FRESHWATER INFLOW RECOMMENDATION FOR THE LAGUNA MADRE ESTUARY SYSTEM

By

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September 2004

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APPENDIX

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September, 2004

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EXECUTIVE SUMMARY

Freshwater inflows (FWI) from rivers, streams, and local runoff maintain the salinity gradients, nutrient loading, and sediment inputs that in combination produce an "ecologically sound and healthy estuary." This report summarizes the studies conducted by Texas Parks and Wildlife Department (TPWD) studies in order to determine the freshwater inflow amounts needed to sustain the unique biological communities and ecosystems characteristic of a "healthy" Laguna Madre estuary system.

Methods for determination of the quantity and quality of FWI needed to maintain Texas' estuaries have been developed by the State Bays and Estuaries Research Program (consisting of the Texas Water Development Board [TWDB] and TPWD). These methods, which rely on computer optimization and hydrodynamic modeling, estimate a minimum FWI (termed the MinQ flow) and maximum catch FWI (termed MaxC flow) for each estuary. In this report, the FWI regimes proposed from the modeling were evaluated for their effectiveness in maintaining historical fisheries production in the Upper and Lower Laguna Madre. In our analysis, fisheries-independent bay trawl survey results from the TPWD Coastal Fisheries Resource Monitoring Database were used to verify the computer simulations. Observed fishery species distributions were evaluated and compared to the FWI regimes proposed from the modeling. The comparisons of the modeled conditions to those of the observed data forms the basis for a recommended FWI amount that is expected to maintain the "biological health and productivity" of the Laguna Madre estuary.

REVIEW OF TWDB/TPWD MODELING RESULTS

The Estuarine Mathematical Programming or Optimization Model (TxEMP) produces a range of solutions that simultaneously predict seasonal (monthly) inflows, and the corresponding estuarine fishery catches, which all satisfy multiple model constraints (see Appendices prepared by TWDB). Minimum and maximum annual inflows (MinQ and MaxQ) computed by TxEMP for the

Upper Laguna Madre (ULM) were 21,530 and 31,010 acre-ft/year, respectively. The model predicted that maximum fisheries catch (MaxC) in the ULM would occur at 22,770 acre-ft/yr. Minimum and maximum annual flows in the Lower Laguna Madre (LLM) were approximately 10-fold greater than those in ULM (MinQ = 214,950 acre-ft/year and MaxQ = 248,900 acre-ft/year). Maximum catch inflow in LLM was also an order-of-magnitude higher than in the ULM (MaxC = 228,330 acre-ft/year).

TPWD STUDIES OF OBSERVED BIOLOGICAL RESPONSES TO TARGET FRESHWATER INFLOWS

Two types of verification analyses were performed on the computed FWI targets identified from TxEMP: 1) Evaluating the seasonal biotic effects of salinity regimes predicted from the TXBLEND model; and 2) Correlating observed abundance of representative fisheries species with historical hydrologic regimes, and comparing these natural flow regimes to the predicted target flows.

Salinity Gradient Effects of MinQ vs. MaxC Flows Predicted from Modeling

Geographic Information System (GIS) techniques were used to compare and contrast the salinity gradients under optimized MinQ and MaxC inflows from the hydrodynamic model (TXBLEND) output. These maps were generated using Arc/Info® software to contour the predicted salinities from various model runs. Two different hydrologic cycles in the Laguna Madre estuary were examined: the 1988-89 period which was a dry cycle (combined surface inflows = 328,845 acre-ft average for both years), and the 1991-92 periods which was a wet weather cycle (623,005 acre-ft/year average). Predicted conditions in LLM under either hydrologic cycle produced only slight differences in salinity (< 1.0 ppt) between the MinQ and MaxC cases. Larger salinity differences (on the order of 7 ppt) were noted in the ULM between MinQ and MaxC, but these differences were seen only during the wet weather cycle. Under either hydrologic model scenario, the overall hypersaline character of the Laguna Madre Estuary system was maintained, with little to no differences in the predicted salinity structure between the MinQ and MaxC solutions throughout the estuary as a whole.

Time Series Analysis of Predicted Salinity at Critical Sites

Time-series analyses were performed on the salinity data from the TXBLEND model at six sites in the estuary system to determine if the model constraints for salinity would be maintained by the target FWI flows (Figures 3.9 – 3.14). The MinQ and MaxC cases were nearly identical, exceeding the salinity constraints on many days during either weather year types (DRY years vs. WET years, see Fig. 3.13). Overall, salinity values predicted by MinQ and MaxC flows under DRY year conditions exceeded salinity constraints similarly in the LLM. Although MinQ and MaxC flows produced a very similar overall salinity structure in the ULM, MaxC flows in the WET weather simulation were more effective in limiting the number of days salinity was above the upper constraint bound at each model node.

Spatial Representations of Fisheries Abundance and Historical Hydrology

Using bay trawl surveys from the period of 1982-2001, conducted under the Coastal Fisheries standardized sampling program, spatial distribution maps of seven target species of shellfish and finfish (brown and white shrimp, blue crab, Atlantic croaker, black drum, spot, and pinfish) found in the estuary were compiled. These GIS plots compared species' seasonal abundance to the historical salinity structure of the bay, allowing for the visualization of any subtle spatial patterns that might provide better insight to the effects of FWI. Salinity plots based on historical data corroborated the salinity structure identified by the TxEMP derived physical modeling, namely that a general hypersaline structure existed throughout the estuary system as a whole, and severely compressed salinity gradients existed only in the immediate areas adjacent to the inflow locations. Little to no relationship was found between the spatial distribution of any of the target species and the freshwater inflow influenced salinity structure of the estuary.

Significant spatial distributions (based on a Savage scored, Kruskal-Wallis nonparametric test) were seen for each of the target species across the five major salinity zones delimited within the estuary (Tables 3.6 & 3.7), but these salinity preferences were not maintained directly by FWI. Larger-scale forcing conditions (e.g., shallow water depths coupled with high evaporation rates, high residence times, and limited precipitation) appeared to be maintaining the salinity structure seen in this estuary. Species distributions are thought to be more closely tied to habitat associations (e.g., with seagrasses, the dominant submerged aquatic vegetation found within the system) than to any direct salinity effects of FWI.

TARGET INFLOW RECOMMENDATION

TPWD recognizes that neither MinQ nor MaxC inflow scenarios produce the broad salinity gradients typical of most estuarine systems in Texas, and as such, these inflow targets need to be placed in the context of the unique geological, hydrological, and climatolgical nature of the Laguna Madre Estuary. While the Laguna Madre does receive substantial FWI amounts (primarily in the LLM via the Arroyo Colorado), these inflows have little effect on any estuary-wide salinity structure. Despite this, the Laguna Madre Estuary remains the one of the most productive bay system in Texas for finfish and this productivity can be ultimately linked to the seagrass-based food web characteristic of this unique system. TPWD staff therefore recommends "No Action" or a status quo in lieu of any specific FWI target value. This recommendation is made with the acknowledgement that, while FWI is recognized to be a vital factor in protecting and maintaining the biological needs of most estuarine systems, the unique characteristics of the Laguna Madre defy the normal classifications applied to estuaries.

SECTION 1: INTRODUCTION

1.1. Background for Bay and Estuary Studies

Each Texas estuary needs freshwater inflow (FWI) to maintain proper salinity regimes, nutrient loading, and sediment inputs to support its geographically unique, historical levels of biological productivity. Freshwater inflow from rivers, streams, and local runoff carries these necessary materials into the receiving estuary, and collectively, these inflow-dependent processes help to maintain an "ecologically sound environment." So that the limited freshwater resources of Texas may be developed while minimizing any associated biological impacts to the State's estuaries, the Texas Parks and Wildlife Department (TPWD) has been charged with identifying specific quantities and qualities of FWI needed to maintain productivity in each receiving bay or estuarine system (Texas Water Code Sec. 11.1491). For water resources management purposes, TPWD describes the maintenance or target FWI as the level of inflow needed to sustain the historical, average biological productivity of economically important and ecologically characteristic fish and shellfish species, in addition to the maintenance of their associated biological communities. This report summarizes the protocol and analyses used to evaluate the minimum target FWI needed to support a healthy fishery community characteristic of the Laguna Madre Estuary system (Figure 1).

The objectives, research design, and analytical methods for the freshwater inflow studies were originally detailed in the published Report by the Texas Water Development Board (TWDB) and TPWD, "Freshwater Inflows to Texas Bays and Estuaries: Ecological Relationships and Methods for Determination of Needs" (Longley 1994). These methodologies are the result of interagency programs conducted in accordance with TWC Sec. 16.058, to collect bay and estuary data and conduct studies to determine conditions necessary to support a sound ecological environment. TWDB developed the hydrologic modeling techniques and compiled data on coastal and physical/hydrologic factors, while TPWD evaluates any trends in the biological survey data and provides ecological data synthesis. The modeling procedures from these earlier efforts (Longley, 1994) have been further refined and applied to three estuary systems (see Pulich et al. (1998) for the Guadalupe Estuary; Lee et al. (2000) for the Trinity-San Jacinto Estuary; and Pulich et al. (2002) for Nueces Estuary).

1.2. Objectives – Assessing Target Flows from Optimization Models

The modeling studies predict two important target flows, a minimum flow, termed MinQ, and a maximum harvest flow, termed MaxH. The concept of MinQ implies there is a minimum threshold at the lower end of the FWI range where one of the primary functions of FWI becomes a limiting factor in biological production (whether it's the maintenance of a salinity regime or the supply of nutrients, particulate organic matter, and/or sediments). MaxH constitutes the target flow to the estuary that is consistent with maximum historical biological productivity as measured by fisheries-dependent commercial landings.

An implied understanding in these biological "target" definitions is that when sufficient river flow does occur, the receiving estuary should receive its full recommended amount prior to any new diversions being implemented. When available flows within a river are lower than the target due to hydrologic conditions, (e.g., drought) flows to the estuary should decrease correspondingly. Management of river flows to supply FWI targets is then regarded as an implementation issue, and obviously, such management depends on the availability of river waters and return flows. The challenge is to develop watershed management strategies which provide the receiving estuary with target flow amounts at nearly the same frequencies as the historical record.

The MinQ target flow is distinct from the lowest subsistence flow, termed MinQ-Sal, which represents the lowest critical inflow level needed to maintain water quality only. Subsistence inflows occur between the MinQ-Sal level and the MinQ target flow. At subsistence inflow levels, biological productivity and fisheries harvest become very unpredictable and, by definition, can become significantly reduced from average historical levels.

TPWD objectives in this report are to evaluate the effectiveness of the predicted MinQ and MaxH target flows in producing and maintaining beneficial environmental conditions for the biota. If, after verification analysis, the predicted MinQ value is shown to maintain historical fisheries levels, then it could be recommended for management purposes. Alternatively, if MaxH is needed to accomplish this, then this value would be recommended. If neither target flows were to meet the stated goals of maintaining the biological productivity and ecological health of the estuary, then the constraints or other inputs to the model would need to be re-evaluated. Because MinQ-Sal is not considered a target flow value (by definition it does not maintain reasonable historical biological productivity levels in the estuary), no evaluation of this subsistence flow was conducted. This report describes the analyses performed to assess the proposed target inflow levels (MinQ and MaxC) in relation to observed biotic responses under known historical inflow conditions.

SECTION 2: ANALYTICAL PROTOCOL AND MODELING OUTPUT

The protocol for verifying the FWI target flows begins with a review of the input of the optimization and hydrodynamic models. Complete analytical details, including model constraints used in the Texas Estuarine Mathematical Programming (TxEMP) or Optimization Model, are presented in the Appendices. TxEMP quantitatively integrates published scientific information, field monitoring data, fisheries-independent catch data, and statistical probability analyses, into a mathematical determination of theoretical inflow targets. Subsequent procedures performed by TPWD to independently verify the predicted FWI targets and develop a FWI recommendation for the Laguna Madre Estuary are the subject of this report.

TxEMP model solutions depend heavily on the assumptions and limiting input constraints developed from hydrological and biological monitoring data sets. TWDB and TPWD formulated salinity constraints used in the TxEMP model for six different regions of the Laguna Madre Estuary (see Appendix A, Tables 2 – 4; and Appendix B, Tables 2 – 4). These critical constraints were developed using historical salinity data collected over 30 years (period of record covers 1970-1999). These long term discrete salinity measurements were supplemented with continuous salinity readings from recent years. Salinity constraints were additionally based on the published salinity tolerance ranges for many indigenous fisheries species. These monthly salinity upper and lower bounds should not be considered optimal limits, but rather the seasonal viability limits for species characteristic of this particular estuarine system.

TxEMP, which uses multi-objective functions while incorporating statistical uncertainty into the inflow solution, produces a range of feasible solutions that simultaneously predict inflows and the corresponding estuarine fishery catch levels (Matsumoto 1994). An important result of the optimization procedure is the delineation of an optimal, seasonal (monthly) inflow pattern characteristic of the estuary. The monthly TxEMP output is then used as input to the hydrodynamic circulation model (TXBLEND), to evaluate hourly and daily effects on salinity distributions and bay circulation. For the Laguna Madre Estuary, two separate TxEMP performance curves were generated, one for the Upper Laguna Madre (ULM) and another for the Lower Laguna Madre (LLM). These two optimal inflow solutions were then used jointly to model the circulation of the estuary with TXBLEND.

2.1. Review of Optimization Model Results

The TxEMP model generates a performance curve (see Longley, 1994) that graphically describes how varying amounts of total annual inflow affect fishery production. Performance curves for Laguna Madre Estuary were produced by first finding the endpoints, the minimum (MinQ) and maximum (MaxQ) annual inflow, which satisfied all model constraints. From this analysis, MinQ for the ULM was found to be 21,530 acre-ft/year and MaxQ was 31,020 acre-ft/year (Fig. 2.1). Model results for the LLM were approximately an order of magnitude higher, with MinQ at 214,950 acre-feet/year and MaxQ at 248,900 acre-feet/year (Fig. 2.2). Even though annual inflow is limited to the minimum amount necessary to satisfy the constraint set, monthly inflows are distributed in a seasonal pattern that is the most beneficial for the organisms.

In past inflow analyses, the ecological integrity and economic productivity of the estuary has been incorporated into TxEMP through the use of equations relating fishery harvest (fisheries-dependent commercial harvest landings in lbs/yr) to bimonthly inflows. In the present analysis, bag seine catch data (fisheries-independent, routine monitoring data as individuals/ha.) were used instead of commercial harvest landings. The rational for using these fisheries-independent data is presented in the Appendices. TxEMP was executed to optimize for biological production as measured by fisheries-independent catch (herein referred to as MaxC instead of MaxH) within the range of annual inflows between MinQ and MaxQ at a 50% salinity probability level. The monthly distribution of inflows was found by allowing TxEMP to optimize for the maximum possible catch (MaxC). Intermediate points on the performance curves were generated by limiting the range of possible inflows to narrow intervals while solving for MaxC. Optimal MaxC values were found at 22,770 acre-feet/yr for ULM and 228,330 acre-feet/year for LLM. The MaxC solutions also revealed an approximate order of magnitude difference between the upper and lower portions of the estuary. Monthly inflow patterns under the MinQ and MaxC constraint scenarios are illustrated in Fig. 2.3, while Table 2.1 (ULM) and Table 2.2 (LLM) lists these monthly inflow levels along with the upper and lower percentile inflows used as constraints for the model. Monthly inflows were distributed in a bimodal fashion, with peak inflows seen during April, May, and June and a secondary peak during September and October. This bimodal distribution of annual inflows in similar to other Texas Bays (see Lee et al. 2000, Pulich et al. 2002)

2.2. Review of TXBLEND Model Summary

The effect of annual and seasonal inflows predicted by TxEMP were assessed using TXBLEND, the two dimensional, finite element hydrodynamic model developed by TWDB that simulates estuarine circulation and predicts salinity patterns resulting from varying freshwater inflow regimes. Annual and seasonal distributions of MaxC and MinQ inflows predicted by TxEMP were used as input for the TXBLEND model under differing scenarios. Because the Laguna Madre Estuary exhibits a high degree of annual variability in its hydrology (Fig. 2.4), two different simulations (a DRY year and a WET year scenario) were carried out in order to compare the MinQ and MaxC output. Actual tidal and climatic conditions measured in 1988-89 (a drought period with combined annual inflows = 328,845 acre-ft/year) were used as input for the DRY weather cycle, while conditions during 1991-92 (annual inflows = 623,005 acre-ft/year) were used to simulate a WET weather cycle.

Table 2.1. Monthly Inflow Bounds (10th and 50th percentile historical inflows) and Predicted Target Inflows (MinQ and MaxC) for the Upper Laguna Madre. Values in thousands of acre-feet.

Month	Inflow Bounds		MinQ	MaxC
	10th	50th		
Jan	0.58	2.23	2.08	2.08
Feb	0.81	2.12	1.55	1.55
Mar	0.60	1.84	1.26	1.36
Apr	0.64	1.75	1.20	1.29
May	1.26	2.64	1.52	1.74
Jun	0.94	3.48	2.01	2.30
Jul	1.24	1.75	1.75	1.75
Aug	1.28	1.82	1.73	1.82
Sep	1.49	2.83	1.49	1.49
Oct	1.97	6.64	3.48	3.48
Nov	0.84	2.14	1.70	2.14
Dec	0.65	1.77	1.77	1.77
Total	12.30	31.01	21.53	22.77

Table 2.2. Monthly Inflow Bounds (10th and 50th percentile historical inflows) and Predicted Target Inflows (MinQ and MaxC) for the Lower Laguna Madre. Values in thousands of acre-feet.

Month	Inflow Bounds		MinQ	MaxC
	10th	50th		
Jan	16.23	21.18	16.23	16.23
Feb	16.02	17.53	16.02	16.02
Mar	16.69	19.72	16.69	19.72
Apr	16.51	22.65	19.17	22.65
May	20.16	27.83	26.25	27.83
Jun	22.09	30.05	22.09	23.00
Jul	18.10	22.89	18.10	18.10
Aug	14.34	19.01	15.03	15.03
Sep	15.51	22.85	15.90	16.72
Oct	16.12	24.67	17.17	18.05
Nov	14.05	19.56	16.93	18.33
Dec	13.78	17.76	15.37	16.65
Total	199.60	265.70	214.95	228.33

The TXBLEND model computed salinity values over 2-hour time-steps at over 8,100 grid nodes in the Laguna Madre Estuary. Simulated salinity regimes resulting from each inflow scenario were illustrated by two output formats of data:

1. Isohalines of average monthly salinity in 5 part per thousand (ppt) increments were plotted for the estuary by month.
2. Time series plots of average daily salinity were plotted for each 2 year weather cycle at three locations in each half of the estuary. For the ULM, time series plots were generated at South Bird Island, another at the mouth of Baffin Bay, and a third in the upper reaches of Baffin Bay. In the LLM, the time series node locations were South of the Land Cut, near the mouth of the Arroyo Colorado, and at Stover Point near the southern-most end of the estuary.

SECTION 3: ANALYSIS OF BIOLOGICAL RESPONSES TO TARGET FRESHWATER INFLOWS

This Section presents the verification analyses using observed fisheries abundance and submerged aquatic vegetation distributional data to assess the predicted inflow targets. This step in the protocol provides a "reality check" of the results predicted by the models. By coupling the hydrologic regimes with field survey data of the dominant fisheries species, a picture of the community dynamics within the Laguna Madre Estuary system emerges. The abundance of typical fishery species, along with their known salinity tolerance limits or habitat requirements within the estuary are the basis for evaluating the impacts of targeted FWI regimes. By comparing effects of the modeled conditions on the estuarine biota with those observed under actual inflow conditions, we can infer whether or not the target inflows are reasonable and appropriate.

Although estuarine productivity can be assessed by a variety of criteria, the relative abundance of characteristic fisheries species was used as the primary index to gauge any effects of the target FWI amounts. Biological monitoring data on the estuarine fishery species used in this analysis were taken from TPWD bay trawl surveys as described in Fuls and McEachron (1995). If inflow regimes, salinity gradients, or other FWI-related factors correlate with the presence or relative abundance of selected indicator species (both flora and fauna), this could provide evidence of the FWI regimes needed to maintain estuarine health. Two major types of biological analyses were performed: 1) Verifying the biotic effects of salinity gradients resulting from the hydrodynamic model runs; and 2) Demonstrating correlations between representative biota and FWI regimes under actual historical hydrological conditions. Based on this fisheries-independent biological impact assessment, a final FWI recommendation can be proposed.

3.1. Effects of MinQ vs. MaxC Flows on Salinity Regimes

The TXBLEND hydrodynamic model predicts salinity gradients and their spatial distributions in the estuary system under specified inflow and weather conditions. Because output from TXBLEND consists of a grid map of salinity values at thousands of nodes throughout the bay, GIS (Geographic Information System) techniques were used to evaluate salinity maps of the model results for biological impacts. After each TXBLEND model run with the MinQ or MaxC target flows as the inflow criteria, salinity zone maps were generated for the Upper and Lower portions of the estuary with ARC/INFO™ software (ESRI, Redlands, CA). Average monthly salinity values at each grid node were subjected to spatial contouring using the Kriging module from ARC/INFO™ to produce isohaline contours in 5-ppt increments. Ten salinity zones were delineated, encompassing a salinity range from near freshwater (oligohaline) to hyperhaline sea water (> 45 ppt). Examples of these monthly salinity contour maps depicting the two different weather years (DRY year = 1988 and WET year =1991) are shown in Figures 3.1 to 3.8. Results are shown for average salinity during March, April, May, and June of each hydrologic year-type.

Examination of the GIS plots reveals that neither hydrologic year-type produced any appreciable difference between the two model inflow solutions (MinQ vs. MaxC) in terms of the salinity structure of the Laguna Madre. Generally, salinities in the Upper Laguna Madre are higher than those in the Lower Laguna Madre, with the highest salinity values routinely encountered in the middle of the estuary near Baffin Bay and the Land Cut region. This general salinity structure is primarily the result of typically low inflow coupled with the high evaporation rates characteristic of the estuary (TDWR 1983) and the circulation patterns driven by the predominant wind field and Gulf tidal passes at Port Mansfield and Brazos-Santagio Pass (Tunnell 2002a). A severely compressed salinity gradient can only be found within the immediate vicinity of the inflow locations (Figures 3.1 & 3.5). In the ULM, the only true salinity gradient (from oligohaline and low mesohaline [5-10 ppt] grading to full strength seawater, 35 ppt) can only be found in the uppermost reaches Cayo del Grullo, where San Fernando

Creek empties into this secondary arm of Baffin Bay. In LLM, the farthest extend of any true salinity gradient is centered within and near the mouth of the Arroyo Colorado (Figures 3.5 – 3.8).

Under the DRY weather scenario, salinity structure over most of the estuary is near full strength seawater (30-35 ppt) or higher (Figures 3.1 – 3.4). During the spring to early summer months, high salinity values (> 45 ppt) spread from the Land Cut region north to the middle of ULM around Bird Island, and encompass large portions of Baffin Bay. In the LLM, the influence of the Gulf passes on large scale salinity structure is evident, with the lower overall salinity in LLM mediated greatly through exchange of Gulf waters at the two tidal passes. Under WET weather conditions, the hypersaline structure of the middle of the estuary is still evident, although average salinities were depressed on the order of 10 ppt (Figures 3.5 – 3.8). The greatest difference seen between the meteorological year-types is a lowering of the magnitude of the hypersaline nature of the ULM. While large portions of the ULM are still hypersaline even under WET weather conditions, salinity values were in the range of 35-40 ppt, instead of 45-50 ppt as seen in the DRY years.

The seasonal changes in salinity gradients indicate that there is virtually no difference between the MinQ and MaxC inflow scenarios throughout the course of the year, except during WET weather conditions in the ULM (Table 3.1). The salinity contour maps showing the spatial extent of salinity zones predicted by both MinQ and MaxC inflows were essentially identical across different seasons, and the direct influence of FWI is limited to the immediate vicinity of the inflow locations. Only under the MaxC solution in the ULM subjected to WET weather conditions were seasonal differences in the simulated salinity zones appreciably different. The relatively small differences in daily mean salinities (< 1 ppt) between MinQ and MaxC flows are not considered to reflect any significant hydrologic differences between the two cases. Overall, the local climate conditions have a greater effect on the overall salinity structure of the Laguna Madre Estuary system than do the direct FWI effects at typical levels. A key characteristic of this estuary is that evaporation greatly exceeds inflow by factors of two to three times (Tunnell 2002a) and this is one of the primary reasons for the hypersaline structure seen in the model solutions.

Table 3.1. Maximum daily salinity differences (absolute value, in ppt) at key nodes in the Upper and Lower Laguna Madre between the MinQ and MaxC model solutions during WET and DRY year meteorological simulations.

	Upper Laguna Madre			Lower Laguna Madre		
Weather Year Type	South Bird Island	Mouth of Baffin Bay	Upper Baffin Bay	South of Land Cut	Arroyo Colorado	Stover Point
ULM						
DRY 88-89	0.05	0.05	0.03		–	
WET 91-92	7.10	4.62	4.84			
LLM						
DRY 88-89		–		0.05	0.27	0.06
WET 91-92				0.06	0.12	0.03

3.2. Time Series Analysis of Salinity at Critical Bay Sites

A time-series analysis was conducted on the salinity data from the TXBLEND circulation model at the six key nodes within the estuary. This technique allowed for graphic demonstration of the daily salinity fluctuations produced by the model inflows at each of these selected locations. Mean daily salinities computed from TXBLEND were also compared to the salinity criteria developed as constraints for the optimization model as listed in Tables 3.2 & 3.3. Simulated daily salinities in relation to the salinity bounds imposed by the model solutions are shown for ULM in Figures 3.9 – 3.11, and for LLM Figures 3.12 – 3.14. Time-series results depicting the DRY weather years (1988-89) and WET weather years (1991-92) are shown only for the MinQ case as the salinity differences between the MinQ and MaxC solutions were generally very small (see Table 3.1).

Table 3.2. Monthly upper (above) and lower (below) salinity bounds used in TxEMP optimization model for the Upper Laguna Madre at South Bird Island, the mouth of Baffin Bay, and the upper reaches of Baffin Bay model nodes.

Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
South Bird Island	30	30	30	30	35	35	35	35	35	35	35	35
	37	37	40	40	42	42	45	45	45	45	41	41
Mouth of Baffin Bay	30	30	25	25	25	25	32	32	32	32	28	28
	40	40	40	40	40	40	45	45	45	45	45	45
Upper Baffin Bay	30	30	25	25	25	20	20	30	30	35	30	30
	45	45	45	45	45	45	53	53	53	53	45	45

Table 3.3. Monthly upper (above) and lower (below) salinity bounds used in TxEMP optimization model for the Lower Laguna Madre at South of the Land Cut, mouth of Arroyo Colorado, and Stover Point model nodes.

Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
South of Land Cut	30	30	30	30	25	30	30	30	30	30	30	30
	45	40	40	40	36	40	40	40	40	45	45	45
Mouth of Arroyo Colorado	20	20	20	20	20	25	25	25	18	18	22	22
	32	32	32	32	35	35	36	36	36	32	32	32
Stover Point	25	25	25	30	30	30	34	34	34	30	25	25
	35	35	35	35	35	40	42	42	42	42	35	35

A further calculation was performed to determine the number of days over the simulation period that the predicted model salinities exceeded the target salinity constraints. This analysis gives a quantitative measure of how effective, on an annual basis, the target inflows from the optimization model (TxEMP) solution maintains the pre-established beneficial salinity ranges. During the DRY weather years in the ULM (1988-89), there was little difference between the model solution flows. As an example, MaxC flows produced average daily salinity values under the upper bound for only a single day more than did the MinQ flows at both the mouth of Baffin Bay and the Upper Baffin Bay nodes (Table 3.4). No difference during the DRY weather simulation was found in the time series at the South Bird Island node. In both cases, a high percentage of daily values beyond the upper salinity constraint were seen. The percentage of values greater-than the upper limit increases with increasing distance from the freshwater inflow point (approximately 31% at the inflow location at the Upper Baffin Bay node and nearly twice that amount at the mouth of Baffin Bay and South Bird Island nodes). For the WET weather conditions, the highest number of values outside the salinity bounds occurred below the lower bound, with the large inflow events of the winter of 1991 and summer of 1992 dramatically depressing salinities throughout ULM, and especially at the Upper Baffin Bay node (Fig. 3.11). Although MinQ and MaxC flows produced a very similar overall salinity structure in the ULM, MaxC flows in the WET weather simulation were more effective in limiting the number of days salinity at each model node was above the upper constraint bound.

Even less of a difference between the weather year types was seen in LLM simulations, with average salinities across the estuary falling only on the order of 2 ppt in the WET weather simulations. This 2 ppt decrease in salinity is consistent across all model nodes, and the number of days in which simulated salinities fell outside the model constraint boundaries was nearly identical (Table 3.5). At the Arroyo Colorado node under DRY weather conditions, greater than 80% of the time salinities were above the upper bound. This trend fell slightly under the WET weather conditions, but salinities were still above the upper bound ~60% of the time. The influence of the Gulf tidal passes (Mansfield Pass and Brazos-

Santiago Pass) in the LLM appears to completely thwart any direct FWI effects in terms of estuarine-wide salinity structure. Channelization in the Laguna Madre (both Gulf passes in LLM in addition to the Gulf Intracoastal Waterway connecting LLM and ULM through the Land Cut) are identified as the primary reasons for the maintenance of the salinity structure occurring in the estuary today (Simmons 1957; McMahan 1968; Quammen and Onuf 1993; Tunnell 2002a).

Table 3.4. Number of days that simulated salinities exceeded the model constraints (upper or lower bounds) at the Upper Laguna Madre modes. Simulated salinities for MaxC and MinQ flows were estimated under either DRY (1988 and 1989) or WET (1991 and 1992) weather conditions. Total number of days in the 730 day simulation above, percentage (% days) of total simulation below.

	DRY MinQ		DRY MaxC		WET MinQ		WET MaxC	
	LB	UB	LB	UB	LB	UB	LB	UB
South Bird Island	8	406	8	406	302	29	382	9
	(1.09)	(55.46)	(1.09)	(55.46)	(41.26)	(3.96)	(52.19)	(1.23)
Mouth of Baffin Bay	0	426	0	425	59	62	88	33
	(0)	(58.20)	(0)	(58.06)	(8.06)	(8.47)	(12.02)	(4.51)
Upper Baffin Bay	0	226	0	225	451	0	486	0
	(0)	(30.87)	(0)	(30.74)	(61.61)	(0)	(66.39)	(0)

Table 3.5. Number of days that simulated salinities exceeded the model constraints (upper or lower bounds) at the Lower Laguna Madre modes. Simulated salinities for MaxC and MinQ flows were estimated under either DRY (1988 and 1989) or WET (1991 and 1992) weather conditions. Total number of days in the 730 day simulation above, percentage (% days) of total simulation below.

	DRY MinQ		DRY MaxC		WET MinQ		WET MaxC	
	LB	UB	LB	UB	LB	UB	LB	UB
South of	0	163	0	162	70	131	70	131
Land Cut	(0)	(22.27)	(0)	(22.13)	(9.56)	(17.89)	(9.56)	(17.89)
Mouth of Arroyo	0	595	0	592	0	444	0	442
Colorado	(0)	(81.28)	(0)	(80.87)	(0)	(60.66)	(0)	(60.38)
Stover	52	80	52	80	103	49	103	49
Point	(7.10)	(10.93)	(7.10)	(10.93)	(14.07)	(6.69)	(14.07)	(6.69)

3.3. Spatial Representations of Fisheries Abundance and Historical Hydrology

For these analyses, the relative abundance of seven estuarine fishery species was used to assess the adequacy of the target FWI amounts. The source of fish and shellfish data was the TPWD Coastal Fisheries Resource Monitoring Program which has been conducting bag seine, trawls, and gill-net surveys in the Laguna Madre Estuary since 1975 (Hensley et. al. 2000). This survey program, based on probabilistic random sampling, collects 20 bag seine samples from around the bay system each month, although prior to 1992 only 10 samples per month were taken, and prior to 1982, 6 samples per month. Beginning in 1983, 10 trawl samples per month have been collected from both the upper and lower halves of the estuary, and prior to then, trawl samples were collected only in the LLM. Information from the gill net collections were not utilized for this report. Along with recording the relative abundance of organisms (as catch per hectare for bag seine collections and catch per unit effort, or CPUE for trawl collections), quantitative as well as qualitative hydrographic data are also collected at each sampling site. The Coastal Fisheries standardized sampling program and its use in assessing species distribution and abundance have been thoroughly discussed in the original Bays and Estuaries Report (see Chapters 6 & 7, Longley 1994,: Lee 1994, Boyd and Green 1994).

The seven target species included both shellfish (white and brown shrimp, and blue crab) and finfish (Atlantic croaker, spot, black drum, and pinfish) which were identified as the dominant (most abundant) species collected in the bag seines and trawls in the Laguna Madre system (Hensley et al. 2000; R. Blankinship personal communication). Bay trawl CPUE data (standardized to a unit effort of 1 hour) were chosen for this analysis because the bag seine data were used to derive the catch-inflow relationships (see Appendices A & B) and the trawl data constituted an additional fisheries-independent, contemporaneous dataset. For the time period covering 1982-2001, monthly average species relative abundance was calculated, and the time of the year (= season) that a species exhibited maximum abundance in the bay was delimited. From this analysis, the seasons of peak monthly occurrence for each species in the ULM (Fig. 3.15) were determined to be:

> Blue Crab (Apr - July), Brown Shrimp (Apr - July), White Shrimp (Aug - Dec),
> Black Drum (Apr - July), Spot (Sep - Dec), Pinfish (Jun - Oct)

and for the LLM (Fig. 3.16), peak seasonal abundance was determined to be:

> Blue Crab (Mar - July), Brown Shrimp (Apr - July), White Shrimp (Sep - Dec),
> Atlantic Croaker (Apr - Sep), Spot (Apr - Sep), Pinfish (Jul - Nov).

3.4. Species Profiles

Blue crab: Blue crabs (*Callinectes sapidus*) are a euryhaline, estuarine-dependent species abundant in the Laguna Madre during all life stages, with juvenile to sub-adults routinely reported from waters of 0 to 50 ppt salinity (Pattillo et al. 1997). Depending on their life stage, individuals can be neretic, estuarine, and/or riverine. Adult males spend most of their time in lower saline waters, and females move from higher to lower saline waters as they approach their terminal molt in order to mate (Steele and Bert 1994). The season of peak abundance is similar between the ULM and LLM, although blue crabs are encountered slightly earlier in the year and show a more abrupt peak in abundance in LLM (Fig. 3.16A). Blue crabs were 2-3 times more abundant in bay trawls in the LLM during their April-July season.

Brown shrimp: Brown shrimp (*Farfantepenaeus aztecus*) are euryhaline to stenohaline depending on life stage. Postlarvae have been collected from salinities from 0.1 ppt to 69 ppt, and juveniles are are distributed over 0 to 45 ppt (Cook and Murphy 1966). Adults can tolerate salinities from 0.8 ppt to 45 ppt, although their optimum range is 24-39 ppt (Zimmerman et al. 1990). In the Laguna Madre, adults are reported as common and juveniles as abundant (Pattillo et al. 1997). This species was collected seasonally from April through July, and CPUE levels were approximately equal in both halves of the estuary (Figures 3.15B & 3.16B). Larger brown shrimp were encountered in the ULM, with a mean size greater than 100 mm vs. those collected in the LLM averaging 70 mm.

White shrimp: White shrimp (*Farfantepenaeus setiferus*) are considered euryhaline because most life stages can tolerate fairly wide salinity ranges (0.3-40 ppt) although postlarvae and juveniles seem to prefer or tolerate lower salinities than do other penaeid species (Zein-Eldin and Renaud 1986). Like brown shrimp, white shrimp are abundant as juveniles and common as adults in the Laguna Madre (Patillo et al. 1997). This species was not collected in trawl samples in significant numbers until mid-summer and into fall, corresponding to the seasonal emigration of juveniles and subadults into Gulf waters for spawning. Interestingly, abundance was higher and emigration was seen earlier in the ULM (Figures 3.15C and 3.16C) despite the lack of a Gulf pass in this half of the estuary.

Atlantic croaker: Atlantic croaker (*Micropogonias undulates*) are a euryhaline, estuary-dependent species collected from waters ranging in salinities from 0-70 ppt, but are most abundant at < 15 ppt (Patillo et al. 1997). In the Laguna Madre, they are abundant as adults, juveniles, and larvae but are approximately three times more abundant in bay trawls in the LLM (Hensley et al. 2000). Atlantic croaker seasonal peak abundance was recorded from April through September (Fig. 13.16D), and peak CPUE in bay trawls was found during June, July, and August. This corresponds to their reported offshore emigration for spawning in the nearshore water of the Gulf from October through January (Ditty et al. 1988).

Black drum: Black drum (*Pogonias cromis*) are a euryhaline, estuarine-dependent species found in waters from 0-80 ppt but is most common at 9-26 ppt (Simmons and Breuer 1962). Larvae are marine to estuarine, juveniles are marine to riverine, and adults are marine to estuarine (Patillo et al. 1997). Juvenile black drum prefer unvegetated muddy bottoms in marsh habitats whereas adults are found over unvegetated sand, mud and oyster/worm reefs in addition to heavily vegetated seagrass beds (Peters and McMichael 1990). Black drum are far more abundant in ULM and have a peak seasonal abundance from April to August. The predominance of black drum in Baffin Bay could correspond with the development of pharyngeal teeth in juveniles and their dietary shift to mulloscs and crabs, which are common throughout the soft-bottom areas in the Bay.

Spot: Spot (*Leiostomus xanthurus*) are a euryhaline, estuarine-dependent species found in waters from 0-60 ppt, with large numbers occurring from 15-40 ppt (Warlen and Chester 1985). Spawning off Texas occurs in mid-shelf to offshore Gulf waters from November through April, and larvae are carried into estuarine areas by cross-shelf transport and tidal flow through Gulf passes (Cowan and Shaw 1988). Spot are abundant as adults, and highly abundant as juveniles in the Laguna Madre (Patillo et al. 1997). Abundance levels and mean sizes are approximately equal between the ULM and LLM (Figures 3.15E & 3.16E), although spot show less seasonality in the LLM. In ULM, spot are not numerous in bay trawls from February to May, whereas in LLM their abundance numbers tended to fluctuate throughout the course of the year.

Pinfish: Pinfish (*Lagodon rhomboides*) are a euryhaline, estuarine-dependent species tolerating salinities from 0-44 ppt. Pinfish can be so abundant and predaceous, they can alter the composition of estuarine faunal communities (Muncy 1984). Vegetation, rather than salinity is reported to have a greater affect on the distribution of this species (Weinstein 1979). Adults are abundant and juveniles are highly abundant in the Laguna Madre (Patillo et al. 1997). Seasonal occurrence of pinfish is highest in summer to early fall in the Laguna Madre (Figures 3.15F & 3.16F), with abundance levels highest in the LLM. This species is numerically dominant in the shallow, subtidal seagrass communities of the Laguna Madre, and its consumption of plant and detrital material is important in the export of organic materials in these estuaries (Patillo et al. 1997)

3.5. GIS Analyses

GIS plots were produced to depict species' spatial distribution and their relative abundance patterns (as CPUE) within the estuary system. This technique allowed the visualization of any subtle spatial patterns that might provide better insights into the FWI effects. Using the contemporaneous salinity data collected with the bag seine and trawl samples, actual salinity zones as measured in the field were contoured by the Kriging technique as previously described for the TXBLEND model outputs. By plotting GIS overlays depicting species abundance and the contoured salinity zones, distribution patterns can be correlated with the observed salinity gradient. Because bay trawl samples are collected only in grid locations with a mean depth greater than 3 feet (Fuls and McEachron 1995), trawl sample locations are not uniform throughout the bay (Figures 3.17 & 3.18). Owing to the relative shallowness of much of the estuary, caution must be used in interpolating the spatial significance of any species' distributional pattern across areas of the bay not sampled.

Figures 3.19 – 3.21 demonstrate the spatial relationships between CPUE relative abundance and the salinity gradient for brown shrimp, blue crab, and black drum in the ULM, and Figures 3.22 – 3.24 demonstrates these spatial relationships for white shrimp, spot, and Atlantic croaker in the LLM system. The observed salinity plots corroborate the salinity structure identified with the TXBLEND model, namely a general hypersaline condition is found throughout the estuary and a severely compressed freshwater to seawater salinity gradient is only found in the immediate vicinity of the inflow points. Little to no relationship exists between the spatial distribution of any target species and the <u>freshwater inflow influenced salinity structure</u> of the estuary.

This is not to imply that salinity-dependent spatial structure of the target species is absent within the Laguna Madre Estuary, only that the salinity structure that these distributions are correlated with is driven by much larger-scale meteorological forcing conditions rather than the direct FWI influenced effects. All the shellfish and finfish species used in this analysis showed significant affinities for areas of specific salinity structure.

Using the quantitative hydrographic information collected in the field, the estuary was divided into five salinity zones and tested for any difference in mean abundance among the zones. For the ULM, the salinity zones were < 30 ppt, 30.01-35 ppt, 35.01-40 ppt, 40.01-45 ppt, and > 45 ppt. A similar zonation was used for the LLM, except all salinity classes were reduced by 5 ppt to better represent the lower overall salinity seen in this part of the estuary. The null hypothesis of no differences in mean CPUE among the salinity zones would support the lack of spatial distributional structure, whereas rejecting the null hypothesis would mean the target species preferred some salinity zones over others. A nonparametric Kruskal-Wallis test (based on Savage scoring of the response variable) was used to test for location and scale differences among the salinity zones. Kruskal-Wallis is the nonparametric analogue to the familiar one-way Analysis of Variance. Given the positively skewed distribution in much of the trawl CPUE data (i.e., the response variable), Savage scoring is most appropriate for this analysis because this method is powerful for comparing scale differences in exponential distributions or location shifts in extreme value distributions (Hajek 1969). Results for the ULM are shown in Table 3.6 and the LLM are shown in Table 3.7.

Table 3.6. Savage scored one-way analysis (Kruskal-Wallis) of target species CPUE across the five salinity zones as measured by bay trawls in the Upper Laguna Madre. Data range includes only the identified season of maximum abundance.

Target Species	χ^2 Test Statistic	DF	*p* value
Blue Crab (Apr - Jul)	94.367	4	<0.0001
Brown Shrimp (Apr - Jul)	48.055	4	<0.0001
White Shrimp (Aug - Dec)	8.091	4	0.0883
Black Drum (Apr - Jul)	62.446	4	<0.0001
Spot (Sep - Dec)	43.911	4	<0.0001
Pinfish (Jul - Oct)	32.013	4	<0.0001

Table 3.7. Savage scored one-way analysis (Kruskal-Wallis) of target species CPUE across the five salinity zones as measured by bay trawls in the Lower Laguna Madre. Data range includes only the identified season of maximum abundance.

Target Species	χ^2 Test Statistic	DF	*p* value
Blue Crab (Mar - Jul)	47.584	4	<0.0001
Brown Shrimp (Apr - Jul)	27.967	4	<0.0001
White Shrimp (Sep - Dec)	25.566	4	<0.0001
Atlantic Croaker (Apr - Sep)	16.824	4	<0.0001
Spot (Apr - Dec)	27.736	4	<0.0001
Pinfish (Jul - Nov)	8.726	4	0.0683

In either half of the estuary, blue crabs were more abundant in the lower salinity zones (Figures 3.25A & 3.25B), with CPUE decreasing dramatically above 35 ppt. A similar pattern was seen with brown shrimp (Figures 3.25B & 3.26B), with the highest CPUE obtained in the lowest salinity zones. This agrees with the salinity tolerances presented in Zimmerman et al. (1990). White shrimp showed little salinity zonation in the ULM, with equivalent CPUE catches recorded in waters < 30 ppt as well as those from waters > 40 ppt. In LLM, white shrimp displayed a more structured distribution, with the greatest CPUE catches coming from the lower saline waters (generally < 30 ppt. see Figures 3.25C and 3.26C). Atlantic croaker in the LLM were collected in significantly higher rates from waters < 30 ppt (Fig. 3.25D), whereas black drum in the ULM had significantly higher catch rates from waters > 45 ppt (3.26D). Spot distributions showed little consistent patterns between ULM and LLM, with higher catches coming from higher salinity waters in ULM (Fig. 3.25E) and lower salinity waters in LLM (Fig. 2.26E). This dichotomy was found at the opposite ends of the spectrum, with catches of spot highest at > 45 ppt in ULM and in waters < 25 ppt in LLM. Pinfish CPUE generally increased up to the 45 ppt zone (Figures 3.25F & 3.26F) and this agrees well with the pinfish life history account presented by Patillo et al. (1997).

In previous studies (Pulich et al. 1997, Lee et al. 2000; Pulich et al. 2002), the methodology of using salinity as a proxy for FWI to establish FWI-species spatial relationships have demonstrated correspondence between abundance and salinity gradients across different estuaries. In the Laguna Madre, true salinity gradients are completely lacking except for the immediate areas surrounding the inflow locations (see Figures 3.1 – 3.9), and the estuary-wide salinity structure appears to be driven by larger-scale forcing conditions that define this unique system. While distributional patterns can be shown for each target species under investigation, these patterns are not the direct results of FWI in maintaining any preferred salinity zones.

SECTION 4: TARGET INFLOW RECOMMENDATION

The Laguna Madre, the largest of the seven bay systems along the Texas coast (Diener 1975) is unique in that it is one of only five hypersaline ecosystems in the world (Javor 1989). It is a shallow, bar-built coastal lagoon bordered by barrier islands and peninsulas to the east and the mainland to the west. No rivers flow into the Upper Laguna Madre, although several ephemeral creeks (San Fernando, Santa Gertrudis, Los Olmos, and others) flow into Baffin Bay when it rains. In the Lower Laguna Madre, the Arroyo Colorado, the dredge-maintained northern distributary channel of the Rio Grande Delta system, and the North Floodway drain much of the agricultural lands of the Rio Grande Valley (Tunnell 2002a). Although the Rio Grande once flowed into South Bay (the southern-most reach of LLM), it now drains directly into the Gulf of Mexico during normal flows and no longer influences the lagoon. While most of the FWI comes from direct precipitation, flood producing rains may occur in any given season. The most frequent inflow events are seen in September and October, and heaviest rains are associated with tropical storms and hurricanes.

The preceding analyses have shown that neither MinQ nor MaxC inflow scenarios produced the typical, broad salinity gradient, ranging from oligohaline to saline coastal ocean waters over most of the Laguna Madre. Rather, rudimentary salinity gradients seen under either model inflow regimes are typically compressed only in the immediate areas surrounding the inflow locations. This situation is quite different from systems previously examined (e.g., Galveston Bay, San Antonio Bay) and no doubt correlates with the unique conditions that define this hypersaline system. Both MinQ and MaxC inflows were considered similar in their effects based on the extent of the salinity gradients and salinity fluctuations at specific model nodes. Statistical analysis of the relationship between CPUE relative abundance and salinity showed that differences in salinity affinities could be demonstrated for each species under investigation, but the salinity structure of the system was not the direct result of FWI.

Despite the overall lack of FWI, Upper and Lower Laguna Madre remain the most productive bays in Texas for finfish and both support important recreational fisheries for species such as spotted seatrout and red drum, as well as a large commercial black drum fishery in ULM (Withers and Dilworth 2002). Historically, the productivity of fish and fisheries in this estuary was ultimately driven by hurricane-opened Gulf passes and/or the accompanying heavy rainfalls that lowered salinities which led to fisheries productivity surging for several years. These boom or bust characters have been altered as a result of navigational development (Gulf Intracoastal Waterway) and pass stabilization (Brazos-Santiago Pass and Port Mansfield Channel). While overall salinities are lower than before these alterations (Quammen and Onuf 1993), the Laguna Madre still cannot be characterized as "estuarine".

Typical estuarine ecosystems are recognized as having large quantities of freshwater inflow, turbid waters with phytoplankton-based primary production, large expanses of open bay bottom habitat, and extensive salt marshes around the margins of the bay. The Laguna Madre is a system characterized by a general lack of freshwater inflow, clear and normally phytoplankton-free waters, barren shorelines, hypersaline conditions, where seagrass meadows dominate the benthic habitat (Onuf 1996; Tunnell 2002b). Seagrasses are frequently recognized as an important estuarine nursery area, and seagrass meadows are one of the most highly productive biological communities on earth (McRoy and McMillan 1977). The spatial abundance patterns seen in the target species are more directly the result of habitat associations with seagrasses than any direct FWI-influenced salinity affinities (Bell et al. 1987: Sogard 1989; Tolan et al. 1997). Numerous studies of seagrasses and their associated fish faunas have identified the abundance of food, sediment stability, and an overall habitat complexity as important factors for different species utilizing the grassbeds (Orth et al. 1984, Bell and Pollard 1989). Similar to the overall salinity structure in the Laguna Madre, the concentration of Texas' seagrass resources (79% of the seagrass cover found in Texas estuaries is found in the Laguna Madre) is also the result of the large-scale climatological factors operating on the system, as seagrasses are found predominately in areas of low rainfall and high evaporation rates with average salinities above 20 ppt (Pulich 1997).

Large-scale factors outside the realm of any water management plan (e.g., high evaporation rates, hurricanes and tropical storms, ephemeral nature of existing surface water drainages) exert the greatest degree of control on the hydrological character of this estuary. TPWD therefore recommends "No Action" or a status quo of any existing water management strategy for the Laguna Madre Estuary. This recommendation is made with the acknowledgement that, while FWI is recognized to be a vital factor in protecting and maintaining the biological needs of most estuary systems, the unique characteristics of the Laguna Madre Estuary defy the normal classifications applied to estuaries.

In this estuary system, the importance of inflows may be highly localized. One example of localized effects is the Arroyo Colorado, which provides the majority of the freshwater inflow into the LLM. While the Arroyo is the natural drainage system for the Lower Rio Grande Valley (Bryan 1971), it provides little natural flow except for rainfall runoff. It does however receive wastewater from several towns across the Valley, in addition to assimilating the effluent from two of the largest shrimp farms in Texas. The role of FWI in addressing some of the long-standing problems occurring within the Arroyo Colorado (i.e., low dissolved oxygen, agriculture contaminants; see Flowers et al. 1998) are the subject of a Total Daily Maximum Load Project (TMDL). If this TMDL subsequently recommends specific inflow levels to rectify localized water quality issues, then those results should be taken into account when adopting any new water management strategies for the Laguna Madre Estuary.

Appendix A - Values and Constraints for the TxEMP Model Used in the Freshwater Inflow Analysis of the Upper Laguna Madre Estuary

Technical Memorandum

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Values and Constraints for the TxEMP Model Used in the Freshwater Inflow Analysis of the Upper Laguna Madre 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 Natural Resource Conservation Commission (TNRCC) providing additional expertise. The Texas Department of Health has also contributed to this effort.

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, spotted seatrout, black drum, southern flounder, and grass shrimp. Historical freshwater inflow data were determined based on standard TWDB hydrology methods, and gauged flow at two stations on rivers and creeks flowing into the Upper Laguna Madre Estuary. Execution of TxEMP yielded minimum inflow (MinQ) of 21,530 acre-ft/yr, maximum inflow (MaxQ) of 31,010 acre-ft/yr, and maximum total catch (MaxC) at inflow of 22,770 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: Christine Ritter, Bill Longley, Roger Wolff, Barney Austin, 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 Jim Tolan, Wen Lee, Warren Pulich, Dave Buzan, Cindy Loeffler, Dan Moulton, and Grace Chen. 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).

SALINITY

Salinity zones

Five areas with a substantial amount of salinity data were defined for the Upper Laguna Madre Estuary, three in Baffin Bay and two in the Upper Laguna Madre (Table 1). From these five areas, three were selected to represent the longitudinal salinity gradient from the river inflow points to the sea: Upper Baffin Bay, Mouth of Baffin Bay, and South Bird Island.

Table 1: Salinity (ppt) statistics for salinity zones of the Upper Laguna Madre Estuary.
"*" = zones used in TxEMP analyses.

Salinity Zone	Median	Mode	Mean	Std. Dev.	Range	N
JFK Causeway	31	30.0	32.08	61.8	6.0 – 53.6	220
South Bird Island*	37	37.0	36.21	7.26	9.7 – 57.8	240
Mouth of Baffin Bay*	35	n.a.	35.20	8.60	4.3 – 58.0	219
Mid Baffin Bay	39	40.0	37.68	12.68	1.6 – 65.6	192
Upper Baffin Bay*	39	38.0	37.45	13.43	0.04 – 63.0	195

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 Natural Resource Conservation Commission (TNRCC) Statewide Monitoring Network, and Texas Department of Health Shellfish Sanitation Monitoring Program. Salinity data were available for years 1970-1999 and reported in parts per thousand (ppt). All data before December 1986 and some data after that date came from measurements made during site visits at various times throughout the year. Beginning in late 1986, ambient water quality data were collected *in situ* with automated instruments (Hydrolab Datasondes) through a series of monthly deployments. Datasondes took measurements 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 1970-1999. 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 1977-1996 to conform to the period of available inflow data. 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 the tables 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 Baffin Bay salinity zone.

Month	Lower Bound	Upper Bound
January	30	45
February	30	45
March	25	45
April	25	45
May	25	45
June	20	45
July	20	53
August	30	53
September	30	53
October	35	53
November	30	45
December	30	45

Table 3: Salinity bounds (ppt) for the Mouth of Baffin Bay salinity zone.

Month	Lower Bound	Upper Bound
January	30	40
February	30	40
March	25	40
April	25	40
May	25	40
June	25	40
July	32	45
August	32	45
September	32	45
October	32	45
November	28	45
December	28	45

Table 4: Salinity bounds (ppt) for the South Bird Island salinity zone.

Month	Lower Bound	Upper Bound
January	30	37
February	30	37
March	30	40
April	30	40
May	35	42
June	35	42
July	35	45
August	35	45
September	35	45
October	35	45
November	35	41
December	35	41

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 data (individuals/ha.) were used instead of harvest landings (lbs/yr). There are two reasons for this change. In the Laguna Madre, 1) effort appeared to unduly influence harvest landings, and 2) a 19-year record of bag seine data was available.

Bag seine catch data were obtained from Texas Parks and Wildlife Department (TPWD) for the period of 1978-1996. Species used in analysis were blue crab, brown shrimp, white shrimp, red drum, spotted seatrout, black drum, southern flounder and grass shrimp. Although not used in previous inflow analyses, grass shrimp was used in the Laguna Madre inflow analysis because of its dominance in bag seine catches and ecological importance to this particular ecosystem. Grass shrimp data were not available prior to 1984.

Catch targets and historical values

Harvest targets were defined for most species as 75% of mean historic monitoring data. Three exceptions were made for flounder, red drum and white shrimp to enable TxEMP to find a solution using reasonable target values as accepted by TPWD, TWDB, and TNRCC. Means were based on data used to derive regression equations and omitted outliers. 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
Black Drum	17	170	5	928	127.6
Southern Flounder	17	7	0	17	5.5
Blue Crab	17	650	267	1354	487.2
Red Drum	17	85	10	321	63.4
Spotted Seatrout	17	83	10	227	62.0
Brown Shrimp	17	2205	642	5007	1653.8
White Shrimp	17	337	22	1635	253.0
Grass Shrimp	14	5961	625	25945	4470.8

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 1996. Combined flow is the sum of gauged and ungauged flow. Gauged 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 Upper Laguna Madre area used to determine inflows were: San Fernando near Alice (id# 08211900) and Los Olmos near Falfurrias (id# 08212400).

Ungauged flow is the water reaching the estuary whose source is below the farthest downstream flow gage, or from an ungauged catchment area (i.e., water is not measured by the gages). Ungauged flow consists of three hydrologic components: modeled runoff from land areas below the farthest downstream gage or ungauged 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. Ungauged 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 ungauged watershed areas. Return flow values came from records of measured and estimated flows for Self-reporting Wastewater Discharges from the TNRCC. Diversion values come from the Water Use databases managed by TNRCC as part of the Water Rights Permitting Program.

Ungauged flow was calculated by adding modeled runoff and return flow, and subtracting diversions. Data sources for gauged 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 TNRCC as monthly totals. Combined flow (acre-ft/day) is calculated as the sum of gauged and ungauged 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 Upper Laguna Madre Estuary, annual inflows have ranged between 0 and 167,000 acre-ft/yr, with median inflow of 8581 acre-ft/yr and mean inflow of 23,027 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 56-year period 1941 to 1996.

Monthly upper and lower inflow bounds

The lower monthly inflow bound was set to the 10th percentile of all inflow data used in the analysis. The upper bound was set to the median of all monthly inflows for the same period in order to develop achievable recommended inflows. Consequently, inflow requirements, as calculated by the TxEMP model, can not exceed the median inflow for any month.

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

Month	Lower Boundary	Upper Boundary
January	0.58	2.23
February	0.81	2.12
March	0.60	1.84
April	0.64	1.75
May	1.26	2.64
June	0.94	3.48
July	1.24	1.75
August	1.28	1.82
September	1.49	2.83
October	1.97	6.64
November	0.84	2.14
December	0.65	1.77

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. Seasonal bounds were set broader than the sum of monthly flow bounds for corresponding months. The sum of the January and February lower bounds totaled 1,390 acre-ft.; the sum of the upper bounds for the same period totaled 4,200 acre-ft. In the table below, the January-February seasonal lower bound was set to a value lower than the sum of the monthly bounds (600 acre-ft) while the upper bound was set to a value higher than the sum of the monthly upper bounds (8,000 acre-ft). 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.

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

Bi-month	Lower Boundary	Upper Boundary
Jan.-Feb.	0.60	8.00
Mar.-Apr.	0.60	6.00
May-Jun.	0.60	10.00
Jul.-Aug.	0.60	9.00
Sept.-Oct.	0.60	4.97
Nov.-Dec.	0.60	6.00

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. Because the nonlinear nature of 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. 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. Data were not converted to units of g/ha because it would be inappropriate to constrain abundance (individuals/ha.) equations with biomass (g/ha) ratios. Lower and upper bounds for catch ratio constraints were calculated as 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.

Catch ratio bounds

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

Species	Catch Ratio	Lower Bound	Upper Bound
Black Drum	0.02	0.00	0.06
Southern Flounder	0.00	0.00	0.002
Blue Crab	0.08	0.03	0.12
Red Drum	0.01	0.00	0.02
Spotted Seatrout	0.01	0.00	0.02
Brown Shrimp	0.27	0.08	0.46
White Shrimp	0.04	0.00	0.10
Grass Shrimp	0.57	0.00	1.00

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 the budget 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 Upper Laguna Madre

The nutrients which fuel estuarine production come mainly from the drainage basin of major tributaries, and from local coastal sources. The watersheds flowing to Upper Laguna Madre are relatively small, some entirely coastal. Thus, the proportion of nutrients coming into the system from upstream sources — categorized here as gauged inflows — is relatively small. Ungauged coastal watersheds are important contributors. 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 the Upper Laguna Madre from major sources. Precipitation and deposition refer to nitrogen input from the atmosphere directly to the bay water surface.

Year	Petronilla Creek	San Fernando Creek	Olmos Creek	N-Fixation	Direct Precip	Dry Dep.	Total
Average	91.62	290.51	99.21	620	138	138	1377
Median	74.22	168.69	41.32	620	140	140	1146

Upper Laguna Madre Nitrogen Status

The Upper Laguna Madre receives the least drainage basin loading (0.75 g/m^3/yr) of the estuaries of the Texas. However, when residence time is also considered, the loading which is actually available for production is more medial. In addition, new findings on nitrogen cycling within the system suggest that the typically high salinities favor microbial activity which retains nitrogen availability, over microbial processes which lead to loss through denitrification. The long term persistence of the brown tide bloom in this system is an indication that productivity in the estuary is not strongly limited by nitrogen supply. The Laguna Madre has been listed as a system susceptible to eutrophication and showing symptoms of moderate eutrophication (NOAA, 1989; Bricker, et al. 1999).

Upper Laguna Madre 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 eutrophication cited above. 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. However, this approach to estimate nutrient requirements is tractable and is the basis for the recommendations presented here for the Upper Laguna Madre.

Prior to growth of the few coastal cities and 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.

Data on concentrations in rangeland runoff in the Baffin Bay and neighboring watersheds are available from Baird et al. (1996). In addition, 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 1.0 mg/l N, as opposed to the flow-weighted average near 2.96 mg/l N for all Baffin Bay tributaries.

An un-impacted inflow TN concentration was combined with average inflow volume to produce an estimate of pre-development nitrogen load to the Upper Laguna Madre. Using an un-impacted stream concentration of 1.0 mg/l N and a median inflow — compensated for diversions, the annual TN load is $140 \cdot 10^6$ g N /y from the drainage basin. This rate is proposed as a target minimal nitrogen load, capable of supporting 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 $140 \cdot 10^6$ g N /y would be delivered by approximately 20,000 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 recommended flow targets.

SEDIMENT CONSTRAINT

Lagoons are a result of shoreline processes and are parallel to the coastline (Le Blanc and Hodgson, 1959). Estuaries are formed by sea level rise and fall, which causes river valley entrenchment and are normal to the coastline. Estuaries can be classified based on principal sediment source. Rusnak (1967) describes positive filled estuaries as having a land sediment source, while negative filled estuaries have a marine sediment source. Neutral filled estuaries are filled from internal sediment sources. Nueces Bay would be a positive filled estuary. Laguna Madre would be classified as a negative filled estuary and lagoon. Most of Laguna Madre is a lagoon type formation with an estuary being formed in the area of Baffin Bay and the Lower Rio Grande Valley. Like the Brazos and Colorado Rivers in the upper part of the coast, the Rio Grande has filled in its estuary and found a path to the Gulf. A Holocene arm of the Rio Grande, the Arroyo Colorado, has moved sediment to the lagoon, which is seen as the Arroyo's deltoid formation at its true mouth at Laguna Madre.

Table 10 shows volumes of sediment delivered to Upper Laguna Madre, from Morton et al. (1998). From this study, the proportion of sediments delivered to the Laguna can be equated with the rate of sediments supplied from each source. This indicates that the sediment supplied from basin runoff is a relatively small. From this figure, one can conclude that runoff carried sediment has been a very minor source for Upper Laguna Madre. Therefore, an inflow-based sediment constraint is not recommended.

Table 10. Estimated sediment volume delivered to Upper Laguna Madre, by source (Morton et al., 1998).

Source	Upper Laguna	%
Runoff	24200	8.44
Eolian	254200	88.64
Tidal	0	0.00
Washover	1200	0.42
Shore	7182	2.50
Total	286782	100.00

SALINITY-INFLOW EQUATIONS

Salinity data for the period 1977 through 1996 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 ppt, Q is the monthly combined inflow in 1000 acre-ft, and ln is the natural logarithm function.

South Bird Island $S_{SB} = 38.143 - 1.1762*\ln(Q1) - 0.6755*\ln(Q2)$

Upper Baffin Bay $S_{UB} = 42.3396 - 1.5542*\ln(Q1) - 2.3764*\ln(Q2)$

Mouth Baffin Bay $S_{MB} = 40.6796 - 1.0782*\ln(Q1) - 1.6788*\ln(Q2)$

Table 11: Salinity-inflow regression equation statistics.

Salinity Zone	N	R^2	Adj. R^2	S.E.	p-value
South Bird Island	193	0.20	0.20	2.2441	<0.05
Upper Baffin Bay	154	0.28	0.27	4.1849	<0.05
Mouth Baffin Bay	272	0.28	0.27	4.5132	<0.025

CATCH-INFLOW EQUATIONS

Catch and inflow data described above were used to developed catch-inflow equations. The fishery-inflow relationships described in Longley (1994) were not used because they were established for use with harvest data, not catch data. Harvest data is comprised of adult fish, whereas catch data is comprised of juveniles. Fishery-inflow relationships used were: 1) year x catch regressed against water year x inflow for black drum, flounder, blue crab, spotted seatrout, brown shrimp, white shrimp and grass shrimp, and 2) year x catch regressed against the average of water years x and x-1 inflow for red drum. 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: $C_{bc} = 471.216 - 30.0828*Q_{JF} + 53.5175*Q_{MA} + 0.717*Q_{JA}$

Brown Shrimp: $C_{bs} = 2065.37 - 618.973*\ln(Q_{SO}) + 887.553*\ln(Q_{ND})$

White Shrimp: $\ln(C_{ws}) = 4.47059 + 0.692696*\ln(Q_{JF}) + 0.366136*\ln(Q_{JA})$
$0.413513*\ln(Q_{SO})$

Red Drum: $\ln(C_{rd}) = 3.50229 - 0.815058*\ln(Q_{JF}) + 1.20778*\ln(Q_{MA})$

Spotted Seatrout: $C_{st} = 4.80382 + 6.89386*(Q_{MA}) + 1.06901*(Q_{SO})$

Black Drum: $C_{bd} = -5.33407 - 0.519675*Q_{JA} + 6.51867*Q_{SO}$

Southern Flounder: $C_{fl} = -0.267272 - 3.15812*\ln(Q_{MA}) + 1.52464*\ln(Q_{MJ}) + 0.9851*\ln(Q_{JA}) +$
$2.71354*\ln(Q_{SO})$

Grass Shrimp: $C_{gs} = 6701.05 + 5876.22*\ln(Q_{MA}) - 6864.88*\ln(Q_{MJ}) - 2657.66*\ln(Q_{SO}) +$
$4326.04 *\ln(Q_{ND})$

Table 12: Catch-inflow equation statistics.

Species	N-used	N-deleted	R^2	Adj. R^2	S.E.	p-value
Black Drum	17	2	0.59	0.53	179.10	0.0019
Flounder	17	2	0.60	0.47	4.10	0.0177
Blue Crab	17	2	0.76	0.71	173.36	0.0002
Red Drum	17	2	0.68	0.63	0.55	0.0004
Spotted Seatrout	17	2	0.64	0.59	44.09	0.0008
Brown Shrimp	17	2	0.51	0.44	1002.09	0.0066
White Shrimp	17	2	0.59	0.50	0.83	0.0073
Grass Shrimp	14	1	0.73	0.61	4668.61	0.0116

RESULTS

Execution of TxEMP yielded minimum inflow (MinQ) of 21,530 acre-ft/yr, maximum inflow (MaxQ) of 31,010 acre-ft/yr, and maximum total catch (MaxC) at inflow of 22,770 acre-ft/yr (Figure 2.1). 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 13. TxEMP inflow solutions for Upper Laguna Madre, thousands of acre-feet.

Month	MinQ-Sal	MinQ	MaxC	MaxQ
Jan	2.08	2.08	2.08	2.23
Feb	1.55	1.55	1.55	2.12
Mar	1.28	1.26	1.36	1.84
Apr	1.21	1.20	1.29	1.75
May	1.46	1.52	1.74	2.64
Jun	0.94	2.01	2.30	3.48
Jul	1.24	1.75	1.75	1.75
Aug	1.28	1.73	1.82	1.82
Sep	1.49	1.49	1.49	2.83
Oct	1.97	3.48	3.48	6.64
Nov	1.70	1.70	2.14	2.14
Dec	1.77	1.77	1.77	1.77
Total	17.97	21.53	22.77	31.01

Appendix B - Values and Constraints for the TxEMP Model Used in the Freshwater Inflow Analysis of the Lower Laguna Madre Estuary

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September, 2004

Values and Constraints for the TxEMP Model Used in the Freshwater Inflow Analysis of the Lower Laguna Madre 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 Natural Resource Conservation Commission (TNRCC) providing additional expertise. The Texas Department of Health has also contributed to this effort.

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, spotted seatrout, black drum, southern flounder and pink shrimp. Historical freshwater inflow data were determined based on standard TWDB hydrology methods, and gauged flow at two stations on rivers and creeks flowing into the Lower Laguna Madre Estuary. Execution of TxEMP yielded minimum inflow (MinQ) of 214,950 acre-ft/yr, maximum inflow (MaxQ) of 248,900 acre-ft/yr, and maximum total catch (MaxC) at inflow of 228,340 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: Christine Ritter, Bill Longley, Roger Wolff, Barney Austin, 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 Jim Tolan, Wen Lee, Warren Pulich, Dave Buzan, Cindy Loeffler, Dan Moulton, and Grace Chen. 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 catch (productivity) values, 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).

SALINITY

Salinity zones

Five areas with a substantial amount of salinity data were defined for the Lower Laguna Madre Estuary (Table 1). From these five areas, three were selected to represent the longitudinal salinity gradient from the river inflow points to the sea: South Land Cut, near the Arroyo Colorado, and Stover Point.

Table 1: Salinity (ppt) statistics for salinity zones of the Upper Laguna Madre Estuary.
"*" = zones used in TxEMP analyses.

Salinity Zone	Median	Mode	Mean	Std. Dev.	Range	N
South Land Cut*	35	45.0	34.93	7.00	14.30 - 49.70	159
Port Mansfield	34	35.0	33.44	7.05	4.90 - 60.40	234
near Arroyo Colorado*	28	30.0	27.03	8.45	2.10 - 50.90	156
Stover Point*	35	40.0	34.73	6.32	11.00 - 45.00	200
Port Isabel	34	35.0	33.30	6.10	0.03 - 55.45	298

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 Natural Resource Conservation Commission (TNRCC) Statewide Monitoring Network, and Texas Department of Health Shellfish Sanitation Monitoring Program. Salinity data were available for years 1970-1999 and reported in parts per thousand (ppt). All data before December 1986 and some data after that date came from measurements made during site visits at various times throughout the year. Beginning in late 1986, ambient water quality data were collected *in situ* with automated instruments (Hydrolab Datasondes) through a series of monthly deployments. Datasondes took measurements 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 1970-1999. 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 1977-1996 to conform to the period of available inflow data. 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 the tables 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 at or below the 25th percentile of the historical salinity distribution.

Table 2: Salinity bounds (ppt) for the South Land Cut salinity zone.

Month	Lower Bound	Upper Bound
January	30	45
February	30	40
March	30	40
April	30	40
May	25	36
June	30	40
July	30	40
August	30	40
September	30	40
October	30	45
November	30	45
December	30	45

Table 3: Salinity bounds (ppt) for the Arroyo Colorado salinity zone.

Month	Lower Bound	Upper Bound
January	20	32
February	20	32
March	20	32
April	20	32
May	20	35
June	25	35
July	25	36
August	25	36
September	18	36
October	18	32
November	22	32
December	22	32

Table 4: Salinity bounds (ppt) for the Stover Point salinity zone.

Month	Lower Bound	Upper Bound
January	25	35
February	25	35
March	25	35
April	30	35
May	30	35
June	30	40
July	34	42
August	34	42
September	34	42
October	30	42
November	25	35
December	25	35

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 TARGET

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 data (individuals/ha.) were used instead of harvest landings (lbs/yr). There are two reasons for this change. In the Laguna Madre, 1) effort appeared to unduly influence harvest landings, and 2) a 19-year record of bag seine data was available.

Bag seine catch data were obtained from Texas Parks and Wildlife Department (TPWD) for the period of 1978-1996. Species used in analysis were blue crab, brown shrimp, white shrimp, red drum, spotted seatrout, black drum, southern flounder and pink shrimp.

Catch targets and historical values

Catch targets were defined for each species as 75% of mean historic catch. The catch target for each species is the value for which TxEMP must maintain a specific probability of achieving. This probability is defined by the catch 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
Black Drum	19	32	0	223	24.3
Southern Flounder	19	50	3	150	37.8
Blue Crab	19	1203	223	2113	902.6
Red Drum	19	283	156	734	212.6
Spotted Seatrout	19	34	4	80	25.3
Brown Shrimp	19	8577	1317	25531	6432.8
White Shrimp	19	3488	260	9003	2616.2
Pink Shrimp	19	581	0	2812	436.1

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 1996. Combined flow is the sum of gauged and ungauged flow. Gauged 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 Nueces area used to determine inflows were: the North floodway near Sebastian (id# 08470200) and the Arroyo Colorado near Harlingen (id# 08470400).

Ungauged flow is the water reaching the estuary whose source is below the farthest downstream flow gage, or from an ungauged catchment area (i.e., water is not measured by the gages). Ungauged flow consists of three hydrologic components: modeled runoff from land areas below the farthest downstream gage or ungauged 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. Ungauged 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 ungauged watershed areas. Return flow values came from records of measured and estimated flows for Self-reporting Wastewater Discharges from the TNRCC. Diversion values come from the Water Use databases managed by TNRCC as part of the Water Rights Permitting Program.

Ungauged flow was calculated by adding modeled runoff and return flow, and subtracting diversions. Data sources for gauged 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 TNRCC as monthly totals. Combined flow (acre-ft/day) is calculated as the sum of gauged and ungauged 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 Lower Laguna Madre Estuary, annual inflows have ranged between 41,000 and 188,600 acre-ft/yr, with median inflow of 255,038 acre-ft/yr and mean inflow of 301,054 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 56-year period 1941 to 1996.

Monthly upper and lower inflow bounds

The lower monthly inflow bound was set to the 10th percentile of all inflow data used in the analysis. The upper bound was set to the median of all monthly inflows for the same period in order to develop achievable recommended inflows. Consequently, inflow requirements, as calculated by the TxEMP model, can not exceed the median inflow for any month.

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

Month	Lower Boundary	Upper Boundary
January	16.23	21.18
February	16.02	17.53
March	16.69	19.72
April	16.51	22.65
May	20.16	27.83
June	22.09	30.05
July	18.10	22.89
August	14.34	19.01
September	15.51	22.85
October	16.12	24.67
November	14.05	19.56
December	13.78	17.76

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. Seasonal bounds were set close to the sum of monthly flow bounds for corresponding pair of months. The sum of the January and February lower bounds totaled 32,200 acre-ft.; the sum of the upper bounds for the same period totaled 38,700 acre-ft. In the table below, the January-February seasonal lower bound was set to a value lower than the sum of the monthly bounds (20,000 acre-ft) while the January-February seasonal upper bound was set to a value higher than the sum of the monthly upper bounds (40,000 acre-ft). The 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.

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

Bi-month	Lower Boundary	Upper Boundary
Jan.-Feb.	20.0	40.0
Mar.-Apr.	20.0	44.0
May-Jun.	40.0	60.0
Jul.-Aug.	30.0	44.0
Sept.-Oct.	30.0	50.0
Nov.-Dec.	25.0	40.0

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. Originally, this was considered to be a convenient way to allow testing of different management options. Unfortunately, the nonlinear nature of some equations occasionally caused calculated catch for some species to be greater than historically observed levels. To remedy this unrealistic tendency, which typically occurred at extremes of inflows, a new constraint was added to refine the optimization routine. The new constraint was designed to ensure that the catch of any species compared to the total catch of all species in the analysis remained within the bounds of a defined range. This constraint is called the catch ratio and is based on historical catch data from the estuary. The constraint guaranteed that the relative species' catch 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. Data were not converted to units of g/ha because it would be inappropriate to constrain abundance (individuals/ha.) equations with biomass (g/ha) ratios. Lower and upper bounds for catch ratio constraints were calculated as 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.

Catch ratio bounds

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

Species	Catch Ratio	Lower Bound	Upper Bound
Black Drum	0.003	0.00	0.01
Flounder	0.003	0.00	0.01
Blue Crab	0.09	0.05	0.14
Red Drum	0.02	0.01	0.04
Spotted Seatrout	0.003	0.001	0.004
Brown Shrimp	0.59	0.24	0.93
White Shrimp	0.25	0.07	0.42
Pink Shrimp	0.05	0.00	0.14

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 Lower Laguna Madre

Although hydrologically isolated from direct tributary inflow, the Laguna historically and now perhaps more frequently receives occasional inputs from the Rio Grande River. Historically, these inputs would have resulted only from major floods of the Rio Grande, spilling into the flood plain and draining through small resacas and arroyos, principally the Arroyo Colorado. Now the Arroyo Colorado carries a more continuous flow indirectly from the Rio Grande, as irrigation run-off and wastewater returns. The watersheds flowing to Lower Laguna Madre are relatively small, with low relief. 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 the Lower Laguna Madre from major sources. Precipitation and deposition refer to nitrogen input from the atmosphere directly to the bay water surface.

	North Floodway	Arroyo Colorado	Coastal W-sheds	Brownsville Ship Chn.	Returns	Subtotal
Average	596.5	1220.2	13.6	72.1	46.0	1948.3
Median	448.8	1169.3	10.5	21.0	40.2	1715.8

	Direct Rain	Dry Deposition	N-fixation	Total
Average	322.2	483.3	757	3638.8
Median	326.6	490.0	757	3417.4

Lower Laguna Madre Nitrogen Status

The Lower Laguna Madre receives moderate drainage basin loading (3.36 g/m^2/yr, 2.08 g/m^3/yr average. However, when residence time is also considered, the loading which is actually available for production is more substantial. In addition, new findings on nitrogen cycling within Upper Laguna Madre suggest that the typically high salinities favor microbial activity which retains nitrogen availability, over microbial processes which lead to loss through denitrification. The Lower Laguna Madre is included as part of the Arroyo Colorado TMDL project, because of concerns for low dissolved oxygen encountered in Laguna waters. This is an indication of potential eutrophication. The Laguna Madre has been listed as a system susceptible to eutrophication and showing symptoms of moderate eutrophication (NOAA, 1989; Bricker, et al. 1999).

Lower Laguna Madre 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 eutrophication cited above. 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 the Lower Laguna Madre, the chief complication is the routing of Rio Grande water to the system. For the purpose of a nutrient based inflow recommendation, it could be assumed that this flow compensates for reduction of natural Rio Grande flood flows to the system, now much reduced by the system of reservoirs on the river channel.

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.

Data on concentrations in rangeland runoff in the Laguna Madre and neighboring watersheds are available from Baird et al. (1996). In addition, 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 1.0 mg/l N, as opposed to the flow-weighted average near 4.35 mg/l N for inflows to the Lower Laguna Madre.

An un-impacted inflow TN concentration was combined with average inflow volume to produce an estimate of pre-development nitrogen load to the Lower Laguna Madre. Using an un-impacted stream concentration of 1.0 mg/l N and a median inflow — compensated for diversions, the annual TN load is $361 \cdot 10^6$ g N /y from the drainage basin. This rate is proposed as a target minimal nitrogen load, capable of supporting 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 $361 \cdot 10^6$ g N /y would be delivered by approximately 67,200 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 recommended flow targets.

SEDIMENT CONSTRAINT

Lagoons are a result of shoreline processes and are parallel to the coastline (Le Blanc and Hodgson, 1959). Estuaries are formed by sea level rise and fall, which causes river valley entrenchment and are normal to the coastline. Estuaries can be classified based on principal sediment source. Rusnak (1967) describes positive filled estuaries as having a land sediment source, while negative filled estuaries have a marine sediment source. Neutral filled estuaries are filled from internal sediment sources. Nueces Bay would be a positive filled estuary. Laguna Madre would be classified as a negative filled estuary and lagoon. Most of Laguna Madre is a lagoon type formation with an estuary being formed in the area of Baffin Bay and the Lower Rio Grande Valley. Like the Brazos and Colorado Rivers in the upper part of the coast, the Rio Grande has filled in its estuary and found a path to the Gulf. A Holocene arm of the

Rio Grande, the Arroyo Colorado, has moved sediment to the lagoon, which is seen as the Arroyo's deltoid formation at its true mouth at Laguna Madre.

Table 10 shows volumes of sediment contributed by various sources to Lower Laguna, from Morton, et al. (1998). The proportion of sediment volumes in the Laguna can be roughly equated with the rate of sediments supplied from each source. This indicates that the percentage of upland sediment supplied to the Lower Laguna Madre relatively small. From this, one can conclude that runoff carried sediment has been a very minor source. Therefore, an inflow-based sediment constraint for the Lower Laguna Madre is not recommended.

Table 10. Estimated sediment volumes delivered to Lower Laguna Madre, by source (Morton et al., 1998).

Source	Lower Laguna	%
Runoff	30000	4.39
Eolian	175000	25.62
Tidal	383000	56.09
Washover	78600	11.51
Shore	16218	2.37
Total	682818	100.00

SALINITY-INFLOW EQUATIONS

Salinity data for the period 1977 through 1998 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 ppt, Q is the monthly combined inflow in 1000 acre-ft, and ln is the natural logarithm function.

South Land Cut: $SSL = 59.6959 - 6.1379*\ln(Q1) - 1.7661*\ln(Q2)$

Arroyo Colorado: $SAC = 47.1484 - 5.0189*\ln(Q1) - 1.2576*\ln(Q2)$

Stover Point: $SSP = 44.0459 - 2.5357*\ln(Q1) - 0.7359*\ln(Q2)$

Table 11: Salinity-inflow regression equation statistics.

Salinity Zone	N	R^2	Adj. R^2	S.E.	p-value
South Land Cut	114	0.20	0.19	2.1924	<0.05
Arroyo Colorado	137	0.30	0.29	3.6531	<0.05
Stover Point	120	0.04	0.02	2.0150	0.10

HARVEST-INFLOW EQUATIONS

Harvest and inflow data described above were used to developed harvest-inflow equations. The fishery-inflow relationships described in Longley (1994) were not used because they were established for use with harvest data, not catch data. Harvest data is comprised of adult fish, whereas catch data is comprised of juveniles. Fishery-inflow relationships used were: 1) year x catch regressed against water year x inflow for black drum, flounder, blue crab, red drum, brown shrimp, white shrimp and grass shrimp, and 2) year x catch regressed against the average of water years x and x-1 inflow for spotted seatrout. 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 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 (P = 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: $C_{bc} = -4198.32 - 541.820*\ln(Q_{JF}) + 244.399*\ln(Q_{MA}) + 1531.30*\ln(Q_{MJ}) - 460.985*\ln(Q_{JA}) + 513.083*\ln(Q_{ND})$

Brown Shrimp: $C_{bs} = 10935 - 4389.10*\ln(Q_{JF}) + 3268.96*\ln(Q_{MA}) + 5645.39*\ln(Q_{MJ}) - 2841.05*\ln(Q_{JA}) - 3072.38*\ln(Q_{SO})$

White Shrimp: $\ln(C_{ws}) = 8.42912 + 0.00833838*Q_{MJ} - 0.0172627*Q_{JA} - 0.00237501*Q_{SO}$

Red Drum: $\ln(C_{rd}) = 10.4958 - 0.376113*\ln(Q_{JF}) + 1.38664*\ln(Q_{JA}) - 2.44292*\ln(Q_{ND})$

Spotted Seatrout: $C_{st} = -132.739 + 42.7205*\ln(Q_{JA})$

Black Drum: $C_{bd} = -46.4256 + 1.52602*Q_{SO}$

Southern Flounder: $C_{fl} = 0.148269 + 0.787779*Q_{JF}$

Pink Shrimp: $C_{ps} = -686.583 - 20.8276*Q_{JF} + 17.9868*Q_{MJ} - 3.90433*Q_{JA} - 3.0176*Q_{SO} + 30.2125*Q_{ND}$

Table 12: Harvest-inflow equation statistics.

Species	N-used	N-deleted	R^2	Adj. R^2	S.E.	p-value
Black Drum	17	2	0.48	0.45	40.82	0.0021
Southern Flounder	17	2	0.34	0.30	33.07	0.0139
Blue Crab	17	2	0.63	0.46	384.78	0.0322
Red Drum	17	2	0.73	0.67	0.32	0.0005
Spotted Seatrout	17	2	0.80	0.79	9.43	0.0000
Brown Shrimp	17	2	0.75	0.64	2248.46	0.0043
White Shrimp	17	2	0.70	0.63	0.50	0.0010
Pink Shrimp	17	2	0.73	0.60	464.9	0.0072

RESULTS

Execution of TxEMP yielded minimum inflow (MinQ) of 214,950 acre-ft/yr, maximum inflow (MaxQ) of 248,900 acre-ft/yr, and maximum total harvest (MaxC) at inflow of 228,340 acre-ft/yr (Figure 2.2). 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 13. Lower Laguna Madre TxEMP optimization results, 1000 acre-feet.

Month	MinQ-Sal	MinQ	MaxC	MaxQ
Jan	16.95	16.23	16.23	21.18
Feb	16.02	16.02	16.02	17.53
Mar	16.69	16.69	19.72	19.72
Apr	19.17	19.17	22.65	22.65
May	22.23	26.25	27.83	27.83
Jun	22.09	22.09	23.00	22.09
Jul	18.10	18.10	18.10	19.22
Aug	15.03	15.03	15.03	15.96
Sep	15.51	15.90	16.72	22.85
Oct	16.75	17.17	18.05	24.67
Nov	16.43	16.93	18.33	18.45
Dec	14.92	15.37	16.65	16.75
Total	209.89	214.95	228.33	248.90

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FIGURES

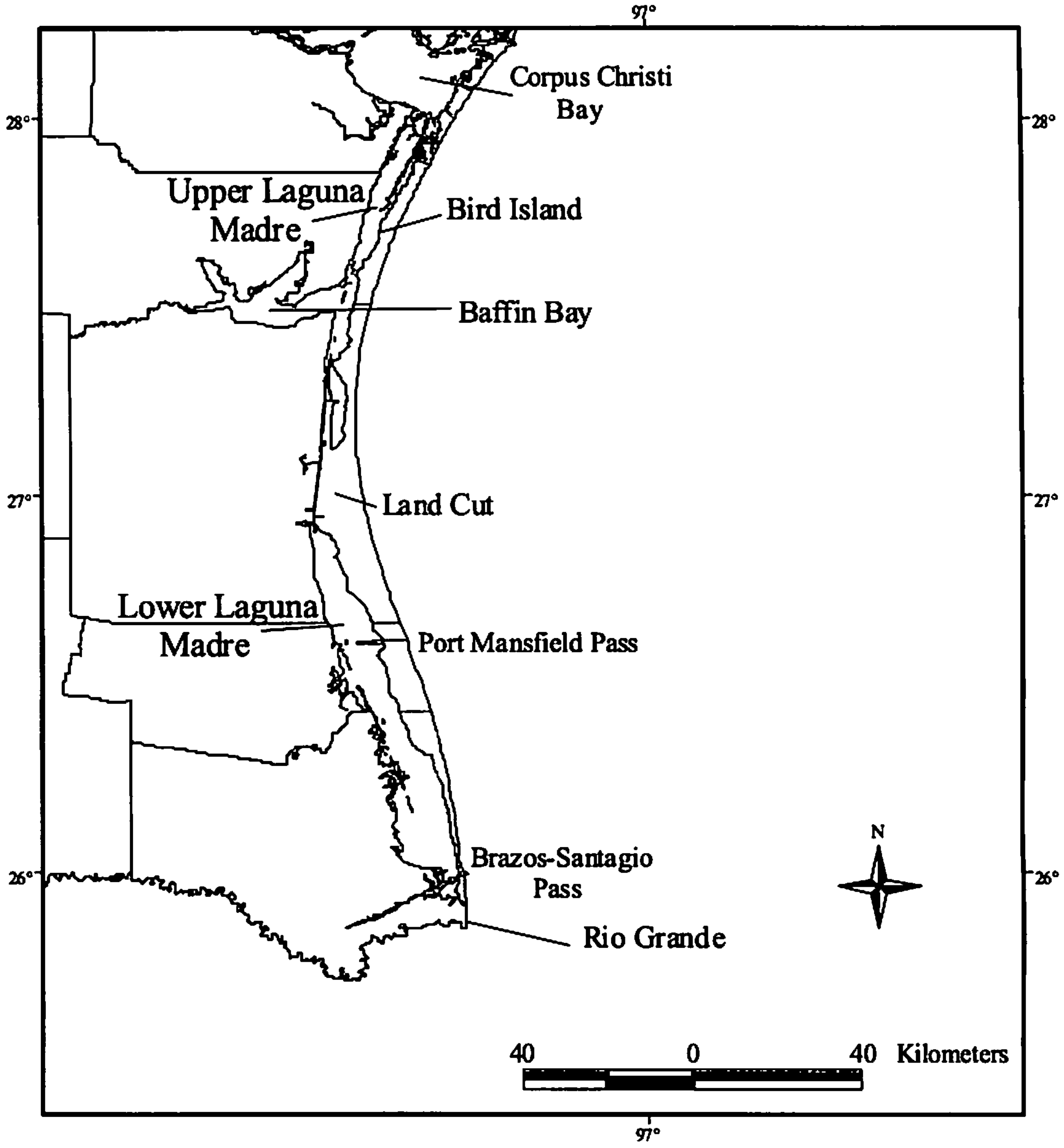

Figure 1. Map of south Texas from Corpus Christi Bay to the Rio Grande River showing the Laguna Madre Estuary system.

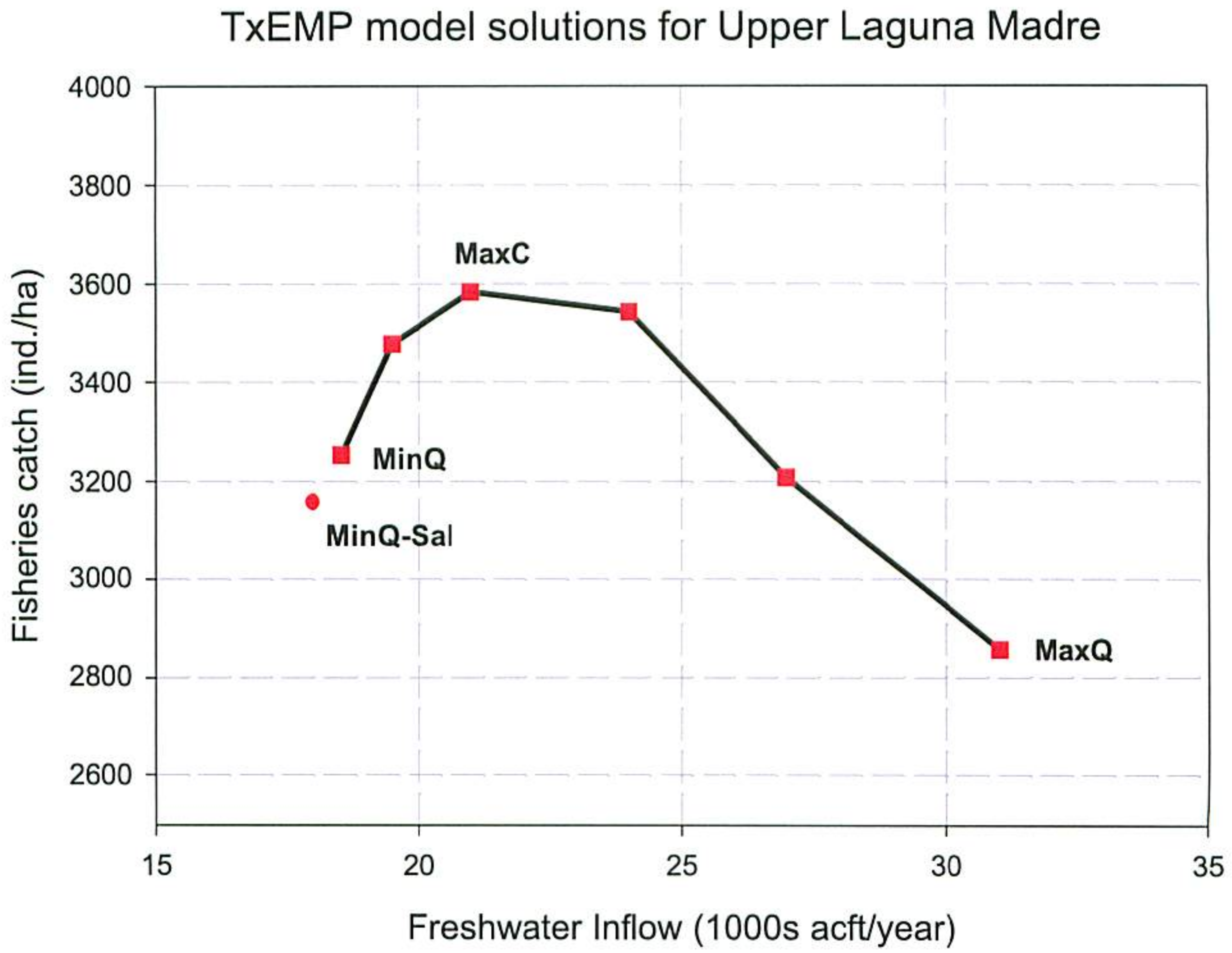

Figure 2.1. TxEMP solution performance curve for the Upper Laguna Madre.

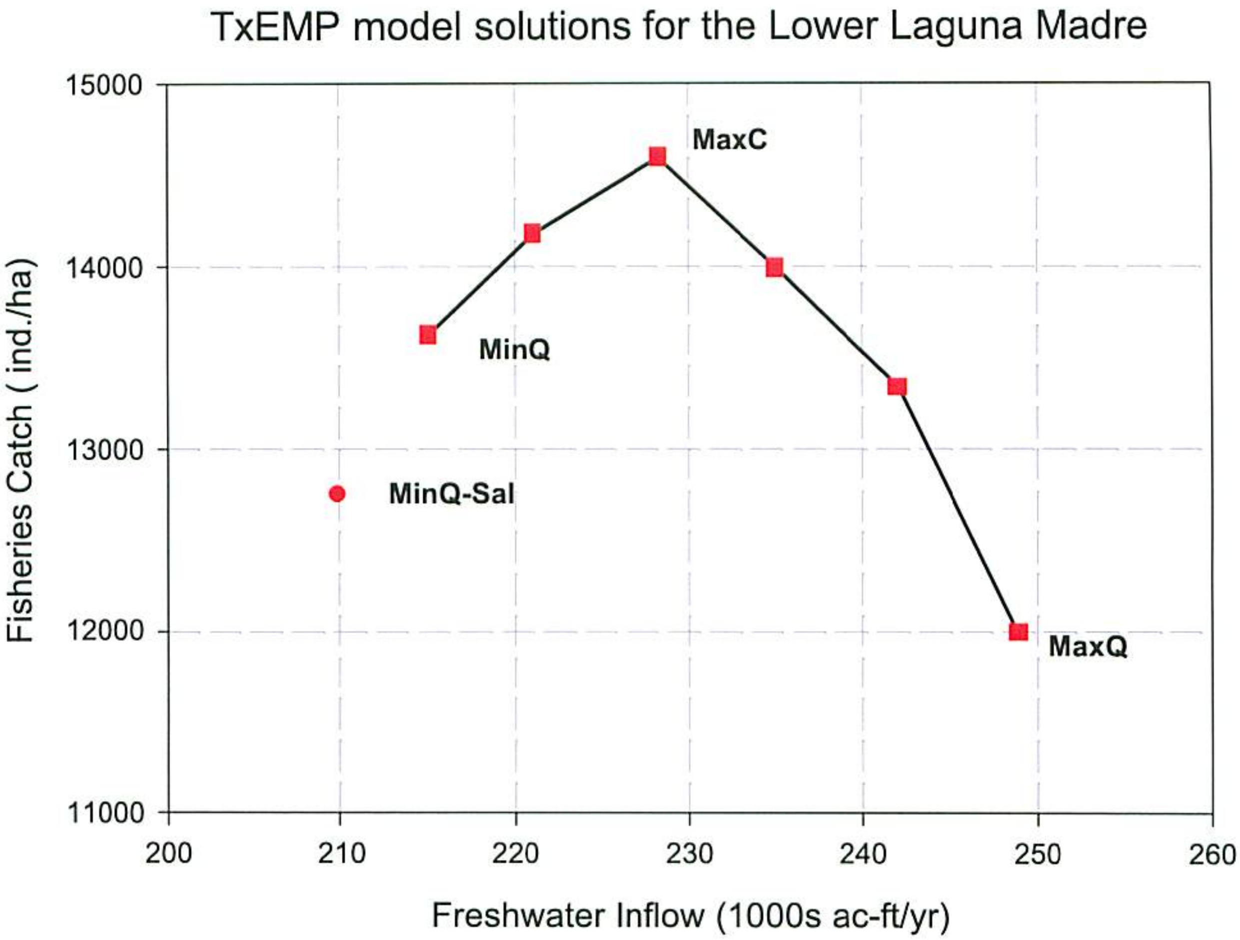

Figure 2.2. TxEMP solution performance curve for the Lower Laguna Madre.

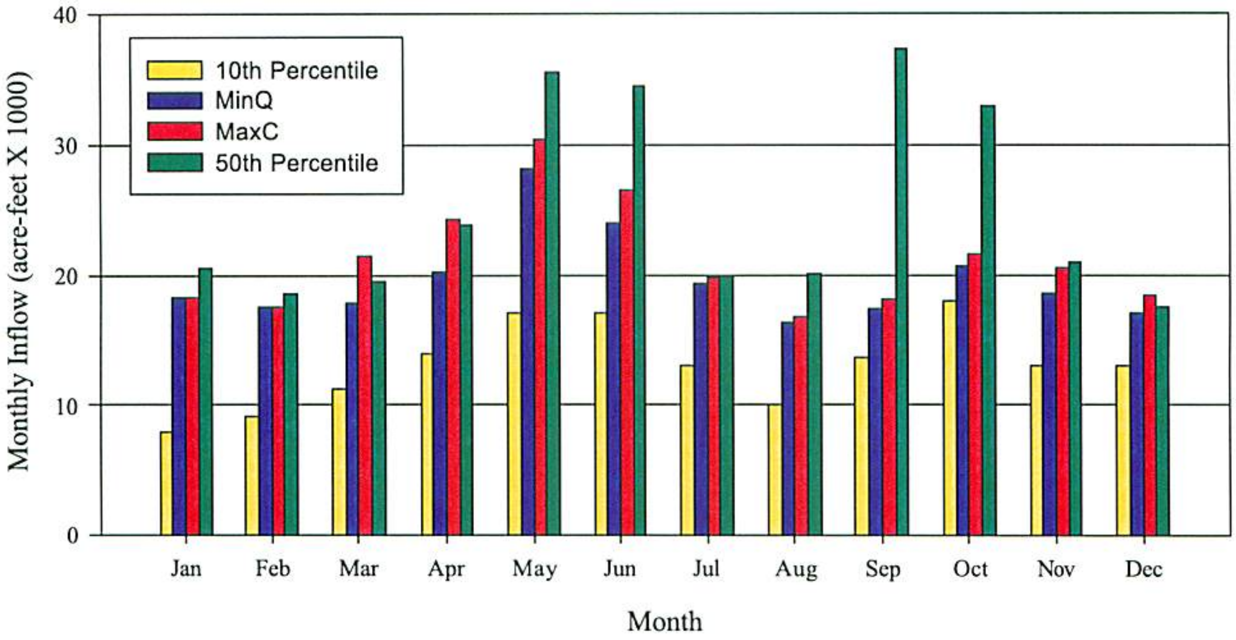

Figure 2.3. TxEMP solution monthly inflow distribution for the Laguna Madre Estuary, comparing model bounds (10th and 50th percentiles), MinQ, and MaxC. Inflow period covers the years 1941-1996. Monthly inflows are for the ULM and LLM combined.

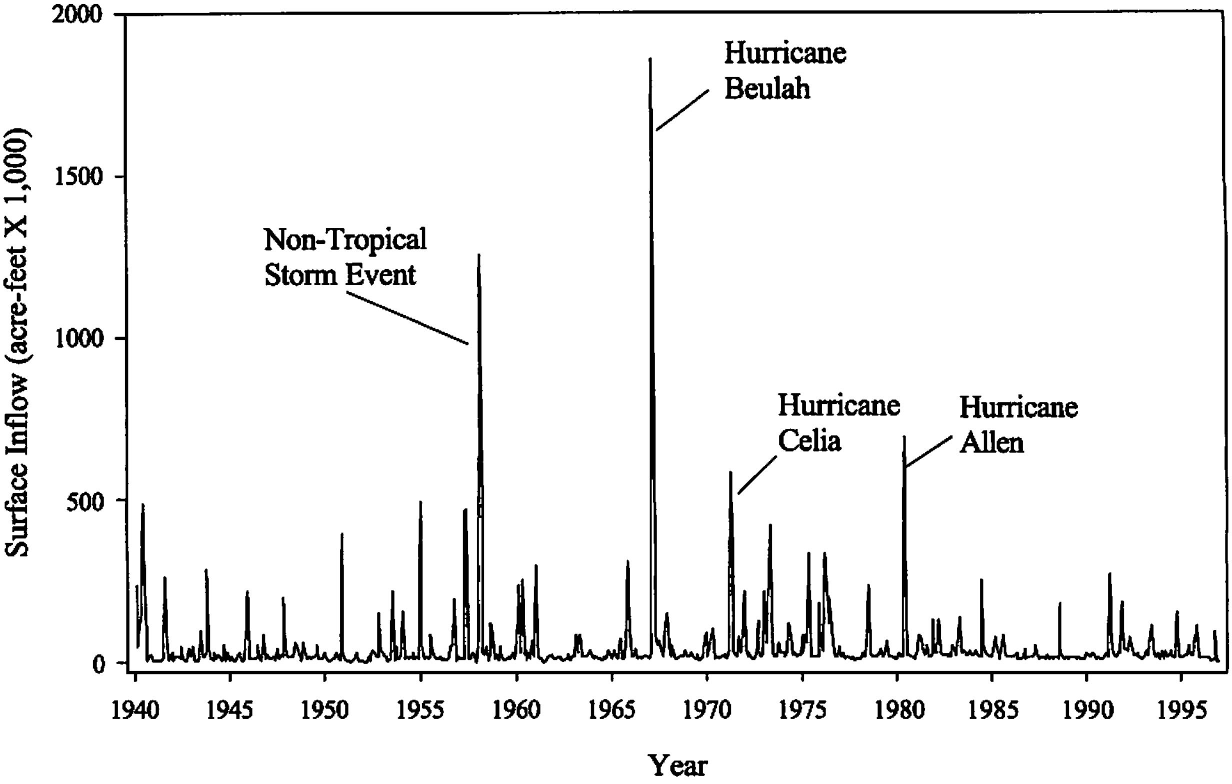

Figure 2.4. Historical inflows into the Laguna Madre Estuary system. Major hurricane systems that contributed large volumes of surface inflow into the estuary are noted.

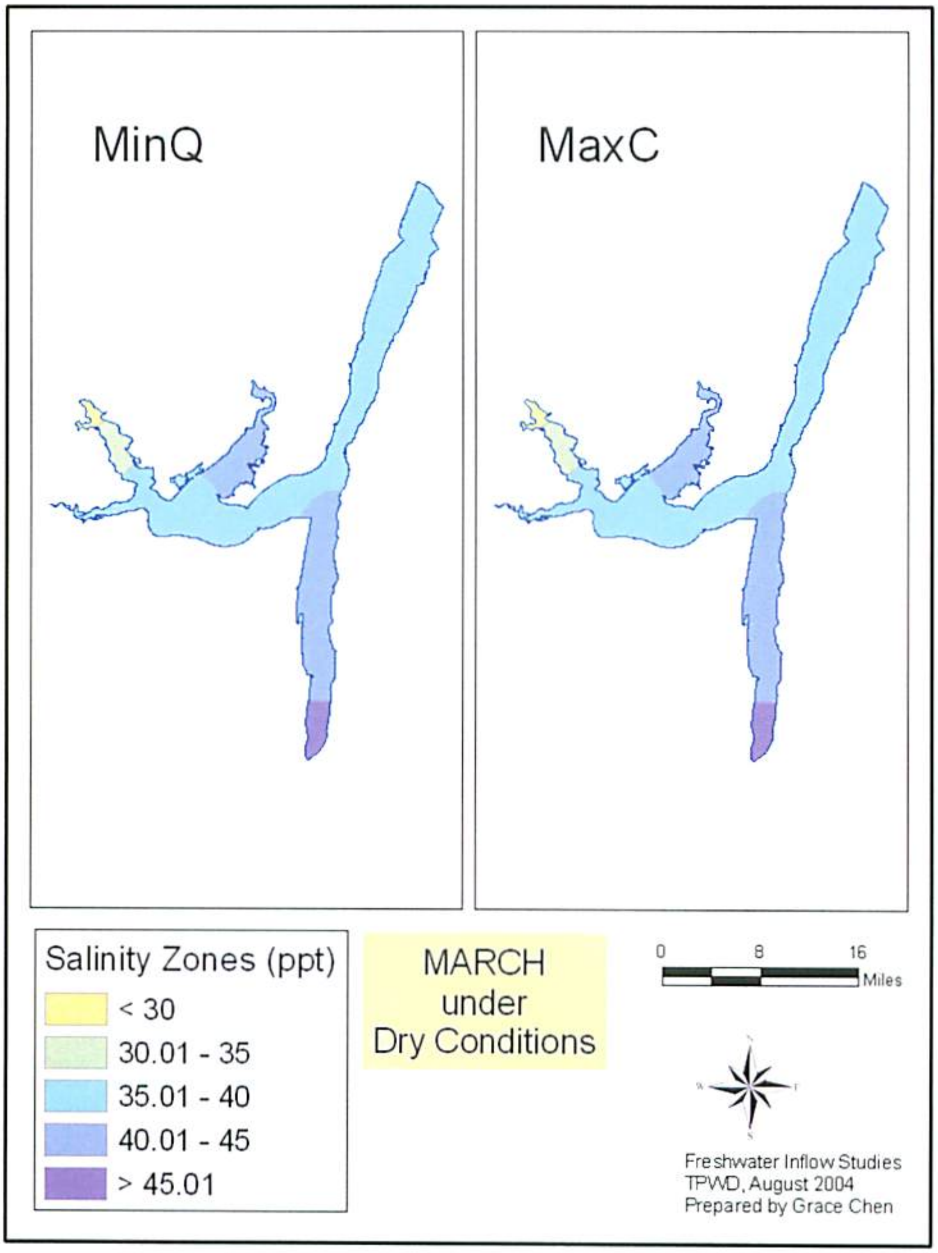

Figure 3.1. Predicted salinity zones for the Upper Laguna Madre during March, based on DRY conditions under TXBLEND simulations.

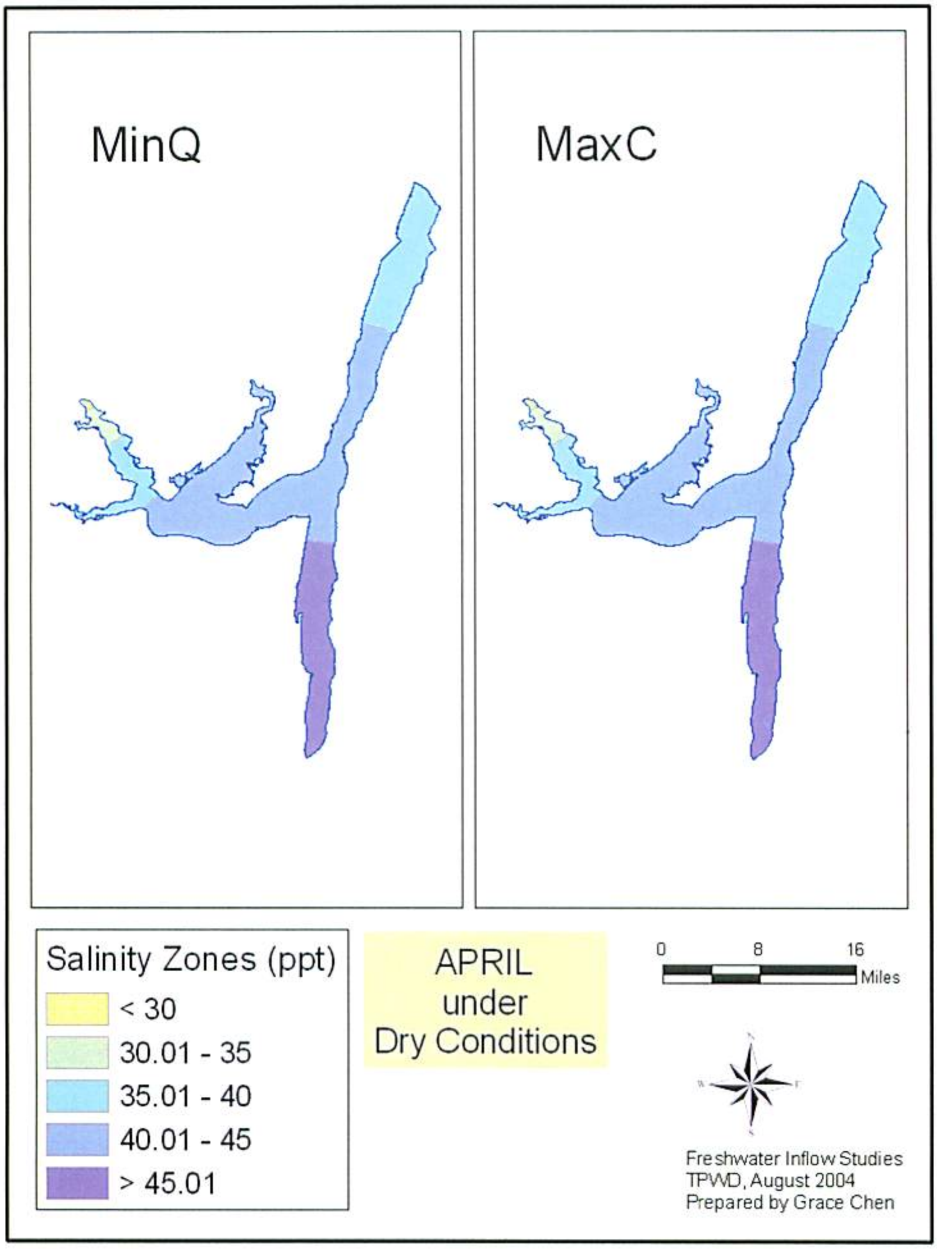

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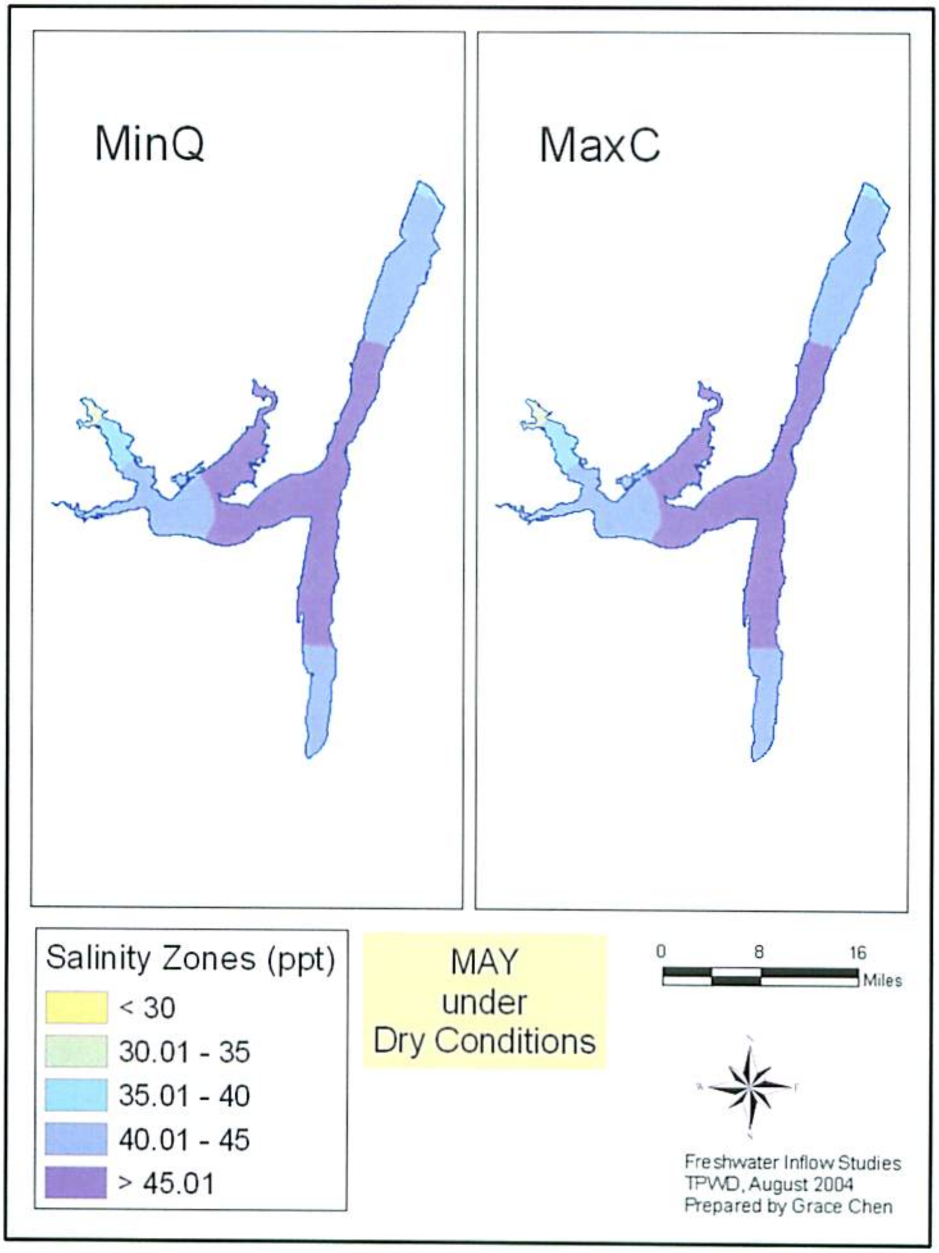
Figure 3.2. Predicted salinity zones for the Upper Laguna Madre during April, based on DRY conditions under TXBLEND simulations.



MinQ

MaxC

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Figure 3.3. Predicted salinity zones for the Upper Laguna Madre during May, based on DRY conditions under TXBLEND simulations.

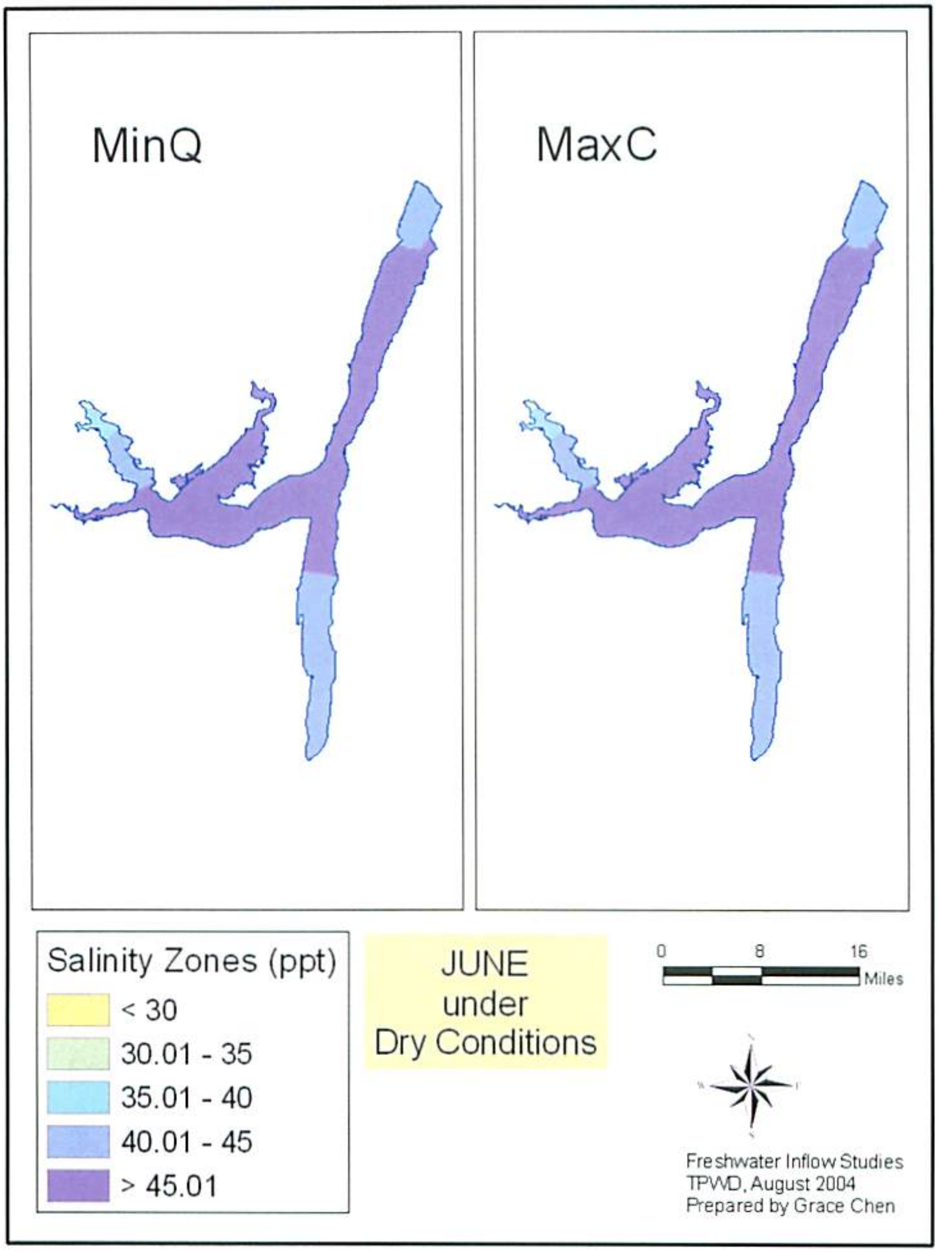

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Figure 3.4. Predicted salinity zones for the Upper Laguna Madre during June, based on DRY conditions under TXBLEND simulations.

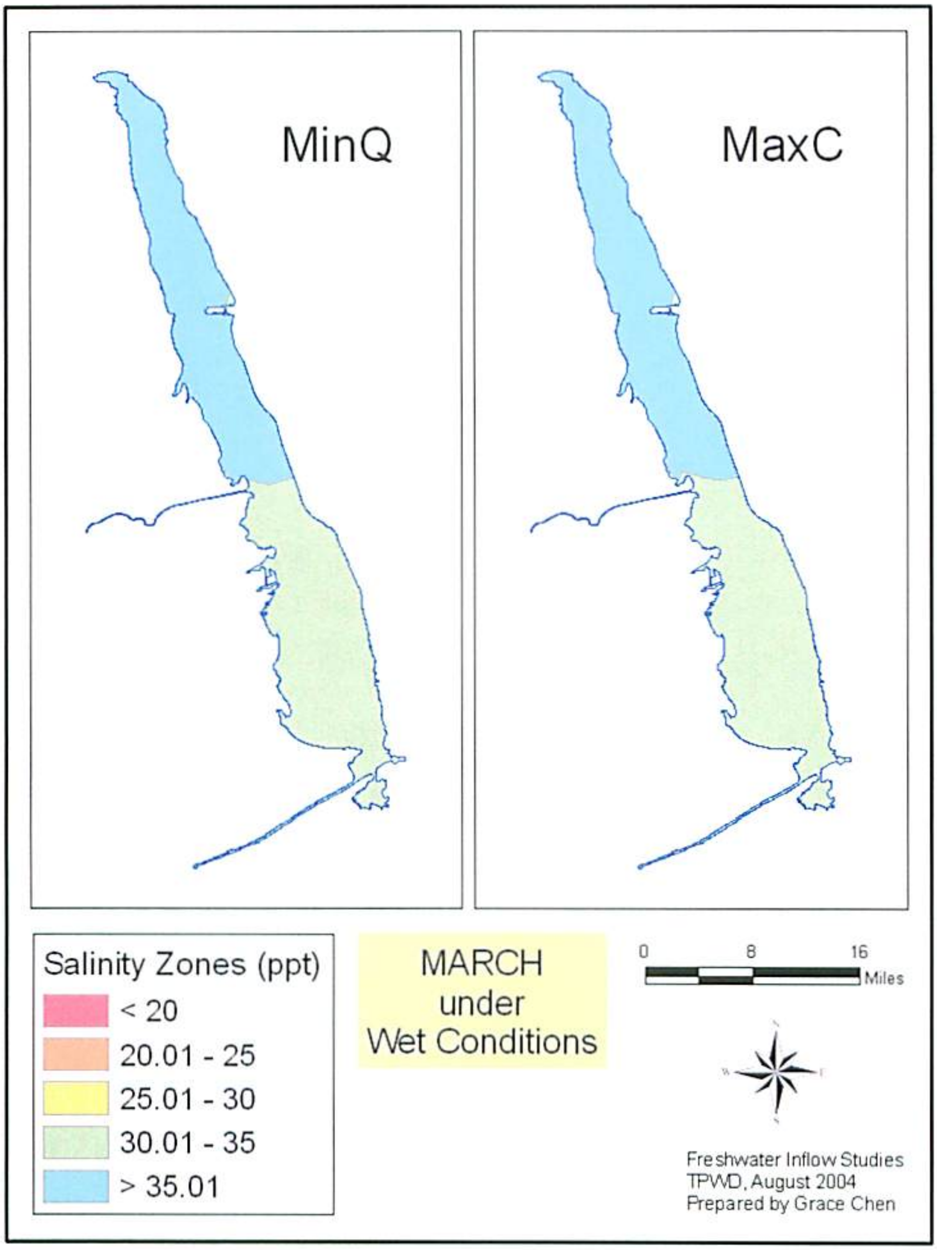

Figure 3.5. Predicted salinity zones for the Lower Laguna Madre during March, based on WET conditions under TXBLEND simulations.

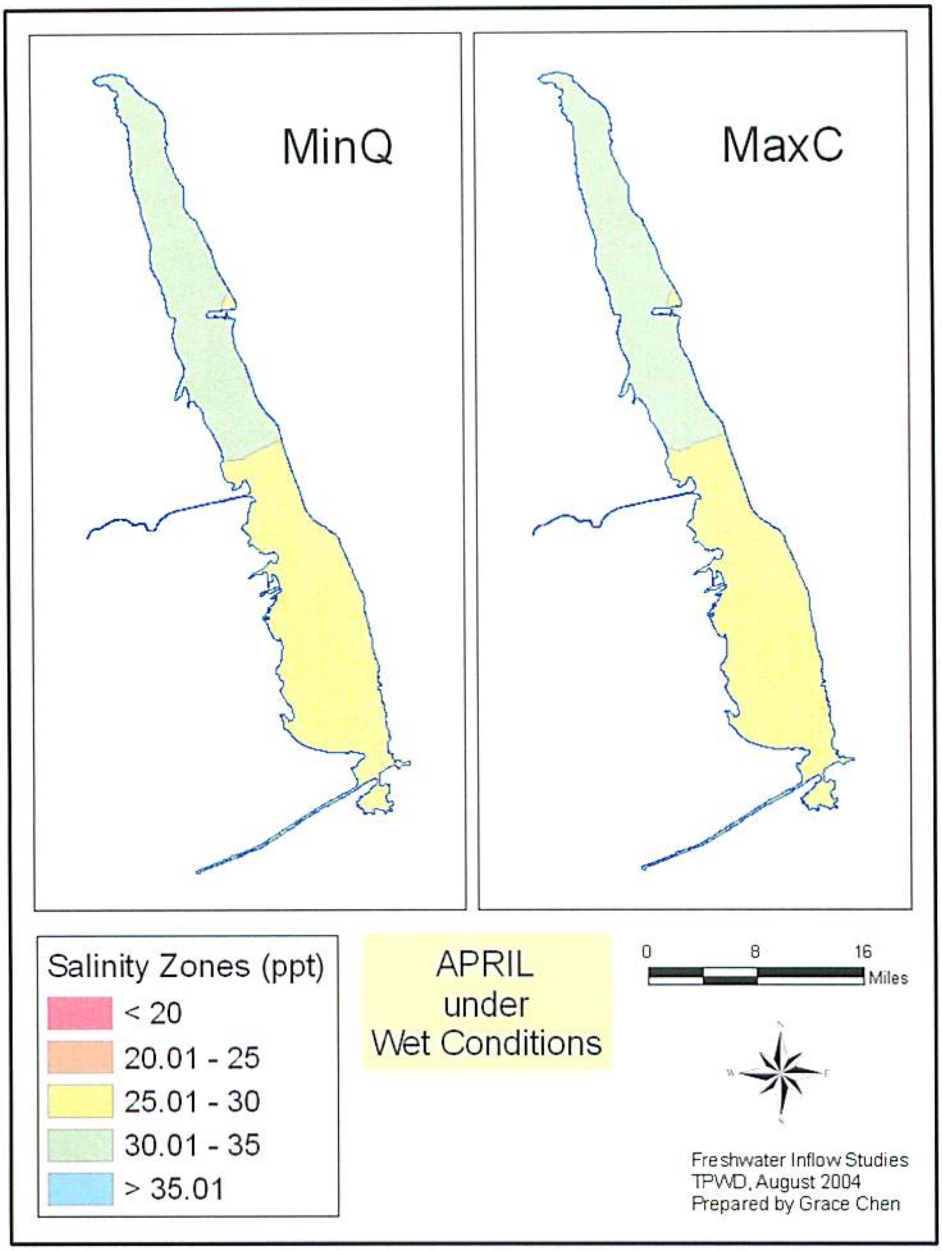

Figure 3.6. Predicted salinity zones for the Lower Laguna Madre during April, based on WET conditions under TXBLEND simulations.

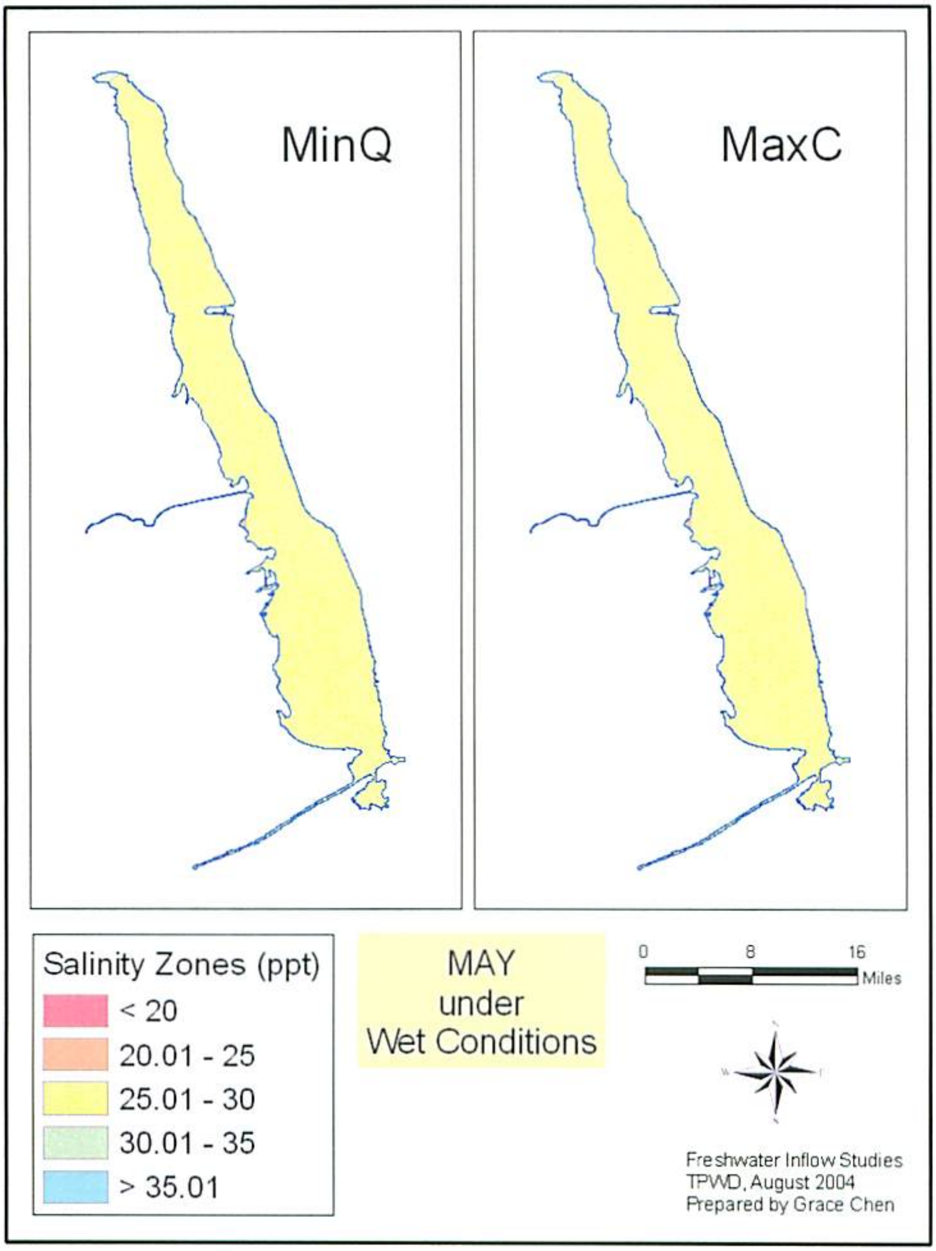

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Figure 3.7. Predicted salinity zones for the Lower Laguna Madre during May, based on WET conditions under TXBLEND simulations.

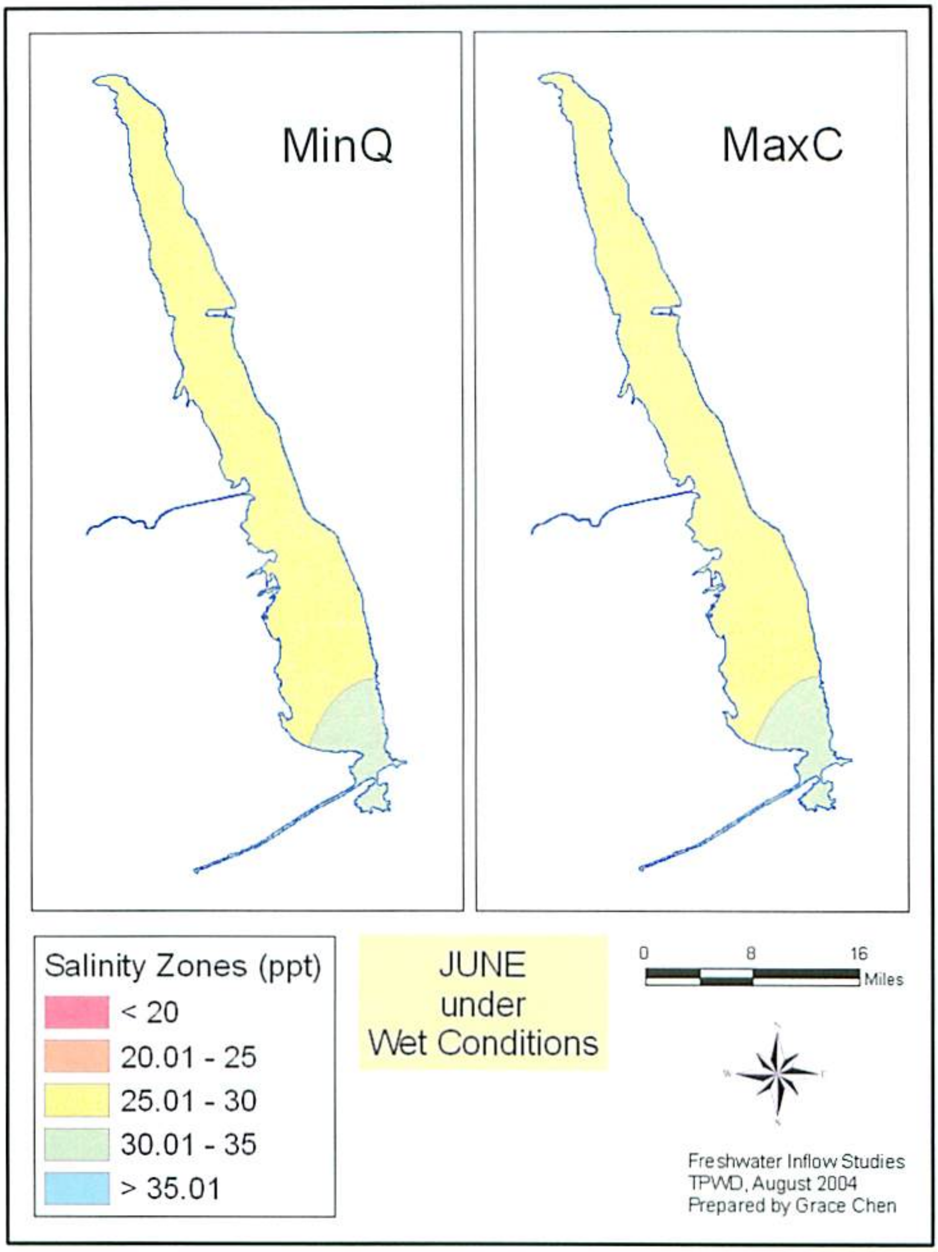

Figure 3.8. Predicted salinity zones for the Lower Laguna Madre during June, based on WET conditions under TXBLEND simulations.

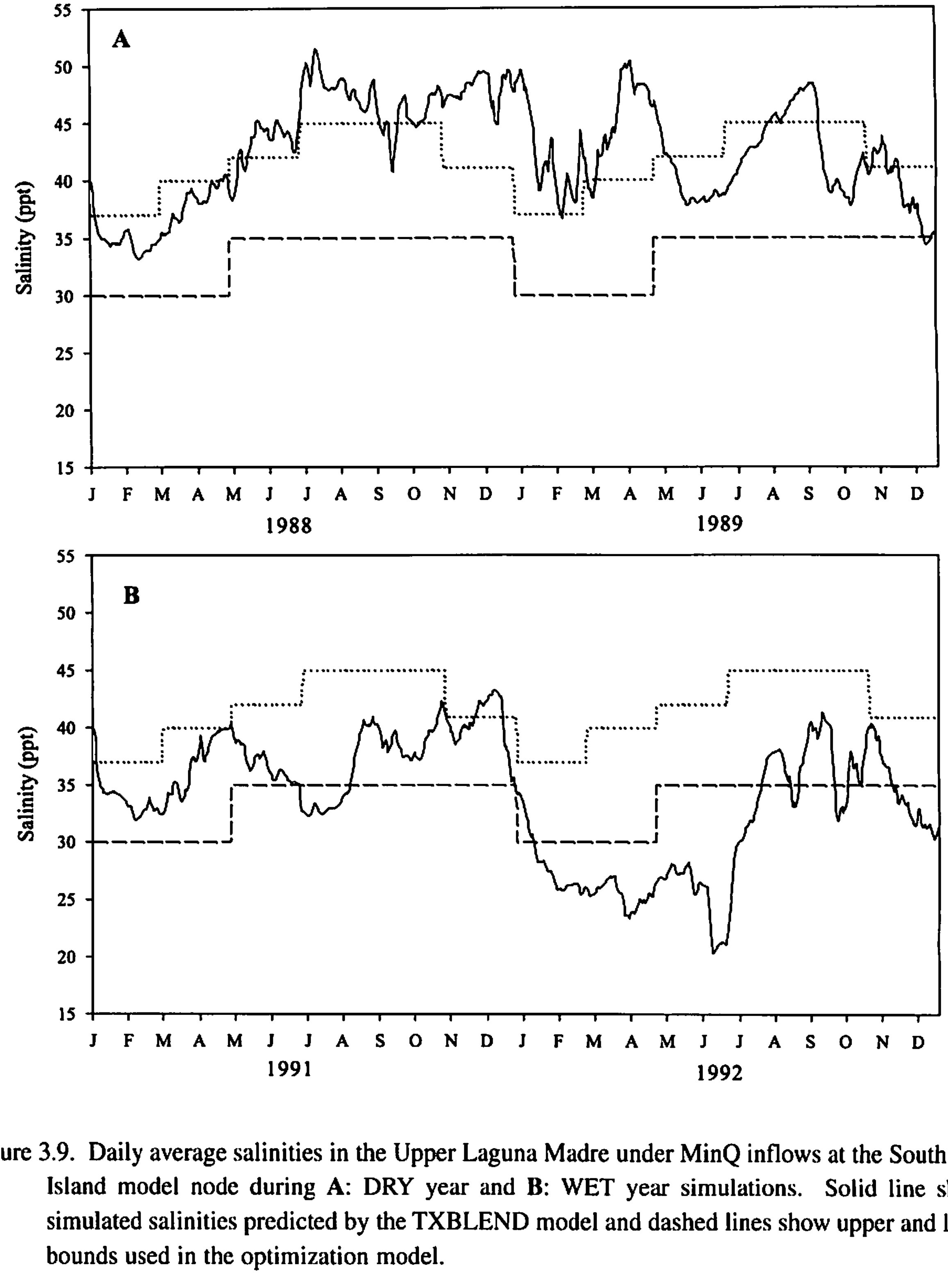

Figure 3.9. Daily average salinities in the Upper Laguna Madre under MinQ inflows at the South Bird Island model node during **A**: DRY year and **B**: WET year simulations. Solid line shows simulated salinities predicted by the TXBLEND model and dashed lines show upper and lower bounds used in the optimization model.

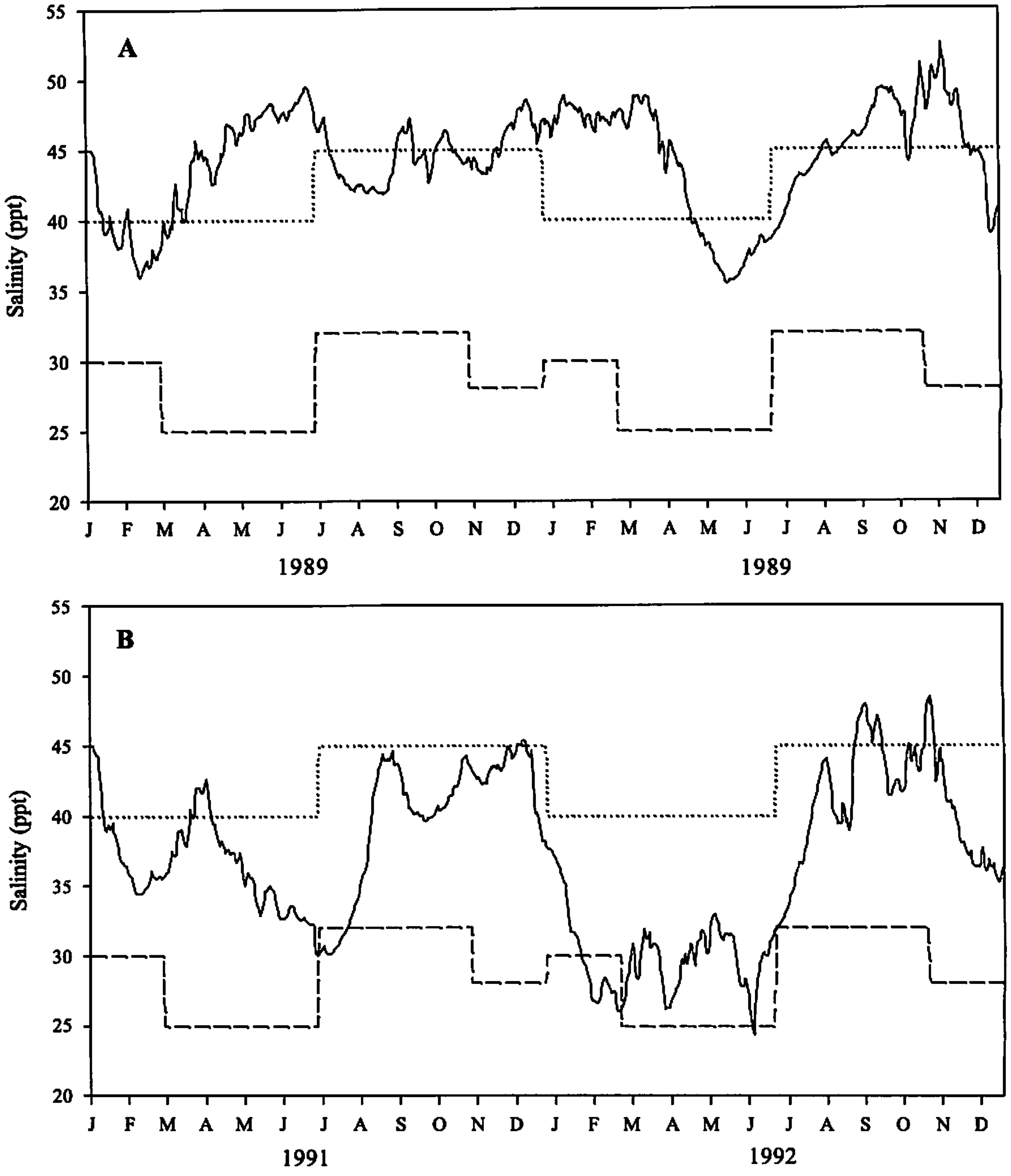

Figure 3.10. Daily average salinities in the Upper Laguna Madre under MinQ inflows at the mouth of Baffin Bay model node during **A**: DRY year and **B**: WET year simulations. Solid line shows simulated salinities predicted by the TXBLEND model and dashed lines show upper and lower bounds used in the optimization model.

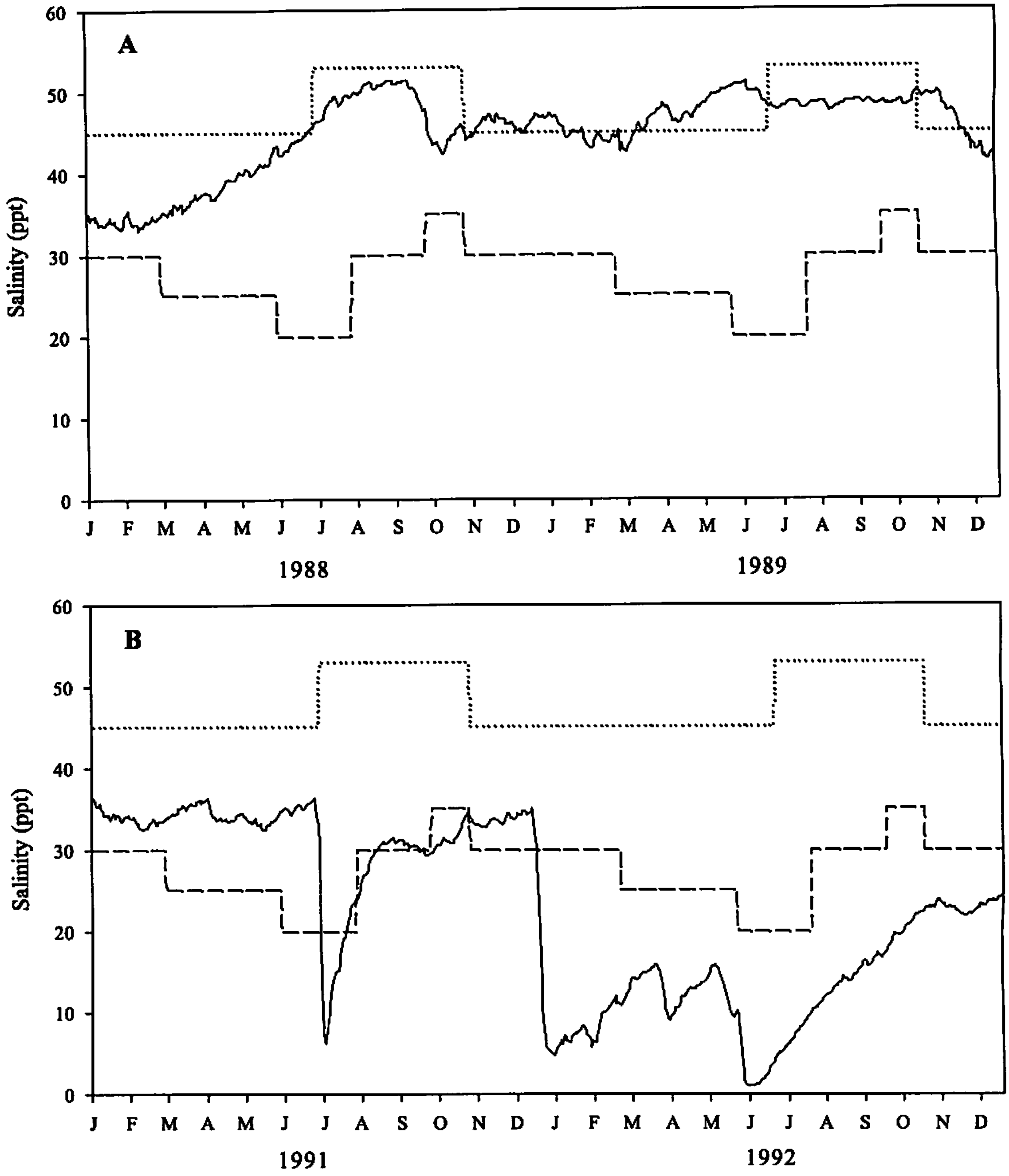

Figure 3.11. Daily average salinities in the Upper Laguna Madre under MinQ inflows at the upper Baffin Bay model node during **A**: DRY year and **B**: WET year simulations. Solid line shows simulated salinities predicted by the TXBLEND model and dashed lines show upper and lower bounds used in the optimization model.

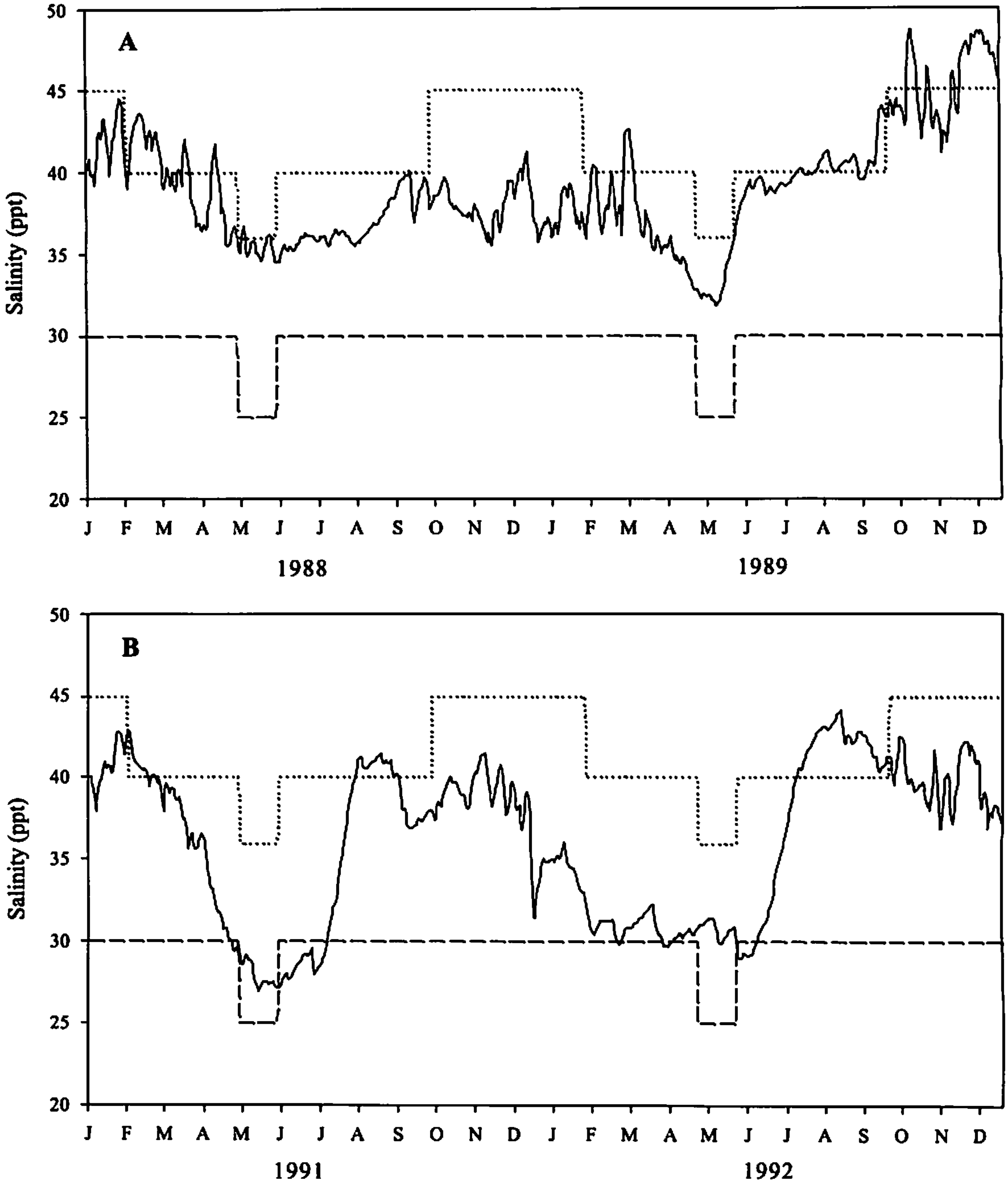

Figure 3.12. Daily average salinities in the Lower Laguna Madre under MinQ inflows at the South of the Land Cut model node during A: DRY year and B: WET year simulations. Solid line shows simulated salinities predicted by the TXBLEND model and dashed lines show upper and lower bounds used in the optimization model.

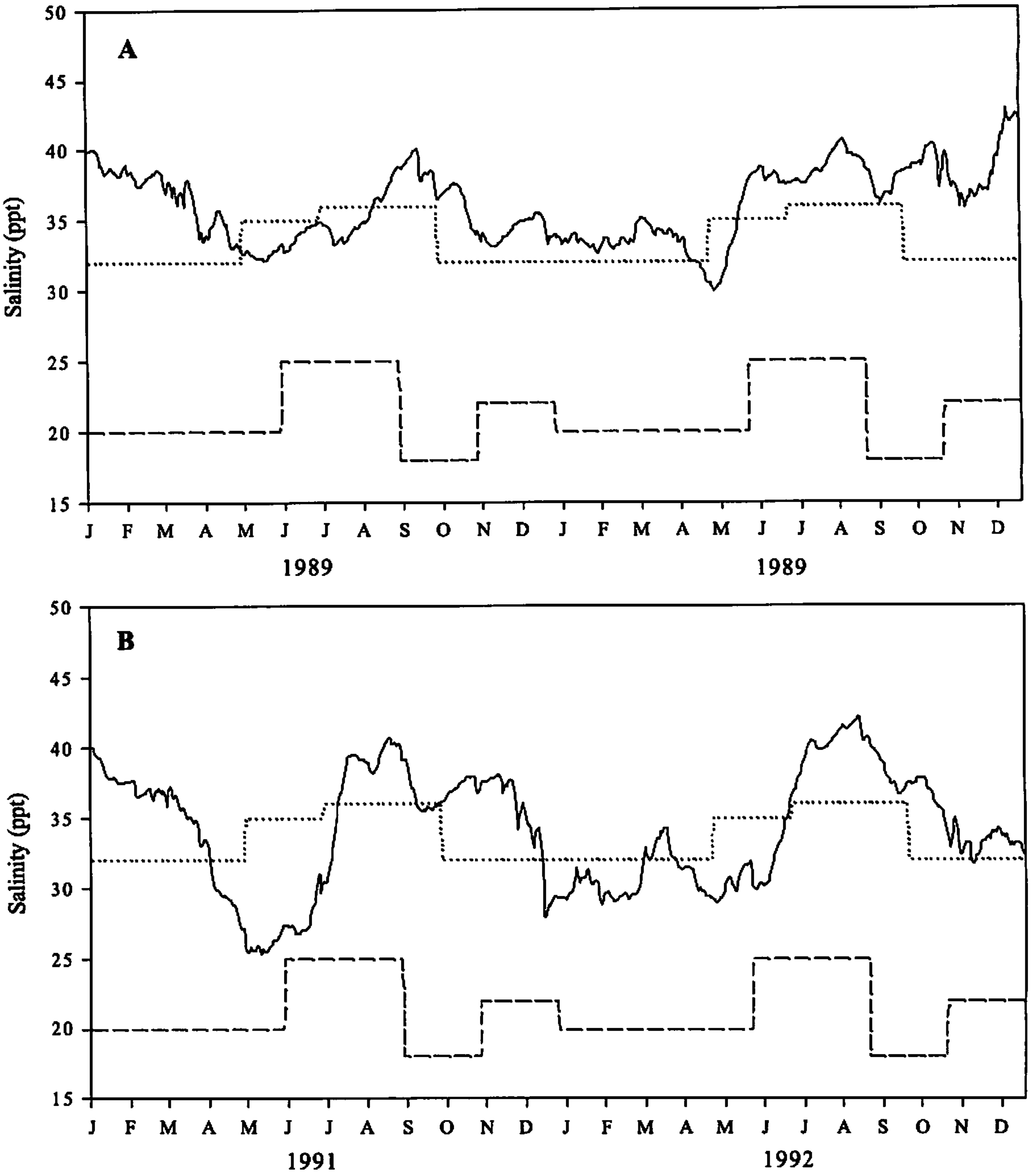

Figure 3.13. Daily average salinities in the Lower Laguna Madre under MinQ inflows at the mouth of Arroyo Colorado model node during **A**: DRY year and **B**: WET year simulations. Solid line shows simulated salinities predicted by the TXBLEND model and dashed lines show upper and lower bounds used in the optimization model.

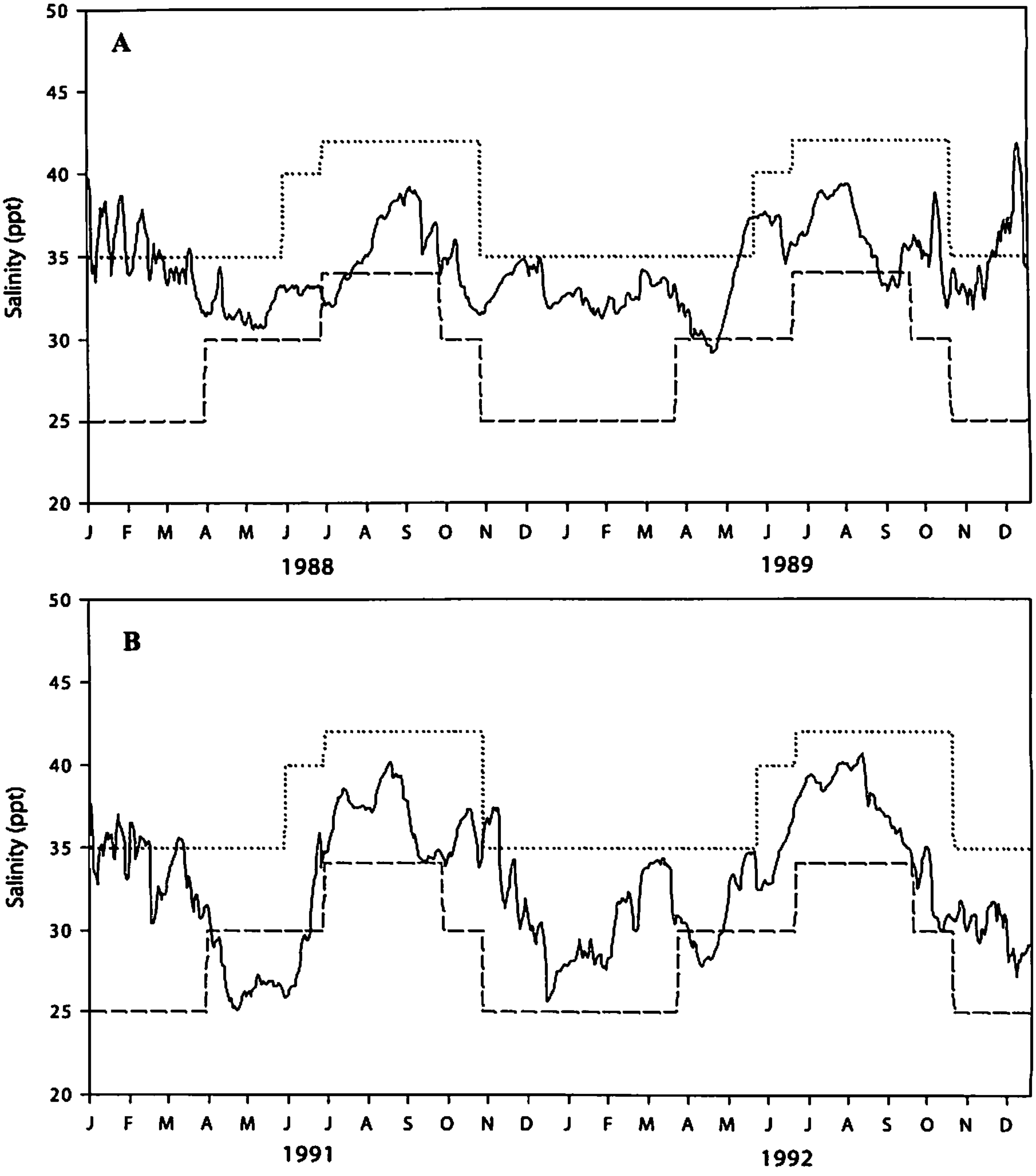

Figure 3.14. Daily average salinities in the Lower Laguna Madre under MinQ inflows at the Stover Point model node during **A**: DRY year and **B**: WET year simulations. Solid line shows simulated salinities predicted by the TXBLEND model and dashed lines show upper and lower bounds used in the optimization model.

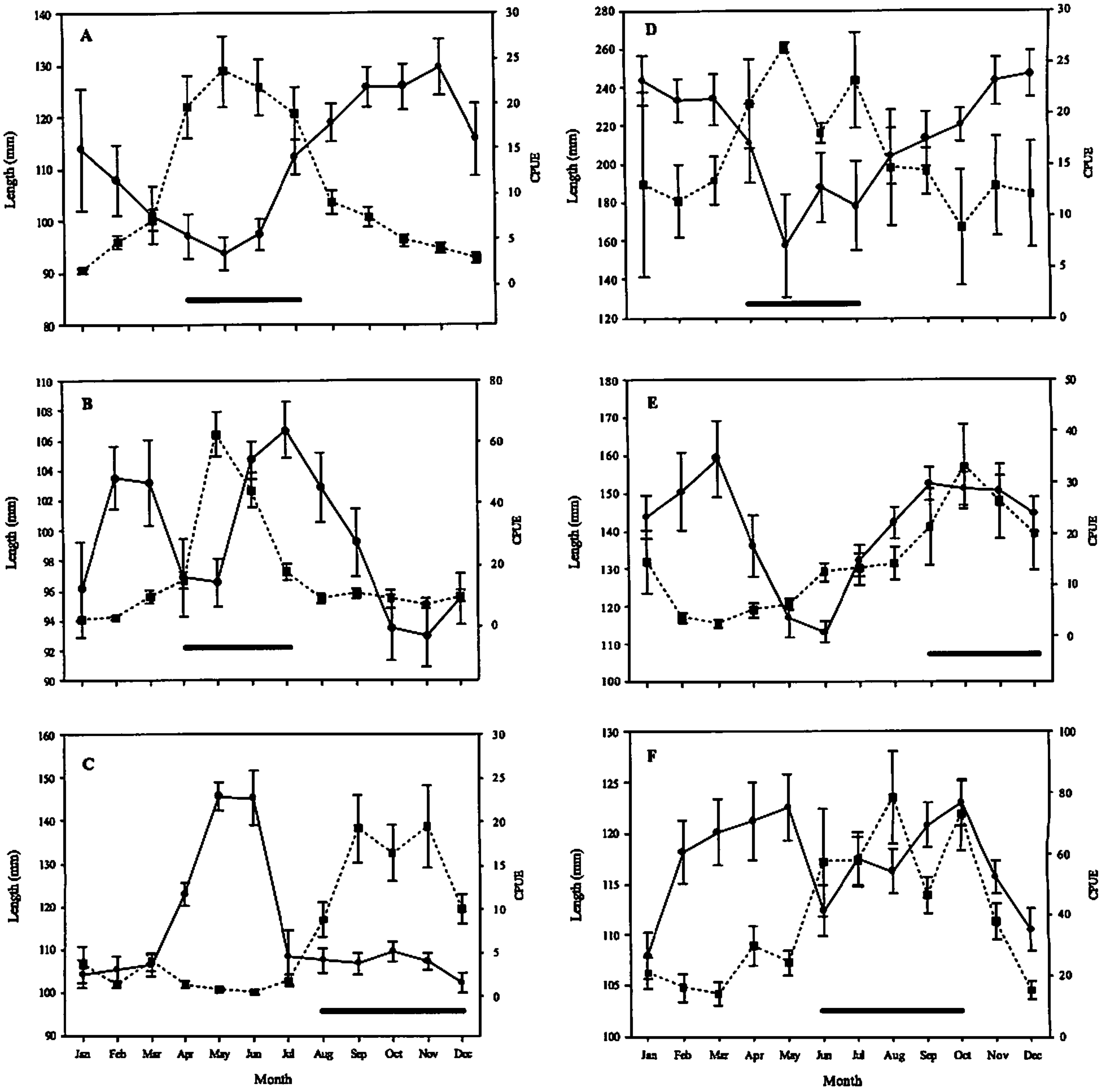

Figure 3.15. Average length (solid line, circle symbols, ± SE) and abundance (CPUE measured as catch per hour; dotted line, square symbols, ± SE) of **A**: Blue crab; **B**: Brown shrimp; **C**: White shrimp; **D**: Black drum; **E**: Spot; and **F**: Pinfish collected with bay trawls in the Upper Laguna Madre. Heavy solid line delineates the season of maximum abundance used for verification analysis.

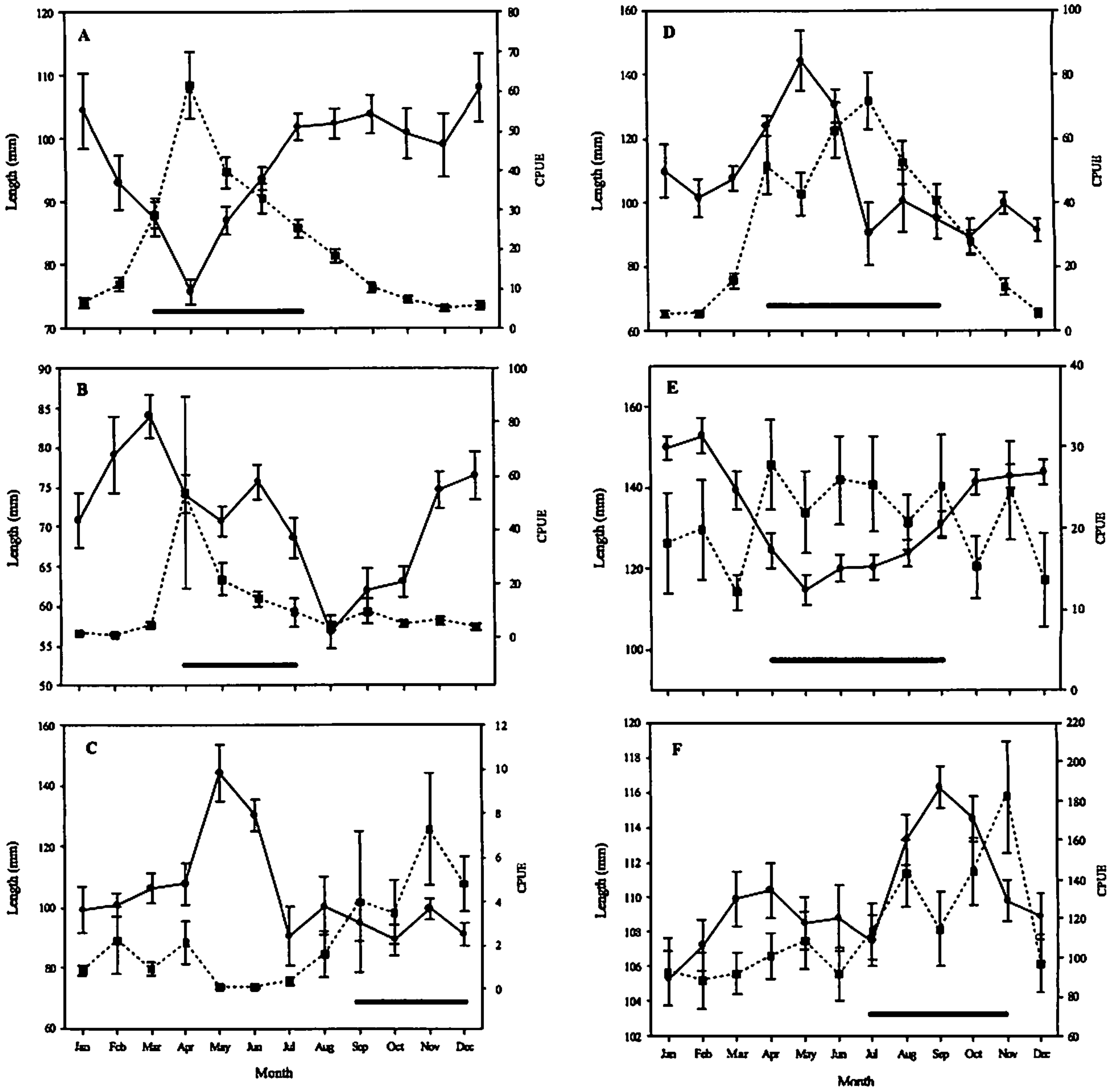

Figure 3.16. Average length (solid line, circle symbols, ± SE) and abundance (CPUE measured as catch per hour; dotted line, square symbols, ± SE) of **A**: Blue crab; **B**: Brown shrimp; **C**: White shrimp; **D**: Atlantic croaker; **E**: Spot; and **F**: Pinfish collected with bay trawls in the Lower Laguna Madre. Heavy solid line delineates the season of maximum abundance used for verification analysis.

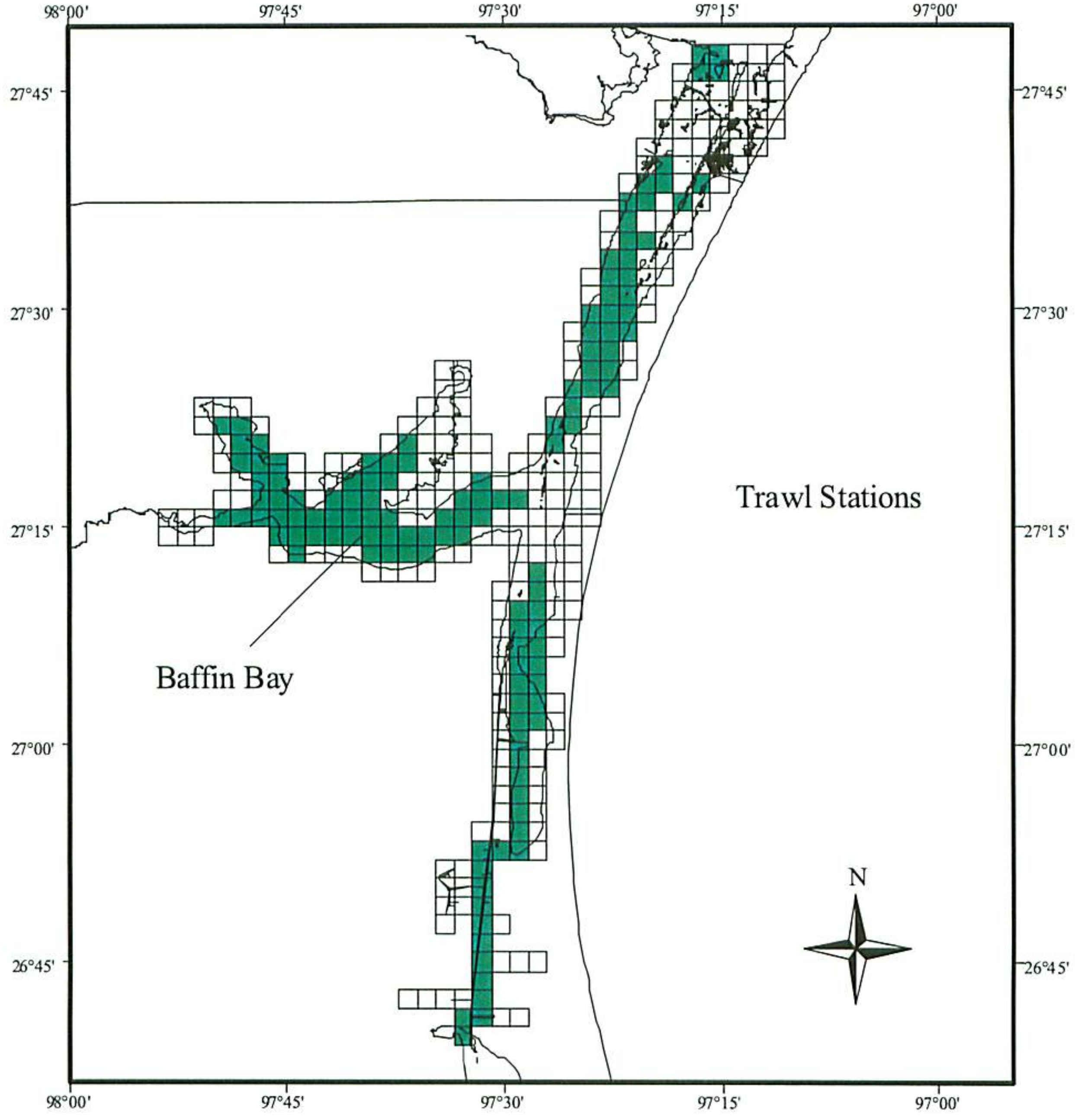

Figure 3.17. Coastal Fisheries Division sample grid used in the Upper Laguna Madre for the randomized sampling protocol. Active trawl sample grids are identified in green.

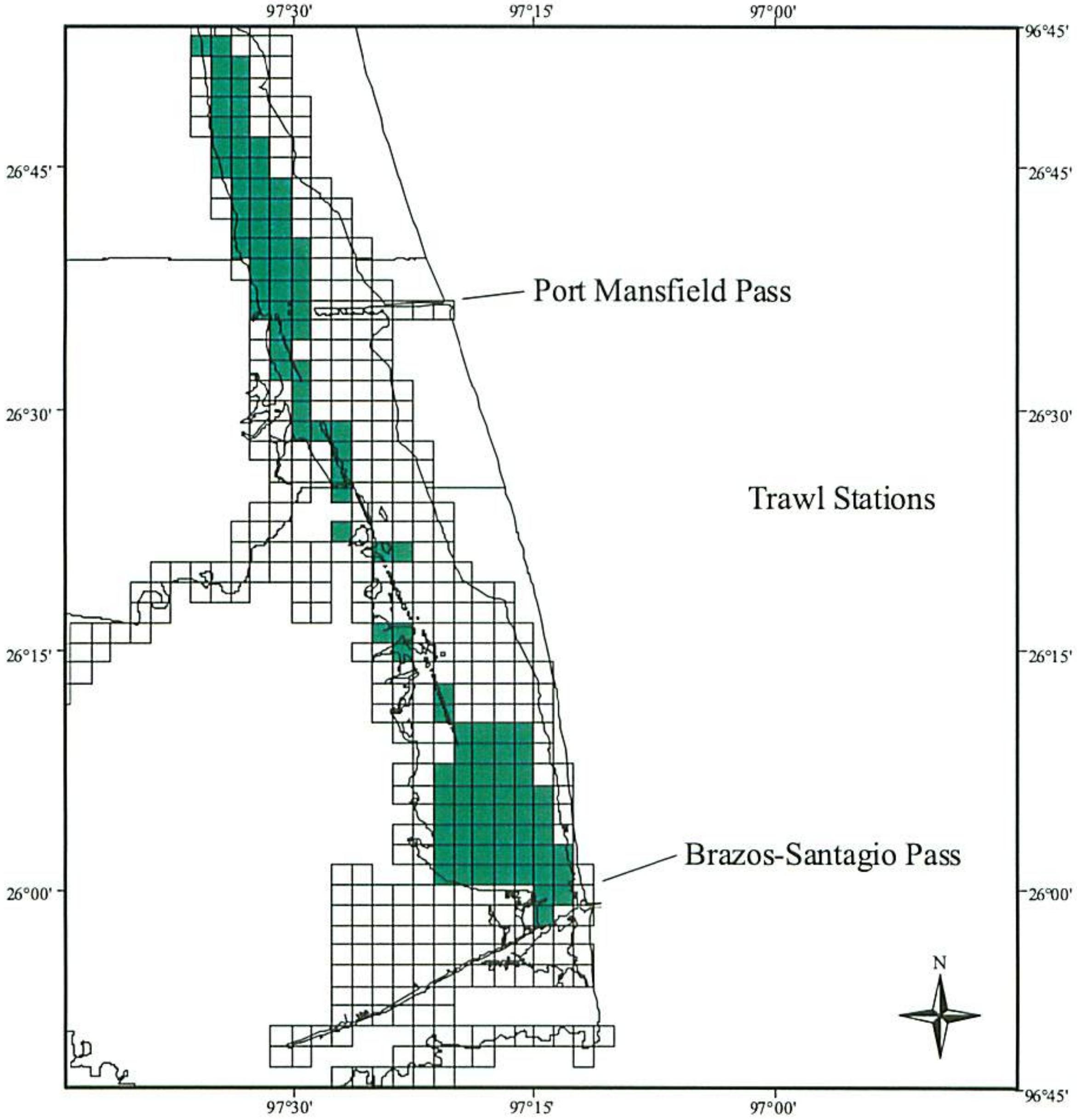

Figure 3.18. Coastal Fisheries Division sample grid used in the Lower Laguna Madre for the randomized sampling protocol. Active trawl sample grids are identified in green.

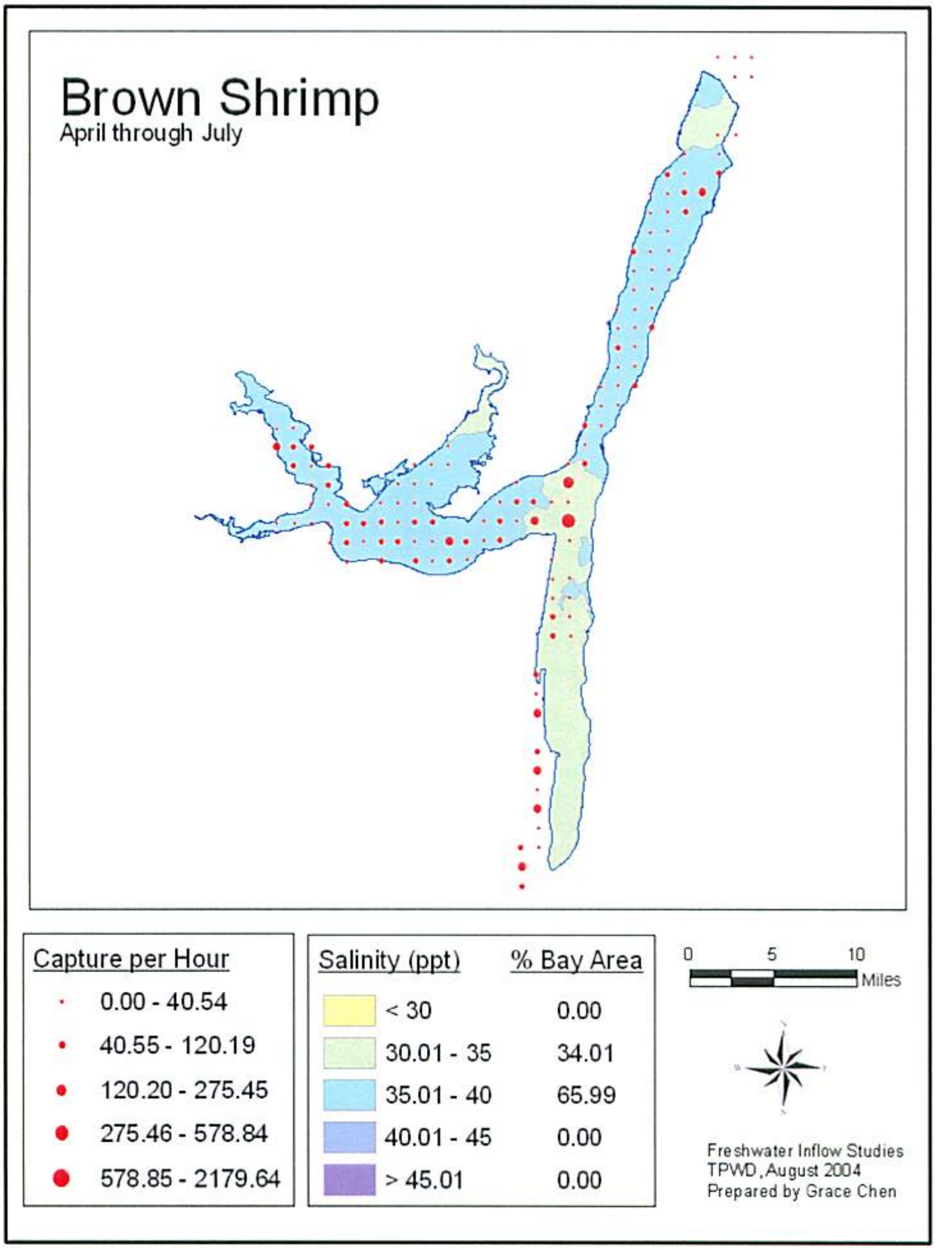

Figure 3.19. Spatial distribution of brown shrimp (April through July) in the Upper Laguna Madre for the period covering 1982-2001.

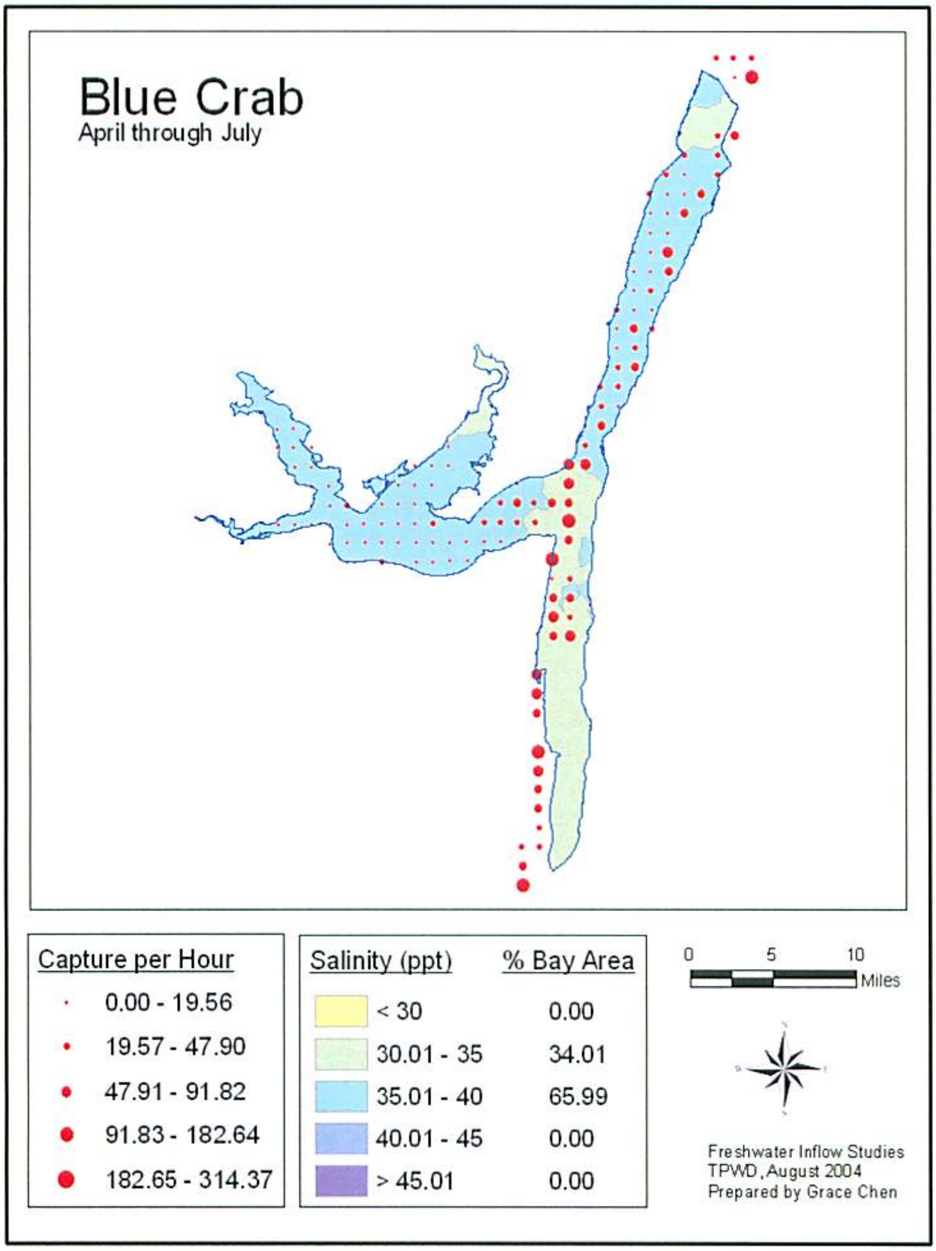

Figure 3.20. Spatial distribution of blue crab in the Upper Laguna Madre for the period covering 1982-2001.

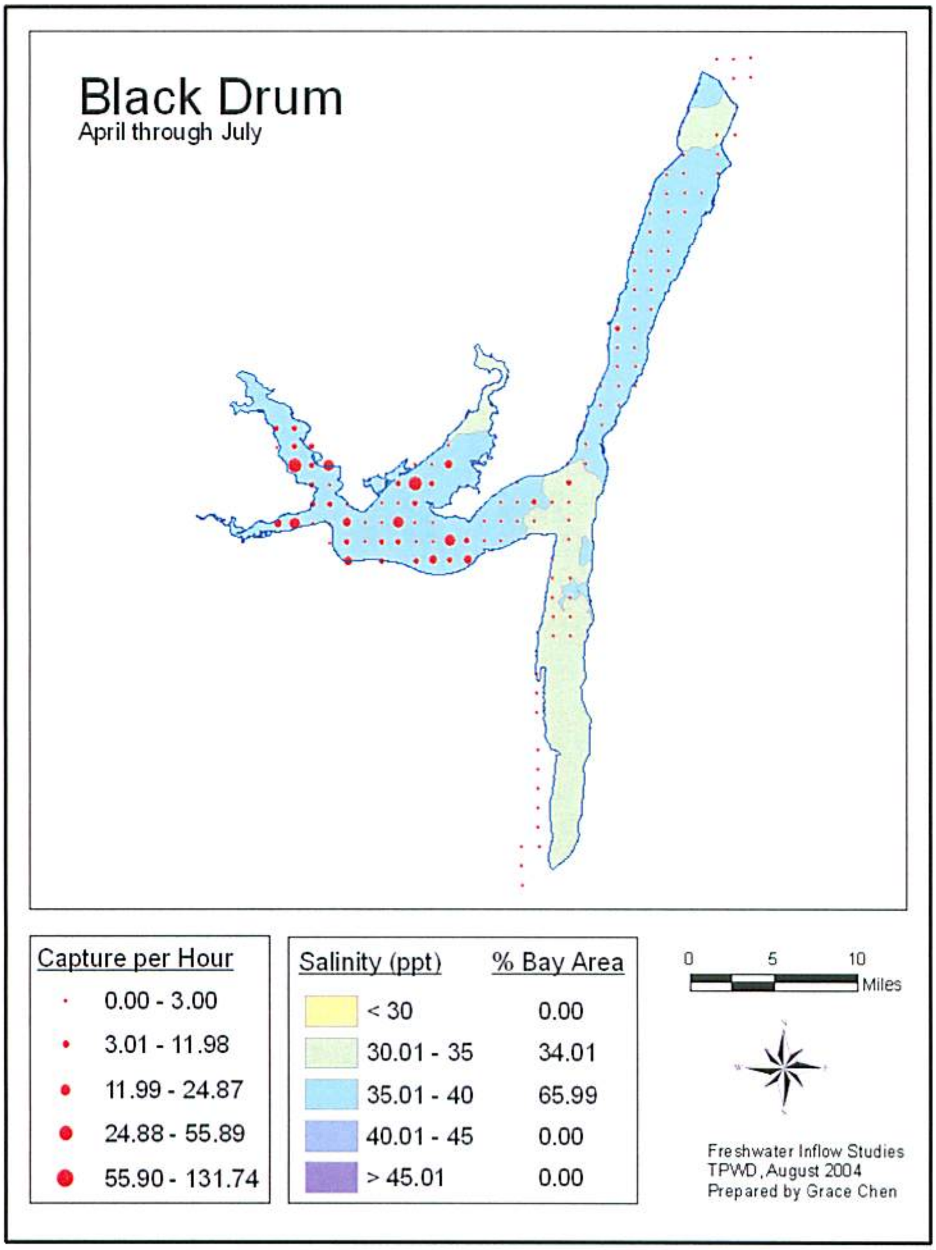

Figure 3.21. Spatial distribution of black drum in the Upper Laguna Madre for the period covering 1982-2001.

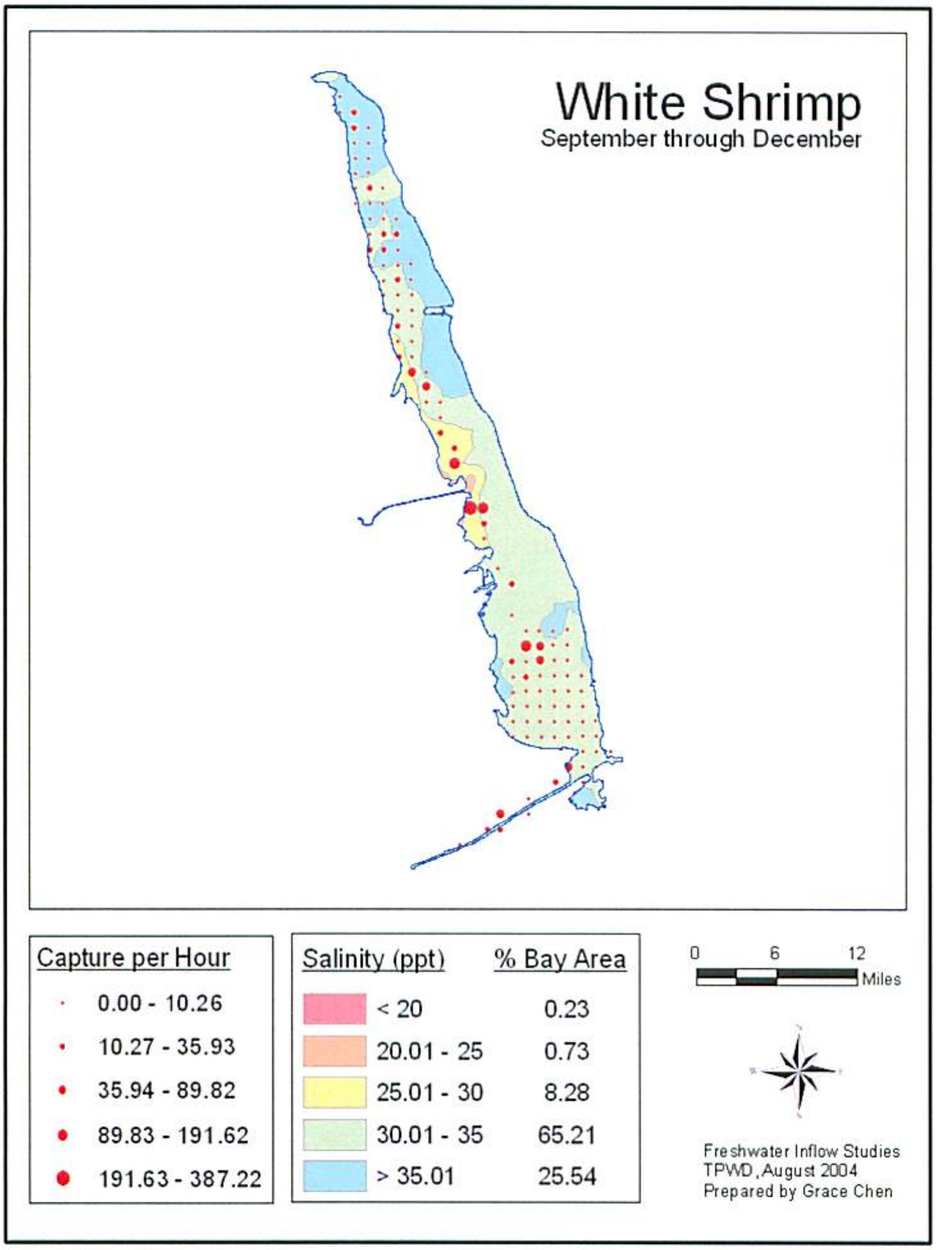

Figure 3.22. Spatial distribution of white shrimp in the Lower Laguna Madre for the period covering 1982-2001.

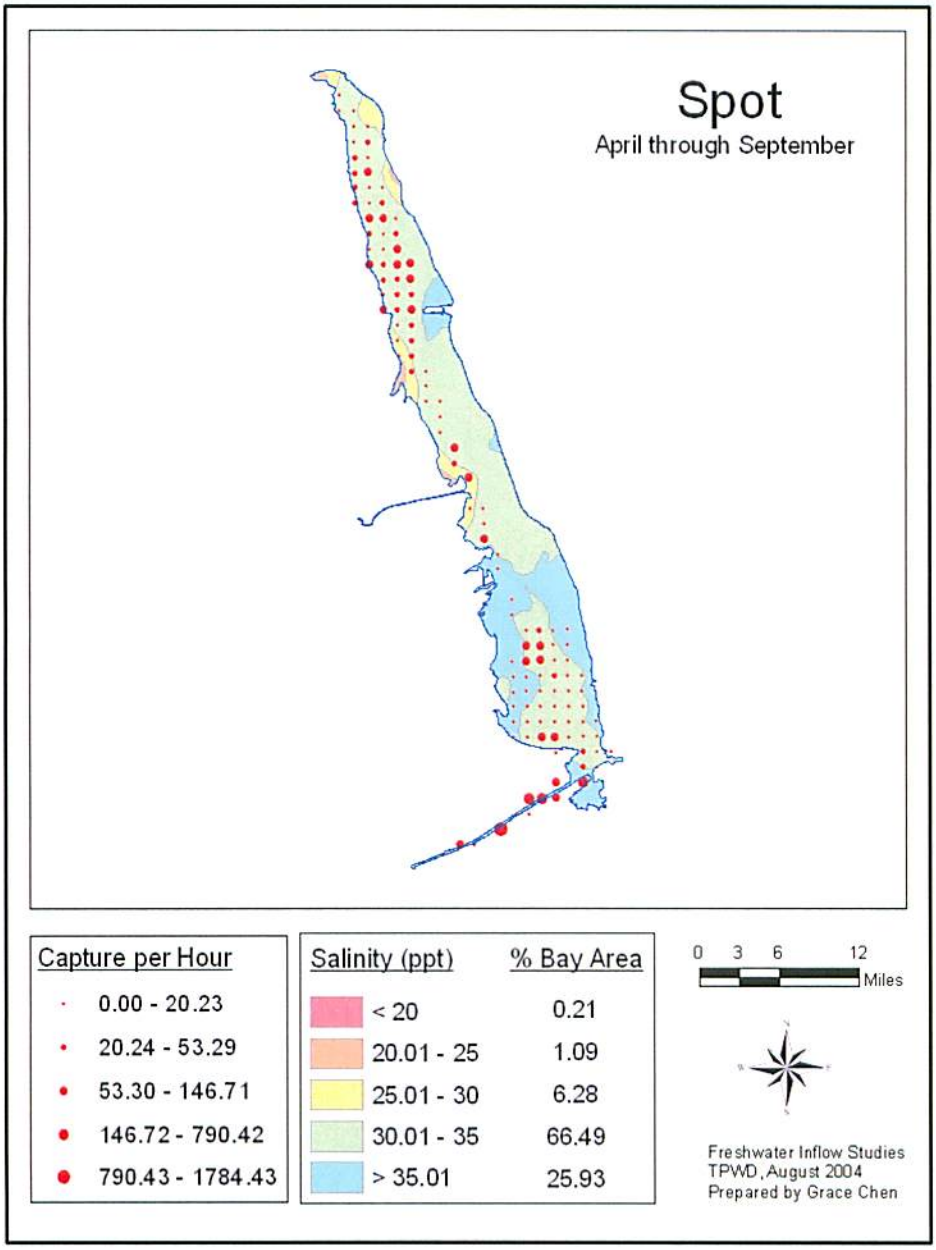

Figure 3.23. Spatial distribution of spot in the Lower Laguna Madre for the period covering 1982-2001.

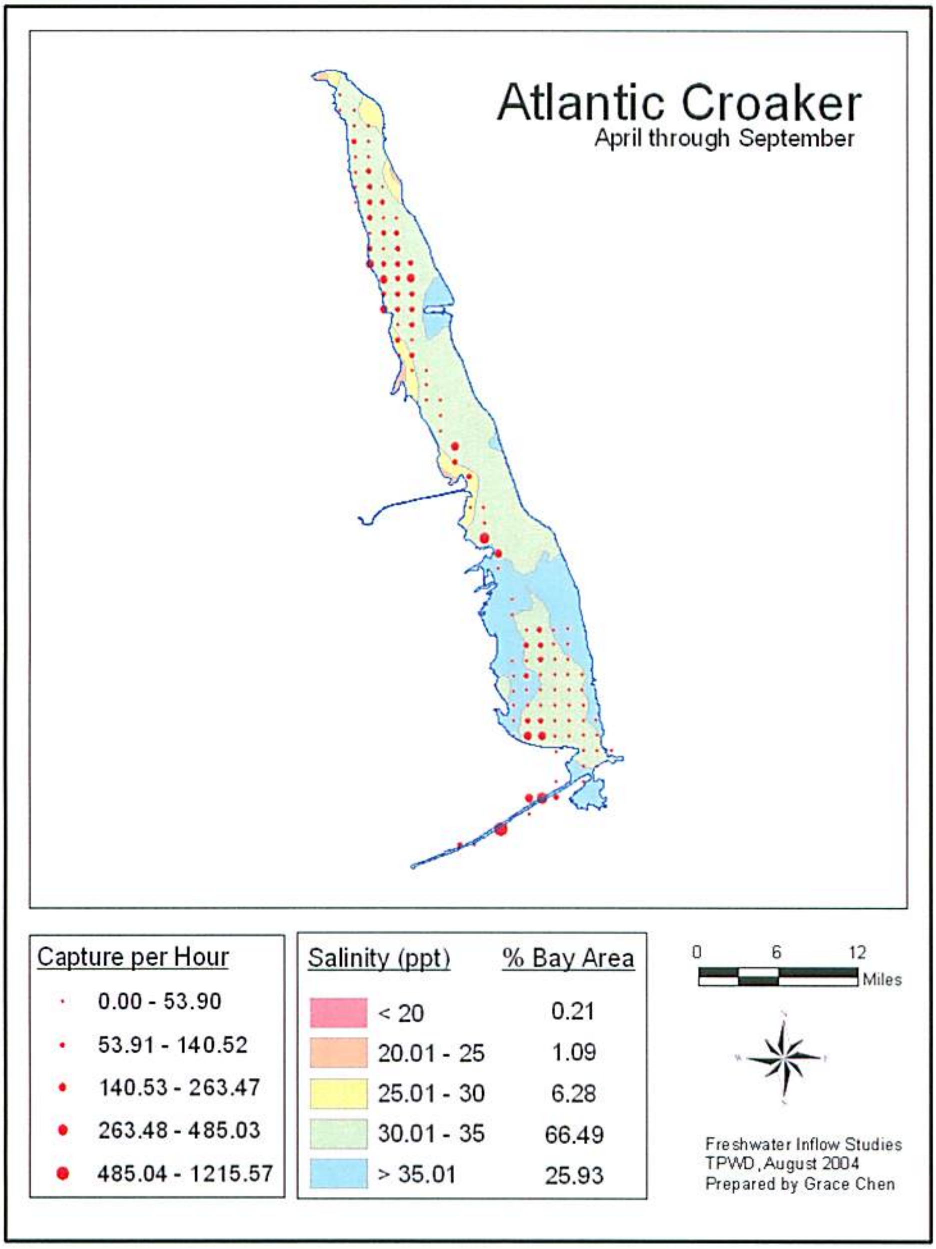

Figure 3.24. Spatial distribution of Atlantic croaker in the Lower Laguna Madre for the period covering 1982-2001.

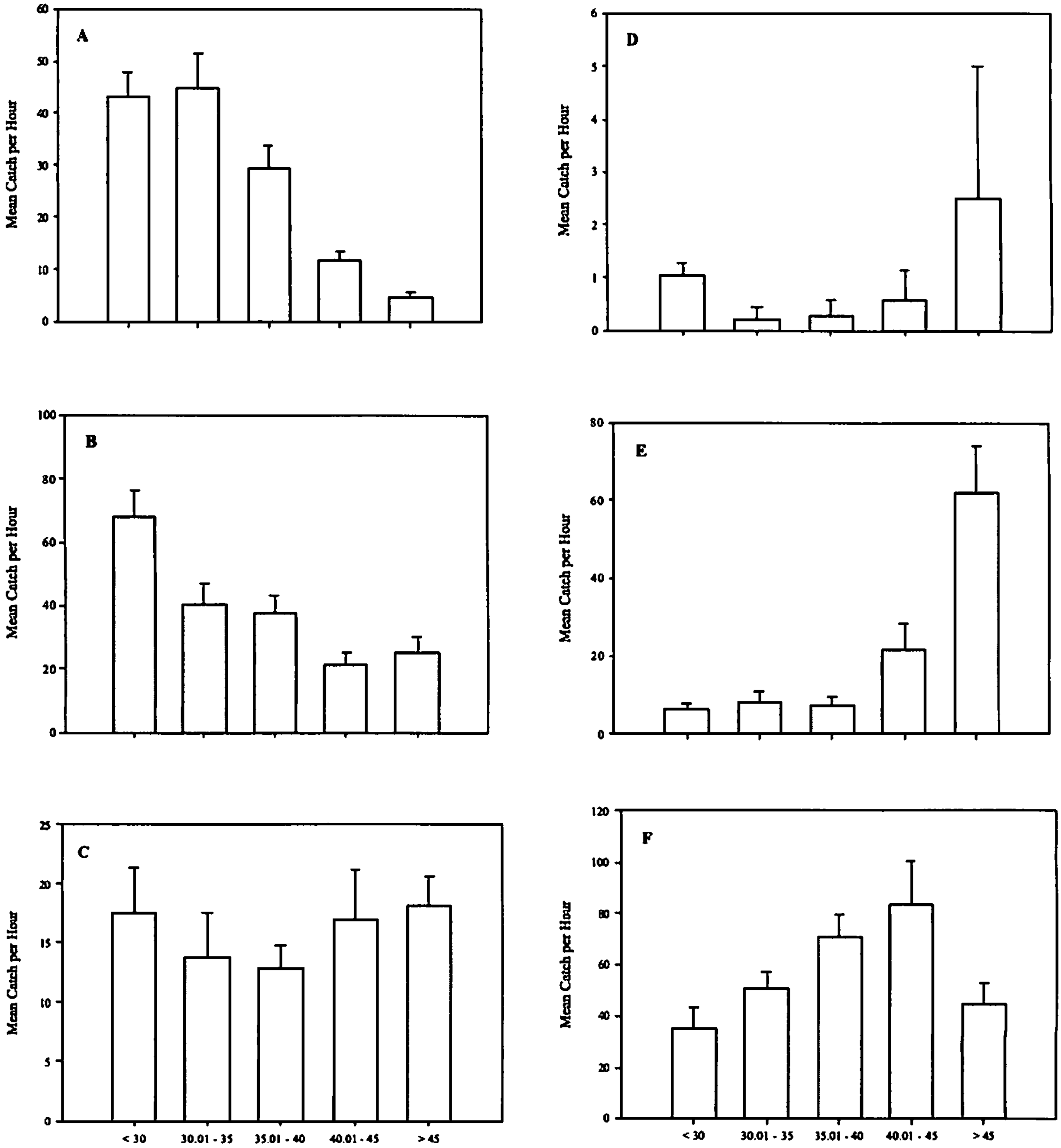

Figure 3.25. Mean catch rates (measured as number per hour ± SE) in bay trawls during season of maximum abundance across the 5 salinity zones in the Upper Laguna Madre for **A**: Blue Crab; **B**: Brown Shrimp; **C**: White Shrimp; **D**: Black Drum; **E**: Spot; and **F**: Pinfish.

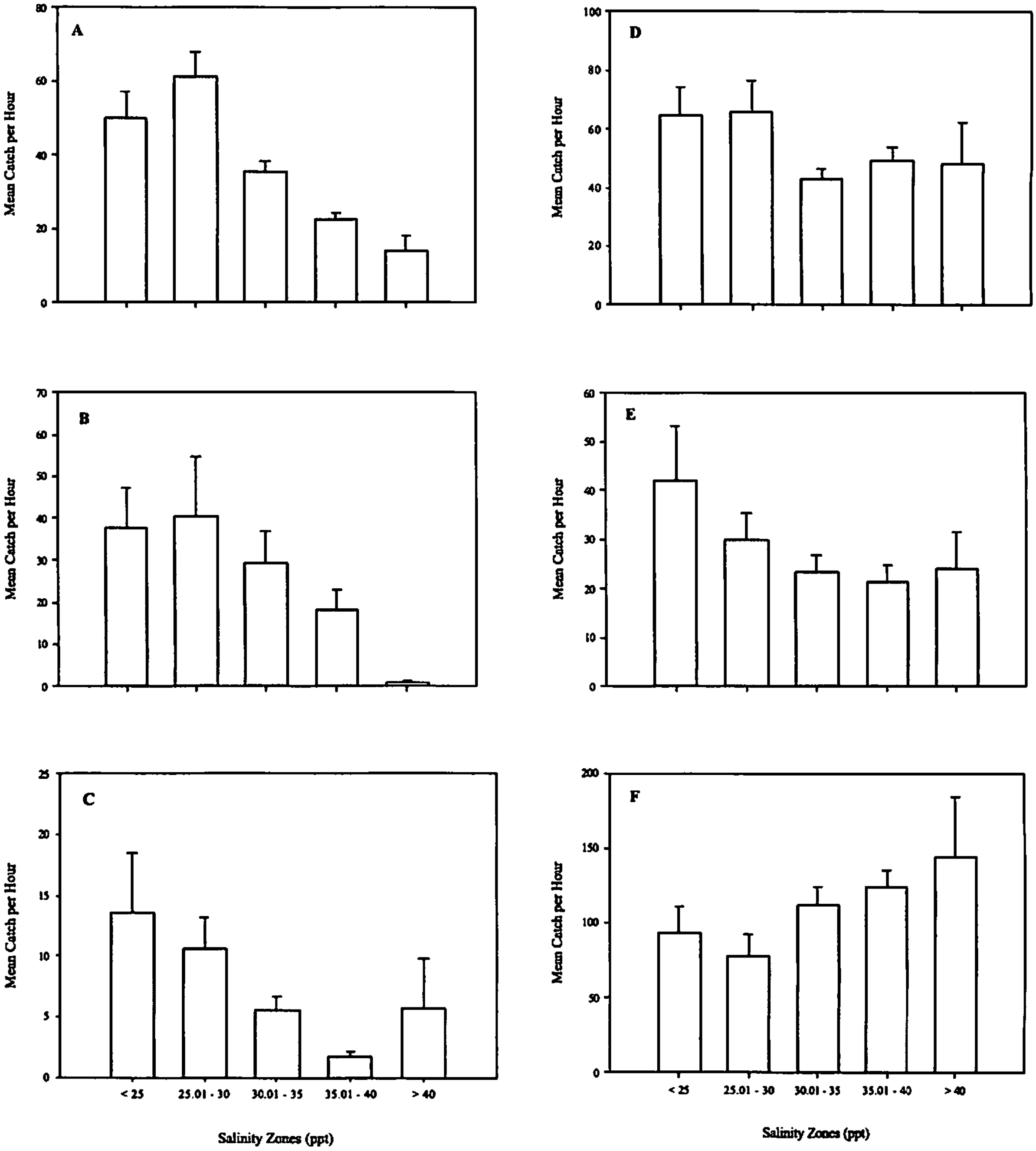

Figure 3.26. Mean catch rate in bay trawls (measured as number per hour ± SE) during season of maximum abundance across the 5 salinity zones in the Lower Laguna Madre for **A**: Blue Crab; **B**: Brown Shrimp; **C**: White Shrimp; **D**: Atlantic Croaker; **E**: Spot; and **F**: Pinfish.