or ungaged catchment areas (simulated using TXRR, a calibrated rainfall-runoff model); return flow from discharges to rivers, streams, or estuaries that occurs below the farthest downstream gage; and diversions of freshwater from rivers and streams that occurs below the last downstream gage. The data used in simulating modeled flows were daily precipitation data from the National Weather Service, and precipitation stations operated by the TWDB. Ungaged watersheds might not contain any precipitation stations, or might contain several. Precipitation was distributed on a watershed basis through the use of a Thiessen network to allocate precipitation to specific ungaged watershed areas. Return flow values came from records of measured and estimated flows for Self-reporting Wastewater Discharges from the TCEQ. Diversion values come from the Water Use databases managed by TCEQ as part of the Water Rights Permitting Program.

Ungaged flow was calculated by adding modeled runoff and return flow, and subtracting diversions. Data sources for gaged and modeled flows provide daily data so flow amounts can be calculated in units of acre-ft/day. The data for return flows and diversions, however, are reported to the TCEQ as monthly totals. Combined flow (acre-ft/day) is calculated as the sum of gaged and ungaged flows. To calculate daily combined flows, estimates of daily return and diversion flows are made by dividing monthly values by the number of days in each month.

In the Sabine Lake Estuary, annual inflows have ranged between 3,182,638 and 29,016,876 acre-ft/yr, with median inflow of 14,318,578 acre-ft/yr and mean inflow of 13,787,853 acre-ft/yr. Three different sets of flow bounds were defined to constrain the solution. Monthly flow bounds limited modeled flow in any monthly period. Seasonal bounds, based on 2-month seasons, corresponded with the 2-month seasonal periods used in catch equations. Annual bounds were used to limit modeled flows on an annual basis. All bounds were based on combined inflow statistics for the 59-year period 1941 to 1999.

Monthly upper and lower inflow bounds

Typically, the lower monthly inflow bounds are set to the 10th percentile of all inflow data used in the analysis and the upper bounds are set to the median of all monthly inflows for the same period in order to develop achievable recommended inflows. Early TxEMP runs showed that these constraints excluded feasible solutions. To remedy that, lower bounds for January through June were set to the 25th percentile inflow and the upper bounds for September and October were set to the mean (Table 6).

Table 6: Lower and upper monthly inflow boundaries (1000 acre-ft.).

Month	Lower Boundary	Upper Boundary
January	624.0	1246.4
February	832.5	1539.2
March	853.7	1867.0
April	778.6	1355.3
May	691.9	1348.0
June	478.7	845.2
July	172.1	547.3
August	70.9	466.5
September	111.6	574.6
October	66.9	537.9
November	95.5	378.1
December	272.8	913.8

Seasonal (2-month) upper and lower inflow bounds

The bounds for bimonthly (i.e., seasonal) flows constitute a separate set of constraints from monthly flow bounds. Both constraints must be satisfied for an optimum solution (Table 7). Seasonal bounds are wider than the sum of monthly flows to allow the TxEMP optimization model plenty of maneuvering room to search for an optimal solution, unless there is a particular reason to set the bound smaller than the sum of monthly flows.

Table 7: Lower and upper bimonthly inflow boundaries (1000 acre-ft.).

Bi-month	Lower Boundary	Upper Boundary
Jan.-Feb.	700	2800
Mar.-Apr.	700	3300
May-Jun.	640	2300
Jul.-Aug.	240	1100
Sept.-Oct.	170	2900
Nov.-Dec.	360	1400

Annual (12-month) upper and lower inflow bounds

A series of annual inflow bounds were set to constrain a series of TxEMP runs in order to provide intermediate points between MinQ and MaxQ. These points were used to define the performance curve.

CATCH RATIOS

The TxEMP model permits catch equations to be weighted for individual species in the calculation of the objective function. Weighting allows control of the relative importance of individual catch equations in the optimization routine. If the weight of an equation was set to zero, that equation would not contribute to total catch included in the objective function. Consequently, the optimization results would be independent of that species' contribution to catch. TxEMP would calculate the catch of that species, but would not include the contribution of that species in optimization. In the same manner, the catch equation of one species can be weighted to contribute more to the catch total of the objective function than another species' equation. In the Sabine Lake application of TxEMP, all catch equations are equally weighted.

Because some equations may cause calculated catch for some species to be greater than historically observed levels (especially at extreme of inflows), a defined proportion of catch range was established for each species to bound allowable calculated catch. This constraint is called the catch ratio and is based on historical bag seine monitoring data from the estuary (Table 8). The constraint guaranteed that the relative catch of species from the optimization model remained within ranges that have been observed for the estuary. Using constraints reduces the problem of the model calculating a solution that provides exceptional catch for one or two species to the detriment of others.

Data

TWDB calculated catch ratios from TPWD's bag seine monitoring data, individuals/ha. Lower and upper bounds for catch ratio constraints were calculated as the mean ratio plus or minus 1.15 times the standard deviation. However, TxEMP was run with the lower and upper ratio bounds set to 0 and 1, respectively, for all species in order to avoid over-constraining the problem. The catch ratios are calculated by TxEMP and then manually inspected to ensure they were within or near the bounds.

Catch ratio bounds

Table 8: Calculated catch mean ratios, and upper and lower catch bounds.

Species	Catch Ratio	Lower Bound	Upper Bound
Brown Shrimp	0.15	0	0.32
Blue Crab	0.02	0.01	0.03
Croaker	0.09	0.04	0.13
Menhaden	0.45	0	0.91
Red Drum	0.01	0	0.02
Spotted Seatrout	0	0	0.01
Spot	0.03	0	0.05
White Shrimp	0.25	0.15	0.35

NUTRIENT CONSTRAINT

The objective of developing a nutrient constraint is to base a recommendation for a minimum inflow requirement on the sufficiency of nutrients supplied by those inflows to support biological productivity in the estuary. Nitrogen is generally the limiting nutrient in most estuaries (Whitledge 1989a,b). It is possible that phosphorus limitation occurs with lesser or greater frequency in this system. However, the nitrogen focus here will allow comparison with other coastal systems. The tally of the nitrogen which helps fuel production in the system is based on total nitrogen (TN), which is TKN + NO_3 + NO_2 (total Kjeldahl N, nitrate N, nitrite N).

The steps involved in the development of the nitrogen loading constraint are not all presented here. The methodology for compilation of nitrogen loading to the estuary and the pieces of the estuary nitrogen budget follow what has been reported for the Nueces Estuary (Brock, 2000). Details of loading and budget results will be presented elsewhere. Pertinent points are presented here from the loading data and from analysis of sources and sinks. This information leads to the rationale and calculation of a recommended minimum nitrogen load and load-based minimum freshwater inflow.

Nitrogen Loading to Sabine Lake

The watersheds include both major rivers, with gaged flow information, a significant urban/industrial area, with nonpoint and point source loadings, and significant marshlands, which may alternate between nutrient sources and sinks. Table 9 shows the contribution of total nitrogen to the estuary, averaged over 1977-1994.

Table 9. Total nitrogen loading (10^6 g N/y) to Sabine Lake from major sources. Precipitation and deposition refer to nitrogen input from the atmosphere directly to the bay water surface.

	Sabine River	**Neches River**	**Coastal W-sheds**	**Returns**	**Subtotal**
Median	4550	4020	4750	3900	17220
Average	4500	3990	4880	4200	17570
	Direct Rain	**Dry Deposition**	**N-fixation**	**Total**	
Median	170	70	900	18360	
Average	160	60	900	18690	

Sabine Lake Nitrogen Status

The loading rates of nutrients into Sabine Lake is high, because the volume of inflows into the estuary is large. However, because the volume of the estuary is small, most of the input travels through the system before it can be assimilated. These nutrients feed productivity in the near offshore.

Sabine Lake Recommended Nitrogen Input

The purpose of this exercise is to establish the magnitude of nutrient inputs which promote or are consistent with characteristic system productivity. It may not be appropriate to assume that maintenance of present nutrient loading rates is consistent with desirable productivity levels, given concerns with potential eutrophication. Several approaches to establishment of a minimum nitrogen loading rate were considered.

An assessment of minimal nitrogen needs for continuance of characteristic productivity can start with the early historical nitrogen loading to the system. We can infer that the estuary was healthy and productive under those pre-modern conditions. The nitrogen loading rate characteristic of those pre-modern conditions should serve as an appropriate minimal loading requirement. There are complications in the application of this concept, because the estuary differed in other ways prior to regional development from its current state, and the influence of these changes can not be completely known. For Sabine Lake, the major reservoirs upstream and the dredged ship channel which by-passes the lake proper comprise major complications to the system.

Prior to growth of the urban areas and irrigated agricultural development in the basin, inflows to the bay would have carried nitrogen at concentrations lower than what we find today. Those pre-modern concentrations should be similar to concentrations now found in streams not impacted by man's activities. Twidwell and Davis (1989) have documented nutrient concentrations in stream segments identified as relatively un-impacted. These data are similar to those compiled by Omernik (1976) for similar landuse categories. From these data, a reasonable estimate of natural stream concentrations is on the order of 0.6 mg/l N. Actually, the recent flow-weighted average TN concentration for all sources to Sabine Lake is only a little higher, at 0.9 mg/l N.

An un-impacted inflow TN concentration was combined with median inflow volume to produce an estimate of pre-development nitrogen load to Sabine Lake. Using an unimpacted stream concentration of 0.6 mg/l N and a median inflow, compensated for diversions, the annual TN load is $11409 \cdot 10^6$ g N /y from the drainage basin. This rate is proposed as a target minimal nitrogen load, capable of supporting an estuary productivity historically characteristic of the system.

The historical TN load from tributary inflow is translated to an inflow requirement by computing how much freshwater inflow would deliver the required nitrogen at today's actual concentrations of TN, and including wastewater inputs from coastal watersheds. A nitrogen loading of $11409 \cdot 10^6$ g N /y would be delivered by approximately 10,281,600 acre-ft/y inflow, at present volume weighted average stream concentrations.

This nutrient constraint was not included explicitly as a constraint in TxEMP, because of the uncertainties which it involves. It was instead used to evaluate the results in discussion of target inflow levels.

SEDIMENT CONSTRAINT

Sediment Estimates for Freshwater Inflows of Sabine Lake

A good deal of data is available related to the suspended sediment load of the Sabine River. As shown in Table 10, the USGS has collected flow data at 7 sites on the lower portion of the Sabine River for an extended period of time. The TWDB has collected daily suspended sediment data at two of these sites, Tatum, TX and Logansport, LA. The USGS has collected some suspended sediment data at Ruliff, TX.

Table 10. Flow and Sediment Data Records on Sabine River

Location	River Mile	USGS Gage #	Flow Record	Sediment Record
Tatum, TX	339.4	08022000	10/1/38-9/30/78	6/1/68-5/31/89[1]
Beckville, TX	327.0	08022040	10/1/78-present	
Logansport, LA	267.1	08022500	7/1/03-4/30/68	10/1/64-2/29/68[1]
Toledo Bend Reservoir, TX	156.5	08025360	10/1/71-present	
Burkeville, TX	139.7	08026000	9/1/55-present	
Bon Weir, TX	97.7	08028500	10/1/23-present	
Ruliff, TX	40.2	08030500	10/1/24-present	10/74-8/95[2]

[1] TWDB daily suspended sediment data.

[2] USGS suspended sediment data on selected dates.

Unfortunately, the data record is not well suited for estimating the sediment inflow requirements for Sabine Lake. The TWDB sediment sampling sites were a considerable distance from the mouth of the Sabine River and upstream of the Toledo Bend Reservoir site. The sediment data collected by the USGS at Ruliff, TX does not begin until 1974, well after October 3, 1966, the date when Toledo Bend Reservoir began impounding water. There are no direct sediment measurements near the mouth of the Sabine River prior to the completion of Toledo Bend Reservoir. As a result, it is impossible to estimate sediment conditions prior to completion of this reservoir project.

Observed suspended sediment data from the USGS gage at Ruliff, TX, can be used to estimate the suspended sediment entering Sabine Lake since completion of Toledo Bend Reservoir. This data is shown in Figure 1. Equations of the following form were developed to fit this data:

$$S = A * Q^{B}$$

where S is the expected sediment load per day in tons, Q is the daily flow in cfs, and A and B are coefficients that vary with the range of flow. Coefficients A and B were chosen to minimize the sum of squared errors between observed and predicted sediment load over the specific flow range. Flow ranges and coefficient values are shown in Table 11.

These equations were combined with the flow record at Ruliff, TX in order to model sediment load for days when sediment data was not available. A complete series of annual sediment loads was developed for the period from 1966 to 1999 and results are shown in Figure 2. From this Figure, it can be seen that annual suspended sediment loads have varied within the range from 80,000 to 500,000 tons per year since the construction of Toledo Bend Reservoir. There is no data available to determine how this compares with pre Toledo Bend conditions.

The daily flow record from USGS gage # 08030500 was analyzed in order to determine if there were any changes in the hydrology of the Sabine River at Ruliff, TX since the completion of Toledo Bend Reservoir. Results, shown in Figure 3, demonstrate what appear to be very minor changes in the flow regime. After completion of Toledo Bend Reservoir, the frequency of flows less than 1000 cfs decreased, while the frequency of flows in the range from 20,000 to 40,000 increased by a very small amount. The frequency of all other flows remained the same.

The effect on sediment inflow to Sabine Lake due to these changes in the hydrology can not be determined from the available data. It is possible to construct a curve showing the amount of the total sediment load that can be attributed to flows in excess of certain values, as shown in Figure 4, for the current conditions. However, this curve may not be suitable for estimating conditions prior to the completion of Toledo Bend Reservoir. If conditions prior to and after completion of Toledo Bend are similar, the decrease in flows less than 1000 cfs should have very little effect on the annual sediment load of the Sabine River. Flows in this range have provided less than 1 percent of the total sediment load during post Toledo Bend conditions. Flows in the range from 20,000 to 40,000 cfs, however, have been responsible for almost 20% of the total sediment load. A small increase in the number of flows in this range could increase the total sediment load. Without data for conditions prior to Toledo Bend Reservoir, however, it is impossible to estimate these changes with any certainty.

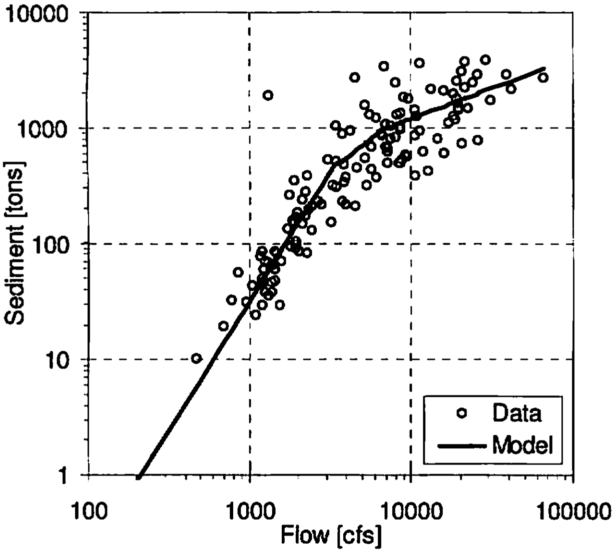

Figure 1. Observed and Modeled Suspended Sediment Load at Ruliff, TX.

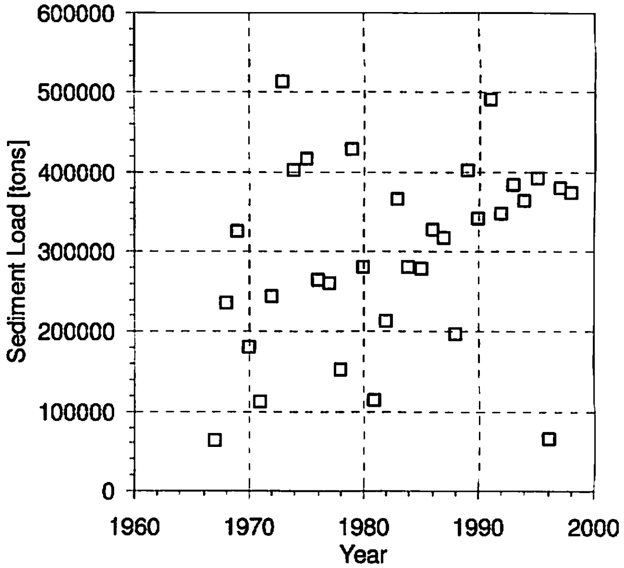

Figure 2. Modeled Annual Suspended Sediment Load at Ruliff, TX.

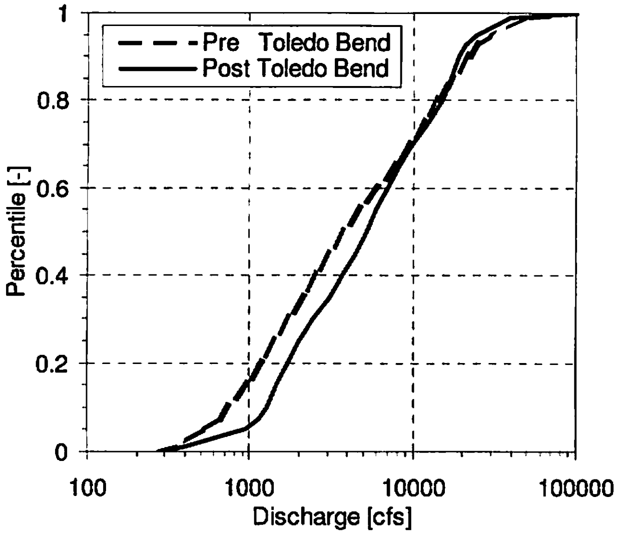

Figure 3. Flow Frequency Curves for Sabine River at Ruliff, TX.

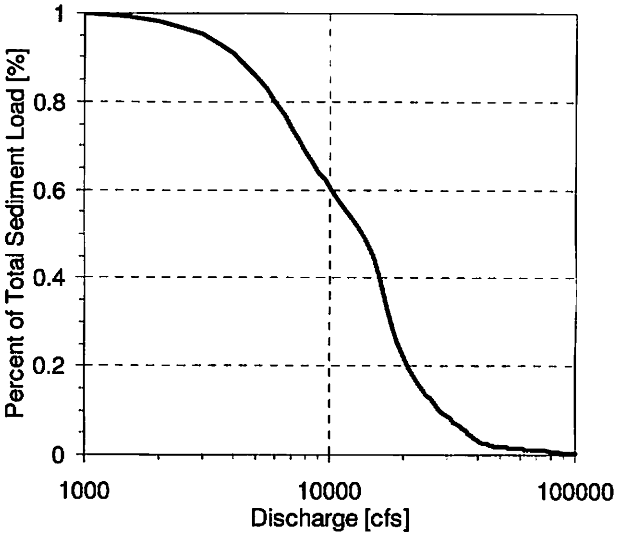

Figure 4. Sediment Load Provided by Flows in Excess of Specified Value.

Table 11. Coefficient Values of Sediment Model for Sabine River at Ruliff, TX.

Coefficient	Q < 200 cfs	200 cfs < Q < 3475 cfs	Q > 7000 cfs
A [tons/cfs]	6.62×10^{-6}	0.0731	8.975
B [unitless]	2.225	1.0749	0.531

SALINITY-INFLOW EQUATIONS

Salinity data for the period 1977 through 1997 were used to prepare the salinity-inflow equations. Salinity was calculated as a function of two values, the total of the inflows in the 30-day period immediately prior to the salinity measurement (Q1) and the total of the inflow in the period 30 to 60 days before to the salinity measurement (Q2). In the equations below, S is salinity in psu, Q is the monthly combined inflow in 1000 acre-ft, and ln is the natural logarithm function.

Upper Sabine Lake $S_{USL} = 41.7760 - 4.3824*\ln(Q1) - 0.9153*\ln(Q2)$

Mid Sabine Lake $S_{MSL} = 42.1146 - 4.6393*\ln(Q1) - 0.7225*\ln(Q2)$

Lower Sabine Lake $S_{LSL} = 61.2663 - 7.1793*\ln(Q1) - 0.0521*\ln(Q2)$

Table 12: Salinity-inflow regression equation statistics.

Salinity Zone	N	Adj. R^2	S.E.	p-value
Upper Sabine Lake	503	0.73	1.8841	>0.01
Mid Sabine Lake	184	0.71	1.0154	>0.01
Lower Sabine Lake	381	0.75	2.8260	>0.01

CATCH-INFLOW EQUATIONS

Catch and inflow data described above were used to developed catch-inflow equations. Because fisheries species are represented by catch data and catch is comprised mostly of juveniles of the species, the inflow lagging for fishery-inflow relationships described in Longley (1994), for fisheries harvests of adults, are not appropriate. Fishery-inflow relationships used were: 1) annual catch regressed against water year inflow for brown shrimp, blue crab, red drum, and spot, 2) annual catch regressed against calendar year inflow for white shrimp, and 3) annual catch regressed against the average of concurrent and previous water years inflow for croaker and spotted seatrout. (Water year is defined as the annual period beginning with inflows in September of the previous calendar year, through the current year August inflow.) In order to improve R^2, outliers were identified via Cook's distance, standardized residual, and Mehalanobis distance, and were omitted from regression analysis on a trial and error basis. No more than 10% of the data were omitted as outliers.

In the equations below, C is annual bag seine catch in number of individuals per hectare (ind./ha.) and Q_p is the sum of inflows for a two-month period in 1000 acre-ft. (Q's subscript, P, is SO for September-October, ND for November-December, JF for January-February, MA for March-April, MJ for May-June, and JA for July-August). "ln" is the natural logarithm function.

Blue Crab: $C_{bc} = 1146.6 - 0.0303*Q_{JF} - 0.05778*Q_{MJ} + 0.0692*Q_{SO} - 0.1661*Q_{ND}$

Brown Shrimp: $C_{bs} = 11073 - 1.2238*Q_{MA} - 0.7837*Q_{MJ}$

Croaker: $C_{cr} = 194.41 - 0.5437*Q_{JF} + 0.8295*Q_{MA} - 0.2000*Q_{JA} + 0.8320*Q_{SO}$

Menhaden: $\ln(C_{mn}) = -12.781 + 0.7758*\ln(Q_{JF}) - 0.2715*\ln(Q_{MJ}) + 3.3412*\ln(Q_{SO}) - 0.7786*\ln(Q_{ND})$

Red Drum: $C_{rd} = 17.606 - 0.0189*Q_{JF} - 0.0190*Q_{MJ} + 0.1281*Q_{JA} + 0.0338*Q_{SO}$

Speckled Trout: $\ln(C_{st}) = 8.2787 + 0.3267*\ln(Q_{MA}) - 1.4519*\ln(Q_{MJ}) + 1.0125*\ln(Q_{JA}) - 0.4809*\ln(Q_{SO})$

Spot: $C_{sp} = 1860.2 - 0.2650*Q_{MA} - 0.0873*Q_{ND}$

White Shrimp: $C_{ws} = 10399 + 0.6125*Q_{JF} - 0.7230*Q_{MA} - 0.6755*Q_{MJ} - 0.6866*Q_{ND}$

Table 13: Catch-inflow equation statistics.

Species	N-Used	Yr deleted	R^2	Adj.R^2	S.E.	P-value	D-W
Brown Shrimp	14	0	0.76	0.71	1885.5	0.0004	1.549
Blue Crab	13	1994	0.80	0.70	115.3	0.0070	1.944
Croaker	13	1996	0.83	0.74	480.7	0.0040	2.023
Menhaden	13	1996	0.74	0.61	0.61	0.0191	2.138
Red Drum	14	0	0.95	0.93	46.4	0.0000	2.246
Spotted Seatrout	13	1995	0.77	0.65	0.29	0.0118	2.345
Spot	14	0	0.73	0.68	340.3	0.0007	1.652
White Shrimp	12	1995,1999	0.80	0.68	1225.65	0.0143	2.022

RESULTS

Execution of TxEMP yielded minimum inflow (MinQ) of 7.11 x 10^6 acre-ft/yr, maximum inflow (MaxQ) of 11.62 x 10^6 acre-ft/yr, and maximum total catch (MaxC) at inflow of 9.60 x 10^6 acre-ft/yr. It is the consensus of the Bays and Estuaries teams from both the TWDB and TPWD that inflow recommendations between MinQ and MaxQ satisfy all constraints and produce biologically feasible results.

Table 14. TxEMP inflow solutions for The Sabine-Neches Estuary, thousands of acre-feet.

Month	MinQ-Sal	MinQ	MaxC	MaxQ
Jan	438.9	624.0	1246.4	1246.4
Feb	354.3	832.5	1539.2	1539.2
Mar	482.0	998.0	1565.8	1867.0
Apr	416.2	778.6	1136.6	1355.3
May	379.8	691.9	691.9	1348.0
Jun	427.5	478.7	478.7	845.2
Jul	377.6	424.4	547.3	547.3
Aug	427.8	361.7	466.5	466.5
Sep	172.6	574.6	574.6	574.6
Oct	429.1	537.9	537.9	537.9
Nov	378.1	237.6	237.6	378.1
Dec	426.7	574.1	574.1	913.8
Total	4710.5	7114.0	9596.6	11619.3

LITERATURE CITED

Armstrong, N. E., G. W. Ward. 1998. Analysis of point source discharges (including oilfield brine discharges) in the Corpus Christi Bay National Estuary Program Study area. CCBNEP-30. Texas Natural Resource Conservation Commission, Austin, Texas. 224 pp.

Baird, C., M. Jennings, D. Ockerman, T. Dybala. 1996. Characterization of nonpoint sources and loadings to the Corpus Christi National Estuary Program Study area. CCBNEP-05. Texas Natural Resource Conservation Commission, Austin, Texas. 225 pp.

Brock, D. A. 2001. Nitrogen budget for low and high freshwater inflows, Nueces Estuary, Texas. Estuaries 24:509-521.

Flint, R.W., G.L. Powell, R.D. Kalke. 1986. Ecological effects from the balance between new and recycled nitrogen in Texas coastal waters. Estuaries 9:284-294.

Fontaine, C. T. and J. W. Neal. 1971. Length-weight relationship for three commercially important penaeid shrimp for the Gulf of Mexico. Transactions of the American Fisheries Society 100:584-586.

Harrington, T. A., G. C. Matlock, and J. E. Weaver. 1979. Standard-total length, total length-whole weight and dressed-whole weight relationships for selected species from Texas bays. Texas Parks and Wildlife Department, Technical Series. No. 26. 6 pp.

Longley, W. L., ed. 1994. Freshwater inflows to Texas bays and estuaries: ecological relationships and methods for determination of needs. Texas Water Development Board and Texas Parks and Wildlife Department, Austin, TX. 386 pp.

Matsumoto, J., G. Powell, and D. Brock. 1994. Freshwater-inflow need of estuary computed by Texas Estuarine MP model. Journal of Water Resources Planning and Management 120:693-714.

National Oceanic and Atmospheric Administration and Environmental Protection Agency. 1989. Strategic assessment of near coastal waters: Susceptibility and status of Gulf of Mexico estuaries to nutrient discharges. Strategic Assessment Branch, National Ocean Service/National Oceans and Atmospheric Administration, Rockville, Maryland. 35 pp.

National Research Council. 2000. Clean Coastal Waters: Understanding and reducing the effects of nutrient pollution. National Academy Press. Washington D.C. 405pp.

Nixon, S. W., J. Ammerman, L. Atkinson, V. Berounsky, G. Billen, W. Boicourt, W. Boynton, T. Church, D. DiToro, R. Elmgren, J. Garber, A. Giblin, R. Jahnke, N. Owens, M. E. Q. Pilson, and S. Seitzinger. 1996. The fate of nitrogen and phosphorus at the land-sea margin of the North Atlantic Ocean. Biogeochemistry 35:141-180.

Omernik, J.M. 1976. The influence of land use on stream nutrient levels. EPA 600/3-76-014. USEPA, Corvallis, OR. 106pp.

Powell, G. L., J. Matsumoto, and D. A. Brock. 2002. Methods for determining minimum freshwater inflow needs of Texas bays and estuaries. Estuaries 25: 1262-1274.

Press, W. H., B. P. Flannery, S. A. Teukolsky, and W. T. Vetterline. 1986. Numerical recipes: the art of scientific computing. Cambridge University Press, NY. 818pp.

Pullen, E. J. and W. L. Trent. 1970. Carapace width-total weight relation of blue crabs from Galveston Bay, Texas. Transactions of the American Fisheries Society 4:795-798.

Ritter, C. and P. A. Montagna. 1999. Seasonal hypoxia and models of benthic response in a Texas bay. Estuaries 22:7-20.

Stockwell, D.A. 1989. Nitrogen process study (NIPS), effects of freshwater inflow on the primary production of a Texas coastal bay system. Report of Texas Water Development Board, by Marine Science Institute, University of Texas at Austin, Port Aransas, TX.

Twidwell, S.R. and J.R. Davis. 1989. An assessment of six least disturbed unclassified Texas streams. LP 89-04, Texas Water Commission. 243pp.

Walker, W. W. 1996. Simplified Procedures for eutrophication assessment and prediction: User manual. Instruction Report W-96-2. US Army Corps of Engineers, Waterways Experiment Station. 235p.

Whitledge, T.E. 1989a. Data Synthesis and Analysis, Nitrogen Process Study (NIPS): Nutrient Distributions and Dynamics in San Antonio Bay in Relation to Freshwater Inflow. Report to Texas Water Development Board, by Marine Science Institute, University of Texas at Austin.

Whitledge, T.E. 1989b. Data Synthesis and Analysis, Nitrogen Process Study (NIPS): Nutrient Distributions and Dynamics in Nueces/Corpus Christi Bays in Relation to Freshwater Inflow. Report to Texas Water Development Board, by Marine Science Institute, University of Texas at Austin. 86 pp.