FRESHWATER INFLOW RECOMMENDATION FOR THE NUECES ESTUARY

by

Texas Parks and Wildlife Department
Resource Protection Division
Coastal Studies Program
Austin, Texas 78744

Appendix

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Texas Water Development Board
Hydrologic and Environmental Monitoring Division
Environmental Section
Austin, Texas 78711

September, 2002

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Report

by

Warren Pulich Jr., James Tolan, Wen Y. Lee, and William Alvis

Texas Parks and Wildlife Department
Resource Protection Division
Coastal Studies Program
Austin, Texas 78744

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EXECUTIVE SUMMARY

This report summarizes studies performed by Texas Parks & Wildlife Department (TPWD) in accordance with Texas Water Code 11.1491 to recommend freshwater inflow targets which sustain the unique biological ecosystems characteristic of an "ecologically sound and healthy" Nueces Estuary. Methods for determining the quantity and quality of freshwater inflows (FWI) needed to maintain biological productivity of Texas' estuaries were developed by the State Bays and Estuaries Research Program [consisting of the Texas Water Development Board (TWDB) and TPWD] under Texas Water Code 16.058. These methods, relying on computer optimization and hydrodynamic modeling, predict a minimum freshwater inflow (termed the MinQ flow) and maximum harvest inflow (the MaxH flow) for each estuary. In this report, the MaxH target flow predicted by modeling studies is critically evaluated for its effectiveness in maintaining historical fisheries production and wetland habitats in the Nueces Estuary. For this analysis, fisheries-independent sampling data from the TPWD Coastal Fisheries Resource Monitoring Program and wetland maps from the TPWD Coastal Studies Program are used to evaluate the computer simulation results.

REVIEW OF TWDB/TPWD MODELING RESULTS (see Appendix)

As presented in the Appendix, the Estuarine Mathematical Programming or Optimization Model (known as TxEMP) was used to compute a range of flows necessary to maintain an "ecologically sound and healthy" environment within the Nueces Estuary. In addition to maximum harvest inflow, TxEMP also identified both the minimum (MinQ = 115,600 acre-ft/year) and maximum (MaxQ = 167,100 acre-ft/year) annual inflows that satisfied all the modeling constraints. The model predicted that maximum fisheries harvest flow (MaxH) occurred at 138,500 acre-ft/yr, with a specific distribution of monthly inflows. Despite a 16.6% volumetric difference between annual MinQ and MaxH target flows, the difference appeared small (only 7.3%) in total commercial fisheries harvest predicted between the two cases (1.992 vs. 2.149 million pounds for MinQ vs. MaxH, respectively). MaxH flow produced slightly higher harvests of red drum, black drum, spotted seatrout, and brown shrimp, but slightly decreased amounts of blue crab. Under MinQ and MaxH scenarios, brown shrimp dominated total harvests, which were 26.7% and 36.6% higher, respectively, than the TxEMP target (70% of mean historical commercial harvest).

TPWD STUDIES VERIFYING BIOLOGICAL RESPONSES TO TARGET INFLOWS

TPWD performed two types of verification analyses on the computed FWI targets: 1) Seasonal salinity gradients predicted by the hydrodynamic model were evaluated for any measurable biotic effects; and 2) Fisheries-independent relative abundance data were correlated with historical hydrologic regimes, thereby allowing comparisons of species abundance under observed inflow regimes to that under modeled inflows.

Salinity Gradient Effects and Time Series Analysis of MinQ vs. MaxH Flows

Geographic Information System (GIS) techniques were used to compare salinity gradient maps from the hydrodynamic model (TXBLEND) output under optimized MaxH or MinQ inflows. Two different hydrologic regimes in Nueces Bay were examined: MinQ or MaxH inflows with tides, winds, and temperatures from the 1988-1989 DRY regime; and MinQ or MaxH inflows with tides, winds, and temperatures from the 1991-1992 WET, cooler period. Salinity change analysis was performed by overlaying monthly MinQ and MaxH salinity maps for each regime, producing salinity difference maps between each target flow condition. Locations of critical marsh nursery habitat in the Nueces Bay delta region (approximately 2000 ha of regularly flooded salt marsh) were given special consideration in this evaluation. Results documented the almost complete lack of a typical estuarine salinity gradient in the system under both WET and DRY regimes, with salinities > 30 ppt found year-round within lower Nueces Bay proper. Slight salinity differences (< 2.0 ppt) were evident between the MaxH and MinQ cases at a few locations in parts of upper Nueces Bay, primarily during May and June,.

Time-series analyses were performed on the salinity data from the TXBLEND model at two key sites (model nodes) in the Estuary, to determine how often model constraints for salinity were exceeded under target FWI flows. Both MinQ and MaxH cases exceeded the model salinity constraints in the upper bay by 5 to 6 ppt on many days during DRY weather years (39% vs. 27%, MinQ vs. MaxH); while during the WET years, few exceedances were observed (5% vs. 2%, MinQ vs. MaxH). Overall, salinity values predicted by MinQ and MaxH flows under DRY conditions exceeded salinity constraints most severely during the spring and late summer, a cause of concern for the critical delta nursery area.

Low- vs. High-Inflow Analysis of Coastal Fisheries Monitoring Data

Because a substantial salinity gradient is lacking within the Corpus Christi Bay system, statistical techniques were used to establish direct correlations between FWI hydrology and fisheries organisms. Simple linear regression, unpaired t-tests, and GIS analyses were used to correlate historical inflows with natural abundance of eight target species in Nueces Estuary: white and brown shrimp, blue crab, Gulf menhaden, Atlantic croaker, bay anchovy, spot, and striped mullet. TPWD Coastal Fisheries monitoring data covering the period 1978 to 1997 were analyzed and statistical correlations were determined between seasonal freshwater inflows and the relative abundance (measured by catch per unit effort, or CPUE) of young animals caught in bag seines. Arc/Info GIS plots (overlays) were also developed with the observed bag seine catch rates and contoured salinity data from the Coastal Fisheries database to determine spatial relationships between species abundance and corresponding habitat locations within the Estuary.

Mean CPUE was compared for LOW- and HIGH-inflow years, with catch data separated according to actual, seasonal surface inflows over the 19-year period. Differences between HIGH- and LOW-inflow years were based on the cumulative surface inflow reaching the estuary during the seasonal periods of peak occurrence of each species. HIGH and LOW inflows were separated using, as a cutoff, the cumulative monthly values of MaxH flows (which is 89,200 acre-ft for the April through July period). Statistical analyses confirmed that shellfish (brown shrimp, white shrimp, and blue crab) and finfish species (Atlantic croaker) differed significantly in average relative abundance between LOW- and HIGH-flow years, as shown by significantly higher catch rates under HIGH flows (i.e., inflows higher than cumulative MaxH of 89,200 acre-ft), compared

to LOW flows (i.e., inflows lower than MaxH). This is interpreted as meaning that observed production of these four species continues to increase with inflows two- and three-fold higher than this seasonal MaxH value. Although results for the four remaining finfish species (bay anchovies, Gulf menhaden, striped mullet, and spot) were not statistically significant, all except menhaden exhibited the trend of higher relative abundance in HIGH-flow as compared to LOW-flow years.

Evaluation of MaxH Flows in relation to Pulsed Historical Hydrology Cycles

When historical inflows from 1941 to 1996 are compared to the MinQ and MaxH target values, the results reveal significant patterns. The monthly quantities for MaxH equal the monthly historical median values in 8 out of 12 months; six of these months are March through August. These median values (the 50th percentile inflows) are, in fact, the upper hydrology bounds (inflow constraints) allowed in the solution of the TxEMP model. This is important because Nueces Estuary historically receives inflows in a highly pulsed or episodic mode. For example, between 1977 and 1997, 64 % (or 9 out of the 14 such large pulses of inflow greater than 100,000 ac-ft per month) occurred in the critical spring-summer months of May and June. Thus, seasonally-required median MaxH target flows are quite significant in that they overlap with these actual May-June monthly pulses.

Various water diversion projects (e.g., Rincon Bayou channel diversion, Allison wastewater treatment plant discharge, etc.) are considered examples of water management solutions with potential to enhance productivity of upper Nueces Bay by increasing the inundation regimes of the Nueces delta. Based on information compiled for the Bureau of Reclamation Rincon Bayou diversion project, predicted MaxH flows were evaluated for effectiveness in producing necessary inundations of the Nueces Delta. In the absence of the Rincon Bayou diversion, MaxH monthly inflows during May and June (approximately 37,000 acre-ft per month or 1,215 acre-ft per day) are much lower than the amount calculated by Bureau of Reclamation actually needed to cause overbanking into the upper Rincon Bayou (approximately 4,170 ac-ft per day). Once the Rincon Bayou diversion project is implemented, the river's minimum flooding threshold is lowered from 1.64 m (5.4 ft mean sea level) to approximately 0.0 m mean sea level. This water project will allow not only more frequent diversions of freshwater into the upper delta; it also will provide daily, bi-directional non-riverine flow events, such as winds and tides, to force water exchanges between the upper delta and the river. Cumulative MaxH flows for May and June, if delivered in a pulsed release over 3-4 weeks, could supply 74,000 acre-ft (at a rate of 2,600–3,500 acre-ft per day) to the delta. Thus, with the diversion project in operation, the cumulative MaxH flows could supply a sufficient inflow pulse to inundate the Nueces delta during critical spring/summer months and maintain productivity of this sensitive nursery area.

TARGET INFLOW RECOMMENDATION

TPWD recommends that: 1) a minimum of the cumulative monthly, April through July, MaxH inflows (equivalent to 89,200 acre-ft) be delivered to Nueces Estuary during the late spring/early summer season as the FWI target protective of the biological needs of this estuary; 2) this cumulative spring/summer inflow be delivered in one or two pulsed events during the April through July period to the critical nursery habitats in the Nueces Bay delta region; and 3) monthly MaxH flows be supplied all other months of the year, except during the fall season (September through November) of years when cumulative spring/early summer MaxH flows have not occurred. In the latter case, cumulative MinQ target flows for these three months (27, 510 acre-ft total) should be provided to maintain refugia in the extreme upper bay, delta, and tidal portion of the Nueces River.

This cumulative spring MaxH flow essentially mimics the pulsed pattern of historical hydrology characteristic of Nueces Estuary inflows. Delivery of spring pulses of this magnitude correlates with higher historical catches demonstrated for important target fishery species (blue crab, brown and white shrimp, and Atlantic croaker). These critical, pulsed spring flows appear to maintain the estuarine wetlands located in the delta and to provide upper estuary nursery habitat conditions when estuarine-dependent species are actively recruiting into the Bay. Dryer conditions during the peak summer months (July through September) are expected to occur naturally, and fishery species dependent upon the estuary at those times (e.g., white shrimp) can tolerate suboptimal conditions if the estuary is provided with adequate inflows earlier in the year.

SECTION 1: INTRODUCTION

Each Texas estuary needs freshwater inflow (FWI) to maintain proper salinity regimes, nutrient loading, and sediment inputs in order to support its unique, historical level of biological productivity. Freshwater inflow from rivers, streams, and local runoff carries these necessary materials into the estuary, and collectively, these inflow-dependent processes produce an "ecologically sound environment." In order that the limited freshwater resources of Texas may be managed without biological impacts to the State's estuaries, TPWD, TWDB (Texas Water Development Board), and TNRCC (Texas Natural Resources Conservation Commission) have been charged with identifying the specific quantities and qualities of FWI needed to maintain biological productivity in each receiving bay or estuarine system (Texas Water Code Sec. 11.1491). For water resources management purposes, TPWD describes this maintenance or target flow as the level of FWI needed to sustain the historical productivity of economically important and ecologically characteristic fish and shellfish species, and their associated biological communities. This report summarizes the protocol and analyses that evaluate the minimum target freshwater inflow needed to support healthy fishery communities' characteristic of the Nueces/Corpus Christi Estuary system.

The objectives, research design, and analytical methods for freshwater inflow studies were originally detailed in the published report by the TWDB and TPWD, "Freshwater Inflows to Texas Bays and Estuaries: Ecological Relationships and Methods for Determination of Needs" (Longley, ed., 1994). This work, legislatively-mandated in accordance with TWC Sec. 16.058, was performed to determine freshwater inflow conditions necessary to support a sound ecological bay environment. TWDB developed the hydrologic modeling techniques and compiled data on coastal physical and hydrologic factors, while TPWD evaluated trends from biological survey data and provided ecological data synthesis. TWDB and TPWD staff worked together to formulate acceptable constraints for the TxEMP model (see Appendix). The modeling procedures from these earlier efforts (Longley, 1994) have since been further refined and rigorously applied to two estuaries [see Pulich et al. (1998) for the Guadalupe Estuary and Lee et al. (2001) for the Galveston Bay System].

The modeling procedures jointly conducted by TWDB and TPWD quantitatively integrate commercial fisheries harvest data and hydrological monitoring data through statistical probability analyses, resulting in mathematical determination of inflow targets. The modeling output consists of flow solutions that satisfy various constraint sets. Among the resulting flows are two identified target flows, a minimum target flow, termed MinQ, and an optimum harvest flow, termed MaxH. MaxH constitutes an optimal target flow to the estuary that is consistent with maximum historical biological productivity as measured by fisheries-dependent commercial harvest landings. The concept of MinQ implies there is a minimum flow threshold at the low end of the FWI range, below which some functions of FWI become limiting to biological production (whether it be maintenance of salinity, or the supply of nutrients, particulate organic matter, or sediments). The MinQ target flow is distinct from the lowest subsistence flow, termed MinQ-Sal, which represents the critical inflow level needed to maintain salinity only. At flows between the critical MinQ-Sal level and MinQ target flow levels, biological productivity and fisheries harvest become very unpredictable and, by definition, are significantly reduced from even the average historical levels. During low-flow conditions below the MinQ level (e.g., during droughts), adequate salinity conditions may be maintained only in some estuarine areas, which act as refugia supporting limited biological productivity. It is important to realize that below the minimum, modeling-derived, target FWI (MinQ), estuarine health and productivity will suffer, often severely.

1.1. Objectives

TPWD objectives in this verification analysis are to evaluate the effectiveness of the predicted MinQ and MaxH modeled target inflows in supporting relative abundance of characteristic estuarine fishery species and wetlands in each estuary. This includes both annual and seasonal (= cumulative monthly) inflow amounts. Because MinQ-Sal (see above) 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 is conducted. Normally, the starting premise (similar to a statistical null hypothesis) would be that MaxH inflows are needed to maintain relatively high historical fisheries abundance and wetland nursery habitat production. If, after verification analysis, MaxH proves to sustain this characteristic production, MaxH would be the recommended inflow target. If MaxH does not meet the stated goals, such a result would suggest that the constraints or other inputs to the TxEMP model would need to be re-evaluated. This report 1) describes the TPWD independent verification analyses performed on the MaxH target inflow predicted for the Nueces Estuary, and 2) evaluates relationships of MaxH flows to observed biotic responses and historical inflow conditions in this system.

SECTION 2: ANALYTICAL PROTOCOL AND MODELING OUTPUT

The protocol for verifying FWI target flows begins with review of the input data to the optimization and hydrodynamic models. The complete analytical details, especially constraints and other input data, for the Estuarine Mathematical Programming or Optimization Model (TxEMP) are presented in the Appendix, compiled by TWDB staff.

TxEMP model solutions depend on limiting input constraints (or bounds) developed from the historical 53-year hydrologic record (1941 – 1994) for the river basin and from concomitant commercial fisheries harvest data reported by National Marine Fisheries Service. TWDB and TPWD also formulated key salinity constraints in the TxEMP model for three different regions of the Nueces Estuary (see Tables 2 - 4 in Appendix). These critical constraints were developed using historical salinity data collected over 30 years, supplemented by continuous datasonde readings in recent years. Salinity data from the 1950's period when the drought of record occurred in Texas were not available. These salinity bounds are also based on known salinity tolerance data for many indigenous estuarine species, both flora and fauna. These broad, monthly salinity values are not considered optimal limits, but rather the seasonal viability limits for species and habitats typically found in the estuary.

TxEMP, which uses multi-objective functions and incorporates statistical uncertainty in the inflow solution, produces a range of feasible solutions (MinQ to MaxH to MaxQ) that simultaneously predict inflows and the corresponding commercial fisheries harvest (Matsumoto 1994). An important result of the optimization process is the delineation of an optimal, monthly inflow pattern characteristic of the estuary. The monthly distribution of MaxH inflows is found by allowing TxEMP to optimize for the maximum possible harvest, while limiting monthly inflows to the monthly median values as the upper bound. The monthly distribution of MinQ inflows is found by minimizing the inflows, while keeping the fishery harvest at or above the specified targets. The MaxQ inflow is found by maximizing the inflows while keeping the same fishery harvest targets as in the MinQ case. 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.

2.1. Review of TxEMP Model Results

The TxEMP model generates a performance curve (see Longley, 1994) that graphically describes how varying amounts of total annual inflow affect fishery harvest. The performance curve for Nueces Estuary (Figure 2.1) was produced by first finding the endpoints, the minimum annual inflow (MinQ) and maximum annual inflow (MaxQ), which satisfy the model constraint set. From this analysis, MinQ was found to be 115,640 acre-ft/year and MaxQ was 167,100 acre-ft/year. In the next step, TxEMP was executed to optimize for fishery harvest (MaxH) within the range of annual inflows between MinQ and MaxQ at a 50% salinity probability level. Intermediate points on the harvest performance curve were generated by limiting the range of possible inflows to narrow intervals while solving for MaxH. The optimal MaxH value was found to be 138,500 acre-feet/year. Figure 2.2 shows graphically the monthly inflow distribution under the MinQ and MaxH constraint scenarios, while Table 2.1 also lists these monthly flow levels along with the 10th and 50th percentile inflows used as constraints for the model.

Total species harvest predicted by TxEMP for each inflow scenario ranged from 1.992 million pounds (MinQ) to 2.149 million pounds (MaxH) (Table 2.2). Despite the 16.6 % difference between MinQ and MaxH levels, the difference in total predicted fisheries harvest between the two cases (1.992 vs. 2.149 million pounds for MinQ vs. MaxH, respectively) is small (only 7.3 %). MaxH flow produced slightly higher harvests of red drum, black drum, spotted seatrout, and brown shrimp than did MinQ, but slightly lower amounts of blue crab. Both cases produced slightly more (ranging from 26.7 % to 36.6 %) commercial harvest than the model target of 70% historical mean harvest, and these increases were accounted for primarily by brown shrimp (Table 2.2). Brown shrimp dominated the biomass harvest within this estuarine system (47.5 % of the historical mean biomass).

Table 2.1. Monthly Inflow Bounds (10th and 50th percentile historical inflows) and Predicted Target Inflows (MinQ and MaxH) for Nueces Estuary. Values are in acre-feet.

Month	Inflow Bounds		MinQ	MaxH
	10th	50th		
Jan	1,420	4,540	2,230	2,230
Feb	1,490	5,660	2,780	2,780
Mar	2,240	4,920	4,410	4,920
Apr	2,410	5,180	5,180	**5,180**
May	3,780	37,770	32,140	**37,770**
Jun	3,870	36,430	19,990	**36,430**
Jul	3,680	9,820	6,980	**9,820**[1]
Aug	3,790	9,750	9,750	9,750
Sep	3,610	23,740	**11,040**	9,600
Oct	4,380	18,680	**8,690**	7,560
Nov	2,660	7,780	**7,780**[2]	7,780
Dec	1,590	4,670	4,670	4,670
Total	34,920	168,940	115,640	138,490

[1] cumulative April - July total (89,200 ac-ft) should be delivered in 1 – 2 pulsed events to Nueces Bay delta between April – July.

[2] cumulative fall seasonal total (27,510 ac-ft) should also be delivered in pulsed events to Nueces Bay delta during September – November if spring MaxH pulses do not occur.

Table 2.2. Range of Historical Harvest and Predicted Harvest (in thousands of pounds) under MinQ and MaxH inflow simulations.

Species	Historical Mean	Target (70% Mean)	MinQ	MaxH
Blue crab	236.5	165.5	165.2	161.4
Brown Shrimp	1067.9	747.6	1168.4	1275.9
White Shrimp	613.6	429.5	429.5	429.9
Red Drum	66.7	46.7	46.7	78.5
Black Drum	131.7	92.2	88.9	96.5
Spotted Seatrout	84.1	58.9	48.7	58.6
Flounder	46.3	32.4	45.3	47.9
Total Harvest	2246.8	1572.7	1992.0	2148.7

2.2. Comparison of MaxH Target Flows to Historical Hydrology

When the monthly inflow distribution is examined (Fig. 2.2), MaxH values equal the monthly median values in 8 out of the 12 months, and the critical March through August period stands out. When compared on an *annual basis*, relative to the annual median (348,000 acre-ft for the period of 1941-1994), the MinQ and MaxH target flows both fall below the 10th percentile of annual historic inflows (Figure 2.3).

The *monthly* hydrographic record over a recent 21-year period from 1977 to 1997 illustrates that the inflow pattern for Nueces Estuary is highly pulsed or episodic in frequency (Figure 2.4). Examination of monthly inflow amounts over these 252 months indicates that monthly MaxH target flows are met only 63% of the time. Moreover, this record shows that the estuary has predictably received most of its 14 largest pulses of inflow (those greater than 100,000 acre-ft per month) over the 21-year period in the two months of May - June (9 out of the 14 times = 64.3%). It is significant therefore that the higher spring monthly MaxH flows overlap with these critical May - June pulses of inflow in these recent 21 years. Results presented by Irlbeck and Ward (2000) also showed that the magnitude, duration, and timing of high flow events into the Nueces Estuary system were also highly episodic.

2.3. Review of TXBLEND Modeling

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 MaxH and MinQ inflows predicted by TxEMP were used as input for the TXBLEND model under two hydrological and meteorological scenarios. Because the Nueces Estuary is characterized by highly pulsed inflow cycles (see Figure 2.4), and exhibits a high degree of annual variability in climatological conditions, two different hydrodynamic simulations (a DRY, warm scenario and a WET, cool scenario) were carried out in order to compare the effects of MinQ and MaxH inflows. Actual tidal and climatic conditions measured in 1988 - 1989 (a hot, drought period with 2-year average annual inflow of only 62,691 acre-ft) were used as input for the DRY weather regime, while cooler, wetter conditions during 1991 – 1992 (2-year average annual inflow of 695,750 acre-ft) were used to simulate a WET weather regime.

The TXBLEND model computes salinity values over 2-hour time-steps at over 4300 grid nodes in the Nueces Estuary (Corpus Christi Bay system). Simulated salinity regimes for the

Estuary resulting from the two different meteorological (weather) scenarios were illustrated by two output formats of data:

1. Isohalines of average monthly salinity in 5 ppt increments were plotted to show the salinity gradient for the estuary by month.
2. Time series plots for average daily salinity were graphed for the 2 year weather cycles at two locations in the Estuary: a site in extreme upper Nueces Bay near the delta, and a mid-bay site at the causeway crossing the junction between Nueces and Corpus Christi Bays.

SECTION 3: EVALUATION OF BIOLOGICAL RESPONSES TO TARGET FRESHWATER INFLOWS

This Section presents the graphical and statistical analyses using observed fisheries abundance and estuarine wetland distribution data to assess the predicted inflow targets. This step in the protocol verifies or provides a "reality check" on the results predicted by the models. The abundance of typical fishery species from actual sampling surveys in the estuary, along with known salinity tolerance limits and nursery habitat requirements, are the bases for evaluating the impacts of target FWI regimes. By coupling the hydrologic regimes with field survey data of both dominant fisheries species and the distribution of estuarine wetlands, a picture emerges of the community dynamics within the Nueces/Corpus Christi Bay System. By comparing effects of modeled conditions on estuarine biota with those observed under actual inflow conditions, we can infer whether or not target flows are reasonable and effective. Based on this fisheries-independent biological impact assessment, a final FWI recommendation is proposed.

Although estuarine productivity can be assessed by a variety of criteria, we used relative abundance of fisheries and wetland nursery habitat distributions as the primary indices to gauge effects of the target FWI amounts. Biological monitoring and sampling data on the estuarine fishery species and wetland habitat types were derived from literature sources, TPWD fisheries surveys, and special project studies (Bureau of Reclamation, 2000). If inflow regimes, salinity gradients, or other FWI-related factors were found to correlate with the presence or abundance of selected indicator species (both flora and fauna), this would provide evidence of FWI regimes necessary for the maintenance of estuarine health. Two major types of biological analyses were performed: 1) Verification of the biotic effects of salinity gradients resulting from the hydrodynamic model runs; and 2) Statistical correlations between representative biota and FWI regimes under actual historical hydrological conditions.

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

The TXBLEND hydrodynamic model predicts the salinity gradient patterns in the Estuary system under specified inflow and weather conditions. Model verification analysis was performed similarly to the two previous studies (see Pulich et al. 1998 and Lee et al. 2001) by comparing the TXBLEND modeled salinity gradients to known distributions of fishery species or their nursery habitat, thereby allowing an evaluation of salinity effects on critical estuarine areas.

Because output from TXBLEND consists of a grid map of salinities at hundreds of nodes throughout the bay, GIS (Geographic Information System) techniques were used to evaluate salinity maps of the model results for biological impacts. This procedure is described in detail in Pulich et al. (1998). After each model run with the monthly MaxH or MinQ target flows, salinity zone maps were generated with Arc/Info™ software (ESRI, Redlands, CA). Average monthly salinity values at each of the model grid nodes were subjected to contouring using the Kriging module from Arc/Info™ to produce isohaline contours in 5-ppt increments. Seven salinity zones were delineated, encompassing a salinity range from near freshwater (oligohaline) to euhaline seawater (> 30 ppt). Examples of these monthly salinity contour maps that depict the two different weather cycles (DRY year = 1988 and WET year = 1991) are shown in Figures 3.1 to 3.8. To contrast the two target inflow cases, these figures show both the MaxH and MinQ scenarios and a third map, representing the salinity difference between each case, for Nueces Bay proper. Results are shown for March, May, September, and October of each year type.

Examination of these GIS plots reveals that during either representative hydrologic year-type, a true salinity gradient is essentially lacking over most of the Estuary system. Generally, salinities in Corpus Christi Bay proper are above 30 ppt (euhaline) all months of the year under both MinQ and MaxH solutions. A highly compressed salinity gradient exists during the spring months (May – June) only in Nueces Bay proper (Figures 3.2 & 3.6), and predominately under WET weather conditions (1991, Fig. 3.6). This gradient ranges from high mesohaline (10 - 15 ppt) around the mouth of the Nueces River, to euhaline (30 - 35 ppt) near the mouth (lower end) of Nueces Bay. Later in the year, the majority of Nueces Bay again exhibits salinities similar to Corpus Christi Bay, greater than 30 ppt in September 1988 (Fig. 3.3) and 25 – 30 ppt in October (Fig. 3.4). It is primarily in the late summer of the WET year (1991) that salinities in the upper estuary (near the Nueces Delta and Nueces River mouth) fall into the high polyhaline range (20 - 25 ppt; see Fig. 3.7). Interestingly, salinities reach low mesohaline values (5-10 ppt) in the open waters of the upper estuary region for only a few days during summer of the WET MaxH simulation (Fig. 3.11). This compressed gradient presumably reflects the small volume ratio of the freshwater inflows from the Nueces River relative to the larger volume of seawater in the Corpus Christi Bay system, coupled with the normally high evaporation rates seen within this system.

The seasonal changes in salinity gradients indicate that there is relatively little difference between the MinQ and MaxH inflow scenarios throughout the course of the year. Salinity difference maps show that both MinQ and MaxH salinity zones are essentially identical from January through March (Figures 3.1 & 3.5). By May, during both WET or DRY year scenarios (Figures 3.2 & 3.6), a gradual difference in salinity zones between the MinQ and Max H cases occurred, but only in the extreme upper to middle reaches of Nueces Bay. However, even these differences between MinQ and MaxH are rather small, with the largest differences observed in May – June 1988 being only 1 to 2 ppt. This trend reverses from June through September (late summer, see Figures 3.3 & 3.7), and by October, the difference between MaxH and MinQ becomes insignificant (Figures 3.4 & 3.8). The similarity in salinity zones remained until the end of the simulation periods. In summary, modeled seasonal differences in salinity zones (< 2 ppt) between MinQ and MaxH flows are not considered to reflect significant hydrologic differences between the two flow cases.

3.2. Salinity Effects on Upper Nueces Bay and Delta

Estuarine-dependent fishes rely on the availability of suitable nursery habitat to serve as an important component in their early life history stages (Lyczkowski-Shultz et al. 1990). Unlike the Atlantic coast, where physical transport of planktonic larvae through tidal passes into estuarine nursery grounds by means of a two-layered, vertically stratified current flow is well documented (Weinstein et al.1980; Henri et al. 1985; Hettler et al. 1997), Gulf of Mexico estuaries tend to be shallow and well mixed, with predominantly wind-driven circulation (Raynie and Shaw 1994). Direct coupling of the ocean/estuary system (rivers feeding into marshes, encompassing secondary bays and primary bays, ultimately leading to the ocean) is frequently broken, with some bays completely isolated from significant freshwater inflow sources. Variations in the intensity of physical processes (FWI, currents, tides, winds) can result in differential abilities of competent individuals to leave the plankton and settle onto areas with favorable juvenile habitat (Sogard 1989).

The shallow estuarine habitats in Nueces Bay that serve as nursery grounds, including emergent marsh, submerged vegetation, and intertidal flats, are physically isolated from the discharge point of the Nueces River. Processes other than salinity driven, stratified current flow, mediates the physical transport of eggs and larvae into these nursery habitats. Although lacking a direct connection to the river, the Nueces Delta is still considered an important nursery ground for many commercially important finfish and shellfish (Henley and Rauschuber 1981; Ruth et al. 1990). Therefore, the need to maintain the wetland communities in and around Nueces Bay as viable nursery habitats, through sufficient FWI regimes, is particularly important for many estuarine-dependent species.

A habitat map of the Nueces estuary (Pulich and Hinson, 1996), based on classified 1992 Landsat thematic mapper imagery, was used to show that a majority of the estuarine emergent wetlands (a prime nursery habitat found within this system) are concentrated in upper Nueces Bay, and particularly in the Nueces River delta region (Fig. 3.9A). Much of the regularly-inundated saline marsh within Nueces Bay is comprised of bulrush (*Scirpus maritimus*) and cordgrass (*Spartina alterniflora* and *S. patens*), species that are fairly sensitive to hypersalinity and require regular inundation regimes (White et al. 1983; Pulich 1994; Dunton and Alexander-Mahala 2000). These fixed wetlands (as well as submerged, hard-bottom substrata, e.g., clam beds, oyster reefs) become severely degraded when high salinities and desiccation make such areas uninhabitable.

Evaluation of the modeled salinity gradients suggests a significant potential for excessive salinities (even hypersalinity) and/or marsh soil desiccation to develop without MaxH or higher flow levels, thus stressing the sensitive, low-lying marsh delta vegetation (Dunton and Alexander-Mahala, 2000). A highly compressed, elevated salinity gradient (e.g., see Figures 3.3 & 3.7), found in most cases except under MaxH during a WET year, could accelerate loss of nursery habitat in the Delta region, with a concomitant reduction in productivity for ecologically and commercially important faunal species (Zimmerman et al. 1990). Sessile species found in these communities are unable to adjust their tolerances when the salinity gradient exceeds their physiological tolerances (Montagna and Kalke 1992). It is only motile faunal species that can move further up into the headwaters of the Bay or into the tidal portions of the Nueces River to seek refuge near freshwater sources that can tolerate these conditions.

Prior to the Rincon Bayou channel diversion project, inflows higher than 4,100 acre-ft per day (2,100 cfs lasting one day) concurrent with high tidal cycles were necessary to produce river overbanking with inundation of the upper delta and marsh interior (Irlbeck and Ward 2000). Upon implementation of this project, daily, bi-directional non-riverine flow events such as winds and tides forcing water exchanges between the upper delta and the river, as well as river overbanking inundation, can be achieved (Bureau of Reclamation 2000). Passing through the cumulative MaxH inflow levels for May and June in a controlled pulse (a total of 74,000 acre-ft of water over the course of 4 weeks or at a rate of 2,600 ac-ft per day) could achieve many of the positive biological benefits identified in the Bureau of Reclamation demonstration project.

3.3. Time Series Analysis of Salinity at Critical Bay Sites

Time-series analysis was conducted on the salinity data from the TXBLEND circulation model at two key model nodes in the Bay. The two nodes consisted of a site in extreme upper Nueces Bay near the delta, and a mid-bay site at the Nueces Causeway between Nueces and Corpus Christi Bays (Figures 3.10 - 3.13). Results for both the MinQ and MaxH cases during

DRY years (1988 – 89) and WET years (1991 – 92) are included. This technique allowed for graphic demonstration of the daily salinity fluctuations at the selected locations produced by model inflows. Mean daily salinities computed from TXBLEND were also compared to the salinity constraints developed for the optimization model listed in Table 3.1.

Table 3.1. Upper and lower salinity constraints used in TxEMP optimization model for Upper Nueces Bay and Nueces Bay Causeway model nodes.

Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Upper	5	5	5	5	1	1	2	2	5	5	5	5
Nueces	36	36	36	32	23	20	25	25	25	30	30	30
Nueces	5	5	5	5	5	5	5	5	5	5	5	5
Causeway	35	35	35	35	30	25	35	35	30	35	35	35

Modeled solutions in both the MinQ and MaxH cases exceed salinity bounds at the Upper Nueces Bay and Nueces Causeway nodes at times. Relatively large deviations (> 8 ppt) from the salinity constraints are frequent during spring and summer in both cases. MinQ and MaxH showed a close parallel in salinity variations through time in Figures 3.10 and 3.11 for the upper Nueces Bay Node, regardless of weather year type. The most prominent differences between the MinQ and MaxH solutions are that MaxH salinities show a lag compared to MinQ salinities when salinities are rising (due to higher MaxH flows) and, conversely, a more rapid drop when salinities are falling (due to increased MaxH flows). When compared to the model constraints, salinity exceedances (or predicted salinities outside the constraint range) in spring and summer indicate that MinQ flows would be more stressful on the overall habitat than those associated with MaxH (Fig. 3.10, Upper Nueces node; Fig. 3.12, Nueces Causeway node). MaxH flows mainly showed significant exceedances (often 8 ppt) during the low flow years at the Upper Nueces Bay node. Characteristically, extended periods of low salinities usually occurred with inflows during late spring and early summer, or with freshets in mid- to late winter (Figures 3.10 & 3.11).

Further calculations were performed to determine the number of days over the simulation period that the predicted model salinities exceeded the target salinity constraints (Table 3.2). This analysis gives a quantitative measure of how effective the target inflows from the optimization model (TxEMP) solution are at maintaining beneficial salinity ranges over yearly cycles. During the DRY, low-flow years (1988 – 89), MaxH and MinQ are partially effective at maintaining salinity bounds: for the upper Bay node, approximately 27 % (for MaxH) and 39 % (for MinQ) of the days exceeded constraint values. For the Nueces Causeway node, approximately 63 % (for MaxH) and 64 % (for MinQ) of the days exceeded salinity constraints under DRY conditions. These exceedances occurred during spring and mid- to late summer, when hypersalinity and soil desiccation in marshes are highly deleterious (Bureau of Reclamation, 2000, Chapter 4). In contrast, during WET, high-flow years (1991-92), both MaxH and MinQ were effective in maintaining daily salinity values, with only 2 – 5 % daily exceedances at the upper bay node, and 25 – 31% daily exceedances at the Nueces Causeway site.

Based on this time-series analysis, the seasonal effects of salinity increases on wetlands habitat distribution (see Fig. 3.9A) must be carefully considered. The increases in salinity during late spring and summer months at the upper Nueces Bay node would be of concern for wetlands habitat quality, with these habitats being primary nursery areas for shrimp and young-of-the-year fishes (Gosselink 1980). Estuarine-dependent species utilize these habitats for shelter and food resources during the critical periods (post-larval and juvenile stages) of their life cycles (Boesch and Turner 1984; Ruth et al. 1990). These delta nursery habitats then, become the focus of attention for management of inflows to the estuary during low flow periods.

Table 3.2. Number of days that simulated salinities exceeded the model constraints at the Upper Nueces Bay and Nueces Causeway nodes. Simulated salinities for MaxH and MinQ inflows were estimated under either DRY year (1988 and 1989) or WET year (1991 and 1992) conditions.

Inflow Condition	Upper Nueces Bay	Nueces Causeway
DRY YEARS – 88/89		
MaxH -1988	90	215
MaxH -1989	106	245
MinQ -1988	136	222
MinQ -1989	150	250
WET YEARS – 91/92		
MaxH -1991	12	117
MaxH -1992	0	68
MinQ -1991	39	138
MinQ -1992	0	91

3.4. Statistical Correlations between Fisheries Abundance and Historical Hydrology

The net seaward movement of estuarine waters, combined with tidal flux, causes problems for biota utilizing the estuary; generally related to either export from or recruitment to the estuary (Boehlert and Mundy 1988, Kneib 1997). Estuarine resident species (residing within the estuary throughout their life cycle) face the recruitment problem of an export of their early life history stages. Transient species (species that periodically utilize the estuary for feeding or spawning as adults) must first locate appropriate habitat; and then, if they spawn there, face the same larval export/transport problems as the resident species. Estuarine-dependent species (those utilizing the estuary as a nursery ground for the early portion of their life cycle) typically spawn well offshore and their eggs and larvae must be transported into coastal and estuarine nursery grounds against this net seaward flow (Valenisi et al. 1997). These species (including several commercially important ones) typically have extended larval periods and their progeny are subjected to the widest degree of physical processes, which can ultimately affect fisheries recruitment (Green and Lee 1994).

For this analysis, the relative abundance of eight estuarine target 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 Nueces Estuary since 1978 (Kana et. al. 1993). This survey program, based on probabilistic random sampling, collects 20 bag seine samples from around each bay system each month (although prior to 1992, sampling effort was only 10 samples per month, and prior to 1982, 6 samples per month). Along with recording the relative abundance of organisms (as catch per unit effort, or CPUE), 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 (Longley 1994, see Chapters 6 & 7; Lee 1994, Boyd and Green 1994).

The eight target species included both shellfish (white and brown shrimp, and blue crab) and finfish (Atlantic croaker, Gulf menhaden, bay anchovy, striped mullet, and spot) that were identified as the dominant (most abundant) species collected in the bag seines and trawls in the Nueces Bay system (see report by Lacson and Lee 1997). Bag seine catch data were chosen for this analysis because the juvenile and subadult animals collected in bag seines represent the life history stages most dependent on the estuary for nursery habitat. In this case, such nursery habitat is located in the upper estuary, particularly in the bay-head delta region. As mentioned in the previous section, the delta and upper estuary regions are considered the most sensitive habitats in the estuary to FWI fluctuations and stress. Thus, it was expected that any secondary effects of FWI on these nursery habitats would be reflected by juvenile animal abundance (e.g., CPUE results) from the bag seine samples.

For the time period covering 1978 – 1997, monthly average relative abundance was calculated only for the time of the year (= season) that a species normally occurred in the bay (see Pulich et al. 1998). By deriving the monthly average CPUE of each target species, the time frame in months of highest abundance was delimited. From this analysis, the seasons of peak monthly occurrence for each species in the Nueces Estuary were determined to be:

> Blue Crab (Mar - July); Brown Shrimp (Apr - July); White Shrimp (July - Nov);
> Atlantic Croaker (Jan - May); Gulf Menhaden (Apr - June);
> Bay Anchovy (Aug – Nov); Spot (Feb - July); Striped Mullet (Jan - July).

3.5. Analytical Approach and Hypothesis

In our previous studies of the Guadalupe and Trinity-San Jacinto Estuaries (Pulich et al. 1998, Lee et al. 2001), we demonstrated correspondence between species abundance and salinity gradients in the bays, where salinity was used as a proxy for FWI to establish FWI – species relationships. For the present analysis of the Nueces Estuary, with an extensive salinity gradient lacking except for the upper reaches of Nueces Bay proper (see Figures 3.1 – 3.8), we developed a different analytical approach to demonstrate the effect of freshwater inflows on species abundance. As a modified analytical approach, we chose to examine statistical correlations between seasonal abundance of key fisheries species and observed monthly surface inflows to the Nueces Estuary. Total surface inflow hydrology data supplied by TWDB were used (monthly data including both gauged and ungauged inflow which are corrected for diversions and return flows) so as to be directly comparable to inflow amounts derived from the TxEMP modeling. The historical time period from 1978 to 1997 was used because it coincided with the period for which Coastal Fisheries sampling data were available.

The analysis examined statistical trends in bay-wide species abundance (measured as average seasonal CPUE) related to total surface inflow, or cumulative inflow, for the same months of each species' seasonal occurrence in the bay. For example, total surface inflow for brown shrimp consisted of flows summed from April through July; for blue crab, flows were summed from March through July, etc. Species abundance was further coded to reflect two different hydrologic year types: HIGH-FLOW YEARS vs. LOW-FLOW YEARS. These flow year designations were based on a cutoff or threshold value equal to the cumulative seasonal MaxH target inflows over the corresponding months of each species occurrence. For the spring-summer season (April through July), this cumulative MaxH threshold amount is 89,200 acre-feet. The objective was to determine if there was any difference in the relative abundance of the target species under inflow regimes greater than or less than the MaxH amount. This would provide presumptive evidence that MaxH inflow levels are sufficient to support the historical levels of fisheries production within the Nueces Estuary, or whether inflows above the MaxH solution produce characteristically higher levels of fisheries production.

3.6. Statistical Analyses

Figure 3.14 for brown shrimp displays a typical graph of the raw bag seine catch data. The cutoff value for MaxH flow (89,200 ac-ft) is marked on each graph to show how abundance data were partition into HIGH-FLOW and LOW-FLOW years. This graph illustrates several points about the datasets. Upon cursory examination, the graph appears to show a poorly defined relationship between cumulative inflows and mean CPUE for the target species. Further examination, however, shows that in several years, mean CPUE values cluster at very high flow levels, and are beyond the range of most other flow data (> 340,000 acre-ft in this case). Despite the unique seasonality identified for each target species, a distinct gap over the 19-year range of inflow data occurred because of the same three years (1981, 1987, 1992) for all species tested. An additional important feature is that mean CPUE was generally reduced at these high flow values, implying a negative feedback operation at these very high flow levels. To some extent, this resembles the response of the performance curve produced by the TxEMP model, with fisheries catch decreasing beyond some optimal inflow level. Three species (blue crab, white shrimp and Gulf menhaden) showed the most severe reductions at these high flows. Because such high flow years would obviously skew the CPUE vs. inflow relationships over the low to moderate range of flows, the decision was made to exclude these years from the next phase of statistical analysis.

Figure 3.14 also underscores the very high variation found in the CPUE datasets, which is not unexpected for biological sampling of organisms with patchy or overdispersed distributions (see Sokal and Rohlf 1981; Neter et al. 1985). To satisfy the assumption of homogenous variance, and correct for positive mean to variance correlations, data were logarithmically transformed prior to analysis [Log_{10} (N + 1)]. After transformation, simple linear regression analyses were then performed on each of the target species. Figures 3.15 – 3.18 present results using log-transformed data for brown shrimp, blue crab, Atlantic croaker, and white shrimp. Significantly positive relationships between inflow and average CPUE over 13 to 16 year time periods were identified for blue crab ($t = 4.31$; df = 15; $p = 0.001$; $R^2 = 0.57$), white shrimp ($t = 3.05$, df = 12, $p = 0.011$; $R^2 = 0.46$), brown shrimp ($t = 2.03$; df = 15, $p = 0.022$, $R^2 = 0.227$), and Atlantic croaker ($t = 2.45$, df = 14, $p = 0.028$; $R^2 = 0.676$). Most other species showed positive CPUE trends with increased inflow, but in each case the regression relationship was poor (R^2's ranging from 0.002 to 0.09) and the p values were not significant (ranging from 0.331 to 0.800).

In the case of white shrimp, timing of FWI appears to be a more critical factor than the flows corresponding directly to the months of white shrimp abundance (viz. July – Nov., see Fig. 3.19 where a negative trend is indicated). Antecedent inflows during the spring and summer months of April through August produce a significant positive trend between CPUE and inflows (Fig. 3.18), in contrast to the situation with the actual flows during fall (when the physical recruitment of white shrimp takes place). This suggests a more complex effect of the FWI on species like white shrimp and bay anchovy, which enter the bay later in the year. The data (not shown) for bay anchovy also showed a similar trend with antecedent spring inflows. Inflows earlier in the year presumably help to prepare the nursery habitat by producing favorable food, shelter, and other habitat conditions for these late-year species.

After species-specific MaxH values were used to separate the hydrologic year types, a statistical comparison was run on the two groups of catch data representing LOW-FLOW and HIGH-FLOW conditions, excluding the three very high inflow years. If the homogenous variance assumption was met, an unpaired t-test was utilized to test for differences in the group means, otherwise the unequal variance t-test was used (Freund and Wilson 1993). Significant differences in the case of blue crab, Atlantic croaker, white shrimp, and brown shrimp are shown in Table 3.3.

While four of the finfish species (bay anchovy, spot, menhaden, and mullet) were not significantly different (all had p values > 0.05), all but Gulf menhaden followed the general trend of having higher relative abundance in HIGH-FLOW years. In some respects these results should be considered conservative, since they were obtained using pooled catch data for the entire bay system and many of the samples consisted of low catch values, with only a few samples containing high numbers of individuals. This exemplifies the problem caused by correlating abundance of a patchily distributed organism with a general linear model. Still, it is notable that seven of the eight species examined showed at least a general trend of higher abundance under HIGH-FLOW conditions as compared to LOW-FLOW conditions.

Table 3.3. Observed seasonal abundance (average CPUE ± STD) of target species at low and high inflow levels (defined as inflows lower or higher than the species-specific MaxH cutoff value). Data are based on bag seine samples from 1978 to 1997 by Coastal Fisheries Resource Monitoring Program. Samples for all 20 years are not represented in *t*-test analysis due to elimination of very high-flow years and a few outlier years.

TARGET SPECIES	**SEASON OF ABUNDANCE IN BAY**	**AVG CPUE AT LOW INFLOWS**	**AVG CPUE AT HIGH INFLOWS**	***P* VALUE OF *T*-TEST**
White Shrimp[1]	July – Nov	17.29 ± 8.48	40.44 ± 13.54	Sig. (*P*=0.011)
Brown Shrimp	April – July	29.19 ± 10.60	47.16 ± 17.05	Sig. (*P*=0.022)
Blue Crab	Mar. – July	3.77 ± 0.76	6.59 ± 2.79	Sig. (*P*=0.001)
Gulf Menhaden	April – June	85.85 ± 140.63	56.06 ± 72.11	n.s. (*P*=0.800)
Atlantic Croaker	Jan. – May	0.44 ± 0.18	1.62 ± 1.02	Sig. (*P*=0.028)
Bay Anchovy[2]	Aug. – Nov	5.08 ± 6.82	7.92 ± 6.82	n.s. (*P*=0.331)
Spot	Feb. – July	17.80 ± 13.63	19.60 ± 11.21	n.s. (*P*=0.488)
Striped Mullet	Jan. – July	5.44 + 3.54	7.03 + 4.84	n.s. (*P*=0.572)

[1] Low and high inflows based on April through August period.

[2] Low and high inflows based on June through September period.

3.7. GIS Analyses

Representative GIS plots were produced that depict species' spatial distributions and relative abundance patterns (as CPUE) within the estuary system. This GIS technique allowed visualization of subtle spatial patterns that might provide better insights into the FWI effects. Using salinity data collected simultaneously with the bag seine samples, salinity zones were contoured by GIS as described previously. Then, by plotting GIS overlays between species abundance and contoured salinity zones, species' distribution patterns can be correlated with the observed salinity gradient. Figures 3.20 - 3.22 demonstrate these spatial relationships between CPUE relative abundance and the salinity gradient for blue crab, brown shrimp, and Atlantic croaker, respectively, in the Nueces Estuary system. CPUE distributions are plotted separately for both HIGH-FLOW (labeled Wet Years) and LOW-FLOW (labeled Dry Years) catch data, with the flow year designations determined according to the species-specific MaxH cutoff values previously described.

These observed salinity plots corroborate the compressed salinity gradient in Nueces Bay previously seen with the TXBLEND model. Even with cumulative WET spring inflows, exemplified by blue crab and brown shrimp (Figures 3.20 & 3.21), salinities still averaged > 25 ppt in Corpus Christi Bay during these wet years. A reasonably large salinity zone of 10 – 20 ppt occurred in Nueces Bay for these years with WET springs, while DRY year salinities remained almost entirely above 30 ppt. Interestingly, the observed salinities in all DRY year cases were considerably higher in Nueces Bay (> 30 ppt) than the salinities for the MinQ model runs (Fig. 3.2), consistent with these observed DRY years providing less than the MinQ seasonal target flows.

Nueces Bay proper is generally regarded as ecologically important nursery habitat within Nueces Estuary. This is further supported by the limited location of the mesohaline salinity zone (10 – 20 ppt) within Nueces Bay proper identified from the GIS plots of Coastal Fisheries Monitoring salinity data, in agreement with salinity patterns from the TXBLEND solution. We therefore used the GIS overlay data to test for differences in average CPUE between HIGH-FLOW (= Wet) and LOW- FLOW (= Dry) years for samples directly influenced by the mesohaline salinity gradient within Nueces Bay. For two of the three cases examined (Atlantic croaker and blue crab), parametric test assumptions were not met even after a logarithmic transformation of the data, and the Mann-Whitney *U* test (the non-parametric analog of the two-sample *t*-test) was used to test the null hypothesis that the two groups came from populations having the same distribution (Sokal and Rohlf 1981).

For Atlantic croaker (Fig. 3.22), visual inspection of the plot suggested a higher catch rate in Nueces Bay proper during Wet years, although no significant statistical difference between the two flow years was actually found (*U* = 4,876; *p* = 0.146, χ^2 approximation = 2.12 with 1 df). Relative abundance in Wet years followed the general pattern identified from the larger, system-wide species abundance analysis (see Statistical Correlations between Fisheries Abundance and Historical Hydrology), with higher mean CPUE in Wet years (3.29 ± 15.63) as compared to Dry years (0.86 ± 3.50). Blue crab (Fig. 3.20) did have significantly higher abundance (*U* = 3389.5, *p*=0.003; χ^2 approximation = 9.01 with 1 df) in Nueces Bay proper during Wet years compared to Dry years (mean CPUE = 5.33 ± 6.93, Wet vs. 3.73 ± 6.89, Dry). Brown Shrimp (Fig. 3.21) also displayed a higher trend in Nueces Bay during Wet years (mean CPUE = 109.9 ± 201.32) than Dry years (mean CPUE = 67.45 ± 143.95), but it was not significant (*t* = -1.73, df = 153; *p* = 0.085).

These results indicate that Nueces Bay proper may comprise a specific environment under the higher flow conditions that concentrates these estuarine species. Favorable environmental conditions as a result of increased inflows would include the combinations of preferred salinity regimes, increased food supplies, and essential nursery habitat factors (Mueller and Matthews 1987). These three species exhibited similar behavior in Nueces Bay to that from literature reports below, and this behavior implies a strong dependence on moderately high seasonal inflows (greater than MaxH) for maximal production.

White shrimp: This species was not collected in bag seine samples in significant numbers until mid-summer into fall. White shrimp are known to prefer salinities from low to moderate (5 - 20 ppt), but can tolerate a fairly wide salinity range (Pattillo et al. 1997). However it has apparently adapted in Nueces estuary to a slightly higher salinity regime compared with that found in San Antonio Bay (see Pulich et al. 1998). In the Nueces Estuary, the peak abundance was recorded at flows two- to three-fold higher than MaxH. White shrimp showed a significant correlation between average CPUE and antecedent inflows from the spring and early summer, not summer-fall inflows.

Brown shrimp: This species was mainly collected in April through July, and peak abundance occurred at flows two- to three-fold greater than MaxH. Brown shrimp did occur late in the year but its numbers were generally low in trawls (< 2 per 10-min tow). The species occurs in higher numbers than white shrimp in this estuary, probably reflecting its higher salinity preference. However, bag seine catches showed higher numbers in Nueces Bay proper in high flow years compared to dry years, with salinities ranging from 10 to 20 ppt.

Blue crab: Juvenile blue crab have been reported in waters of 0 to 30 ppt salinity, adult males were found in waters < 10 ppt, and gravid females inhabited waters of > 20 ppt (Pattillo et al. 1997). In Nueces Bay, crab peak abundance (CPUE ~ 6 per tow) in bag seine samples was recorded during wet years. Like white shrimp, blue crab may be adapted to higher salinity waters (15-25 ppt) in Nueces Bay compared to San Antonio Bay.

Gulf menhaden: This species has been reported from freshwater to hypersaline areas, and abundance in the Corpus Bay area generally conformed to this pattern. Non-gravid and developing adults occupy mid-range salinities in the deeper parts of estuaries, with high abundances at 20 – 25 ppt reported (Shaw et al. 1985). There was little direct correlation detected between CPUE and FWI regime.

Atlantic croaker: This species is estuary-dependent and displayed a salinity preference similar to blue crab and brown shrimp. In Texas and Louisiana bays, both juvenile and adult croaker have been found most abundant in waters < 15 ppt. In Nueces Bay, Atlantic croaker seasonal abundance peak was recorded in Feb. through May, and peak CPUE was found at flow regimes two-fold greater than MaxH.

Bay anchovy: In Texas bays, juvenile and adult anchovy have been collected at salinities from 0.5 to 40‰. In Nueces Bay, this species had a seasonal peak in late summer and fall. Similar to white shrimp, the mean CPUE was not correlated with the actual fall inflow regimes. Rather there was a positive trend between relative abundance and antecedent inflows from spring and summer.

SECTION 4: MAINTENANCE OF FRESHWATER INFLOWS TO NUECES BAY NURSERY HABITAT

The Nueces Delta system is an estuarine nursery ground disjunct from major riverine input. Though lacking a direct link to freshwater inflow, the vegetated habitats found within the delta are focal points for populations of fish and crustaceans, especially during their larval and juvenile life stages (Texas Department of Water Resources 1981). These salt marshes act as nursery grounds for the developing species, providing both protection from predators and supplying a rich source of food, either directly or through transport from surrounding tidal creeks (Stout 1984; Bao et al. 1989; Chamberlain and Barnhart 1993). Occasionally, large flood events spill over the river's north bank and inundate the delta with freshwater. These sporadic floods, usually tied to spring frontal system passage or tropical storm activity in the fall, supply fresh water to plant communities, transport vegetation and/or sediment detrital materials, provide nutrient import, and buffer the salinity in the bay.

As noted in previous sections, this lack of a direct connection to FWI (except in the high-flow, overbanking events) can lead to soil hypersalinity and decreased mash production. The natural salinity stress conditions found in the marsh are attributed to the semiarid climate, low annual rainfall, and hot, dry summers often producing water deficits (evaporation can exceed precipitation by > 152 cm per year; see Longley 1994). Concomitant to the natural hypersalinity conditions present, human-induced FWI restrictions (the construction of upper watershed reservoirs and the diversion of large amounts of FWI for municipal, industrial, and agricultural uses) have greatly reduced the opportunities for freshwater flooding events into the deltaic marshes. Since the completion of Choke Canyon Reservoir in 1982, it has been estimated that the annual, mean volume of fresh water reaching the Nueces Delta has been reduced by greater than 99% compared to previously (Irlbeck and Ward 2000). Current conditions are such that nearly all river flow events bypass the delta, providing Nueces Bay with freshwater inflow but doing little to mitigate the environmental stress factors found within the marsh nursery habitats.

The operating policies of the two watershed reservoirs (Lake Corpus Christi and Choke Canyon Reservoir) call for monthly pass-through releases of water for bay and estuary environmental needs. These pass-through targets, first incorporated in 1992 and based on preliminary model estimates of MinQ, are designed to mimic the natural seasonal inflow patterns into the estuary system. Additionally, these target amounts are adjusted on a sliding scale to reflect overall system storage and are tied directly to the combined monthly inflows to the receiving reservoirs. The combination of sporadic rainfall patterns inherent within the watershed and the reservoirs dampening effect of capturing most high-flow events leads to pass-through amounts that are typically well below the flooding threshold of the river's north bank. These conditions decrease the overall probability that beneficial fresh water can reach the critical nursery habitats found within the delta.

A five year study (conducted between 1994 and 1999) by the United States Department of the Interior, Bureau of Reclamation, considered some of the limiting constraints of the hydrography of the Nueces estuary and attempted to restore some historic flow patterns of the river into the delta region. One of the expressed purposes of this study was to increase the opportunity for natural freshwater flow events into the upper Nueces Delta (by excavating an overflow channel along the northern riverbank and thus lowering the minimum flooding threshold). Some of the information gained from this project indicated that fresh water passing through the upper delta provided a more direct benefit to the estuary ecosystem than water by-passing the delta and flowing directly into Nueces Bay (Bureau of Reclamation 2000). Furthermore, they recommended that timing the reservoir pass-throughs (they call for larger, quarterly or possibly semi-annual releases) to the observed seasonality of the ecology of Nueces Delta (both floral and benthic infaunal communities) would be more directly beneficial to the delta ecosystem than the smaller, monthly releases now mandated. The idea of larger, "pulsed" inflow events reflects more realistically the natural FWI variability to which the organisms within the estuary have become adapted.

SECTION 5: DISCUSSION AND INFLOW RECOMMENDATION

The preceding analyses have shown that observed hydrologic inflow regimes, as well as the modeled MaxH inflow scenario, do not typically produce a broad salinity gradient ranging from oligohaline to open ocean waters over most of the Nueces/Corpus Christi Bay system. Rather, a rudimentary salinity gradient under MinQ and MaxH flow regimes is typically compressed into the upper portions of Nueces Bay proper. This situation is quite different from previous systems examined (e.g., Galveston Bay or San Antonio Bay) and no doubt correlates with the extremely pulsed hydrology and inflow dynamics, combined with the very high evaporation rate observed in the Nueces watershed. This greatly emphasizes the importance of the limited moderate-salinity zones in Nueces Bay proper as fishery nursery area. The analysis also raises interesting questions of how FWI provides and maintains a productive, high quality estuarine habitat for the fishery species within this system.

Both MinQ and MaxH inflows were fairly similar in their hydrologic effects on the estuary, based on spatial extent of the modeled salinity gradients produced and also the time course of salinity exceedances at two geographic locations within the bay. Salinity values predicted by both target flows at upper and lower Nueces Bay nodes were generally within the TxEMP model salinity constraints, except during dry-weather years typical of drought. During these dry years, however, MaxH inflows appeared more protective than MinQ of key fishery and wetland habitats in upper Nueces Bay, especially during critical spring seasons. Based on the salinity exceedance time series analysis, decline of nursery habitat conditions for sensitive shellfish and finfish species in Nueces Bay proper would be expected when inflows drop below MaxH target values.

A separate statistical analysis of TPWD fisheries-independent sampling data, covering the period from 1978 – 1997, correlated seasonal relative abundance (CPUE) of eight dominant species to observed hydrology, using MaxH monthly values as a cutoff between dry (Low-flow) and wet (High-flow) years. Significant statistical relationships between bag seine CPUE values and total cumulative surface inflow showed that four of the species (brown and white shrimp, blue crab, and Atlantic croaker) benefited from spring seasonal inflows two- to threefold higher than the corresponding cumulative seasonal MaxH flow value (which was 89,200 acre-ft for the April through July period). While not statistically significant, three other finfish species (bay anchovy, spot, and striped mullet) all followed the overall trend of higher average CPUE at inflows higher than the cumulative MaxH cutoff. The importance of spring and early summer inflows was further emphasized by the results for white shrimp and bay anchovy. Although recruitment into the bay occurs later in the year for these species, their abundance also showed a strong positive correlation with antecedent inflows during spring and early summer compared to inflows during their actual months of occurrence. These results demonstrate that seasonal spring/summer inflow pulses higher than cumulative MaxH consistently support increased production of these characteristic Nueces Estuary fisheries species, as well as better protect the fisheries nursery habitat in the upper estuary and delta wetlands region.

This statistical analysis of fisheries independent data and corresponding seasonal hydrology also establishes a logical basis for using cumulative seasonal MaxH amounts as an inflow target value. Because of the young life-history stage of these target species, the positive, cumulative biological benefits of the seasonal FWI are considered more significant than individual months within a season. For each species, success of that year's total production is more dependent on the sum of the inflows over those months (i.e. seasons) when the species occurs in the bay. As a result, we advocate that freshwater inflow relationships should not be determined strictly on a monthly basis where months are treated as independent of one another. A more appropriate approach is to allow for evaluation of cumulative monthly effects, reflecting the seasonal inflow requirements of target species.

The pulsed, historical hydrology pattern for the Nueces Estuary represents an environmental stress to which the biota have adapted. Ecologically, the estuarine biota respond to the extreme hydrologic events, whether flooding or drought, as opposed to "average" or even "median" frequency events. Therefore, it would be appropriate to model the freshwater inflow needs of the Nueces Estuary biota based on these pulsed hydrology conditions. Future refinement of the FWI analysis protocol should seek to incorporate the variance for these extreme conditions into calculation of inflow targets.

Recommendation

TPWD therefore recommends as a FWI target, that the total April through July cumulative monthly MaxH inflow (equivalent to 89,200 acre-ft) be delivered during the spring/summer season (April through July), to protect the biological needs of the Nueces Estuary. In all other months not specified in conditions below, MaxH monthly target flows would be sufficient. The cumulative, spring/summer target flow is recommended as a minimum value with two stipulations. First, if these high spring monthly flows do not occur (e.g., during low flow years, but not necessarily a drought), then cumulative MinQ target flows in the fall months (specifically September through November, total flow equivalent to 27,500 ac-ft) should also be provided to maintain a refugium in the extreme upper bay and tidal portion of the Nueces River. **Second,** the cumulative spring/summer inflow amount should be delivered to upper Nueces Bay proper in proximity to the delta, the most critical habitat in the estuary. This cumulative amount could be delivered in one or two pulsed events in any of the four months (April through July).

This cumulative spring/summer MaxH flow is postulated to mimic the effect of the pulsed hydrology pattern characteristic of this system. Pulsed flows much higher than May or June individual monthly MaxH values are necessary to cause river over-banking and delta inundation. Thus discharge at higher flow rates is critical to sustaining the Nueces River delta estuarine nursery and refugium functions. This sensitive region can only be enhanced by over-banking flows that provide flushing of the Rincon Bayou and other delta marsh systems. Historical seasonal flows in spring and early summer may in fact have a direct stimulatory effect on the wetlands habitat, and only secondary effects on salinity response by the fisheries organisms themselves. An expanded area of nursery habitat from large, periodic inflow pulses would enhance recruitment conditions of key fishery species.

Management of river flows to supply these FWI targets is regarded as an implementation issue, and obviously, such management depends on the availability of river waters and return flows. When available flows within a river are lower than the target due to climatic conditions (e.g., drought), flows to the estuary should decrease correspondingly. The challenge is to develop watershed management strategies that provide the estuary with targeted or critical flow amounts at nearly the same frequencies that occurred in the past, retaining as much historical variability at higher flows (greater than MaxH) as possible. Under moderate river flow conditions, however, the frequency of reduced inflow levels should not be artificially increased beyond historical occurrences. When sufficient river flows do occur, the receiving estuary should receive the recommended amount(s) prior to new permits for diversions being implemented. During low flow periods, meaningful water conservation plans should be implemented, thereby balancing the overall needs of the water users with the needs of the environment.

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APPENDIX

Values and Constraints for the TXEMP Model Used in the Freshwater Inflow Analysis of the Nueces Estuary

Technical Memorandum

By

Christine Ritter
Mark Wentzel
David Brock
Barney Austin
Junji Matsumoto
Greg Malstaff
Ruben Solis
Zhenwen Jia
William Longley
Gary Powell

Texas Water Development Board
Hydrologic and Environmental Monitoring Division
Environmental Section
1700 N. Congress Ave.
P.O. Box 13231
Austin, TX 78711-3231

Performed in Cooperation with
Texas Parks and Wildlife Department
Resource Protection Division
4200 Smith School Road
Austin, TX 78744-3292

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Values and Constraints for the TxEMP Model Used in the Freshwater Inflow Analysis of the Nueces 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 1.003, 11.147, 11.1491, and 16.058. 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 oversight. 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 harvest data with corresponding bi-monthly inflows. Seven species were considered: blue crab, brown shrimp, white shrimp, red drum, spotted seatrout, black drum, and southern flounder. Historical freshwater inflow data were determined based on standard TWDB hydrology methods, and gaged flow at two stations on rivers and creeks flowing into the Nueces Estuary. Execution of TxEMP yielded minimum inflow (MinQ) of 115,640 acre feet per year (ac-ft/yr), maximum inflow (MaxQ) of 167,070 ac-ft/yr, and maximum total harvest (MaxH) at inflow of 138,490 ac-ft/yr. It is the consensus of the Bays and Estuaries teams from both TWDB and TPWD that inflow solutions between MinQ and MaxQ satisfy all constraints in the optimization model, and produce biologically feasible results for the estuary system.

INTRODUCTION

Values and constraints for the TxEMP mathematical programming model were developed for salinity conditions in the estuary, historical fisheries harvest values, freshwater inflows, ratios of species harvest, nutrient loading, sediment loading, salinity-inflow equations, and harvest-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). A partial analysis of inflow needs for the Nueces Estuary by Powell and Matsumoto (1994) produced results similar to those given here in greater detail.

SALINITY

Salinity zones

Six areas with a substantial amount of salinity data were defined for the Nueces Estuary, two within Nueces Bay, three within Corpus Christi Bay, and one within Redfish Bay (Table 1). From these six areas, three were selected to represent the longitudinal salinity gradient from the river inflow points to the sea: head of the Nueces Estuary, Mid-Nueces Bay, and Mid-Corpus Christi Bay.

Table 1: Salinity (practical salinity units, psu) statistics for salinity zones of the Nueces Estuary. "*" = zones used in TxEMP analyses.

Salinity Zone	Median	Mode	Mean	Std. Dev.	Range	N
Head of Nueces Estuary*	21.60	32.00	19.70	10.34	0.00 – 47.00	242
Mid-Nueces Bay*	27.60	30.00	26.35	8.75	0.06 – 47.75	728
Mid-Corpus Christi Bay*	30.65	30.00	30.55	5.15	7.93 – 49.11	480
Point of Mustang Island	29.52	30.00	29.27	4.58	13.25 – 43.00	299
Naval Air Station	31.24	30.00	31.46	4.93	11.71 – 49.00	288
Redfish Bay	26.51	28.00	25.71	3.58	19.31 – 34.00	28

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 1969-1998 and reported in parts per thousand (psu). 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.

To keep Datasonde data from overly influencing less-frequently collected historical single-measurement data, Datasonde data were averaged daily, and sub-sampled every 15th day. The 15-day interval was chosen because the median interval between non-automated data samplings was 14 days, with a mean of 23 days, and this interval had been used before. This interval makes the Datasonde monitoring data roughly consistent with non-automated data, in terms of average temporal coverage. The 7-day binning method used previously was also tried. Regression results of binning and sub-sampling were very similar. The sub-sampling method was chosen because it is a simple approach and avoids the artificial reduction of natural variation that can occur with averaging.

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 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 (psu) for the Head of Nueces Estuary salinity zone.

Month	Lower Bound	Upper Bound
January	5.0	36.0
February	5.0	36.0
March	5.0	36.0
April	5.0	32.0
May	1.0	23.0
June	1.0	20.0
July	2.0	25.0
August	2.0	25.0
September	5.0	25.0
October	5.0	30.0
November	5.0	30.0
December	5.0	30.0

Table 3: Salinity bounds (psu) for the Mid-Nueces Bay salinity zone.

Month	Lower Bound	Upper Bound
January	5.0	35.0
February	5.0	35.0
March	5.0	35.0
April	5.0	35.0
May	5.0	30.0
June	5.0	25.0
July	5.0	35.0
August	5.0	35.0
September	5.0	30.0
October	5.0	35.0
November	5.0	35.0
December	5.0	35.0

Table 4: Salinity bounds (psu) for the Mid-Corpus Christi Bay salinity zone.

Month	Lower Bound	Upper Bound
January	20.0	37.0
February	20.0	37.0
March	20.0	37.0
April	20.0	37.0
May	20.0	37.0
June	20.0	37.0
July	20.0	37.0
August	20.0	37.0
September	20.0	37.0
October	20.0	37.0
November	20.0	37.0
December	20.0	37.0

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.

HARVEST TARGET

Data

Fisheries harvest is used as a surrogate for estuarine productivity. Harvest data (lbs.) for blue crab, brown shrimp, white shrimp, red drum, spotted seatrout, black drum, and southern flounder were obtained from Texas Landings, a cooperative publication of Texas Parks and Wildlife Department (TPWD) and U.S. Department of Interior (USDOI) for the years 1963 to 1969. Data were also obtained from a cooperative publication of the TPWD and U.S. Department of Commerce (USDOC) for the years 1970 to 1978. Thereafter, the landings information came from TPWD publications. Brown and white shrimp data were taken from the National Marine Fisheries Service Gulf Coast Shrimp Database.

Harvest targets and historical values

Harvest targets were defined for each species as 70% of mean historic harvest. 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 harvest (1000 lbs.), and for white shrimp catch per unit effort (CPUE).

Species	Mean	Min.	Max.	Target
Black Drum	131.69	8.0	400.8	92.2
Flounder	46.32	5.9	120.6	32.4
Blue Crab	236.46	7.7	973.6	165.5
Red Drum	66.27	2.6	214.1	46.7
Spotted Seatrout	84.08	12.0	192.3	58.9
Brown Shrimp	1067.94	51.8	2451.5	747.6
White Shrimp	613.59	88.1	1357.2	429.5
White Shrimp (CPUE)	76.6	159.04	332.8	53.62

Harvest chance constraint bounds

The harvest chance constraint is the minimum probability that the calculated harvest equals or exceeds the harvest target. For TxEMP analysis, the harvest chance constraint was set to 50%, corresponding to the mean. 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 inflow solutions.

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 1994. Combined flow is the sum of gaged and ungaged flow. Gaged flow is the measured flow at the last U.S. Geological Survey (USGS) stream gage on a river or creek that flows toward the estuary. USGS gages in the Nueces area used to determine inflows were: the Nueces River near Mathis (id# 08211000) and Oso Creek at Corpus Christi (id# 08211520).

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

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

In the Nueces Estuary, annual inflows have ranged between 42,551 and 2,744,260 ac-ft/yr, with median inflow of 347,696 ac-ft/yr and mean inflow of 581,779 ac-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 harvest equations. Annual bounds were used to limit modeled flows on an annual basis. All bounds were based on combined inflow statistics for the 54-year period 1941 to 1994.

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 ac-feet.).

Month	Lower Boundary	Upper Boundary
January	1.42	4.54
February	1.49	5.66
March	2.24	4.92
April	2.41	5.18
May	3.78	37.77
June	3.87	36.43
July	3.68	9.82
August	3.79	9.75
September	3.61	23.74
October	4.38	18.68
November	2.66	7.78
December	1.59	4.67

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 2,900 ac-ft.; the sum of the upper bounds for the same period totaled 10,200 ac-ft. In the table below, the January-February seasonal lower bound was set to a value lower than the sum of the monthly bounds (2,800 ac-ft) while the January-February seasonal upper bound was set to a value higher than the sum of the monthly upper bounds (11,000 ac-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 ac-ft.).

Bi-month	Lower Boundary	Upper Boundary
Jan.-Feb.	2.8	11.0
Mar.-Apr.	4.6	11.0
May-Jun.	7.5	76.0
Jul.-Aug.	7.3	21.0
Sept.-Oct.	7.9	44.0
Nov.-Dec.	4.1	14.0

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.

HARVEST RATIOS

The TxEMP model permits harvest equations to be weighted for individual species in the calculation of the objective function. Weighting allows control of the relative importance of individual harvest equations in the optimization routine. If the weight of an equation were set to zero, that equation would not contribute to total harvest included in the objective function. Consequently, the optimization results would be independent of that species' contribution to harvest. TxEMP would calculate the harvest of that species, but would not include the contribution of that species in optimization. In the same manner, the harvest equation of one species can be weighted to contribute more to the harvest 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 harvest 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 harvest of any species compared to the total harvest of all species in the analysis remained within the bounds of a defined range. This constraint is called the harvest ratio and is based on historical harvest data from the estuary. The constraint guaranteed that the relative harvests 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 harvest for one or two species to the detriment of others.

Data

Ratios were calculated from monitoring (grams/hectare, g/ha) and commercial harvest (dockside landings, lbs) data and compared. TPWD calculated biomass ratios using bag seine data (catch/ha) converted to grams/hectare (g/ha). Data were converted by species according to Fontaine and Neal (1971), Pullen and Trent (1970), and Harrington et al. (1979). TWDB calculated harvest ratios based on the data described in the Harvest Target Section.

Harvest ratios were used in the execution of TxEMP because the harvest and biomass ratios were similar for the dominant species (white and brown shrimp), but different for other species, and because harvest data were used to derive fishery regression equations. The lower and upper bounds for harvest ratio constraints were set at mean plus or minus 1.15 times the standard deviation. However, TxEMP was run with the lower and upper ratio bounds set to 0 and 1, respectively, for all species in order to avoid over-constraining the problem. The results were analyzed against the harvest ratio bounds.

Harvest ratio bounds

Table 8: Biomass and harvest mean ratios, and upper and lower harvest bound constraints.

Species	Biomass Ratio	Harvest Ratio	Lower Bound	Upper Bound
Black Drum	0.016	0.062	0.001	0.123
Southern Flounder	0.002	0.022	0.006	0.038
Blue Crab	0.135	0.111	0.000	0.265
Red Drum	0.006	0.031	0.000	0.064
Spotted Seatrout	0.007	0.040	0.006	0.073
Brown Shrimp	0.581	0.502	0.118	0.886
White Shrimp	0.253	0.233	0.045	0.420

MINIMUM INFLOWS TO MAINTAIN SUFFICIENT NITROGEN LOADING TO THE NUECES ESTUARY

The objective of this section is to recommend a minimum inflow requirement based on the sufficiency of nutrients supplied by historical inflows to support biological productivity in the estuary. Nitrogen is the limiting nutrient in most estuaries (Whitledge 1989a; 1989b; NRC, 2000). Preliminary analysis of water quality data collected between 1984 and 1989 indicates the Nueces Estuary is nitrogen limited; dissolved inorganic nitrogen (DIN) concentrations were below detection limits nine times more often than dissolved phosphorus (DIP) concentrations.

Data preparation

Concentrations of dissolved solids and nitrogen species were obtained for the Nueces River and Oso Creek by monitoring programs of the TNRCC and the USGS. Monthly loads were calculated, using the FLUX program (Walker, 1996). The FLUX program computes monthly loadings, based on flow-concentration relationships. Where inflow-concentration relationships were not strong, a flow-weighted average concentration calculated by the program was the basis for loading estimates.

Input concentrations for northern ungaged watersheds were estimated as the flow-weighted average from the Aransas River, assuming similarity of soils and land use. Rainfall runoff inputs from urban Corpus Christi areas were computed using urban runoff average concentrations (Baird, et al. 1996).

Total dissolved solids, where not measured (residue at 180° C), were estimated from conductivity or salinity via regression. Total nitrogen (TN) is defined as TKN + NO_3 + NO_2 (total Kjeldahl N, nitrate N, nitrite N), with TKN measured from unfiltered water. TN in stream inputs was also estimated from regression on DIN (NH_4+NO_2+NO_3) or from NO_3, when TKN or other data were unavailable. Bay TN levels were computed from NO_3 and TP, based on significant regression from monitoring data, 1968-1989. Values of nitrogen species reported as less than detection limits were assigned a value of half of the detection threshold. The concentration of nitrogen in rainwater was obtained from the National Atmospheric Deposition Program (NADP, 1993), which maintains a site at Beeville, roughly 61 km inland from Nueces River delta. Nitrogen inputs from rain were based on Theissen network estimates of precipitation volume falling directly on the bay surface (Longley 1994), and on the combined concentrations of nitrate and ammonia nitrogen in NADP samples, averaged over several years (0.53 mg/l). Dry deposition may add significantly to atmospheric contributions of some materials, such as nitrogen. Although measurements of dry deposition at the Beeville NADP site were available, the methods used to collect dry samples may admit contamination. Thus, these data are not included in the present analysis. Instead, dry deposition was estimated to be 60% of wet deposition (Wade, 1998).

Wastewater return flows include volumes from many different sources with widely variant concentration profiles. Only sources not already included in gauged inflow volumes were considered. Volumes of discharges were obtained from self-reporting records on file at the TNRCC. Concentrations reported as part of waste discharge permit compliance often do not include all nutrient species required in the budget. Armstrong and Ward (1998) estimated local point sources collectively to average 14 milligrams nitrogen per liter (mg N/l). They also estimated contributions of oil and gas industry produced-waters from which brine input was estimated.

Materials Loadings and Budgets

Water, total dissolved solids (TDS), and total nitrogen budgets were prepared for four years, two low inflow and two high inflow, to test our understanding of nitrogen sources and sinks. The water budget combined freshwater hydrologic data with net flows between bays from the circulation model. TDS is assumed to act conservatively, with no diminution in the estuary except for hydraulic processes. Thus, TDS budgets are used to check data source completeness and budget component specifications, and to adjust transport components. This was required because the tidal entrainment component of net hydraulic transport had to be estimated. Details of budget procedures and results for water and TDS budgets are reported in Brock (2000). Confidence bounds on budget figures are based on a first-order estimate from uncertainty levels associated with each contributing element.

In each budget (Table 9), more nitrogen leaves the estuary than can be accounted for as inputs, indicating some model parameters may not be adequately estimated. There are a number of possible explanations. The largest sinks in the budget are also sinks with considerable unknowns. Denitrification was measured at only four stations within the estuary. The budget deficit may be the result of inappropriate extrapolation of these measurements to the whole estuary. Inputs from, and losses to, the Gulf of Mexico are based on poorly known concentrations from the lower bay and the near-coastal Gulf. The range of uncertainty connected with inflows and outflows to the Gulf is +/- 10%, and may not be supported by better data. Moderate errors in concentrations or rates associated with the biggest loss terms (i.e., to Gulf, to Laguna Madre, denitrification) could easily explain much of the deficit. Failure of the budget analysis may indicate that our knowledge of the system is not complete enough to allow us to model directly system processes to obtain a nitrogen requirement.

Table 9. Total nitrogen budget for the Nueces Estuary, 10^6 g N y^{-1}.

	1988		1989		1991		1992	
	Load	Confidence Bounds	Load	Confidence Bounds	Load	Confidence Bounds	Load	Confidence Bounds
Gaged	22	21 – 23	13	12 – 14	223	210 – 236	1722	1619 – 1825
Ungaged	72	58 – 87	24	20 – 29	275	223 – 333	693	561 – 838
Wastewater	823	494 – 1235	681	409 – 1022	1058	635 – 1587	1026	738 – 1354
From Aransas	882	715 – 1068	689	558 – 834	1106	789 – 1179	1457	1227 – 1833
From Gulf	709	574 – 858	1107	897 – 1340	1079	874 – 1306	1870	1515 – 2263
From Laguna	840	680 – 1016	908	736 – 1099	845	686 – 1024	1203	974 – 1454
To Aransas	-21	-25 – -17	-49	-59 – -40	-82	-95 – -69	-225	-224 – -173
To Gulf	-1185	-1433 – -960	-2101	-2542 – -1702	-2306	-2801 – -1875	-5193	-6251 – -4185
To Laguna	-1699	-2055 – -1376	-1645	-1991 – -1333	-1600	-1938 – -1297	-1819	-2190 – -1466
Storage	108	97 – 119	-347	-381 – -312	0	0 – 0	187	166 – 203
Deposition	452	282 – 625	185	146 – 228	944	589 – 1307	1002	624 – 1386
Brine input	2	1 – 2	2	1 – 2	2	1 – 2	2	1 – 2
N-fixation	408	204 – 612	408	204 – 612	408	204 – 612	408	204 – 612
Burial	-669	-1004 – -335	-669	-1004 – -335	-669	-1003 – -334	-669	-1003 – -334
Denitrif	-2771	-3602 – -1940	-2771	-3602 – -1940	-2771	-3602 – -1940	-2771	-3602 – -1940
Fisheries	-176	-264 – -88	-150	-225 – -75	-199	-299 – -100	-157	-236 – -79
Balance	-2202	-2738 – -1588	-3714	-4624 – -2753	-1687	-2152 – -1404	-1265	-1756 – -546

Nutrient Loading and Inflow Relationships with Estuarine Productivity

Nutrients available to fuel productivity rise with inflow up to a point. Above this point, estuary flushing rate and physical transport of nutrients out of the estuary reduce the effects of loading. Eutrophication-related problems in the Nueces Estuary are expected to increase if the loading threshold is exceeded, leading to more frequent occurrences of anoxia and toxic algal blooms. The threshold above which problems begin to occur may be determined by biological community complexity. In Texas bays, where light commonly limits primary production, the threshold for problems may be higher than it would be in clearer waters. However, higher turbidity in Texas bays also means that seagrasses suffer biogenic light limitation at a lower level of nitrogen loading, as phytoplankton increase. Seagrass decline is but one example of how increased nitrogen loading alters the quality and quantity of production.

Nueces Estuary Nitrogen Status

The Nueces Estuary receives moderate nitrogen loading; of major Texas estuaries, it is second lowest in terms of kg/m3, and third lowest in load per residence-time and volume. However, productivity in the estuary may not be limited by nitrogen supply. Given total organic carbon loading of 11 g C/m^2/yr (Table 4.3.1, Longley, 1994), and average phytoplankton carbon production of 310 g/m^2/yr (Stockwell, 1989; Flint et al., 1985), the Nueces Estuary exceeds the eutrophic estuary threshold proposed by Nixon et al. (1995).

Nutrient loading to the Nueces estuary should also be evaluated in the context of relative rates of export versus retention. The system has a high physical "dissolved concentration potential" (NOAA/EPA, 1989), meaning the estuary will retain nutrient inputs, and become more easily over-loaded and eutrophic. Recent documentation of hypoxia in the main portion of Corpus Christi Bay (Ritter and Montagna 1999), and problems associated with nuisance algal blooms (Bricker et al. 1999) also indicate the estuary has high productivity that is likely caused by a more than adequate nutrient supply.

Some inference about the estuary nitrogen status can be made from monitoring data. DIN, dissolved inorganic nitrogen, is the sum of ammonium, nitrate, and nitrite nitrogen. At concentrations of DIN < 1.0 μM (0.0142 mg/l) estuarine phytoplankton are limited by nitrogen availability (Dortch and Whitledge, 1992). Data from TWDB Corpus Christi Bay and Nueces Bay monitoring stations, 1968 through 1989, indicate DIN concentrations were below detection limits (< 0.01 mg/l for each N species) 350 times out of 1062 samples, whereas ortho-phosphate concentrations were below detection limits only 126 times. Both nitrogen and phosphorus were below detection in 58 samples. Thus, nitrogen limitation is likely to be more common than phosphorus limitation, although low nitrogen concentrations are not common. Based on DIN concentration data, the estuary appears to have more nitrogen than required to support present production indicating an upper nutrient loading threshold for the Nueces Estuary may be as pertinent to the health of the system as the determination of a minimum loading requirement.

Nueces Estuary Recommended Nitrogen Input

The purpose of this nutrient budget is to estimate a nutrient constraint based on nutrient inputs that promote, or are consistent with, characteristic system productivity. The nutrient budget approach is ideal because it is based on a detailed model of nutrients in the system that allows system components to fluctuate with inflows and nutrient inputs. However, the data necessary to adequately calibrate such a model is difficult to obtain and often not available with sufficient precision. Although the purpose of the nutrient constraint is to identify a minimum loading required by the bay, it may not be appropriate to assume that maintenance of present nutrient loading rates is consistent with desirable productivity levels, because the Nueces system has characteristics that may predispose it to eutrophication.

Another means of estimating a nutrient constraint is to determine the minimum nitrogen load required to maintain characteristic system productivity. This approach begins with an estimate of historical nitrogen loading to the system. Prior to urbanization and extensive agricultural development in the basin, inflows to the estuary would have provided nitrogen at rates determined by concentrations found in streams not affected by man's activities. The estuary is assumed to have been healthy and productive under such conditions.

We can estimate drainage basin loadings prior to anthropogenic activities that increased stream nutrient concentrations. Nutrient concentrations in streams draining various landuse types have been estimated (Omernik 1976). Inferences can be made about routine loadings to an estuary based on vegetative communities of its watershed. Data on nutrient concentrations in rangeland runoff in the Nueces and neighboring watersheds are available from Baird et al. (1996). From these data, a reasonable estimate of natural stream concentrations is roughly 0.7 - 0.9 mg N/l. In addition, Twidwell and Davis (1989) documented nutrient concentrations in stream segments identified as relatively un-impacted. From their data, an un-impacted stream TN concentration average is 1.35 mg N/l, compared to a modern flow-weighted average near 1.99 mg N/l for the Nueces Estuary tributaries, and 3.63 mg N/l for tributaries and wastewater combined.

The un-impacted inflow TN concentration can be combined with median inflow volume to produce the normal historic nitrogen load to the Nueces Estuary. Using median inflows compensated for diversions, a non-anthropogenic TN load is estimated to have been $523 \cdot 10^6$ g N/yr from the Nueces drainage basin. This historic input serves as a target minimum nitrogen load, capable of supporting an estuary productivity historically characteristic of the system.

A nitrogen loading of $523 \cdot 10^6$ g N/yr would be delivered by approximately 117,000 ac-ft/yr inflow, at present volume weighted average stream concentrations. With reference to TN loading computed for recent years, above, it is clear that wastewater return flows now supply the estuary with a TN load higher than would be characteristic of non-anthropogenic inputs. A drainage basin combined inflow target of 117,000 ac-ft/yr would meet the minimum estuary nitrogen requirements. This flow is approximately a 9th percentile annual volume.

SEDIMENT ESTIMATES FOR FRESHWATER INFLOWS

A good deal of data related to sediment inflow to Nueces Bay is available. USGS gage # 08211000 has been collecting flow data on the Nueces River near Mathis, TX since September 1939. This site is approximately 50 miles upstream of where the river empties into Nueces Bay. The TWDB has collected daily sediment samples at this site from February 1942 to September 1989. Most of this data is in electronic format that can be easily analyzed.

For this investigation, flow and sediment data were divided into three groups as shown in Table 10. These groupings conform to the dates of completion of major reservoir projects within the Nueces River watershed. The old Mathis Dam, less than a mile upstream of the USGS gage site, was completed on July 24, 1934. No flow or sediment data were collected prior to that time. On April 26, 1958, Wesley E. Seale Dam was completed at a site between the USGS gage and the old Mathis Dam site. The Seale Dam created a large impoundment that submerged the old Mathis Dam. Choke Canyon Dam was completed on the Frio River, a main tributary of the Nueces River, on October 12, 1982. Observed sediment load versus flow data for the three periods are shown in Figures 1 through 3.

Table 10. Available Flow and Sediment Data for Nueces River near Mathis, TX.

	Pre Seale Dam	Between Seale and Choke Canyon Dams	Post Choke Canyon Dam
Dates	Prior to 4/26/58	4/26/58 to 10/11/82	After 10/12/82
Flow Data Observed	9/1/39 to 4/25/58	4/26/58 to 10/11/82	10/12/82 to 9/30/99
Sediment Data			
Observed	2/1/42 to 4/25/58	4/26 to 8/31/58, 10/1/64 to 10/11/82	10/12/82 to 9/30/89
Modeled	9/1/39 to 1/31/42	9/1/58 to 9/30/64	10/1/89 to 9/30/99

Using observed data, equations of the following form were developed:

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

where S is the expected sediment load per day in tons, Q is the daily flow in cfs-d, and A and B are coefficients that vary with the range of flow and the time period. Coefficients A and B were chosen to minimize the sum of squared errors between observed and predicted sediment load over the specific flow ranges. Results are shown in Figure 4 and Table 11.

The equations were used to model sediment load for days when sediment data were not available. By combining observed and modeled data, a complete series of annual sediment loads was developed for the period from 1940 to 1998. Results, shown in Figure 5, demonstrate a decreased sediment supply to Nueces Bay over this period. In addition to the Wesley E. Seale and Choke Canyon Dams, other factors such as changes in land use and practices within the watershed may have contributed to the reduction in sediment load.

Modeled and observed data were also used to create the double-mass curve shown in Figure 6. Note the sharp change in slope in 1958, about the time Seale Dam was built. The slope of the curve remains relatively constant, however, after completion of Choke Canyon Dam in 1982.

Flow frequency curves for the Nueces River at Mathis, TX for the three periods of interest are shown in Figure 7. The effect of the Seale and Choke Canyon Dams on the hydrology of the river can be observed by comparing these curves. Since construction of the Seale and Choke Canyon Dams, the magnitude of flows below the 70th percentile has increased. In contrast, the magnitude of flows above the 70th percentile has decreased. The latter change is of greatest significance to the sediment transporting characteristics of the river.

Figure 8 shows the percentage of total sediment load carried by flows of various magnitudes on the Nueces River at Mathis, TX prior to construction of Seale Dam. As shown in the figure, flows less than 2,000 cubic feet per second-day (cfs, and cfs-d) were responsible for moving about 10% of the total sediment moved by the river. In contrast, flows in excess of 10,000 cfs moved more than 60% of the total sediment. Flows of this magnitude have occurred much less frequently since the completion of the Wesley E. Seale and Choke Canyon Dams, a factor contributing to the reduction in sediment load.

Further analysis was conducted to determine if increasing the size of infrequent, large magnitude flow events could restore the sediment characteristics of the Nueces River. Average sediment yield was calculated for flow events within specified ranges for each of the three historical periods. In Figure 9, results are plotted versus the modal values of the flow ranges. Smoothed trend lines have been added to this figure.

The reduction in sediment yield since the completion of Seale Dam is significant, especially for large flows. For example, before construction of Seale Dam, the average sediment yield for flows between 8,000 and 10,000 cfs-d was 0.656 tons per cfs-d. After construction of Seale Dam, average yield for flows in this range was reduced to 0.087 tons per cfs-d. For a daily flow of 9,000 cfs-d, the expected sediment load would be reduced from almost 6,000 tons before Seale Dam to less than 800 tons after Seale Dam. Because of reduced yield, providing large flows at pre-Seale Dam magnitudes and frequencies would not be sufficient to restore annual sediment loads.

The Choke Canyon Dam does not appear to have affected sediment characteristics on the Nueces River as dramatically as the Wesley A. Seale Dam. From Figure 9, it can be seen that sediment yields have not changed dramatically since Choke Canyon Dam was constructed. In addition, a lake survey conducted by the TWDB in 1993 confirms that there was no significant build up of sediment behind the dam after approximately 10 years of operation. A similar lake survey has not been completed for Lake Corpus Christi, the reservoir behind the Wesley A. Seale Dam.

The change in slope of the double-mass curve (Figure 6) indicates that sediment is being trapped behind Seale Dam. This dam may not have features such as low-level outlets that allow operators to effectively flush sediment. Without such a capability, sediment that historically has been carried to Nueces Bay is likely to be retained behind the dam. This results in an undesirable reduction of reservoir capacity, as well as potential environmental impacts to the bay. No studies, however, have been completed to determine the extent of these impacts.

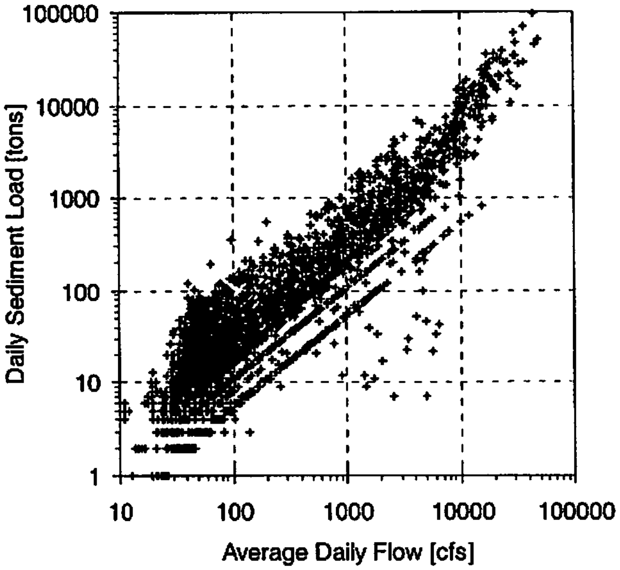

Figure 1. Sediment Load vs. Flow Before Seale Dam.

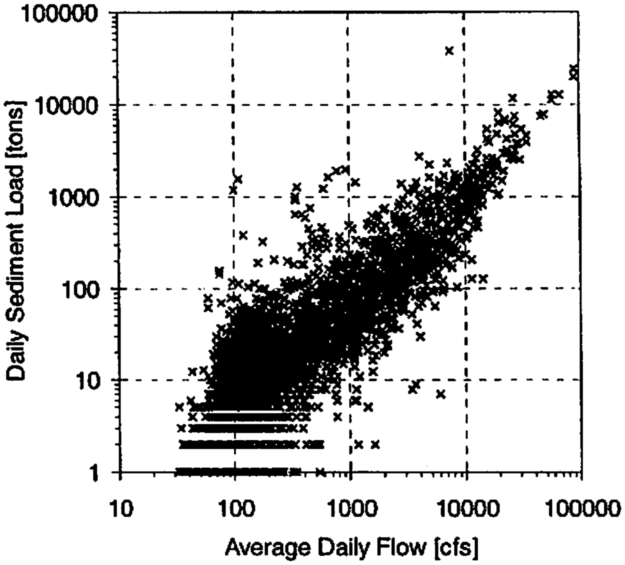

Figure 2. Sediment vs. Flow Between Seale and Choke Canyon.

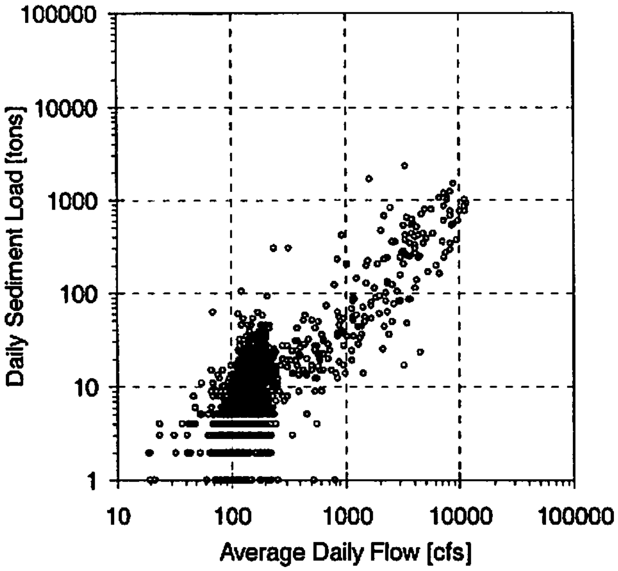

Figure 3. Sediment vs. Flow After Choke Canyon Dam.

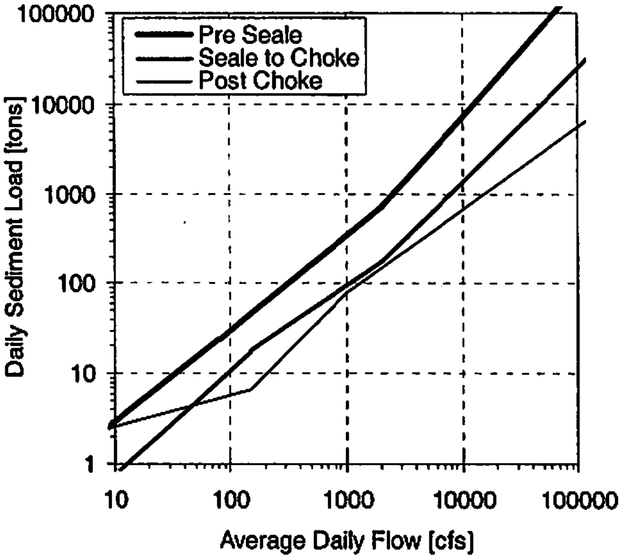

Figure 4. Modeled Sediment Load for Nueces River at Mathis, TX.

Table 11. Coefficient Values for Sediment Model.

Pre Seale Dam	Q < 80 cfs-d	80 cfs-d < Q < 2000 cfs-d	Q > 2000 cfs-d
A [tons/cfs-d]	0.293	0.2379	0.0122
B [unitless]	1.002	1.053	1.439
Between Seale and Choke	Q < 150 cfs-d	150 cfs-d < Q < 2000 cfs-d	Q > 2000 cfs-d
A [tons/cfs-d]	0.0534	0.2019	0.00542
B [unitless]	1.092	0.8908	1.33
Post Choke Canyon Dam	Q < 150 cfs-d	150 cfs-d < Q < 1000 cfs-d	Q > 1000 cfs-d
A [tons/cfs-d]	1.173	0.01005	0.3225
B [unitless]	0.3707	1.298	0.8482

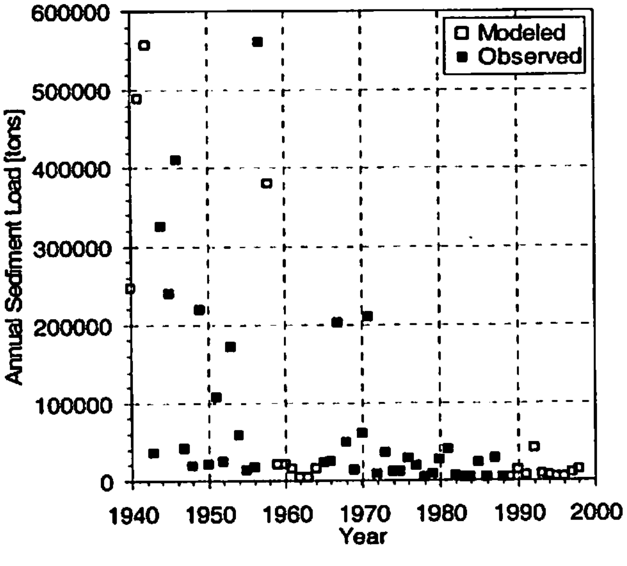

Figure 5. Annual Sediment Load for Nueces River at Mathis,TX.

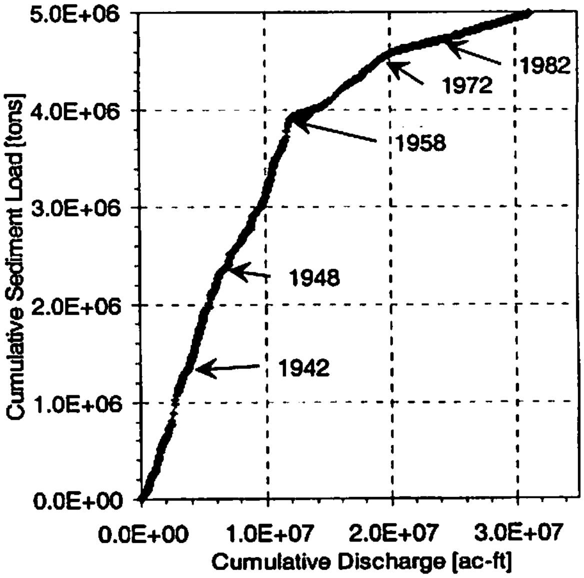

Figure 6. Double-Mass Curve for Nueces River at Mathis, TX.

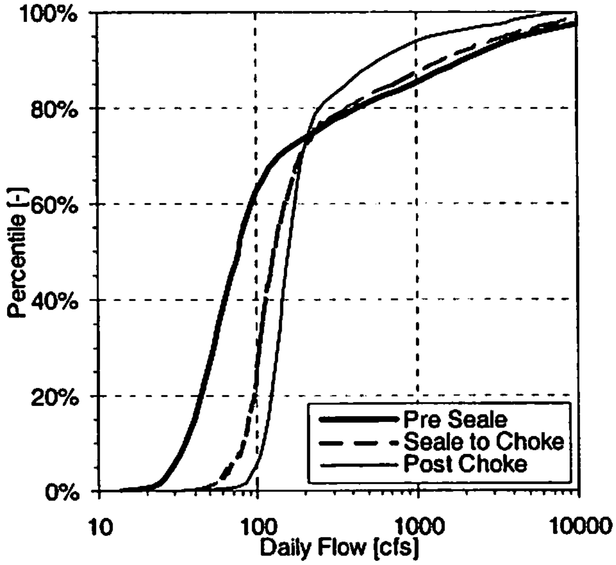

Figure 7. Flow Frequency Curves for Nueces River at Mathis, TX.

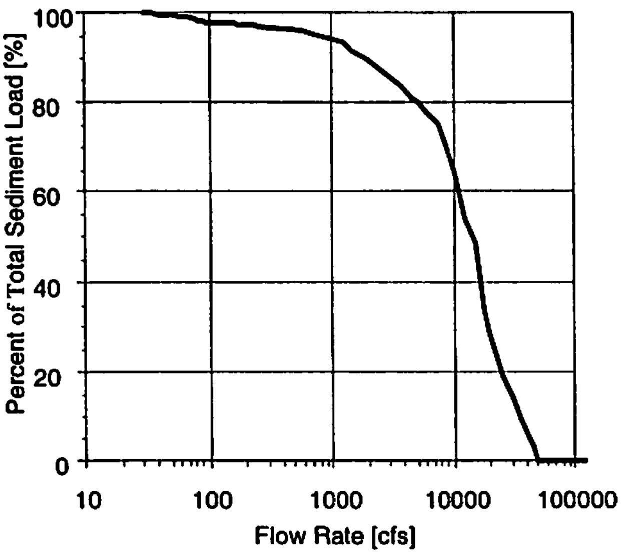

Figure 8. Sediment Load Provided by Flows in Excess of Specified Value for Pre-Seale Dam Conditions.

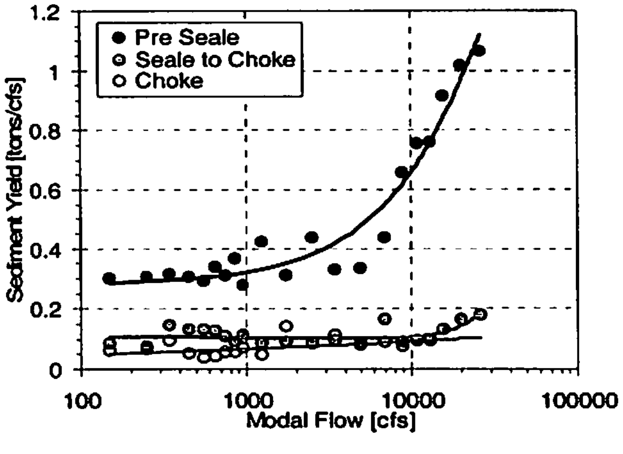

Figure 9. Sediment Yield for Flow Events Within Various Ranges.

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 psu, Q is the monthly combined inflow in 1000 ac-ft, and ln is the natural logarithm function.

Head of Nueces Estuary: $S_{HN} = 44.934 - 6.026*\ln(Q_1) - 2.744*\ln(Q_2)$

Mid-Nueces Bay: $S_{MN} = 39.756 - 3.697*\ln(Q_1) - 1.621*\ln(Q_2)$

Mid-Corpus Christi Bay: $S_{MCC} = 35.918 - 1.284*\ln(Q_1) - 0.783*\ln(Q_2)$

Table 8: Salinity-inflow regression equation statistics.

Salinity Zone	N	R^2	Adj. R^2	S.E.	p-value
Head of Nueces Estuary	186	0.76	0.76	5.303	< 0.0001
Mid-Nueces Bay	551	0.52	0.52	5.879	< 0.0001
Mid-Corpus Christi Bay	455	0.21	0.21	4.617	< 0.0001

HARVEST-INFLOW EQUATIONS

Harvest and inflow data described above were used to developed harvest-inflow equations. 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. Observations for which harvest was not reported were also omitted because the lack of reported harvest is a function of effort rather than production. For white shrimp, catch per unit effort (CPUE), as opposed to harvest, was regressed against bi-monthly inflows in order to eliminate statistical noise and derive an acceptable equation. CPUE is in units of lbs./trip, and is not a true measure of catch per unit effort because trip is not temporally defined. In the equations below, H is annual harvest in pounds per year (lbs/yr) and Q_p is the sum of inflows for a two-month period in 1000 ac-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: $\ln(H_{bc}) = 5.1185 + 0.00671*Q_{MA} - 0.00725*Q_{JA} + 0.00272*Q_{SO}$

Brown Shrimp: $\ln(H_{bs}) = 7.941 + 0.2989*\ln(Q_{MA}) - 0.5207*\ln(Q_{SO})$

White Shrimp: $\ln(CPUE_{ws}) = 3.170 + 0.2837*\ln(Q_{MA}) + 0.0814*\ln(Q_{JA}) + 0.1909*\ln(Q_{SO})$

Red Drum: $\ln(H_{rd}) = -1.6013 - 1.022*\ln(Q_{JF}) + 1.472*\ln(Q_{MJ}) + 0.5037*\ln(Q_{ND})$

Spotted Seatrout: $\ln(H_{st}) = 2.8554 - 0.3499*(Q_{JF})^{1/2} + 0.2054*(Q_{MA})^{1/2} + 0.1320*(Q_{MJ})^{1/2} + 0.0504*(Q_{SO})^{1/2}$

Black Drum: $H_{bd} = -82.94 - 47.71*\ln(Q_{JF}) + 44.50*(Q_{MA})^{1/2} + 25.55*\ln(Q_{JA}) + 15.55*\ln(Q_{ND})$

Southern Flounder: $\ln(H_{fl}) = 3.392 + 0.2203*\ln(Q_{MA}) + 0.3720*\ln(Q_{MJ}) - 0.5495*\ln(Q_{JA})$

Table 11: Harvest-inflow equation statistics.

Species	N-used	N-deleted	R^2	Adj. R^2	S.E.	p-value
Black Drum	31	2	0.79	0.76	56.78	0.0005
Soouthern Flounder	23	10	0.52	0.45	0.6238	0.0023
Blue Crab	27	6	0.37	0.28	0.9743	0.0134
Red Drum	20	0	0.85	0.82	0.5819	0.0001
Spotted Seatrout	20	0	0.93	0.91	0.2910	0.0001
Brown Shrimp	22	14	0.62	0.58	0.6072	0.0001
White Shrimp	16	20	0.64	0.55	0.2634	0.0056

RESULTS

Execution of TxEMP yielded minimum inflow (MinQ) of 115,640 ac-ft/yr, maximum inflow (MaxQ) of 167,070 ac-ft/yr, and maximum total harvest (MaxH) at inflow of 138,490 ac-ft/yr (Figure 6). 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. The following table presents MinQ and MaxH from the solution set, and also presents MinQ-Sal, which is the result of running TxEMP with only salinity constraints.

Month	MinQ-Sal	MinQ	MaxH
Jan	2,230	2,230	2,230
Feb	2,780	2,780	2,780
Mar	4,410	4,410	4,920
Apr	5,180	5,180	5,180
May	32,130	32,140	37,770
Jun	9,280	19,990	36,430
Jul	9,820	6,980	9,820
Aug	9,750	9,750	9,750
Sep	9,600	11,040	9,600
Oct	4,380	8,690	7,560
Nov	6,410	7,780	7,780
Dec	4,670	4,670	4,670
Total	100,640	115,640	138,490

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FIGURES

Figure 2.1. TxEMP Model Performance Curve for the Nueces Estuary

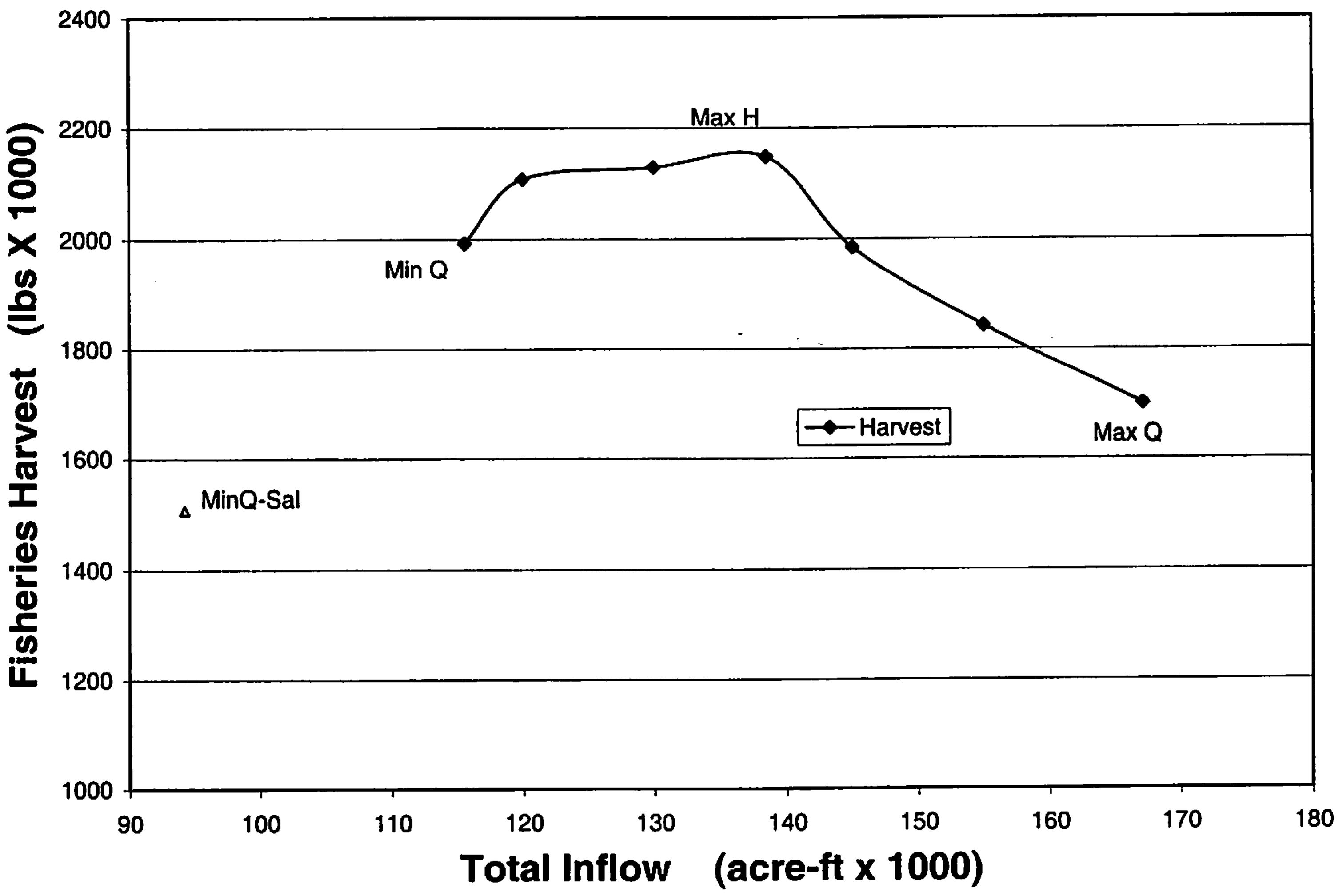


Figure 2.2. TxEMP Monthly Inflow Distribution for Nueces Estuary

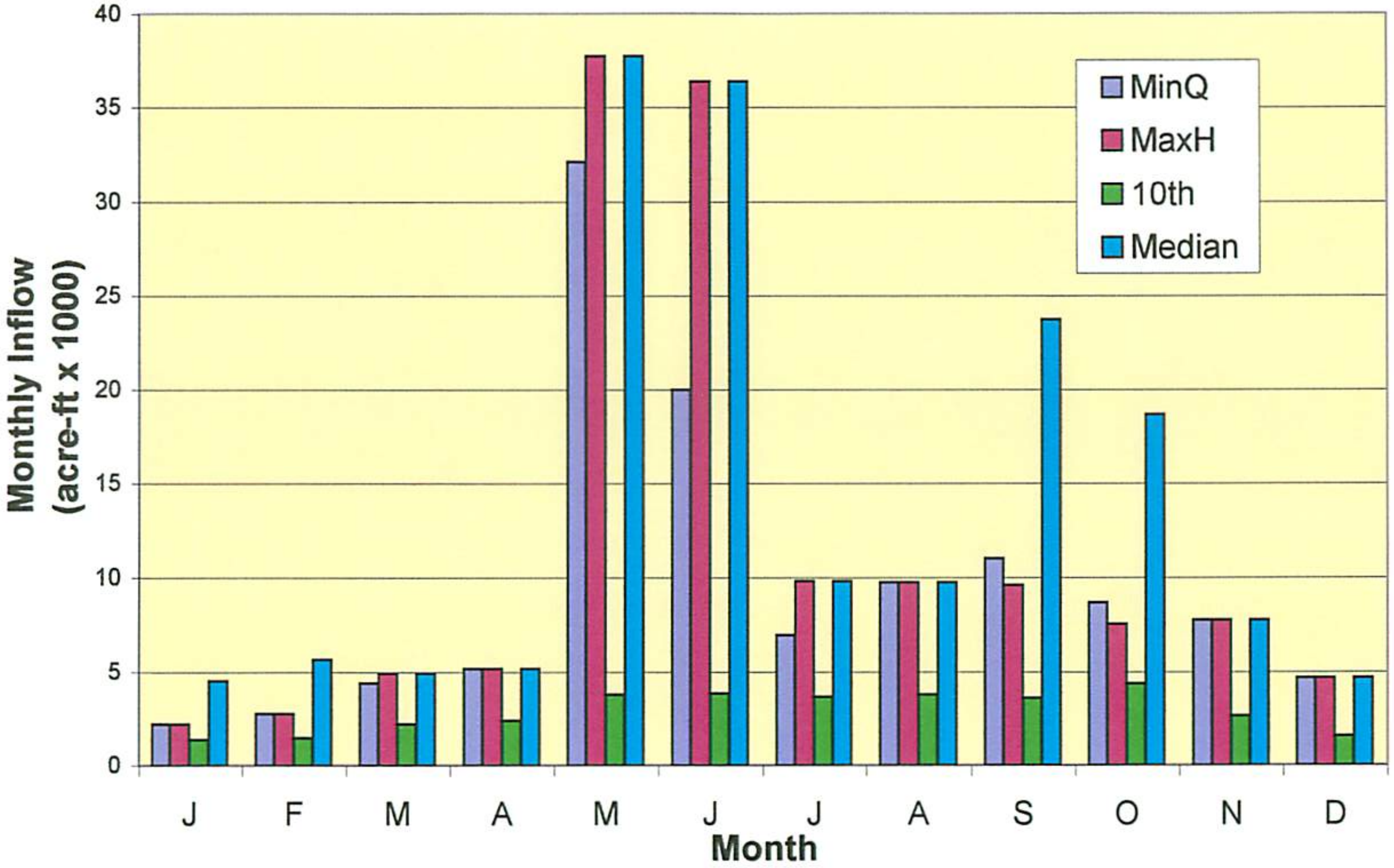


Figure 2.3. Historical Inflows (1941 - 1994) compared to Modeled Inflows for Nueces Estuary

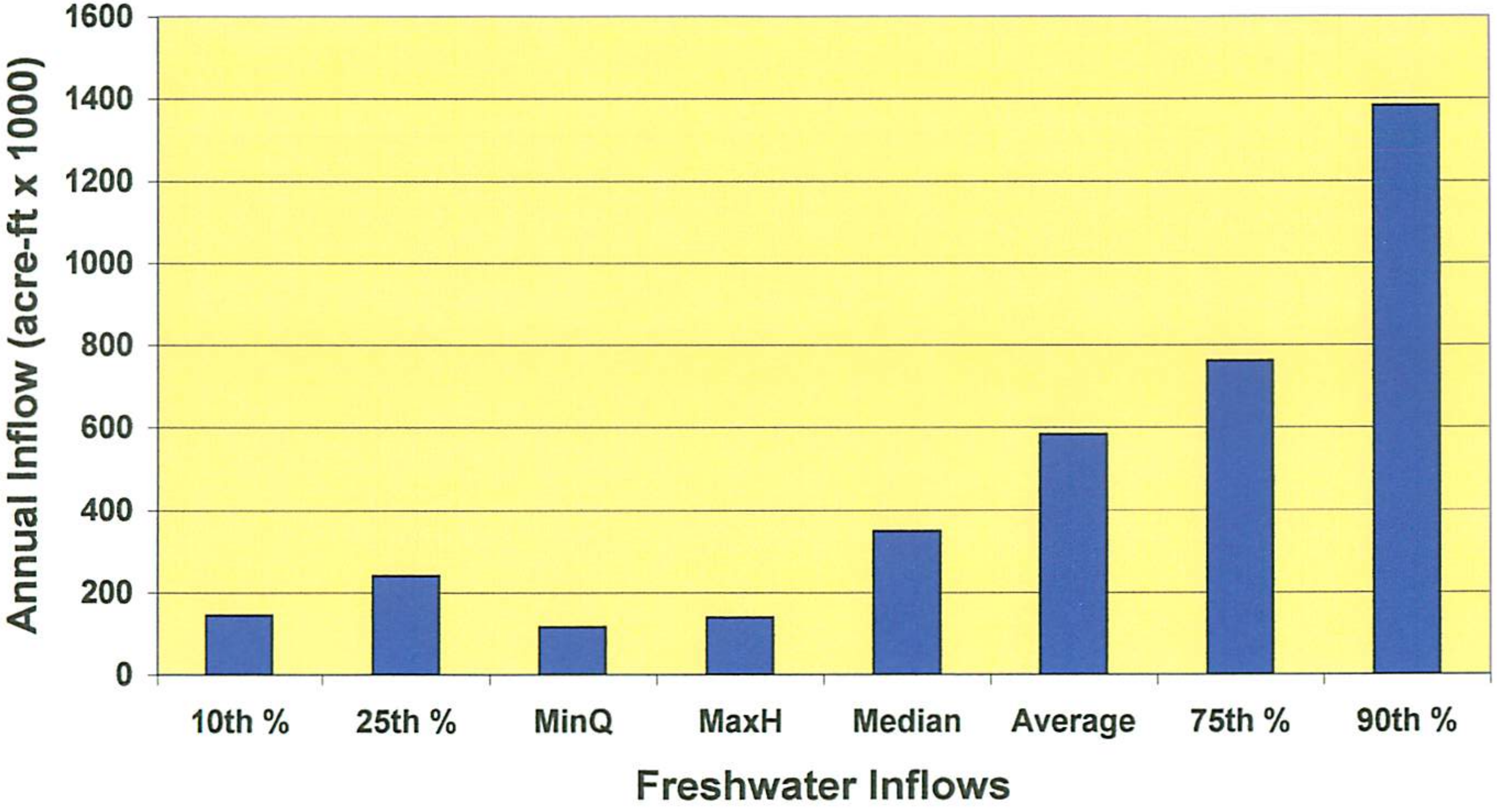


Figure 2.4. Nueces Bay Monthly Total Inflows (1977 - 1997) vs. MaxH Monthly Flows

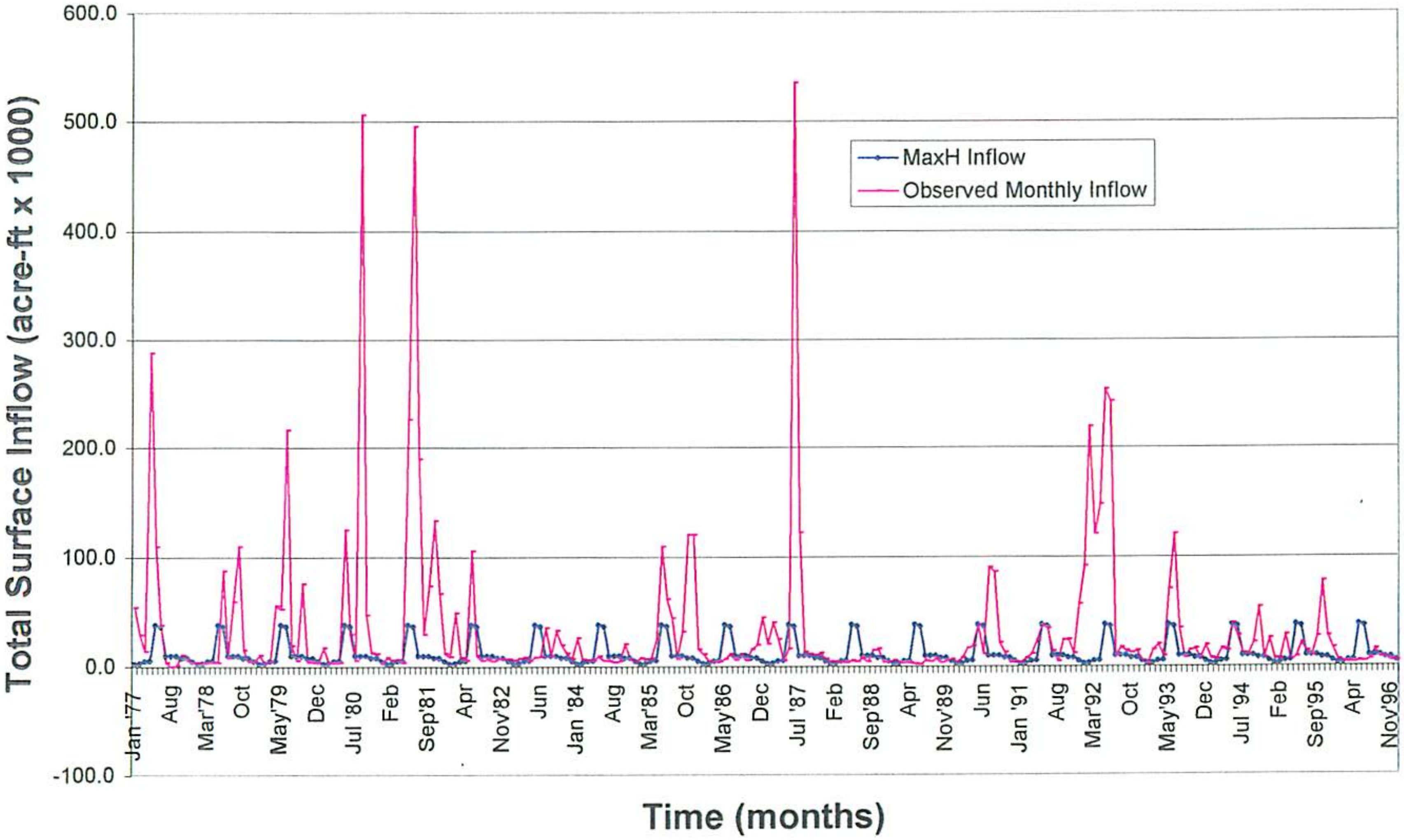


Figure 3.1
Max H vs. Min Q
Nueces Estuary Salinity Zones
March 1988

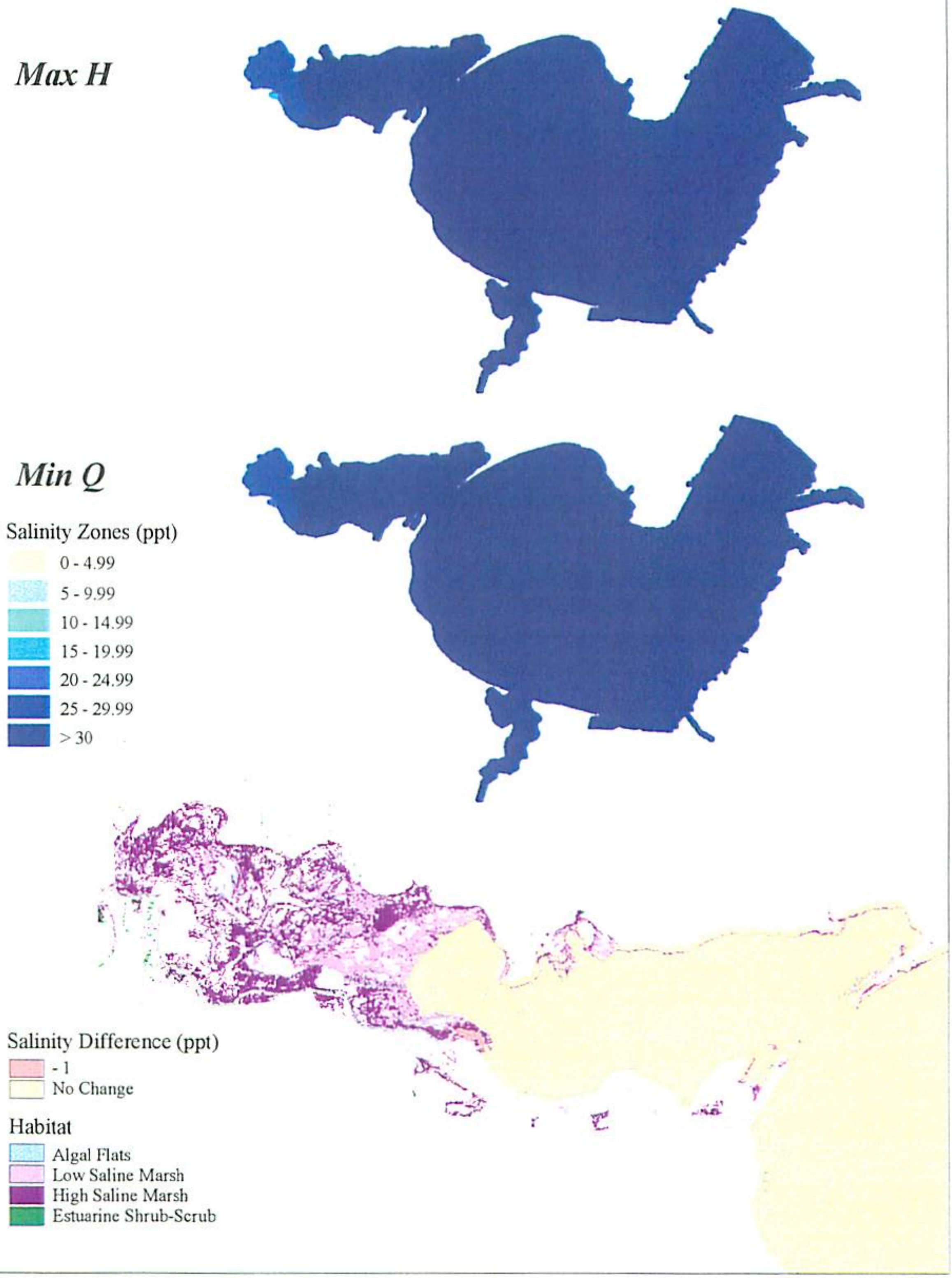


Figure 3.2

Max H vs. Min Q
Nueces Estuary Salinity Zones
May 1988

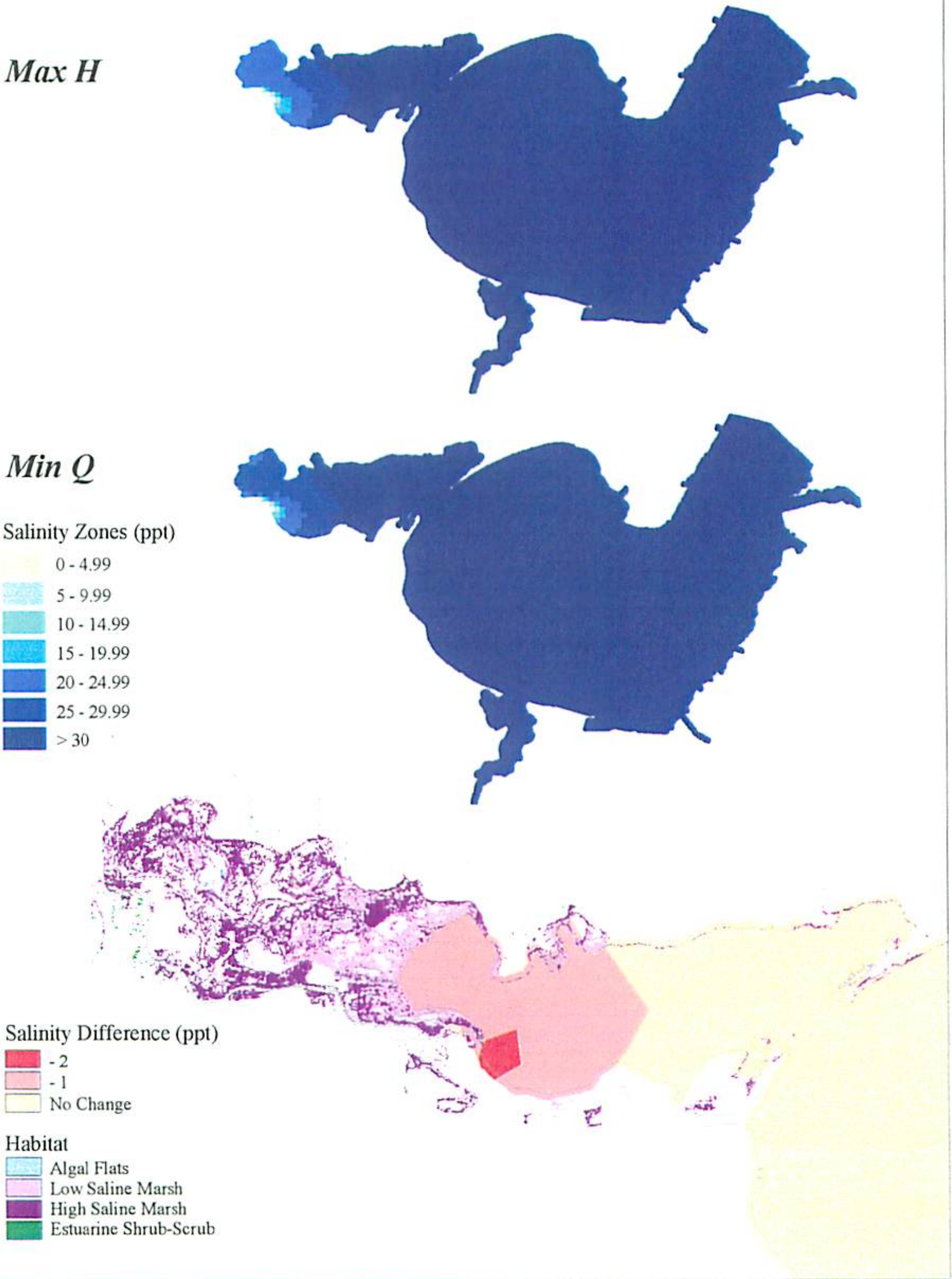


Figure 3.3
Max H vs. Min Q
Nueces Estuary Salinity Zones
September 1988

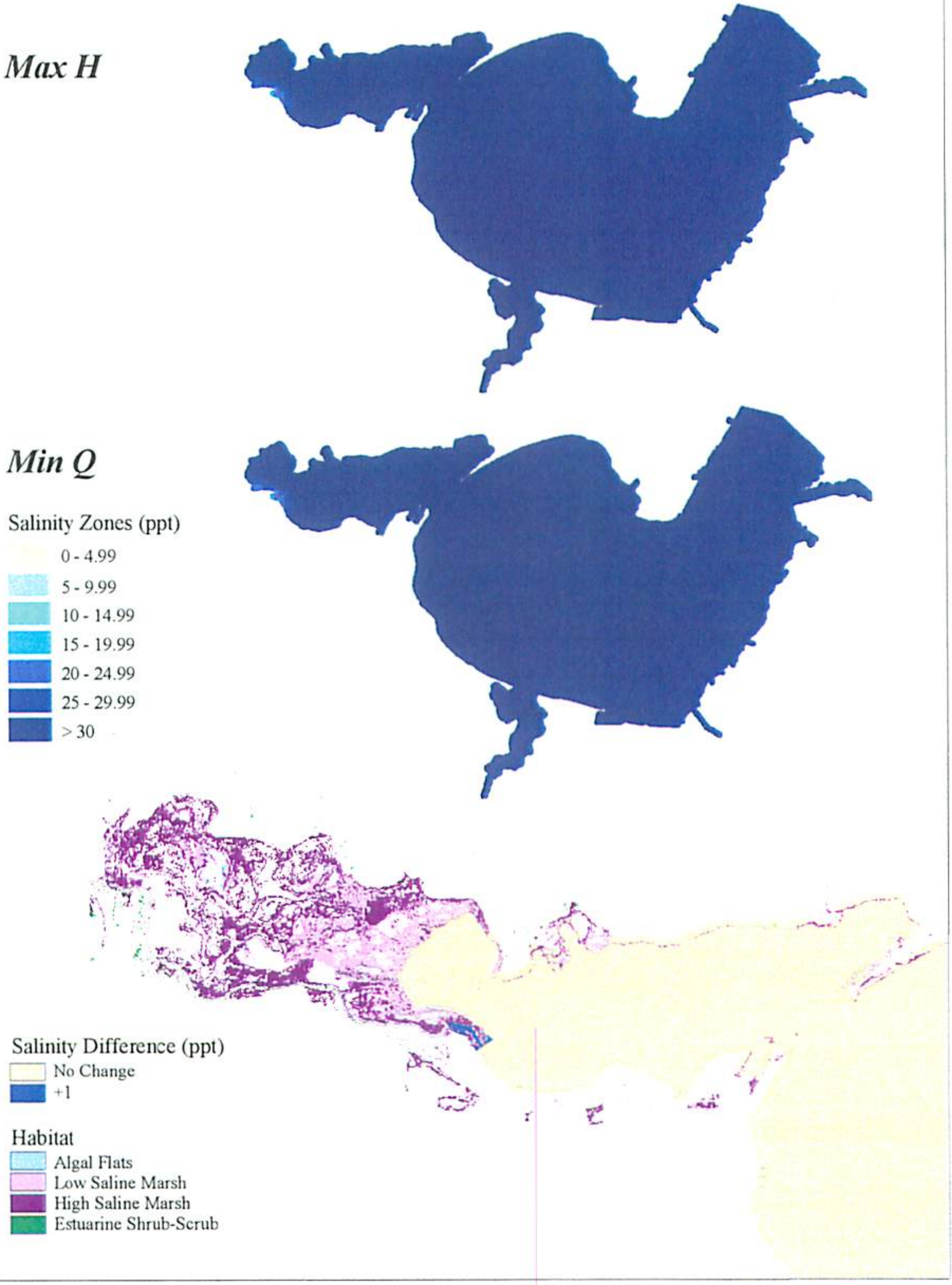
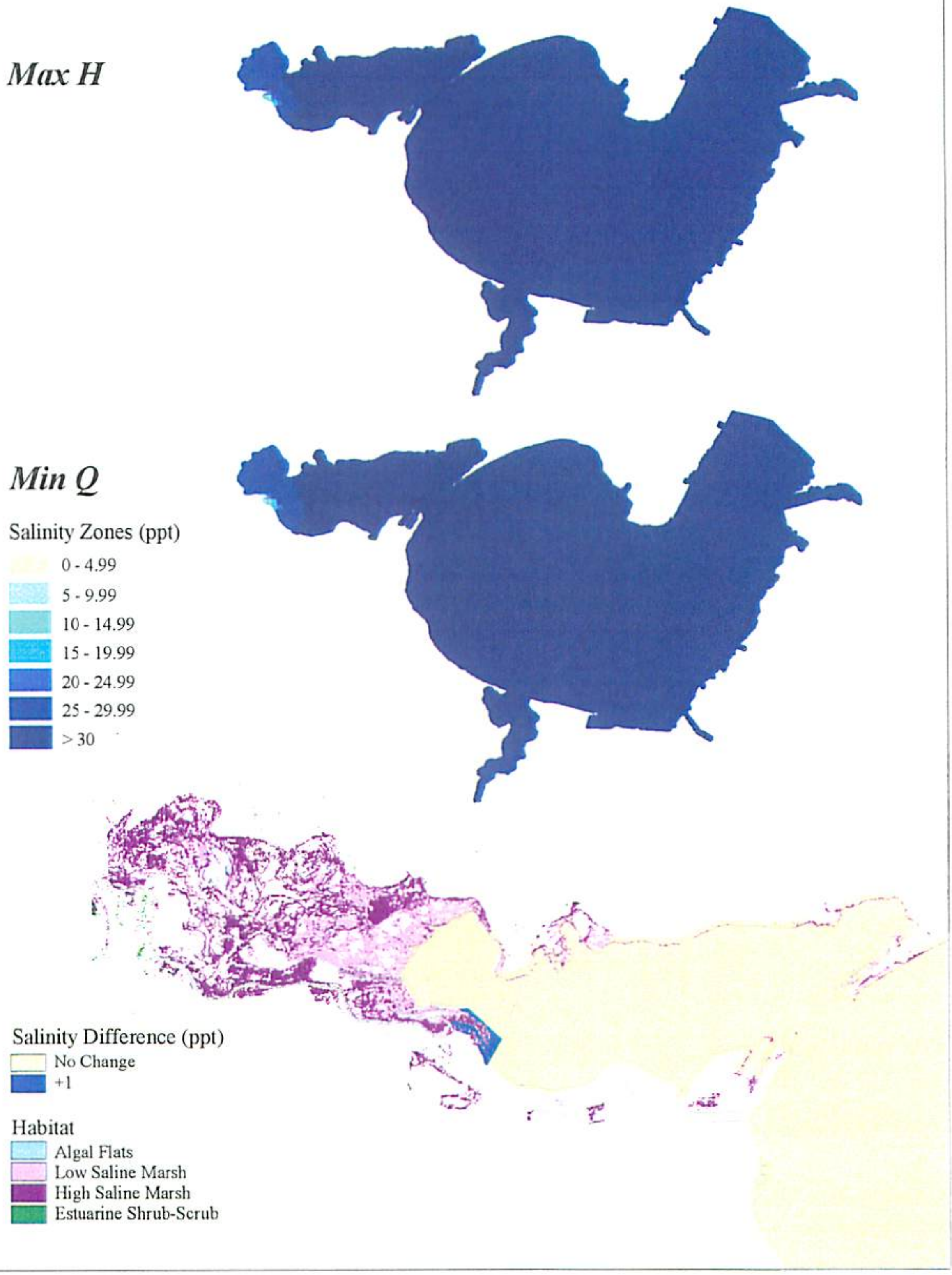


Figure 3.4
Max H vs. Min Q
Nueces Estuary Salinity Zones
October 1988



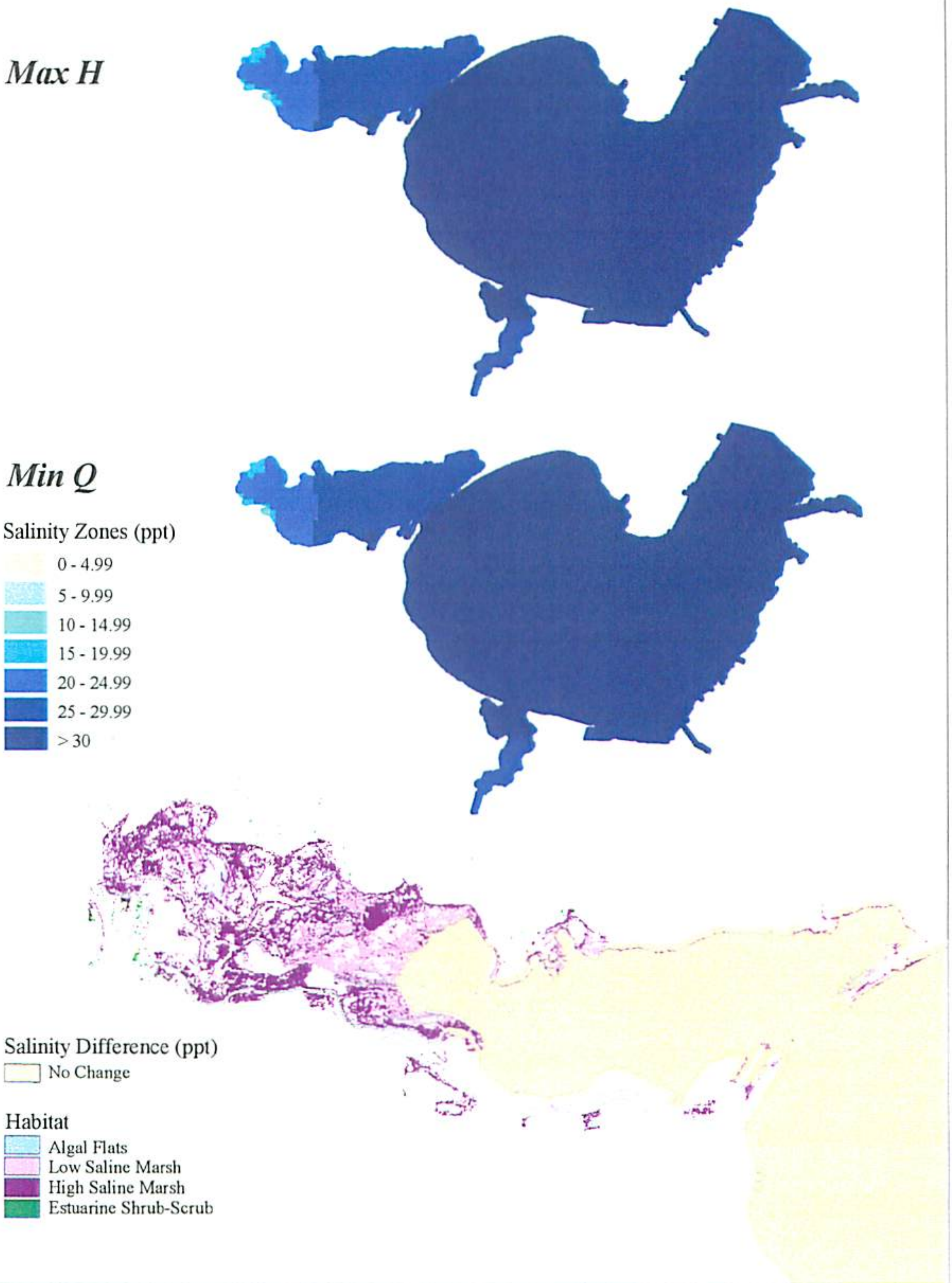
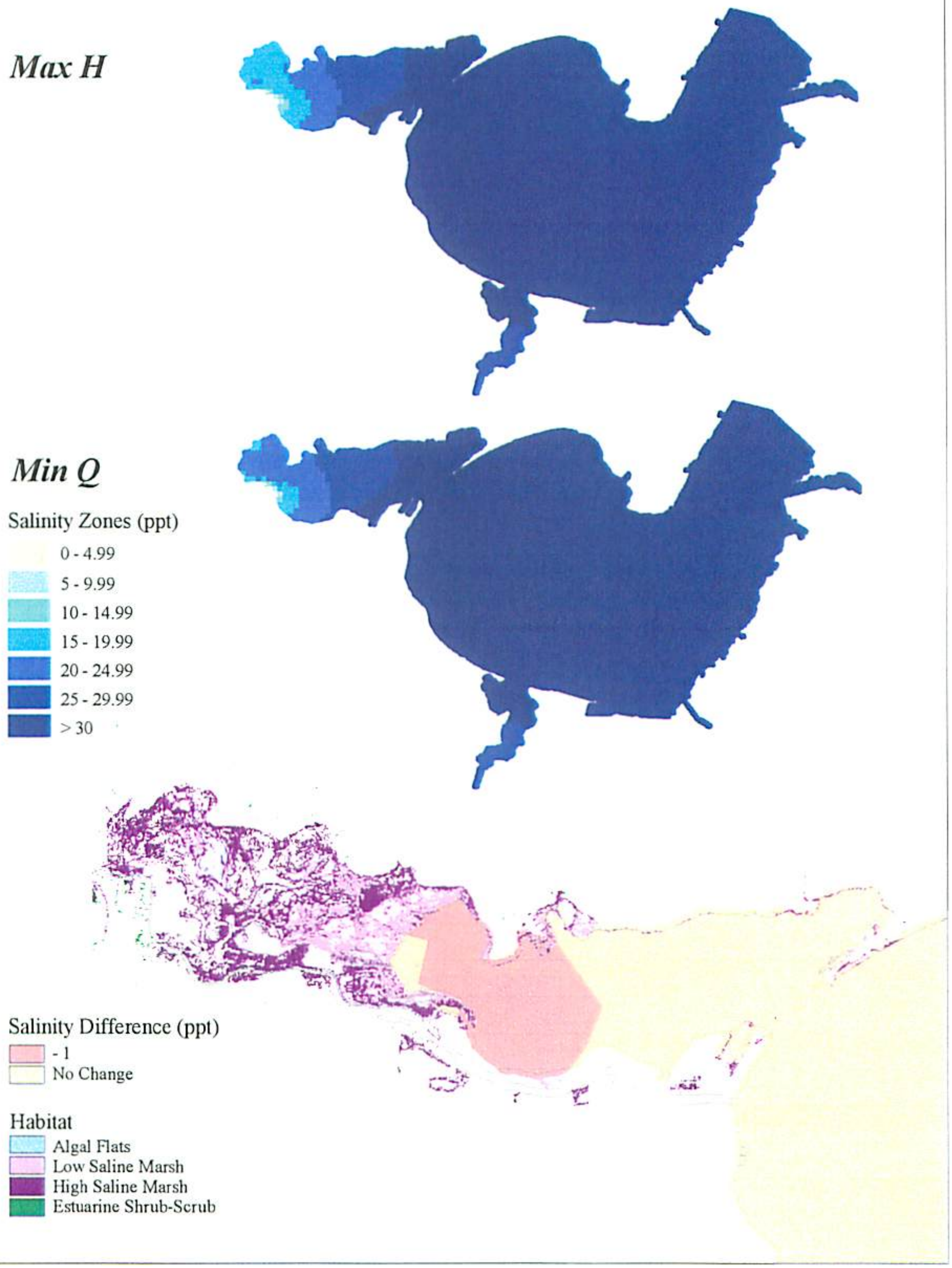


Figure 3.5
Max H vs. Min Q
Nueces Estuary Salinity Zones
March 1991

Figure 3.6
Max H vs. Min Q
Nueces Estuary Salinity Zones
May 1991



Max H

Min Q

Figure 3.7
Max H vs. Min Q
Nueces Estuary Salinity Zones
September 1991

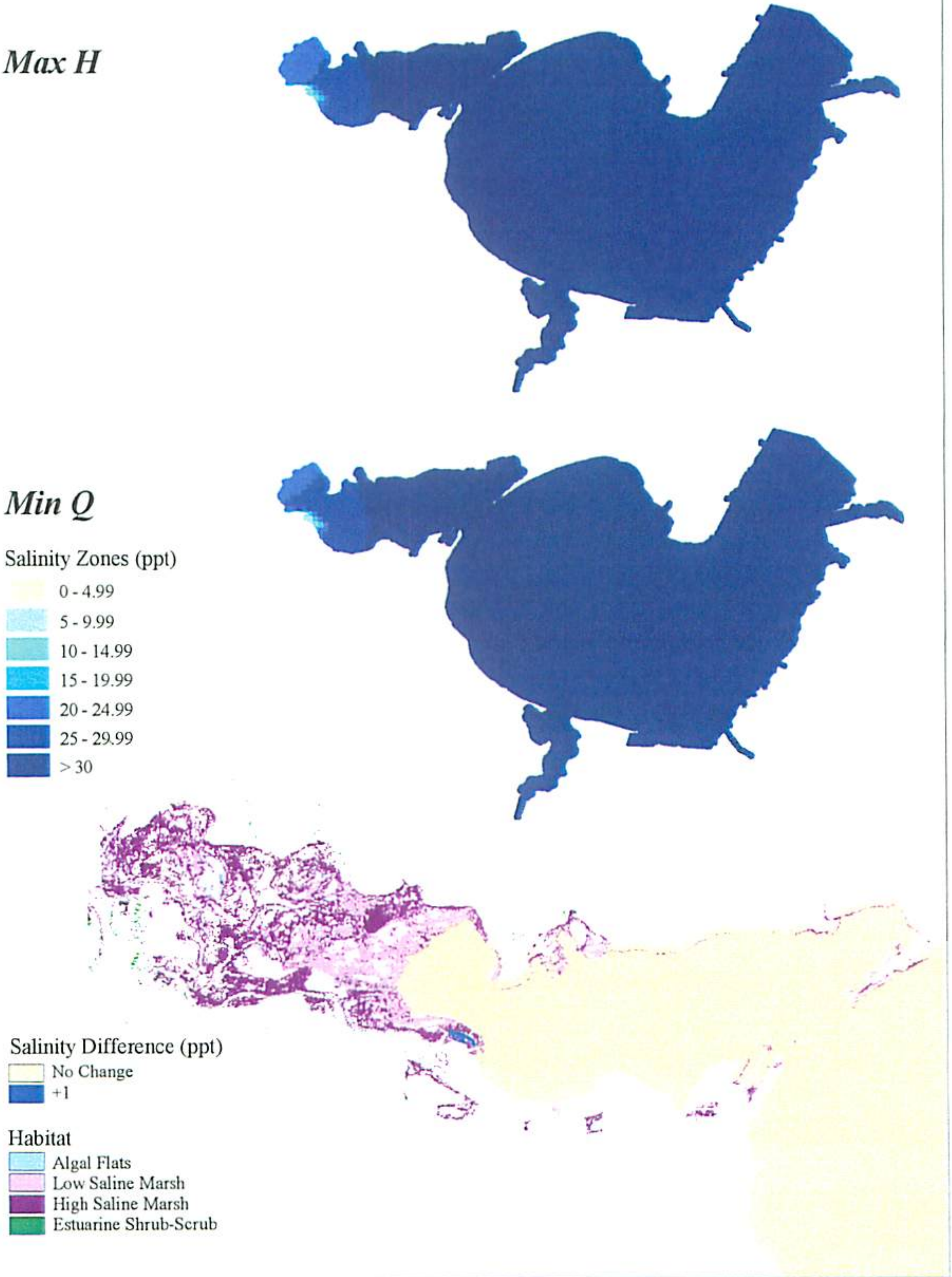
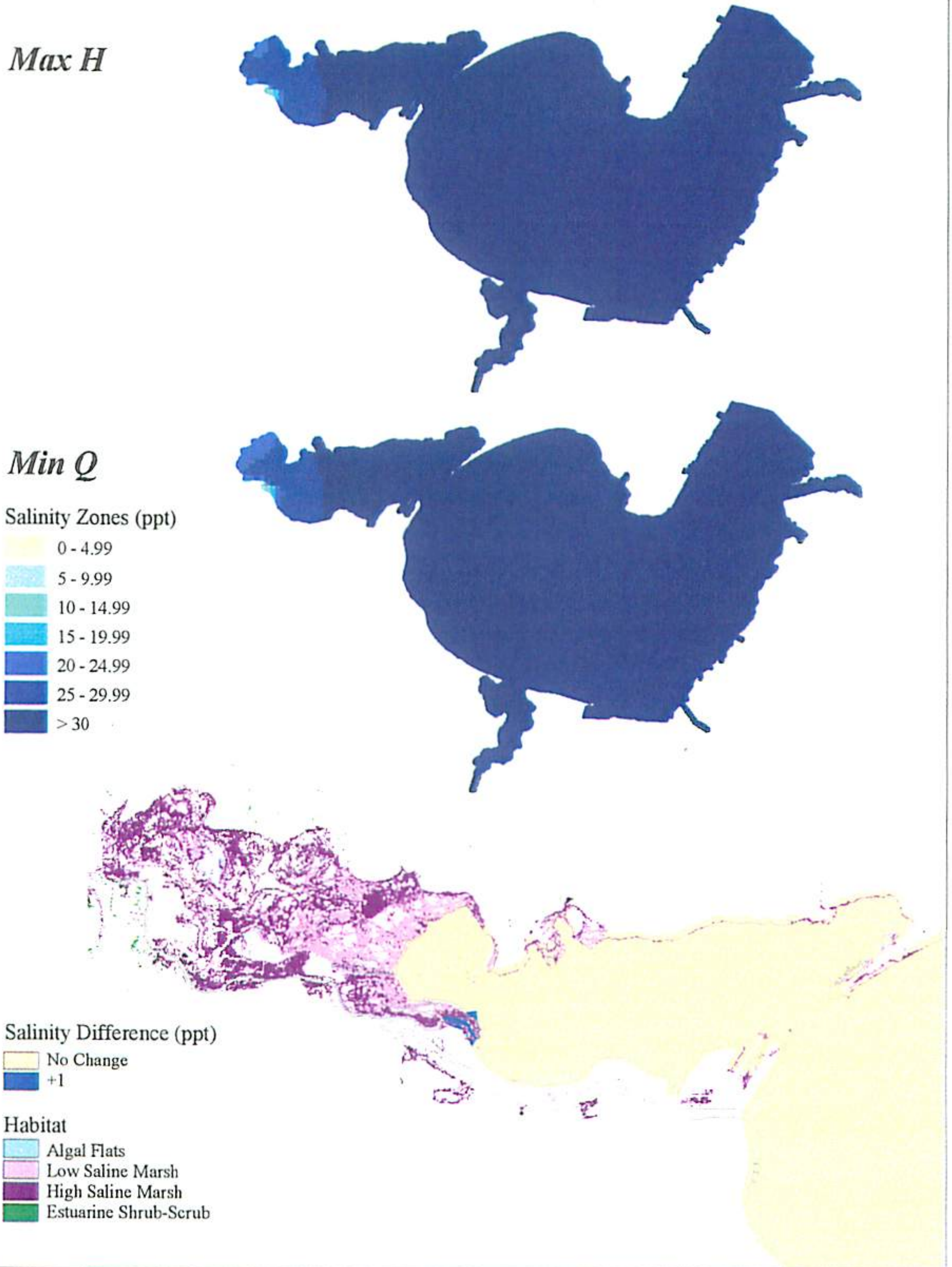


Figure 3.8
Max H vs. Min Q
Nueces Estuary Salinity Zones
October 1991



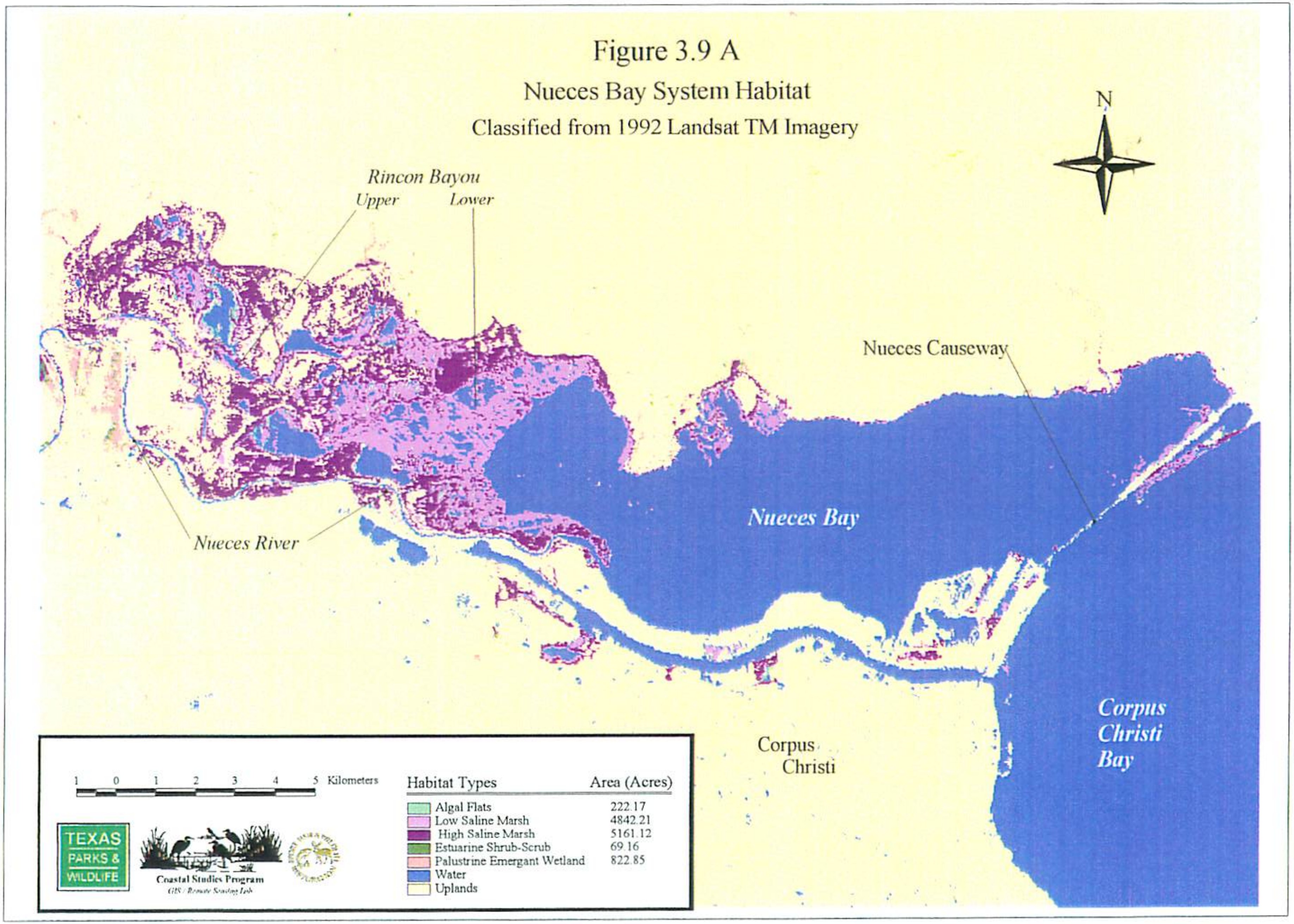


Figure 3.9 A

Nueces Bay System Habitat

Classified from 1992 Landsat TM Imagery

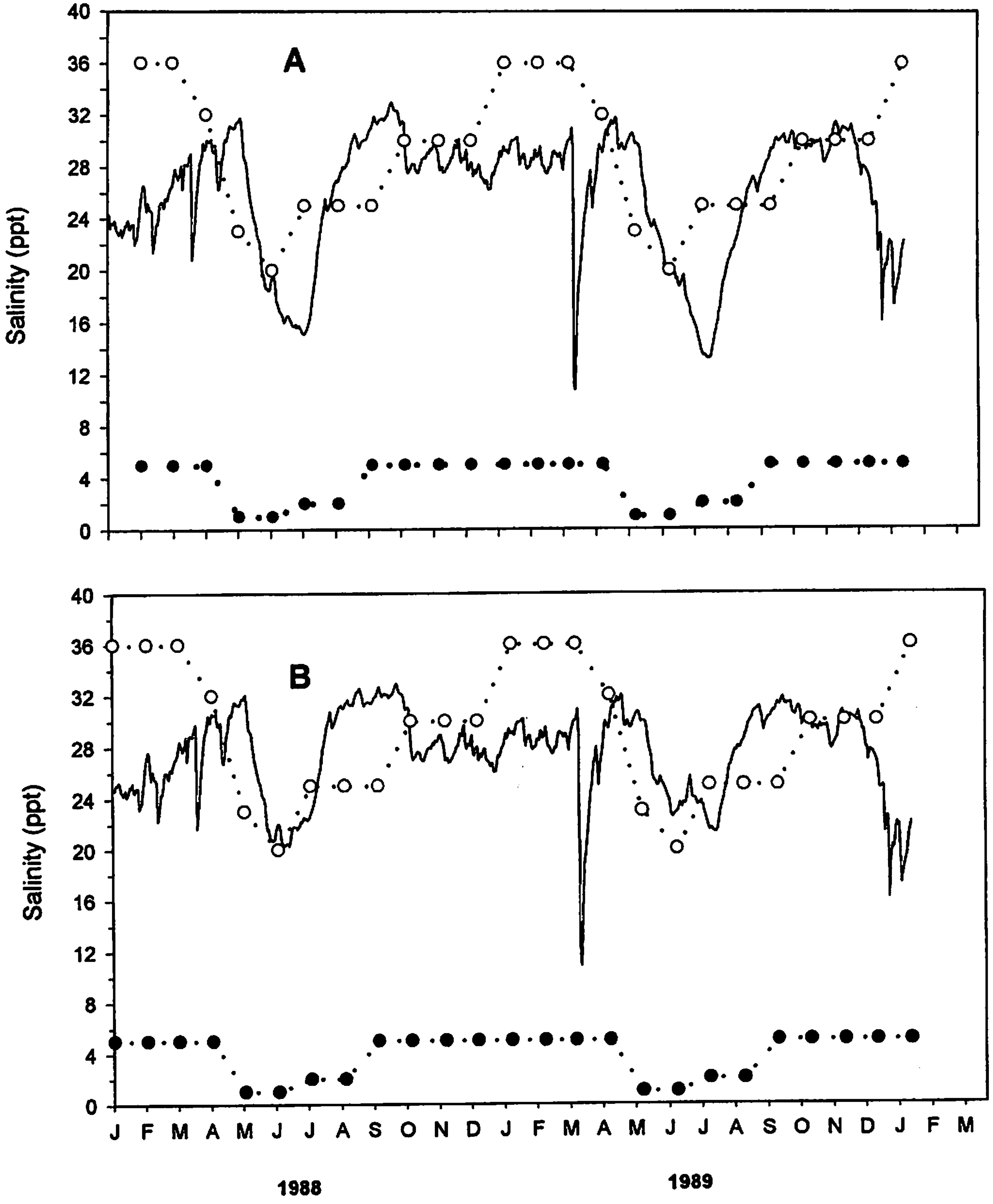


Figure 3.10. Daily average salinity under A: MaxH-8889 and B:MinQ-8889 for the upper Nueces Bay. Solid line shows simulated salinities from hydrodynamic model and dashed lines show lower and upper salinity bounds used for the upper bay constraints in the optimization model.

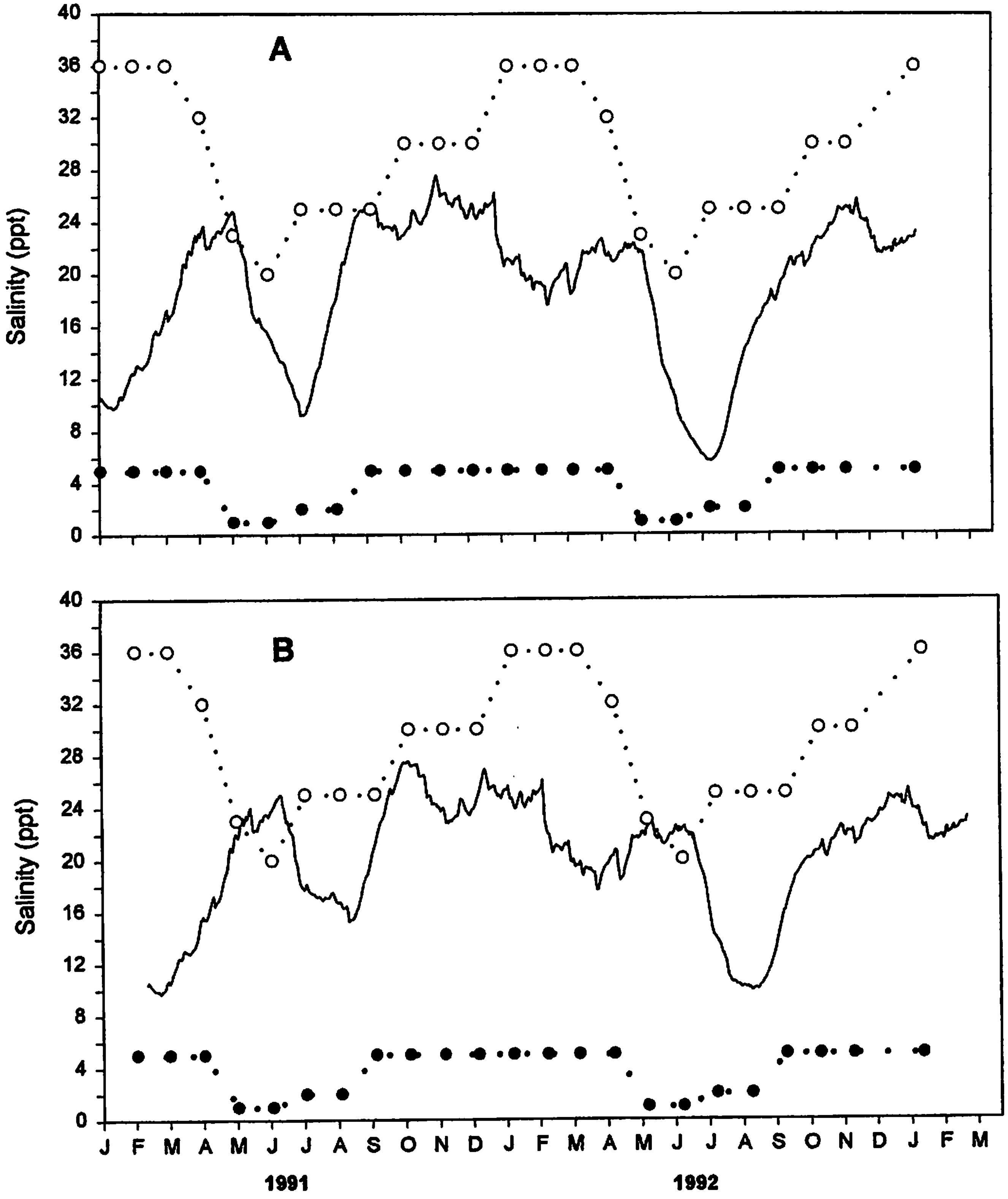


Figure 3.11. Daily average salinity under A:MaxH-9192 and B:MinQ-9192 for the upper Nueces Bay. Solid line shows simulated salinities from hydrodynamic model and dashed lines show lower and upper salinity bounds used for the upper bay constraints in the optimization model.

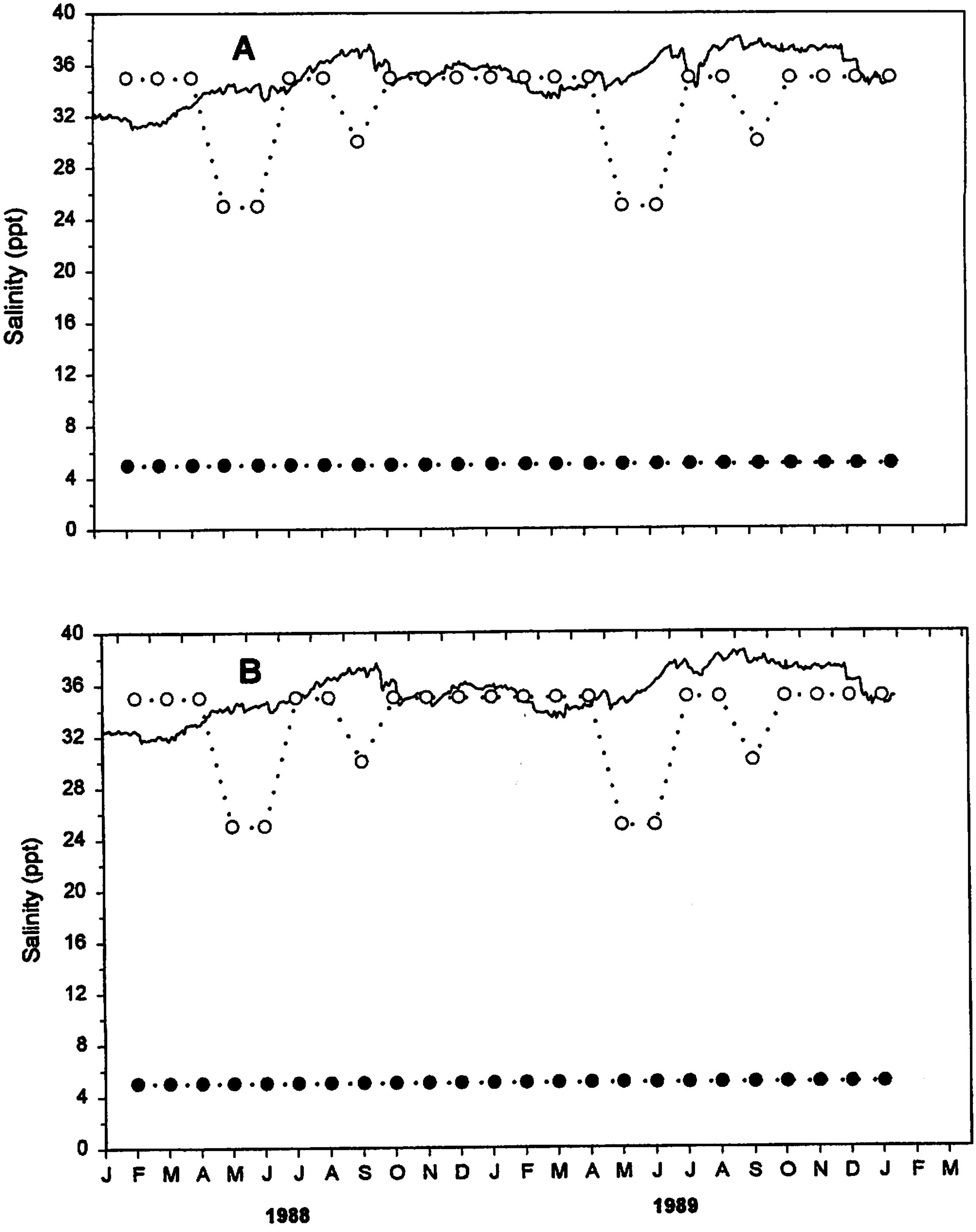


Figure 3.12. Daily average salinity under A:MaxH-8889 and B:MinQ-8889 for the Nueces Causeway. Solid line shows simulated salinities from hydrodynamic model and dashed lines show lower and upper salinity bounds used for the mid-Nueces Bay constraints in the optimization model.

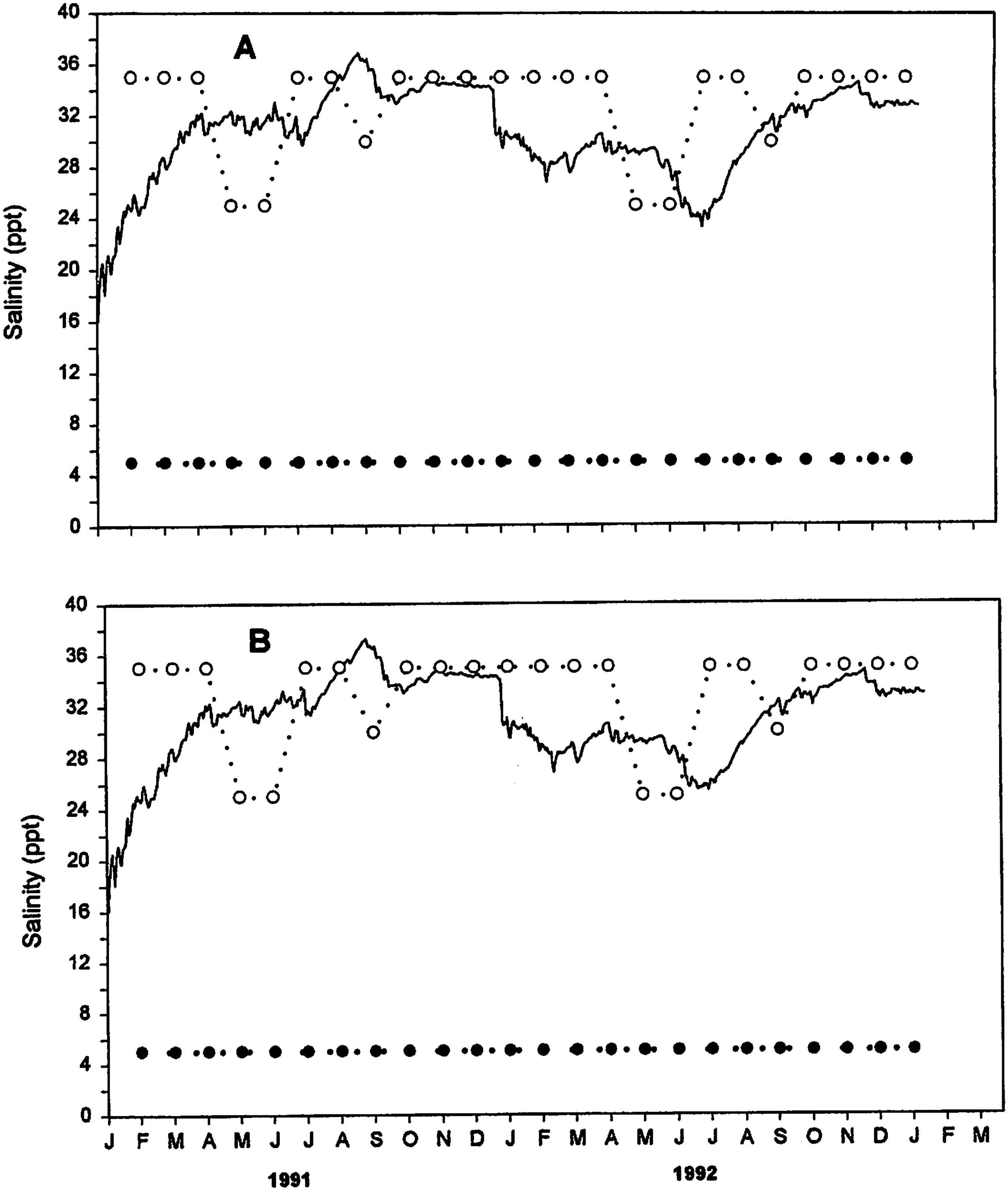


Figure 3.13. Daily average salinity under A:MaxH-9192 and B:MinQ-9192 for the Nueces Causeway. Solid line shows simulated salinities from hydrodynamic model and dashed lines show lower and upper salinity bounds used for the mid-Nueces Bay constraints in the optimization model.

Figure 3.14. Brown Shrimp catch vs. sum of April - July inflow (all years data, nontransformed)

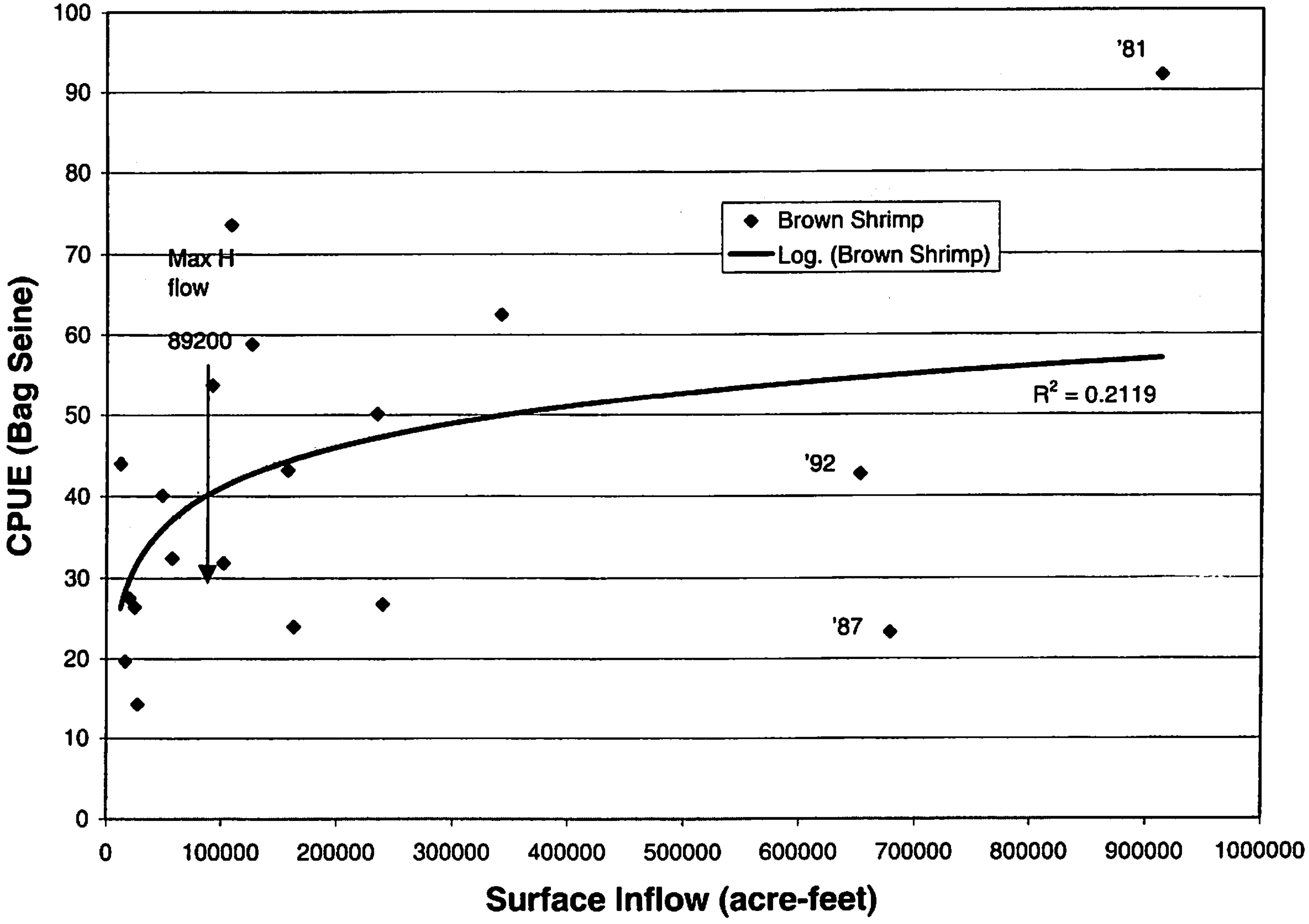


Figure 3.15 . Brown Shrimp catch vs. sum of April - July inflow (log-transformed data)

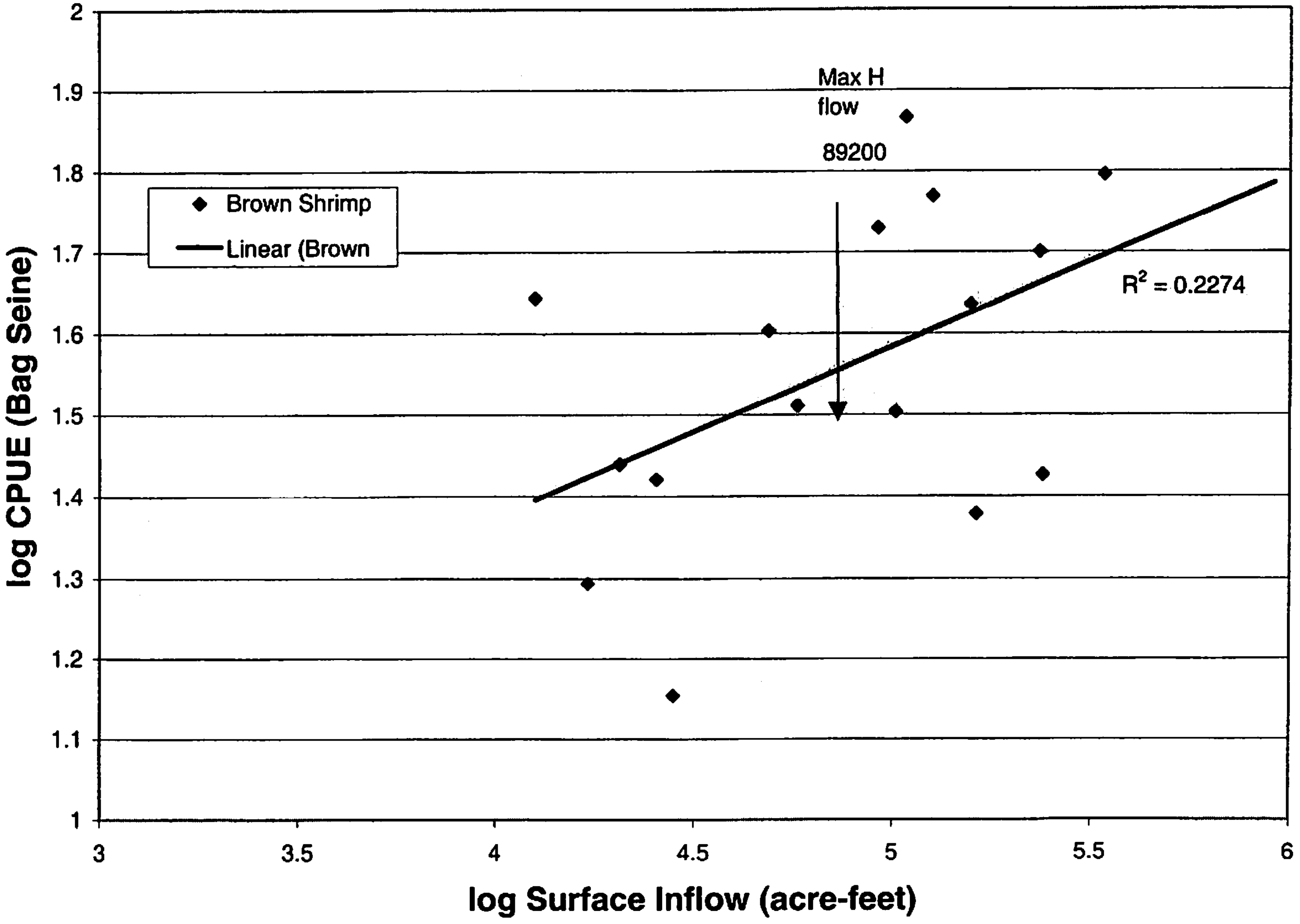


Figure 3.16. Blue Crab catch vs. sum of March - July inflow

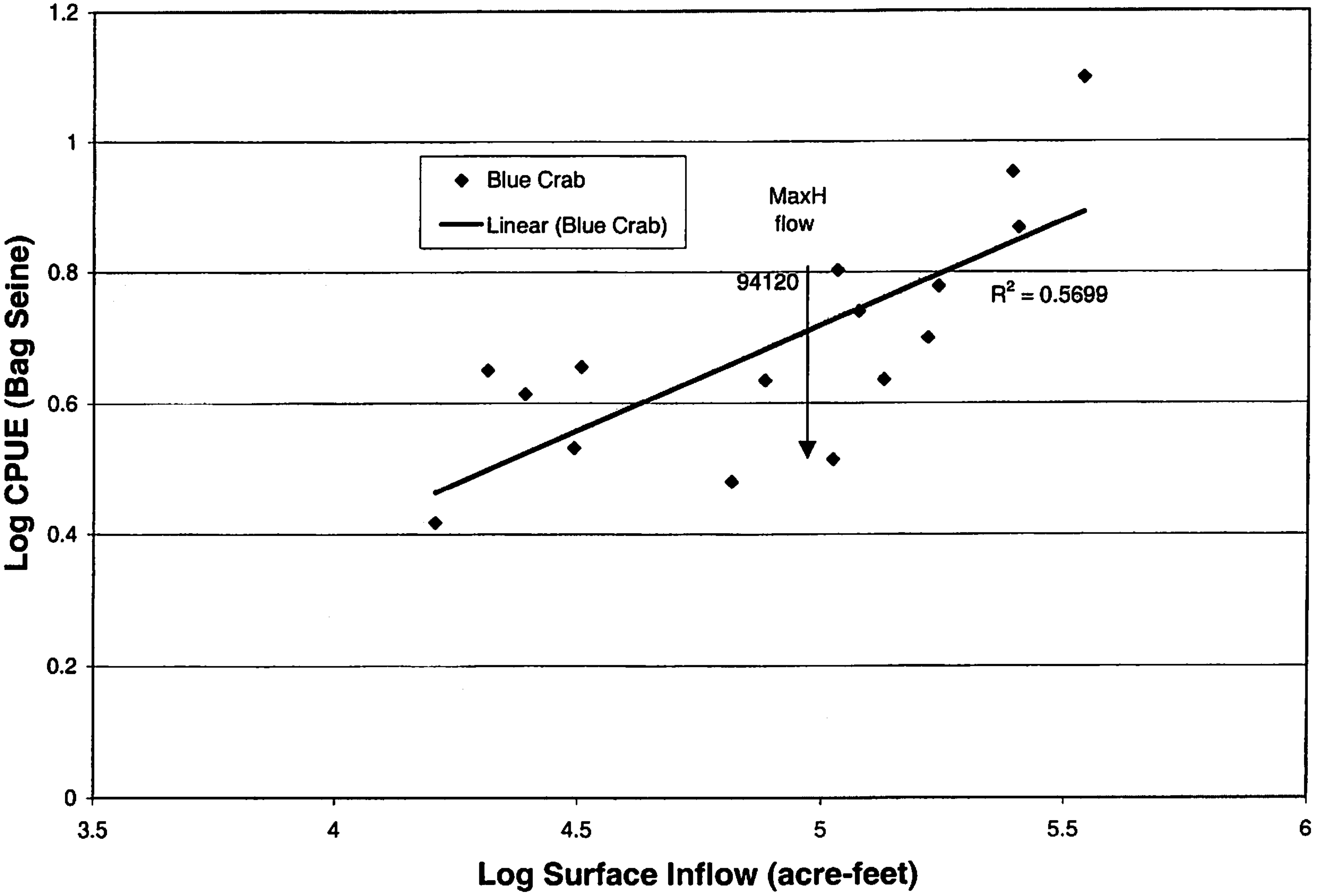


Figure 3. 17. Atlantic Croaker catch vs. sum of January - May inflows

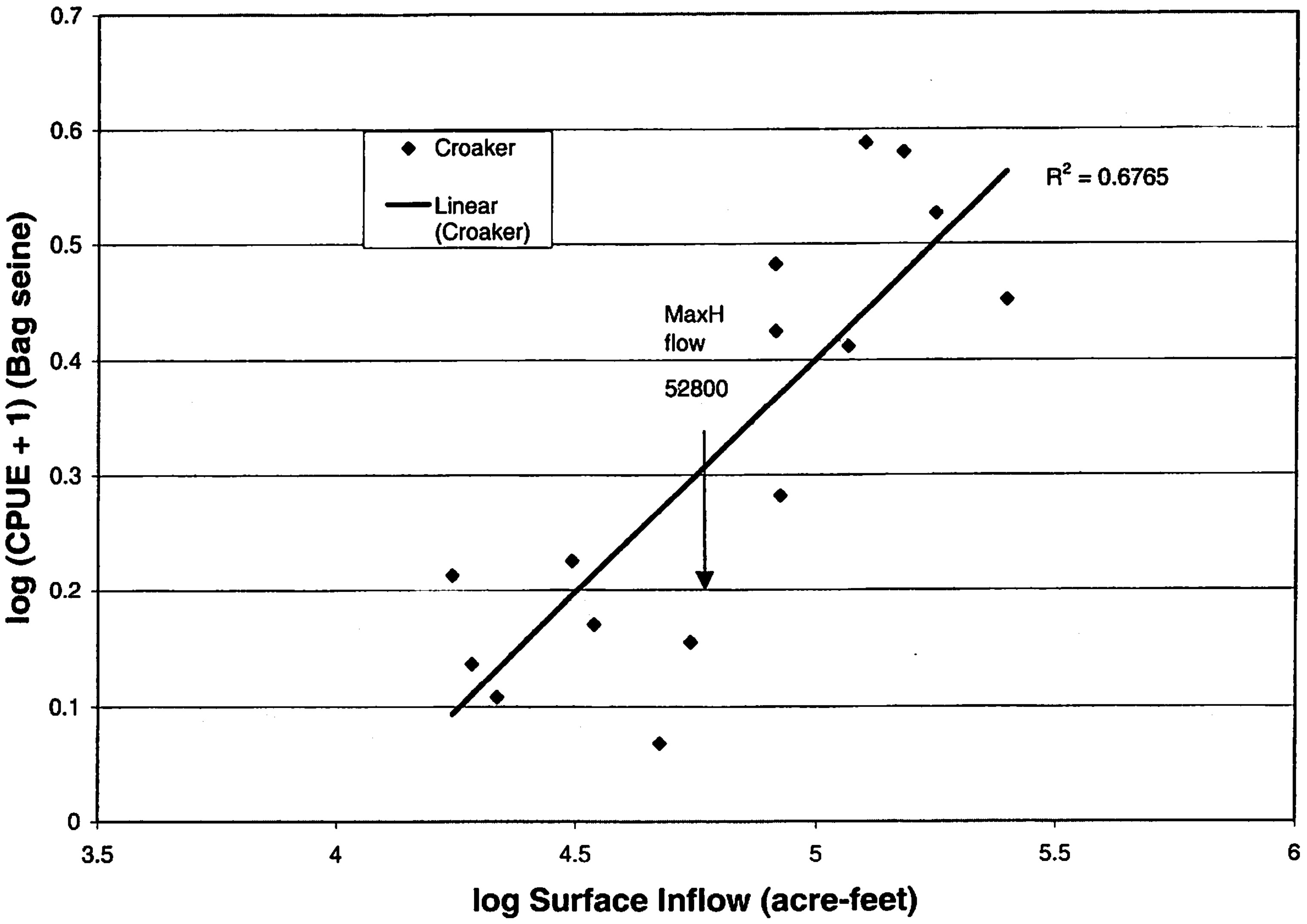


Figure 3.18. White Shrimp catch vs. sum of April - August inflow

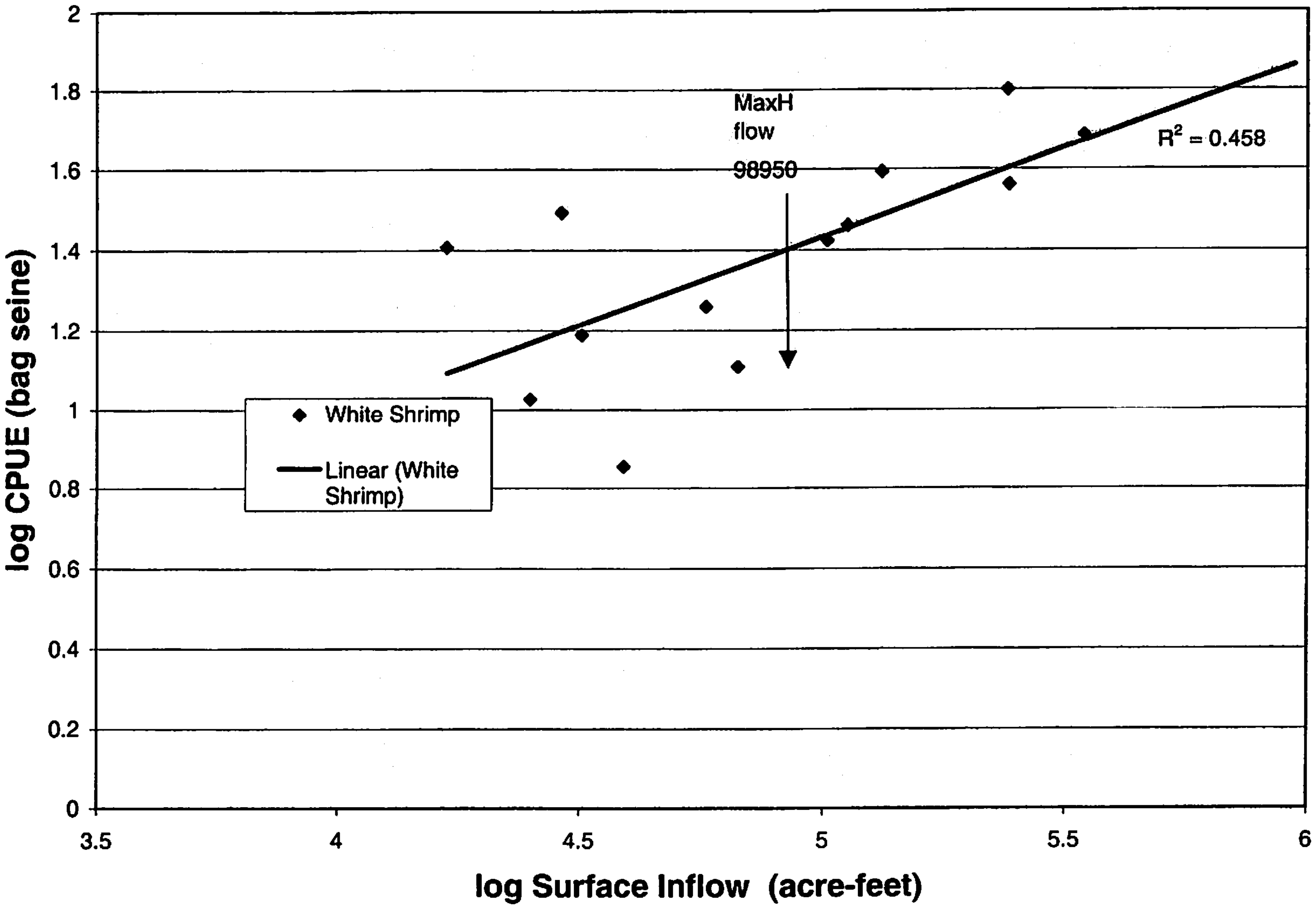


Figure 3.19. White Shrimp catch vs. sum of July - November inflow

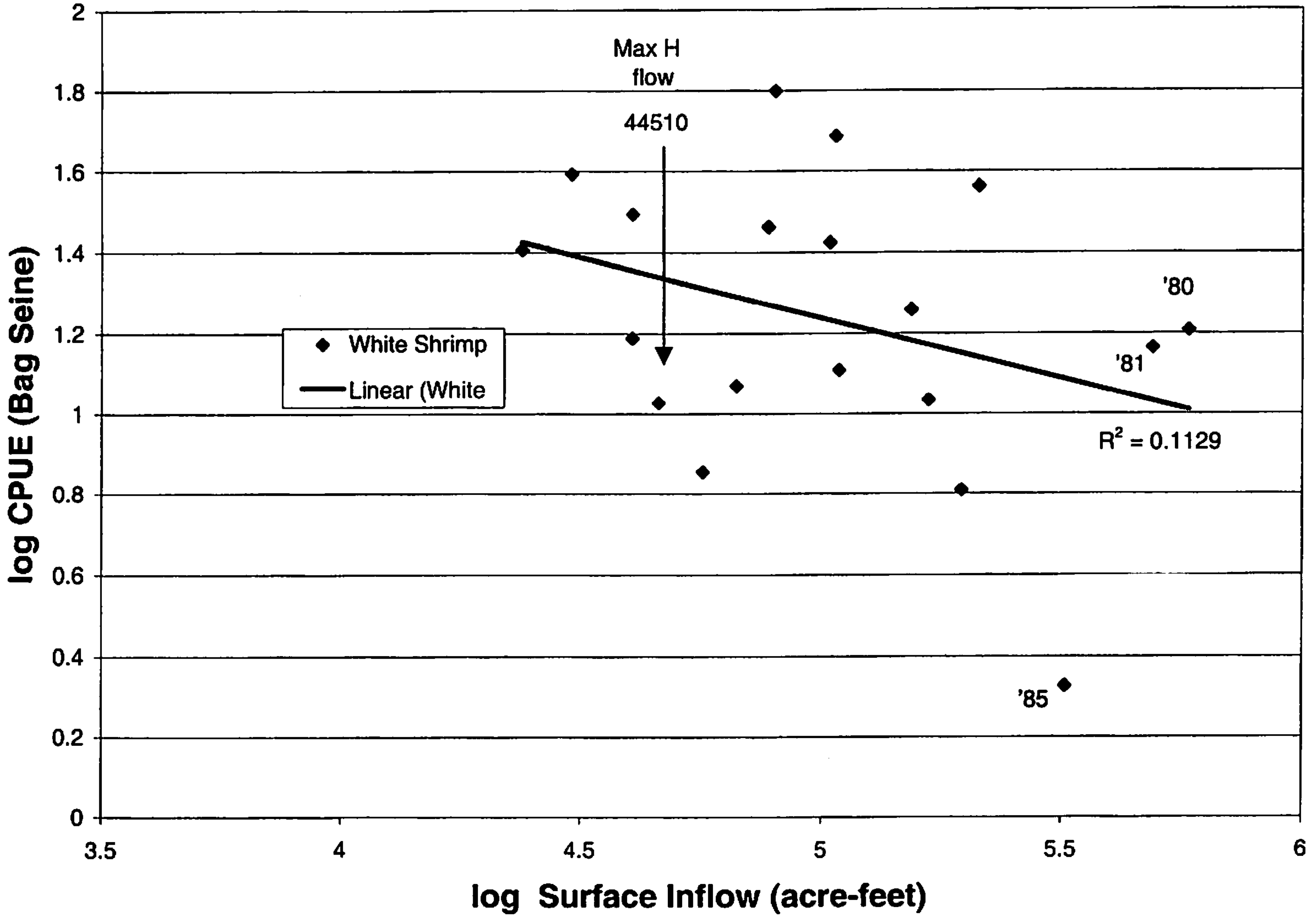


Figure 3.20

Spatial Distribution of Blue Crab
in Nueces Estuary for Wet and Dry Years
March through July

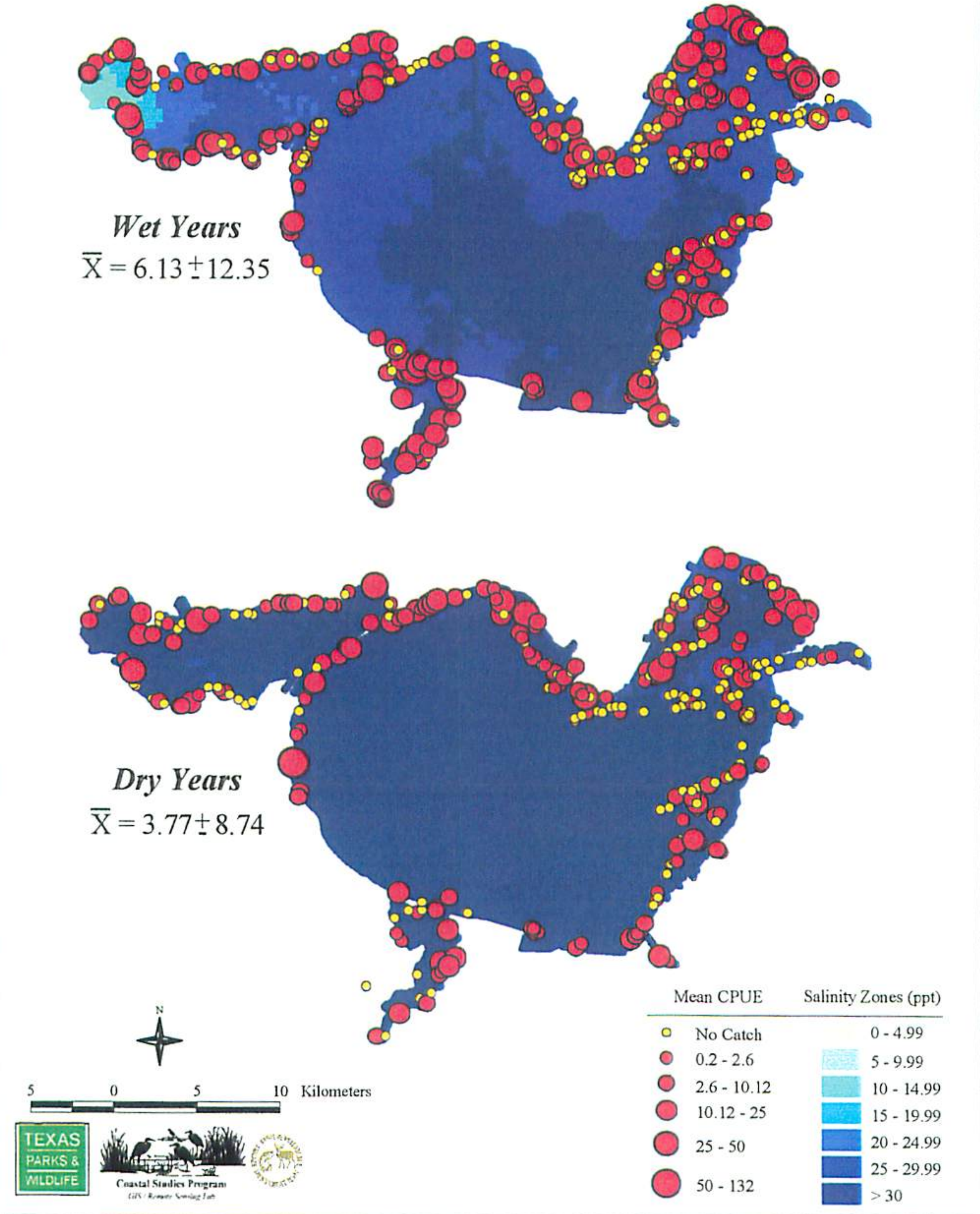


Figure 3.21

Spatial Distribution of Brown Shrimp
in Nueces Estuary for Wet and Dry Years
April through July

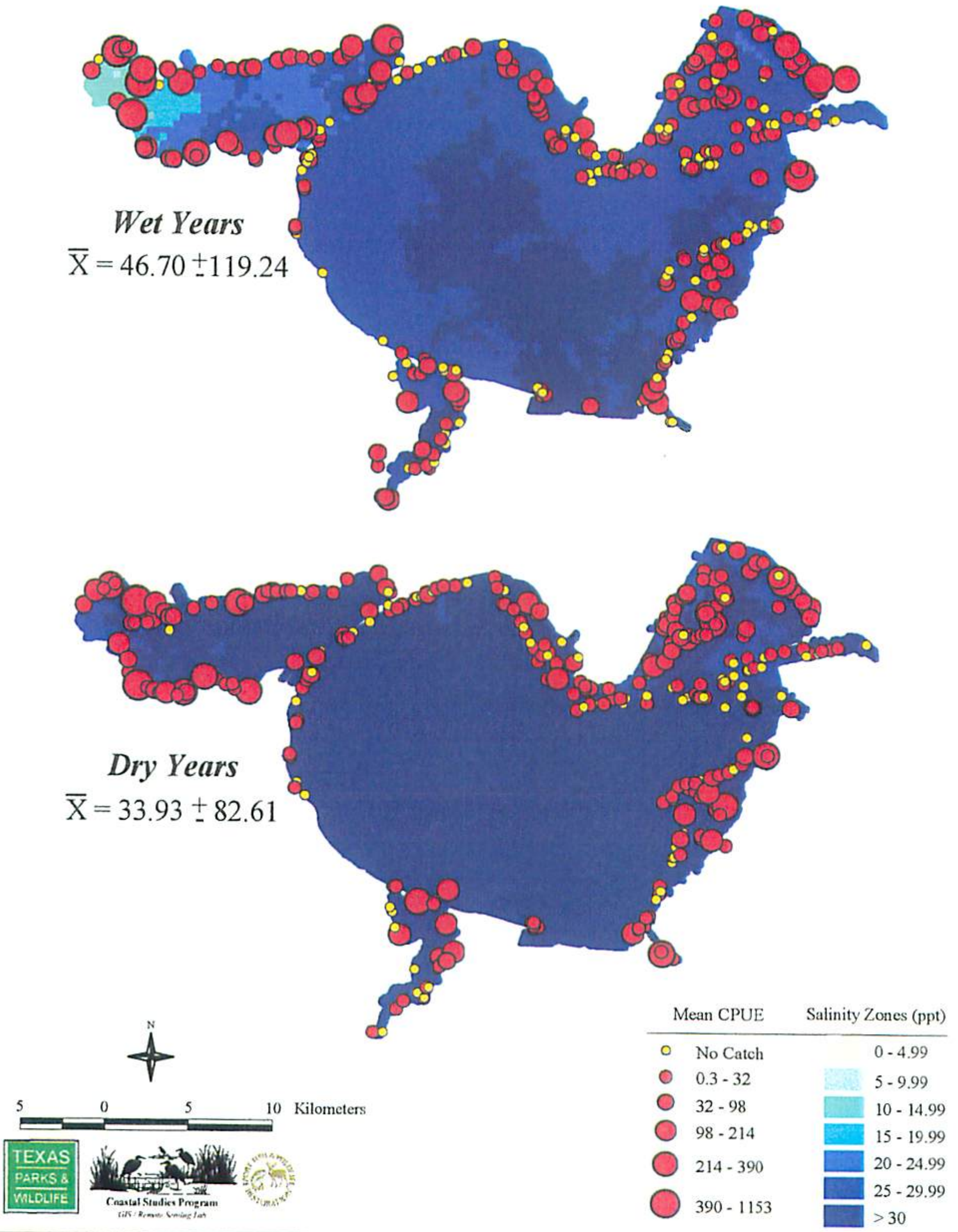


Figure 3.22

Spatial Distribution of Atlantic Croaker
in Nueces Estuary for Wet and Dry Years

January through May