Freshwater Inflow Recommendation for the Guadalupe Estuary of Texas

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December, 1998
Coastal Studies Technical Report No. 98-1

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ACKNOWLEDGEMENTS

Although the Coastal Studies Program of TPWD has been primarily responsible, this special study to recommend target inflows for the Guadalupe Estuary has been supported by many other persons at both Texas Parks & Wildlife and the Texas Water Development Board. The authors wish to thank TPWD management, especially Albert Green (ret.) and Larry McKinney, for their unfailing support and patience during the course of the studies. Numerous discussions with them and others generated some of the concepts and data analyses which were used to test ecological relationships involving freshwater inflows.

Several reviewers contributed substantial time and effort to provide constructive comments that we hope have vastly improved the report. This includes three major draft reviews. These reviewers were: William Longley and Gary Powell at TWDB, National Marine Fisheries Service staff at Galveston Fisheries Laboratory, Albert Green (TPWD), Larry McEachron (TPWD-Rockport), and Terry Whitledge (UTMSI).

This work was partially supported through funding from the Sport Fish Restoration Program (U.S. Fish and Wildlife Service) under Federal Aid Project F-37-TA.

EXECUTIVE SUMMARY

Freshwater inflows (FWI) from rivers, streams, and local runoff maintain the proper salinity gradients, nutrient loadings, and sediment inputs that in combination produce an "ecologically sound and healthy Estuary." This report summarizes studies which form the basis for TPWD's recommendation of target freshwater inflows needed to maintain the unique biological communities and ecosystems characteristic of a healthy Guadalupe Estuary in Texas.

Methods for determination of coastal freshwater inflows, developed by the State Bays and Estuaries Research Program [consisting of the Texas Water Development Board (TWDB) and Texas Parks & Wildlife Department (TPWD)], start with computer optimization and hydrodynamic modeling as basic predictive techniques. *The Appendix to this report contains technical details related to running the optimization model.* Modeling produces theoretical estimates of a minimum FWI (termed the MinQ flow) and maximum harvest FWI (termed MaxH flow) for each Estuary. The MinQ and MaxH target flows predicted from optimization modeling are then critically evaluated by TPWD for effectiveness in satisfying biotic needs of the Estuary. TPWD studies focus on empirically evaluating fisheries survey data from the TPWD Coastal Fisheries Resource Monitoring Database. By comparing predicted results from the theoretical modeling with observed fisheries sampling data, a final recommendation is proposed consistent with TPWD's goal of FWI needed for a "biologically healthy and productive" Guadalupe Estuary.

REVIEW OF TWDB/TPWD MODELING RESULTS

The Estuarine Mathematical Programming or Optimization Model (TXEMP) produces a range of solutions that simultaneously predict seasonal (monthly) inflows (Fig. 2.1) and the corresponding estuarine fishery harvests (Fig. 2.2), which satisfy model input constraints. The monthly flow targets for MinQ and MaxH cases are listed in Table 2.1. Output from TXEMP serves as input to the two dimensional, finite element hydrodynamic circulation model

(TXBLEND) which simulates patterns of salinity distributions and bay circulation.

Minimum annual inflow (MinQ) was computed to be 1.03 million acre-ft/year and MaxQ was 1.29 million acre-ft/yr. Optimal flow producing maximum fisheries harvest (MaxH) within the range of inflows between MinQ and MaxQ was determined to be 1.15 million acre-ft/yr. Figure 2.2 compares the monthly inflow distributions for MinQ and MaxH cases to the two historical inflow boundary cases, namely the median (50th percentile) and 10th percentile flows. Despite the small difference between MinQ and MaxH flows (*ca* 9 %), the difference in total fisheries harvest between the two cases (2.54 vs. 2.93 million pounds for MinQ vs. MaxH, respectively) is significantly larger (*ca* 15 %), as shown in Table 2.2. The MaxH flow produces higher harvests of blue crab, oysters, and brown shrimp than does MinQ.

VERIFYING BIOLOGICAL RESPONSES TO HISTORICAL FRESHWATER INFLOWS

Two types of biological assessments were performed in order to validate the computed FWI targets: 1) Evaluation of the biotic suitability of seasonal salinity zones predicted from the hydrodynamic model; and 2) Demonstrating correlations between observed abundance of representative fisheries biota and corresponding seasonal salinity gradients (as a proxy for FWI).

Effects of MinQ vs. MaxH Salinity Regimes Predicted by Modeling

Geographic information system (GIS) techniques were used to compare salinity maps from the hydrodynamic model under optimized MaxH or MinQ inflows. Salinity zone maps were generated by contouring the salinity output from model runs using Arc/Info GIS software. Salinity change analysis was performed by overlaying MinQ and MaxH salinity maps for each month, producing salinity difference maps between MaxH and MinQ (Fig. 3.3). Locations of wetlands and oyster reefs were also overlaid onto the monthly plots of predicted salinity zones to aid in interpreting impacts. The distribution of sensitive marsh wetlands in the Guadalupe Bay Delta (2,634 ha of brackish marsh and 2,664 ha of intermediate/fresh marsh) and 4,300 ha of submerged vegetation (seagrass) in other parts of the Bay were considered critical to this evaluation.

Examination of salinity difference maps indicated that salinity zones were essentially identical (< 1.0 ppt difference) between MaxH and MinQ cases from January until May. From May to September, progressively larger salinity differences were evident between the two cases in the Upper and Middle parts of the Bay. The largest actual difference in salinities for the entire year between the two model cases (a high of 3 ppt near the Delta in the Upper Bay) was observed for the month of September (Fig. 3.3). These moderately higher MinQ values (*ca* 10 - 14.9 ppt) compared to MaxH conditions near the Delta are noteworthy. Some stress to salt-sensitive wetland vegetation or benthic fauna near the Delta could be caused by these MinQ salinity regimes during summer to early fall.

Time Series Analysis of Salinity at Critical Bay Sites

Time-series analyses were also performed on the salinity data from the TXBLEND model at selected sites in the Bay to determine when the salinity constraints would be exceeded (Figures 3.4 & 3.5). The MinQ case had slightly higher average salinities and exceeded salinity constraints in the Upper Bay more often than did the MaxH. During the critical summer months when shrimp, crabs and young-of-the-year fish species depend on the estuary for habitat and food resources, the MinQ case exceeded the maximum salinity constraint for 49 days by an average of 1.7 ppt in the Upper bay.

Spatial Correlation Analysis between Salinity Zones and Target Faunal Density using Coastal Fisheries Catch Data

GIS spatial analyses were applied to demonstrate statistical associations between abundance of seven target species and salinity zones in the Estuary: white and brown shrimp, blue crab, Gulf menhaden, Atlantic croaker, bay anchovy, and pinfish. Using the extensive TPWD Coastal Fisheries Resource Monitoring database, we analyzed catch data for the bay covering the range of inflow conditions from 1982 to 1993. Relative abundance of young animals caught in open-water otter trawls during the appropriate season was used to determine their distribution along the salinity gradient. Spatial correlations were derived between average salinity gradients over the 12 years and average relative catch (CPUE) of each species. Arc/Info GIS overlays were then performed between trawl sample CPUE and contoured salinity zones from the Coastal Fisheries database. (See Figures 3.10 & 3.12 for blue crab and brown shrimp).

From the Arc/Info GIS analysis, two critical data values for each species were calculated: 1) the percent abundance of animals in discrete salinity zones, and 2) the percent of bay area occupied by salinity zones. Correlations between salinity zone area and relative abundance allowed open-water habitat zones, where peak density occurred, to be derived for each species (Figures 3.17 & 3.19).

Nonparametric statistical tests confirmed that shellfish (brown shrimp, white shrimp and blue crab) and finfish (bay anchovy, Gulf menhaden, Atlantic croaker and pinfish) varied in their distribution according to specific salinity gradients. Each species showed a significant affinity for a particular salinity regime, defined as the optimum habitat zone where density was highest (Table 3.3). Five species (including white shrimp, brown shrimp, blue crab, Atlantic croaker, and Gulf menhaden), all had peak density zones between at least 5 and 19.9 ppt, i.e. the mesohaline region of the bay. Two species (white shrimp and blue crab) showed peak density zones lower than 15 ppt, in the low- to mid-brackish range. Anchovy showed a slightly higher peak density zone from 20 - 25 ppt, while pinfish showed a still higher affinity for 25 - 30 ppt. As an example, the peak density zone for brown shrimp averaged 47.2% of bay area and accounted for 66.4% of total abundance in the bay.

Comparison of Observed Peak Density Zones vs. MinQ or MaxH Predicted Salinity Zones

Additional comparisons were made between observed peak density zones and salinity zones predicted from modeling to determine whether MinQ and MaxH inflows produced sufficient bay area of the peak density zone. Salinity contour maps from the observed fisheries data for each species were compared to salinity maps created by contouring the MinQ and MaxH predicted salinity zones for the same time period. These GIS plots were used to calculate percent of bay area in the various salinity zones under the two model cases (MinQ or MaxH), and the observed samples case (see Figures 3.24 & 3.26 for blue crab and brown shrimp). The suitability of predicted flows for producing the peak density zone salinities was evaluated based on relative comparisons of areal percentages (Table 3.11).

For white shrimp, blue crab, and brown shrimp (Table 3.11), MaxH flows produced between 33% and 60 % less bay area within the peak density salinity zone than the observed samples case. The reduction in area was smallest for white shrimp (33 %), and largest for brown shrimp (60 %). MinQ flows produced correspondingly less peak density areas than MaxH (52 % less for white shrimp; 65 % less for brown shrimp). For all seven species, the percentage correspondence between peak density zones for the MaxH and observed samples case ranged from a low of 40 % (brown shrimp) to a high of 101 % (bay anchovy). Because of the many key functions supported by these peak density, low salinity (mesohaline) habitats (food, shelter, energy maintenance, etc.), inflow levels at least as high as MaxH flows are considered critical to maintaining such brackish- water conditions.

INFLOW RECOMMENDATION SUMMARY

TPWD staff recommends MaxH (1.15 million ac-ft per yr) inflows as the lowest target value to fulfill the biological needs of the Guadalupe Estuary System on a seasonal basis. TPWD prefers this conservative value of MaxH since it was shown to produce conditions closer to many of the peak density salinity zones of the target species and wetlands examined in this analysis. This is in contrast to the MinQ case (1.03 million ac-ft per yr). The distribution of flows approximating the historical monthly median pattern provides the most adequate salinity conditions during the critical spring months of May and June. Dryer conditions during summer months (July and August) are expected naturally and can be tolerated if the estuary is prepared by earlier inflows.

The following key biological results support the TPWD inflow recommendation:

1) <u>Correlations between target species' historical average densities and the mesohaline</u>

salinity zones of the bay. Densities of five species (white and brown shrimp, blue crab, Atlantic croaker, and Gulf menhaden) all showed significant positive correlations with peak density salinity areas of the bay between 5 to 20 ppt. These peak density salinities are generally produced by inflows at least as great as MaxH during May through October.

2) GIS overlays and time series analyses of salinity regimes at Upper bay sites. These results show that MinQ salinities at critical times of the year are on the borderline compared to MaxH salinity regimes for sensitive wetland plant species in Upper San Antonio Bay and oyster communities in the Middle Bay. Salinity zone conditions in Upper and Middle Bay areas are better maintained under MaxH flows than under MinQ flows during the critical period, June through September.

3) Comparison of total fisheries harvest predicted from the optimization model. The optimization model actually predicts significantly higher (15%) fisheries harvest for the bay under MaxH inflows compared to MinQ levels. The species composition of both the MaxH and MinQ harvests are close to the historical 24-year median harvest, but MaxH supports more blue crab, oyster, red drum, and brown shrimp harvest.

4) The GIS results of observed fisheries samples vs. modeled salinity gradients clearly establish that average salinity gradients correlated with peak densities of target species would be best provided by FWI regimes at least equal to the MaxH case.

IMPLEMENTATION OF TARGET FRESHWATER INFLOWS

Although the recommended target inflow (MaxH) is 1.15 million acre-feet per year, examination of the hydrologic record (Figure 4.1) shows that during the past 47-year record, the Guadalupe Estuary received greater than 1.52 million acre-feet (the median annual inflow) 50% of the years. Only 23% of the years did the Estuary receive less than the 1.15 million acre-feet target amount for MaxH, and this is substantially lower than the median inflow of 1.52 million acre-feet. When considered in this perspective, the MinQ flow of 1.03 million-acre feet, occurring in less than about 15 % of years, can be judged as being at the lower end of the inflow range. The slightly higher MaxH flows, which only occurred in about 23% of years, would be particularly important in loading the system with nutrient and sediment reserves that are needed during lower-flow years.

During drought conditions, inflows would be much lower than the 1.15 million ac-ft per year (MaxH) amount estimated to meet the biological needs of the Guadalupe Estuary system or the minimum threshold level of 1.03 million ac-ft per year (MinQ). At the lower subsistence inflow levels (below MinQ), wetland productivity and fisheries harvest would be expected to greatly decrease. A major concern of TPWD is that any exacerbated increase in the severity, frequency, or duration of droughts will alter the ecosystem structure by either reducing overall estuarine production or by favoring one species' production at the expense of others, thereby reducing biodiversity.

Under reduced riverflow management conditions, however, the frequency of reduced bay inflow levels should not be increased beyond historical occurrences. Watershed management programs should provide target and lower flows at almost the same frequency at which they occurred in the past and retain as much historical variability at higher flows as possible. Although drought cannot be avoided in many cases, the adverse environmental effects due to human-induced increases in the magnitude and duration of naturally occurring droughts should be minimized.

SECTION 1: INTRODUCTION

Each Texas estuary needs freshwater inflows (FWI) to maintain the proper salinity regimes, nutrient loadings, and sediment input that in combination support unique, historical levels of biological productivity (Copeland 1966, Turner 1977, Deegan et al. 1986, Turek et al. 1987). Freshwater inflows from rivers, streams, and local runoff act as mechanisms to transport these necessary materials and to produce the salinity gradient in an estuary. Collectively, these factors and processes produce an "ecologically sound and healthy estuary." In a holistic sense, the annual and seasonal dynamics of FWI allow for a range of inflow conditions that satisfy an estuary's ecological needs. However, there is an expected minimum threshold at the low end of this FWI range where one or more of the functions of FWI will become limiting to the ecosystem. This could be maintenance of salinities, supplying nutrients and particulate organic matter, or input of sediments. It is important to realize that below this critical minimum FWI, estuarine health and productivity will suffer, perhaps drastically (Copeland 1966).

In order that water resources may be developed with minimal biological damage to Texas estuaries, TPWD seeks to identify for management purposes this annual threshold amount of FWI and its necessary seasonal distribution pattern. TPWD describes this level of FWI that will sustain the historical, average biological productivity and typical biodiversity of a specific bay or estuarine system as a maintenance or target flow. This report will summarize the protocol and analyses used to validate the target freshwater inflow needed to support historical biological communities and healthy ecosystems characteristic of one such Texas estuary, the Guadalupe Estuary (also referred to as the San Antonio Bay System).

The work reported herein represents a final phase in the State of Texas Bays and Estuaries Freshwater Inflow Research Program studies (see Texas Water Code, Section 16.058) targeting the Guadalupe Estuary. This interagency program reflects the State's coordinated approach to water resources planning and determination of freshwater inflows needed for estuarine maintenance in coastal regions. TWDB has been responsible for developing engineering modeling techniques that estimate FWI hydrology and for evaluating trends in coastal physical factors, while TPWD has been responsible for determining trends in coastal fishery resources and assessing estuarine ecological impacts from FWI alterations. The general objectives, technical studies, and analytical modeling methods developed through the Bays and Estuary Program were previously published in a joint report by the TWDB and TPWD, Freshwater Inflows to Texas Bays and Estuaries: Ecological Relationships and Methods for Determination of Needs (Longley, ed. 1994).

Optimization modeling (TXEMP) procedures outlined in the 1994 report (Matsumoto 1994) have been further rigorously refined and applied to the Guadalupe Estuary. Continuing studies since then have resulted in a final calculation of the *minimum FWI target (termed the MinQ flow)* and *maximum harvest FWI (termed MaxH flow)* for this Estuary. The Appendix at the end of this report, compiled by TWDB staff, contains a summary of the TXEMP model constraints and input parameters that were used to determine these final MinQ and MaxH case results. Section 2 of the current report gives a brief overview of the final model output results (ie. inflow and harvest targets) and sensitivity analyses used to validate its operation.

1.1. Objectives

TPWD objectives in this report are to critically evaluate the effectiveness of MinQ and MaxH target inflows predicted from optimization modeling to produce desired seasonal conditions for aquatic biota in the Guadalupe Estuary (see Texas Water Code, Sections 11.1491 & 11.147). If the predicted MaxH conditions actually maintain fisheries production and wetlands habitat at historical levels, then this level can be recommended for management purposes. Alternatively, if MinQ conditions will suffice, then MinQ levels can be recommended. If neither level meets the proposed goal of maintaining historical estuarine biological productivity, then a higher inflow than MaxH should be recommended. This report will describe the protocol and analytical results verifying the proposed target inflow for this estuary.

Chart 2 A.

Determining Freshwater Inflows for a Healthy Estuary

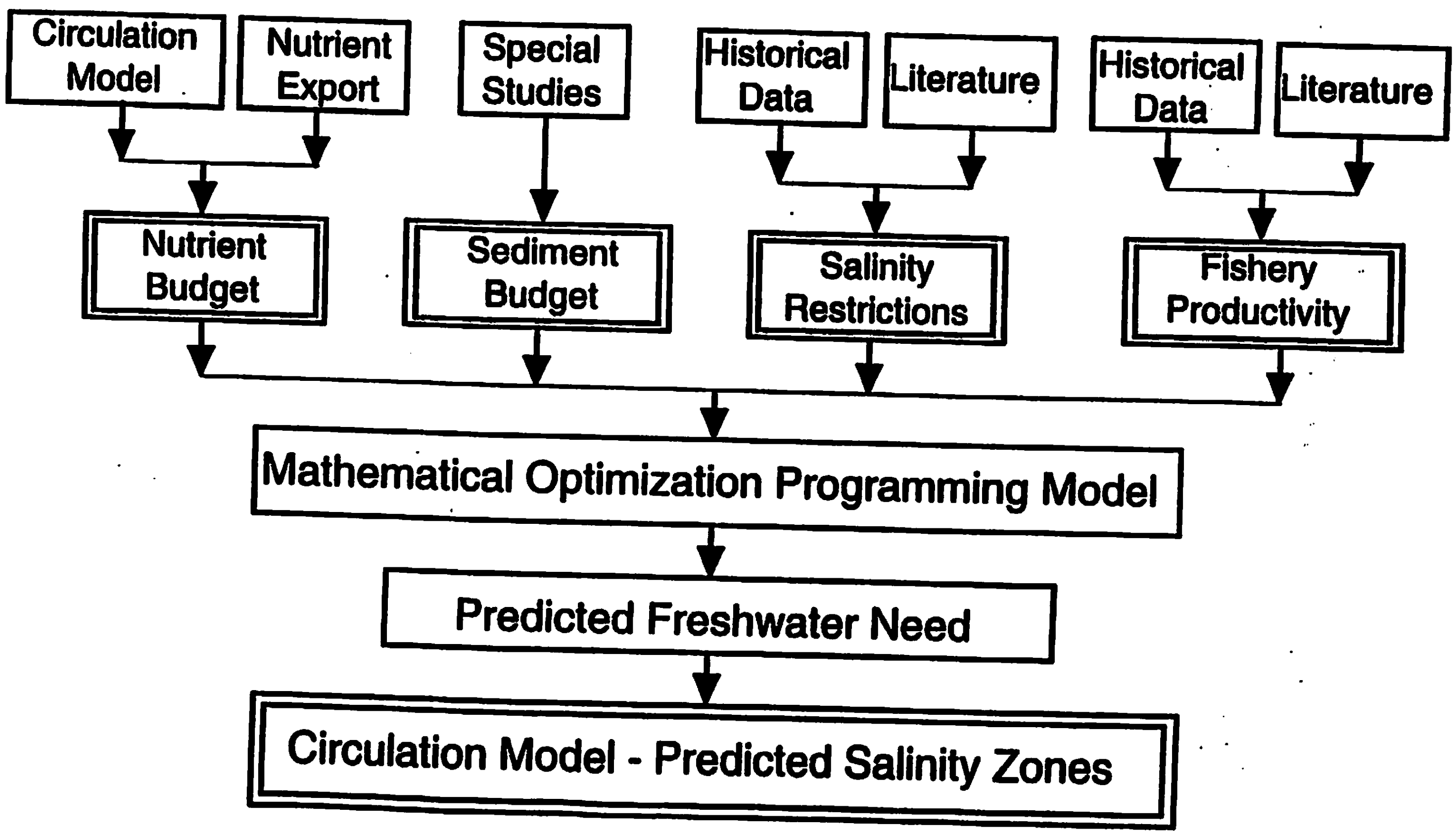
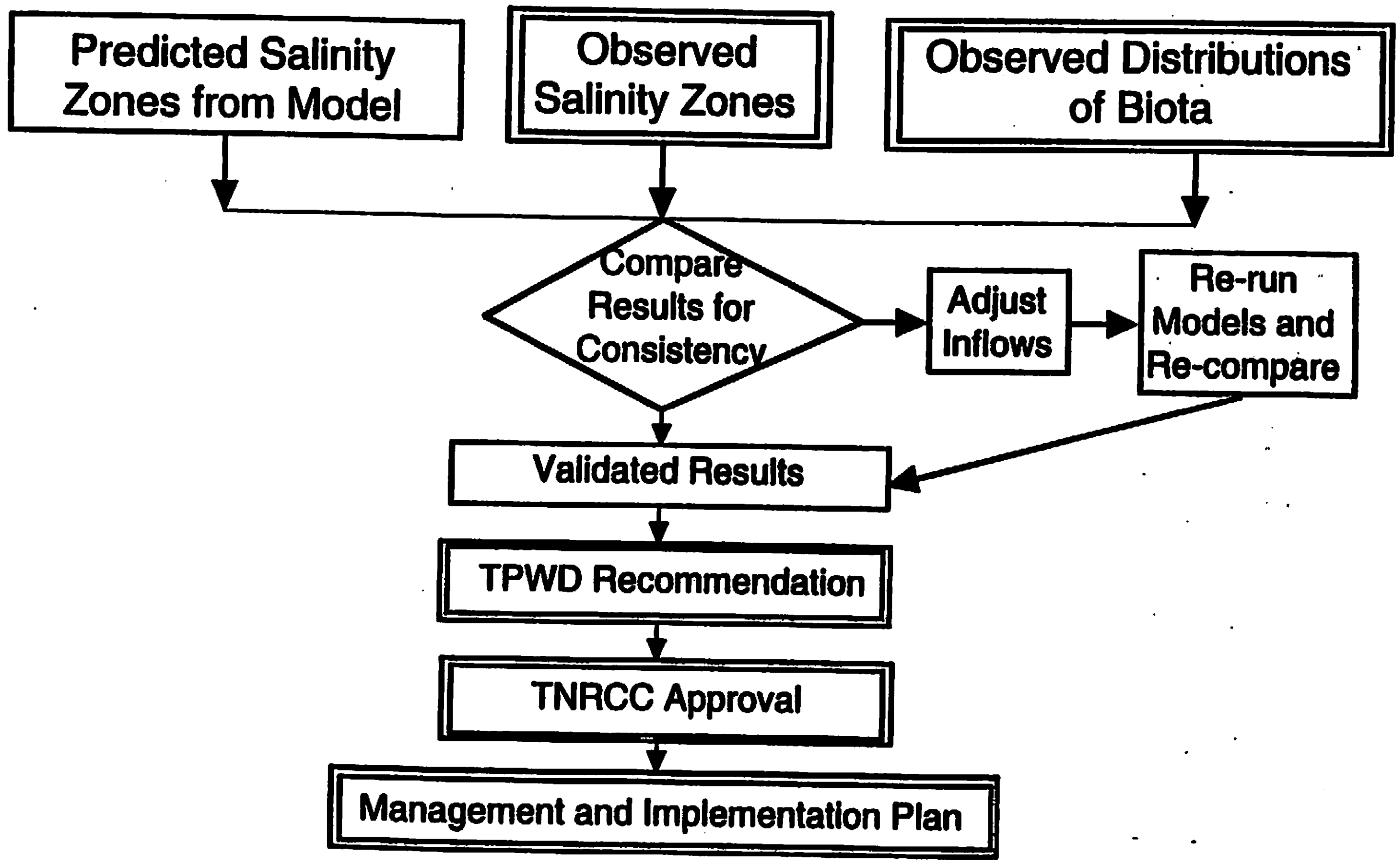


Chart 2 B.

Recommending Freshwater Inflows for a Healthy Estuary



SECTION 2: ANALYTICAL PROCEDURES AND MODELING

2.1. Freshwater Inflow Evaluation Protocol

Sound decisions concerning FWI management must be based on appropriate scientific data and analytical methods. For this purpose, the general protocol outlined in the attached flow diagrams (Charts 2A & 2B) has guided the FWI determination process. Chart 2A indicates the relationships between scientific data sources and the analytical sequence developed by TWDB and TPWD to jointly determine target inflows (**see also Appendix**). Early in this process, optimization and hydrodynamic modeling constitute chiefly predictive techniques used (Matsumoto 1994). Subsequently, work was performed by TPWD to independently validate predicted FWI targets and to develop a FWI recommendation for the Guadalupe Estuary as authorized in the Texas Water Code, Section 11.147 (Chart 2 B). The final step of the protocol indicates that any recommended annual inflow target must then be delivered to the estuary based on a separate management implementation plan. This last step of the procedure requires that TNRCC, TPWD, TWDB, and project sponsors develop a strategy and implementation plan to ensure that the estuary receives the needed fresh water.

This validation phase in the protocol (Chart 2 B) offers a "reality check" to assess previous model predictions. Observed abundances of typical estuarine fishery organisms forms the basis for independently evaluating impacts of the proposed FWI regimes from theoretical modeling. The main part of our report [Section (3)] presents the results of spatial and statistical analyses of long-term fishery survey data collected by TPWD. These data produce an historical picture of the typical habitat and environmental conditions characteristic of the Guadalupe Estuary. When historical trends in species abundance are correlated with corresponding historical salinity gradients, actual responses of bay fishery communities to FWI cycles, for which salinity is a proxy, can be described. By comparing predicted modeling results with actual field sampling data, we can infer whether or not model results are reasonable and appropriate. Based on this empirical assessment, a final FWI recommendation is proposed consistent with TPWD's goal of FWI needed to support an "ecologically sound and productive" Guadalupe Estuary, ie. one whose fishery populations resemble those present over a historical period of record.

2.2. Review of TXEMP Model Results

We begin this report with a brief review of results from the optimization and hydrodynamic modeling. These models rely on a combination of measured field data, mathematical objective functions, and calculated input constraints (Matsumoto 1994). **The Appendix provides supporting details on procedures and datasets used in the modeling, and specifies the input values and constraints for the Guadalupe Estuary analysis.** The Estuarine Mathematical Programming or Optimization Model (TXEMP) uses multiobjective functions, but incorporates statistical uncertainty in the inflow solution. Analytical methods for deriving Salinity or Fishery Harvest vs. Inflow regressions, and the sediment and nutrient constraints, are also described in detail in the Appendix. TXEMP produces a range of predicted, "feasible" solutions that simultaneously predict seasonal (monthly) inflows, and the corresponding estuarine fishery harvests, which are satisfied by the constraints. *The most important result of the optimization process is the delineation of target monthly inflows characteristic of the historical, monthly pattern for the estuary.* Output from the TXEMP model is then used as input to the hydrodynamic circulation model (TXBLEND) which calculates patterns of salinity distributions and bay circulation.

Optimization Model (TXEMP). The TXEMP model generates a performance curve (Matsumoto 1994) that graphically describes how varying amounts of annual inflow affect fishery harvest. Annual inflows are computed by summing monthly amounts estimated by the model. The performance curve (Figure 2.1) is generated by first finding its endpoints, the minimum annual inflow (MinQ) and maximum annual inflow (MaxQ), which satisfy the constraint sets. From the analysis at the 50% statistical probability level, MinQ was found to be 1.03 million acre-ft/year and MaxQ was 1.29 million acre-ft/yr. The monthly distribution of inflows was found by allowing TXEMP to optimize for the maximum possible harvest while limiting inflow to the minimum amount necessary to satisfy the constraint set, distributed in the seasonal pattern most beneficial to the organisms.

In addition, TXEMP was executed to optimize for flows producing maximum fisheries harvest (MaxH) within the range of inflows between MinQ and MaxQ. Intermediate points on the harvest performance curve were generated by limiting the range of possible inflows to narrow intervals to solve for MaxH. The resulting MaxH was determined to be 1.15 million acre-ft/yr. Figure 2.1 graphically presents the performance curve, while Table 2.1 lists the monthly inflow targets for MinQ and MaxH cases. Figure 2.2 is presented to compare the monthly inflow distributions for MinQ and MaxH cases to two important historical cases, viz. the median (50th percentile) and 10th percentile flows. Total and individual species harvests predicted by TXEMP for each inflow scenario are presented in Table 2.2. It is of interest that, despite the small difference between MinQ and MaxH flows (ca 9 %), the difference in total fisheries harvest between the two cases shown in Table 2.2 (2.54 vs. 2.93 million pounds for MinQ vs. MaxH, respectively) was significantly larger (ca 15 %). Substantially higher harvests of blue crab, Eastern oysters, and brown shrimp occurred under the MaxH inflows.

2.3. TXBLEND Summary

The effect of these annual and seasonal inflows predicted by TXEMP were assessed using TXBLEND, the two dimensional, finite element hydrodynamic model that simulates estuarine circulation and predicts salinity patterns resulting from varying freshwater inflow regimes. Two main scenarios were previously simulated in this analysis: MinQ and MaxH inflows at the 50 % probability level. Annual and seasonal (monthly) distributions of inflows predicted by TXEMP were used as input to TXBLEND. Actual tidal and climate conditions for the Estuary measured in 1984 were used as input for both scenarios. The TXBLEND model computes salinity values over 2-hour time-steps at 1241 nodes in the Guadalupe Estuary producing the grid pattern as shown in Figure 2.3. Simulated salinity regimes resulting from each inflow scenario are illustrated by output in two formats:

1. GIS maps were plotted showing salinity isohalines (average monthly salinity) for the estuary for each month.

2. Time series plots were graphed for average daily salinity for 365 days at 5 locations in San Antonio Bay: Seadrift, mid bay, lower bay, near Panther Point, and Lucas Lake.

Table 2.1. Monthly Inflow Needs (in thousands of acre-feet) of Guadalupe Estuary for Two Simulations.

Month	Min Q	Max H
Jan	111.2	111.2
Feb	124.2	124.2
Mar	52.4	52.4
Apr	52.4	52.4
May	186.0	222.6
Jun	136.0	162.7
July	60.8	88.6
Aug	60.8	88.3
Sep	52.4	52.4
Oct	52.4	52.4
Nov	73.8	73.8
Dec	66.2	66.2
Total	1028.8	1147.4

Table 2.2. Predicted Species Landings (in thousands of pounds) under two inflow simulations.

Species	Min Q	Max H
Blue crab	255.5	379.9
Oyster	609.7	702.7
Red Drum	63.8	84.0
Black Drum	32.4	32.4
Spotted Seatrout	113.0	114.8
Brown Shrimp	547.8	704.0
White Shrimp	918.2	910.3
Total Harvest	2540.4	2928.0

SECTION 3: VERIFICATION OF BIOLOGICAL RESPONSES TO HISTORICAL FRESHWATER INFLOWS

Modeling results present a picture of estuarine dynamics suggesting direct response to FWI on a seasonal basis, and indirectly on a total annual basis. If we examine historical sampling data for trends in estuarine fishery dynamics related to FWI, this same seasonal approach must be used. Because most estuarine species demonstrate seasonal abundance in their life cycles, correlations between biological productivity and FWI must consider this seasonality factor. In this next study phase, our analysis of estuarine FWI requirements is based on the hypothesis that historical, seasonal abundance of target fishery species reflects the influence of historical, target FWI needed by the Guadalupe Estuary.

Although estuarine productivity can be assessed by a number of criteria, we used fisheries species abundance, and occurrence of sensitive, rooted wetland plants, as primary indices in our analysis to gauge FWI effects (Boyd and Green 1994, Pulich 1994) If *salinities and other FWI-related factors* satisfy the growth requirements of these sensitive indicator species at key stages in their life cycle, then we may conclude that particular FWI regimes which maintain these salinity and other conditions, are adequate for maintaining the dependent estuarine communities. Two key types of biological analyses were performed using observed field data: 1) Evaluation of the biotic suitability of seasonal salinity zones (ie. the salinity gradient) produced from the hydrodynamic model runs; and 2) Demonstration of correlations between historical abundance of representative fishery organisms and seasonal FWI regimes through its proxy, salinity.

Biological monitoring and sampling data of estuarine fishery species and wetland habitats were obtained from literature sources, TPWD databases, and field surveys by Department staff. For purposes of this report, seven target fishery species, their growth requirements, and environmental tolerance limits were used to assess the adequacy of different FWI regimes. The source of fisheries survey data was the TPWD Coastal Fisheries Resource Monitoring Program which started bay trawl and bag seine surveys in the late 1970's (Kana et al. 1993, Fuls et. al. 1995).

This survey program collects trawl and bag seine samples (at 20 random stations, each gear type) from all Texas bays on a monthly basis, using a fixed 1-mile grid to locate stations. Along with abundance of organisms, salinity and other data are also collected at all sampling sites. The Coastal Fisheries database and its application to describing species' distributions are further discussed in the original Bays and Estuaries Report, Chapters 6 and 7 (Lee 1994, Boyd and Green 1994).

Wetland habitat data consisted of thematic maps prepared by photointerpretation from aerial photography. Oyster reef maps were derived from 1975 studies by TPWD (Coastal Fisheries Division, Rockport, Texas; see Childress et al., 1975), while wetlands were mapped from 1987 NASA high altitude color infrared photography (Pulich 1994). These habitat maps delineate the fixed sites in the estuary which are considered the highest quality, most critical areas for providing food, shelter, and other nursery functions to the aquatic fauna. The most sensitive wetlands for FWI analysis purposes were considered to be the 2,634 ha of brackish marsh and 2,664 ha of intermediate/fresh marsh located in the Guadalupe River Delta region of the estuary, where fresh river inflows generally begin to mix with saline bay waters (see Figures 3.1 - 3.3).

3.1. Effects of MinQ vs. MaxH Salinity Regimes Predicted by TXBLEND Model

Spatial analysis was performed to confirm the effects of predicted salinity regimes from the hydrodynamic model on sensitive wetland habitats and sessile oyster reefs. This model evaluation step involved assessment of biological responses to FWI-dependent salinity conditions at discrete sites in the estuary.

Salinity maps were developed from the TXBLEND model output which consists of a salinity grid at the 1241 nodes throughout the bay (see Fig. 2.3). Geographic information system (GIS) techniques were used to compare these salinity output maps from different inflows. After the hydrodynamic model was run with MaxH or MinQ inflows from the optimization step, salinity zone maps were generated with Arc/Info software by contouring the salinity point data output from each model run. Average monthly salinity values from each of the 1241 grid nodes were subjected to contouring using the TIN module from Arc/Info (ESRI 1992) to produce salinity zones of 5-ppt increments. These salinity contour plots were displayed on a monthly basis; and sample plots for months of June, July, and September are shown in Figures 3.1 to 3.3. For reference, locations of critical brackish wetlands and oyster reefs were also overlaid onto the monthly plots of predicted salinity zones for the two inflow cases.

To contrast the MaxH and MinQ inflows, salinity change analysis was performed by overlaying MinQ and MaxH salinity maps each month. The result of this change analysis is also shown in Figs. 3.1 -3.3 as a salinity difference map (in 1-ppt increments) between MaxH and MinQ. Examination of salinity difference plots indicated that salinity zones were essentially identical (< 1.0 ppt difference) between the two cases from January until May. In May, slightly different salinity patterns (1 ppt) were evident between the two cases in the Upper part of the bay. By June, this same area was now 2 ppt different and the 1 ppt difference area had spread further into the Upper and Middle-to-Lower parts of the Bay (Fig. 3.1). For the MaxH case in June, salinity ranged from 0 - 9.9 ppt near the Upper Bay Delta region, to 10 - 19.9 ppt in the Middle Bay, to 20 - 24.9 ppt in the Lower Bay. For the MinQ case during June, the salinity gradient differed from the MaxH case by 2 ppt near Seadrift in the Upper Bay, and 1 ppt in the Middle Bay area (Fig. 3.1).

By July (Fig. 3.2), salinities were at least 3 ppt different in the Upper bay near Seadrift and the Delta, and the entire Middle Bay was 2 ppt different. It is noteworthy that by July and August, salinity under the MinQ case was between 10 - 14.9 ppt for most of the Upper Bay /Delta area.

The largest actual difference in salinities for the entire year between these two model cases was observed for the month of September (Fig. 3.3). During September, salinity for the MaxH case ranged from 0 - 14.9 ppt in the Upper Bay/Delta region, to 15 - 24.9 ppt in Mid Bay, to 20 - 29.9 ppt in the Lower Bay (Fig. 3.3); while salinity for the MinQ case ranged from 5 - 14.9 ppt in the Upper Bay/Delta, to 15 - 24.9 ppt in the Middle bay, to 25 - 30+ ppt in the Lower Bay. The salinity gradient difference reached a high of 3 ppt near the Delta and Seadrift in the Upper

Bay, all the way down to the Lower Bay regions. A similar analysis of October results indicated decreasing differences in the salinity gradient, such that the largest difference between MinQ and MaxH cases was around 2 ppt in the Middle Bay. In summary, observed differences in seasonal salinity zones between MinQ and MaxH model cases reached significant values (ie. as high as 3 ppt), in the Upper Bay from July through September.

It is most significant that, under the MinQ case, salinities in the Upper Bay region near the Delta will exceed moderately mesohaline values (*ca* 10 - 14.9 ppt) over the July to September period. Stress to sessile wetland vegetation or benthic fauna in this area caused by excessive salinity regimes would be cause for concern. During late spring to early fall, salt-sensitive brackish and oligohaline marsh plants at Upper Bay locations are growing most rapidly and would be most affected by such higher salinities. The peak of the growing season for the aquatic vegetation is precisely during these months when high summer temperatures require inundation of plants with low-brackish salinity (< 10 ppt) water. Loss of habitat can occur if these rooted plants are subjected at this time to increased frequency or duration of inundation with higher salinity waters (see Pulich 1994). Significance of lower salinity regimes for the Delta under MaxH flows are further explained in the following section on time series analysis.

3.2. Time Series Analysis of Salinity and Oyster Growth at Critical Bay Sites

Time-series analyses were performed on the salinity data from the circulation model (TXBLEND) at selected sites in the Bay (Figures 3.4 - 3.5). The analysis objective was to evaluate the effect of the annual inflow predictions from the optimization model, and hence salinity, on the bay biota. Mean daily salinities for several locations were computed from TXBLEND output and were used in the time-series analysis by plotting grand means of the daily means. Salinity criteria for the Upper and Lower Bay, developed as constraints for the optimization model, also bracket the tolerance ranges of important indigenous species. At representative sites in these two bay regions, we used time-series analyses to determine when the salinity constraints would be exceeded (Figures 3.4 - 3.5) using MinQ, MaxH, and 1990 inflow cases. The 1990 scenario was of interest because annual inflows to San Antonio Bay were 1.01 million acre-ft, a quantity of inflow approximately equal to that predicted for MinQ.

Because fisheries harvest equations in the TXEMP model had been developed mostly for motile species, we ran time-series analyses on an important sessile species— the Eastern oyster (Figures 3.7 - 3.8). Simple salinity tolerances were not appropriate for the oyster time-series analysis because its production is so strongly affected by epizootic parasite growth. We used an alternate form of analyses in which interactions between the oyster and its epizootic parasite *(Perkinsus marinus)* are considered (Powell et al. 1992). We evaluated the effect of salinity on the oyster indirectly by comparing the potential for disease at each site. *Perkinsus marinus* has devastated oyster populations of Chesapeake Bay and has been found to control much of the oyster production in Texas estuaries with its prevalence exceeding 60% in nearly all oyster populations (Powell et al. 1994).

Salinity Time Series. Upper Bay sites showed large variations in salinity with season (Figure 3.4). Low salinities occurred most notably in spring and summer in the MaxH and MinQ whereas 1990 inflow cases had the lowest salinites in the summer and late autumn. The Lower Bay nodes remained relatively constant between 20 - 30 ppt throughout the year in all cases (Figure 3.5). Meteorological conditions often caused rapid changes in salinity in the Upper Bay while a radical salinity fluctuation occurred in the 1990 inflow case during July due to rain (Figure 3.4C). This freshet did not affect salinities at Lower Bay sites, suggesting salinities there react to inflow events on a longer time scale than salinities in the Upper Bay (Figure 3.5C). The MinQ case had slightly higher average salinities and exceeded salinity constraints in the Upper and Lower Bay more often than did the MaxH but less often than 1990 inflow cases. During the critical summer months when shrimp and young-of-the-year fish species depend on the estuary for habitat and food resources, the MinQ case exceeded the maximum salinity constraint for 49 days, but only by an average of 1.7 ppt in the Upper bay. The 1990 inflow case exceeds the same constraint for 36 day with a mean exceedance of 2.0 ppt. In both the MinQ and the MaxQ cases freshwater inflow during April and May in combination with bay residence time maintained salinities near or below salinity constraints. In the 1990 case a July freshet reduced salinities during the critical summer months.

Oyster Production and Disease. In this time-series analysis, oyster filtration rates and epizootic growth rate were compared over an annual cycle using MinQ, MaxH, and 1990 inflow cases. The epizootic parasite functions by consuming oyster food reserves, creating a negative energy balance (Powell et al. 1994). As a result, small differences in oyster and parasite relative growth rates alternately allow the oyster to outgrow the parasite or be overcome by the epizootic parasite. Since both salinity and temperature affect oyster and the epizootic *P. marinus* production (Powell et al. 1994), the interplay between temperature and salinity become important to the success of the oyster. Salinity profiles for this analysis were used with a representative annual temperature profile prepared by pooling the data, collected by TWDB (1977-1992) at the Upper Bay node, by Julian day. The resulting time-series data was fit to a fourth degree polynomial (Figure 3.6). Oyster filtering and epizootic growth rates were calculated as described by Powell et al. (1992, 1994).

The time-series of oyster filtering rates and *P. marinus* net specific growth rates were both correlated with seasonal variations in temperature (compare Figure 3.6 to Figures 3.7, 3.8). Whereas slightly elevated growth of the parasite was predicted for the Upper San Antonio Bay site (Figure 3.7), no differences in epizootic growth between MinQ and the other cases occurred at the Mid-San Antonio Bay site where oysters are now most abundant (Figure 3.8). The July freshet in the 1990 case reduced growth of the epizootic parasite and the oyster sharply. The analysis suggests oyster and parasite production would be roughly equivalent for the MinQ, MaxH, and the 1990 inflow cases.

3.3. Concept of Optimal Open-water Habitat and Peak Density Zones for Target Species

GIS spatial analyses were designed to demonstrate the normal affinity of target estuarine species for preferred habitat along the salinity gradient in the San Antonio Bay System. These investigations examined faunal associations with salinity zones in the bay as manifested through geographic patterns of species' relative abundance and peak density. Studies were based on the extensive TPWD Coastal Fisheries Resource Monitoring database (Fuls et al. 1995) and covered the range of inflow conditions from 1982 to 1993. The main analysis focused on spatial correlations between average salinity gradients over this 12-year range and average relative abundance (CPUE) of species in the bay.

We hypothesized that peak density patterns based on the 12-year dataset over a range of conditions would reflect areas of optimal estuarine habitat, where growth and survival of the species were maximized. We recognize that many habitat factors (such as salinity, food, bottom sediment type, vegetative habitat cover, predators, other materials transported by river flows, etc.) are involved in distribution of estuarine species. However, a number of reports emphasize the role of salinity as a major habitat quality determinant in maximum production of estuarine species (Gunter 1967, Kinne 1971, Wolfe et al. 1987, Sheridan et al. 1988, Vernberg and Piyatiratitivorakul 1998). In addition, the salinity gradient can be considered a reasonable proxy for FWI itself. Interactions between salinity and other factors may also occur, leading to autocorrelations with the salinity gradient. If species' distribution patterns correlate with certain estuarine salinity gradients, then we should be able to interpret the distribution in terms of FWI dynamics. Therefore, as a result of the salinity vs.peak abundance relationships derived from our analyses, appropriate FWI regimes needed to produce the peak density patterns were inferred.

Furthermore, our analysis was designed to address the specialized format of the TPWD trawl sample datasets. Previous studies (Green and Lee 1994) have shown that salinity does not have a direct influence on abundance of large, adult finfish collected by gill nets; thus our study focused on the smaller, subadult animals caught in open-bay waters with otter trawls. Since trawl samples are collected monthly from the open bay using a statistical, 1-mile grid sampling design, data can easily be stratified based on salinity zones or other open water factors. This open-water zone, moreover, constitutes different bay habitat from the shallow, shoreline wetlands, and is expected to contain animals of an older life stage compared to the more abundant juvenile stages which concentrate in these shoreline nursery areas (Zimmerman and Minello 1984, Zimmerman et al. 1990).

Seven target species were analysed: white and brown shrimp, blue crab, Gulf menhaden, Atlantic croaker, bay anchovy, and pinfish. These species are representative dominant fishery organisms or ecologically important prey species common in the Guadalupe Estuary based on TPWD Coastal Fisheries Program surveys (Fuls et al. 1995). By performing GIS overlays between trawl sample catch rates and interpolated salinity zones from the Coastal Fisheries database, average abundance of these older organisms found in open waters was related to the corresponding salinity gradient of bay waters.

3.4. Spatial Correlation Analysis of Fauna Distributions and Salinity Zones

Species Abundance. Datasets were developed for the time of year that each species normally occurred in abundance within the bay. Relative abundance of species for the 1982 to 1993 period was calculated by dividing the total catch in trawl samples by the sample time (CPUE) and normalized for 10 minutes. Seasons of high abundance were determined by plotting the average monthly CPUE for a species at all sampling stations in the bay, and examining the monthly abundance pattern graphically. An example of the technique is given in Figure 3.9, which shows the monthly occurrence for blue crab. From this graph, blue crab seasonality within the bay was determined to be January through June. Similar datasets were prepared for the other target species and the resulting times of abundance are listed in Table 3.1. All samples collected at each station during these seasonal periods were then pooled and the average CPUE value at that station was used in subsequent spatial analysis.

Salinity Interpolation Methods. Arc/Info techniques were applied to detect spatial correlations between species' average CPUE during the appropriate season and contoured salinity zones. Salinity zones were also derived from TPWD Coastal Fisheries trawl data in the Arc/Info database. ArcView was used to query the Arc/Info salinity datasets based on time interval and species composition. ArcView scripts in Avenue programming language were developed to

Table 3.1. Target species and seasonal occurrence used for spatial distribution analyses in San Antonio Bay System.

Species	Months of Occurrence	Total Months
White Shrimp	July - December	6
Brown Shrimp	April - September	6
Blue Crab	January - June	6
Atlantic Croaker	February - July	6
Gulf Menhaden	All months	12
Bay Anchovy	All months	12
Pinfish	June - November	6

automate the salinity calculations and to produce summary point files (SPF) by geographic location. Several Arc/Info AML's (Arc Macro Language commands) were initiated through a Remote Procedure Call (RPC) from ArcView to: 1) randomize the SPF data, 2) interpolate SPF data to area estimates, and 3) create polygons.

1.) Randomization of SPF data. Since the Kriging method (see Step 2) requires a set of randomly distributed points, salinity sample values at each fixed sample point were randomly shifted around these point locations within a 200 m zone.

2.) Interpolation of SPF data to area estimates. Interpolation was accomplished using the Kriging method (ESRI 1996). The Kriging program incorporated the SPF point datasets using the gaussian or normal distribution interpolation method. Kriging calculates the semi-variance values for a set of random points with a z value. The semi-variance was then modeled to create a 400 m lattice. A lattice is a surface representation method created by a rectangular array of points spaced at constant intervals relative to a set origin (ESRI 1996) A polygon coverage file comprising the San Antonio Bay system shoreline was used as the interpolation barrier.

3.) Polygon creation. The final polygon product was created by converting the lattice from step 2 to a polygon coverage with the Arc/Info GRID technique (ESRI 1996). Salinity polygon limits were defined by grouping the salinity values in cells into seven salinity zones, namely 0.0-4.9, 5.0-9.9, 10.0-14.9, 15.0-19.9, 20.0-24.9, 25.0-29.9 and ≥ 30 ppt.

4.) Sample CPUE coverages. Mean CPUE's, which were calculated at each sample location, were linked with the location coverage to create a mean CPUE coverage. This CPUE coverage was then overlaid with the salinity polygon coverage to link the CPUE data with the seven salinity zones. The data table was finally related to the original resource table and the data were output into an ASCII file for further statistical analysis. The bay area was normalized to 60,900 ha, and the areas of individual salinity zones were multiplied by an estimated density to give the total species abundance for each salinity zone.

GIS Maps. GIS overlay maps were plotted for each species using the mean CPUE and salinity zone coverages (see Figs. 3.10 - 3.16). These species abundance vs. salinity maps constitute species-specific salinity gradients for the estuary since they were derived from different combinations of months. Two critical data values were calculated from the GIS overlay maps: 1) the percent of total abundance of animals in each salinity zone, and 2) the percent of bay area occupied by that salinity zone. This information was tabulated on each GIS map. Species abundance, salinity zones, and bay area were further correlated graphically for each species (see Figs. 3.17 - 3.23). The numerical statistics for pooled samples associated with the interpolated salinity zones are listed in Table 3.2. Subsequent statistical tests on relationships between salinity zone area and species' relative abundance (CPUE) allowed open-water habitat zones (where peak density occurred) to be derived.

Statistical Analysis. One-way ANOVA was used to determine how species' spatial distributions were significantly associated with the salinity zones. All CPUE data were first log-transformed and then ANOVA assumptions for normality were checked before analysis. If the normality test failed, the non-parametric method, Kruskal-Wallis one-way ANOVA, was employed. Assuming that the null hypothesis was rejected, additional analyses to determine the relationship between salinity and species density were then conducted when three or more groups were involved. The most common method for all pairwise comparisons and for cases with unequal sample size in the different group was Dunn's test (Toothaker 1993). This method computes the Q test statistic which reveals whether or not $p < 0.05$ occurred for each group pair

Table 3.3. Spatial distribution of selected fish and shellfish along the salinity gradient in the San Antonio Bay system. Mean species CPUE's decline from left to right and are grouped by Dunn's multiple comparison procedure. Actual CPUE values for each species are found in Table 3.2., but all species CPUE's were log(CPUE + 1) transformed before the application of one-way ANOVA. Salinity zones underscored by the same segment are not significantly different ($p > 0.05$) in their log-transformed mean CPUE's. Salinity zones are designated as 0 for 0 - 4.9 ppt, 5 for 5 - 9.9 ppt, 10 for 10-14.9 ppt, 15 for 15-19.9 pt, 20 for 20-24.9 ppt, and 25 for 25-29.9 ppt.

Species	Salinity Zones Compared	Zones Excluded*
White shrimp	5 10 15 20 25	0
Brown shrimp	10 15 5 20	0, 25
Blue crab	5 10 15 20 25	0
Atlantic croaker	15 10 5 20	0, 25
Gulf menhaden	15 5 10 20 25	0
Bay anchovy	20 15 25 10 5	0
Pinfish	25 20 15 10 5	0

* Insufficient data - salinity zones with mean sample size < 1/month.

with salinities of 0 to 12 ppt (Copeland and Bechtel, 1974). In San Antonio Bay, Gulf menhaden peak densities were observed in the salinity zones of 5 to 9.9 ppt and 15 to 19.9 ppt. The peak density zones for menhaden averaged 32.7 % of the bay area, and contained about 52.1 % of total menhaden in the bay.

Atlantic croaker: (Fig. 3.21) This species is estuarine dependent and is also considered one of the most abundant species along the Gulf of Mexico and Atlantic coasts (Joseph, 1972). In San Antonio Bay, Atlantic croaker showed a peak density zone (5 to 19.9 ppt) generally similar to that for Gulf menhaden. This zone occupied about 63 % of the bay area, and comprised about 79.2 % of the total population. At salinities higher than the peak density zone value, abundance dropped quickly.

Bay Anchovy: (Fig. 3.22) The anchovy, one of the most abundant estuarine species in the northern Gulf of Mexico, is generally considered euryhaline (Pattillo et al., 1997). In the San Antonio Bay system, bay anchovies were most abundant in the 20 to 24.9 ppt salinity zone, where peak density was also observed. Outside this optimum region, higher densities were found in the polyhaline compared to the oligohaline regions. The zone of peak abundance averaged 32.2 % of the bay area, but accounted for about 45.8 % of the anchovy population in the bay.

Pinfish: (Fig. 3.23) This species, very abundant in estuaries along the Gulf coast, has been reported in salinities as low as 1 ppt and as high as 75 ppt (Hellier, 1962). In San Antonio Bay, peak density occurred in the higher range of salinities (25 to 29.9 ppt), then declined toward the oligohaline zone, opposite to the cases for white and brown shrimps, and blue crab.

Summary Interpretation. Statistical analyses, summarized in Table 3.3, confirmed that both shellfish (brown shrimp, white shrimp and blue crab) and finfish (bay anchovy, Gulf menhaden, Atlantic croaker and pinfish) target species varied in distribution depending on estuarine salinity gradients. Each species showed a significant affinity for a particular salinity zone, defined as the optimum habitat zone(s) with peak density. This zone of highest density (no. per unit area) of animals is not always the same zone as highest animal abundance because of absolute zone area differences. Five species (including white shrimp, brown shrimp, blue crab, Gulf menhaden, and Atlantic croaker) had peak density zones between 5 - 15 ppt, or low to moderate mesohaline.

Although no cause-and-effect relationship has been demonstrated here between salinity and species distribution, the patterns observed should be considered highly significant for those species whose peak densities correlate with low to moderate bay salinities. These preferred lower salinity habitats should be interpreted as reflecting FWI requirements high enough to produce the characteristic salinity gradient. If other habitat factors (eg. food, vegetation, predators, etc.) are autocorrelated with these lower salinities, then they too appear to depend on FWI to maintain the requisite levels. Because this habitat index is based on density (no. animals per area), this model can also be used to determine spatial correlations for other habitat factors when those datasets are available.

3.5. Comparison of Observed Peak Density Zones with MinQ or MaxH Salinity Zones

From the previous analysis of Observed Fisheries Sampling data, we verified that peak densities of some target species are correlated with specific low- to moderate-salinity regimes and, by inference, their corresponding FWI regimes. A further analysis was conducted which compared these Observed Fisheries Density Zones to predicted MinQ or MaxH salinity zones. We attempted to directly compare how effective the predicted MinQ or MaxH inflows were in achieving the salinity of the Observed Density zones. From examination of salinity gradient patterns, the bay area within the peak density salinity zone under MinQ and MaxH inflows was compared to bay area of peak density zones from the Observed Fisheries Sample cases.

Analytical Methods. Salinity gradient maps from the previous Arc/Info GIS analysis, developed by interpolating discrete, observed salinity zones for each species, were compared to salinity maps created by interpolating the MinQ and MaxH predicted salinity data for the same time period. Salinity contours for seven discrete zones were produced using the Arc/Info KRIGING technique as described in the previous section. These GIS plots were then used to calculate percent of bay area occupied by the various salinity zone polygons for the two model cases, MinQ or MaxH, and the Observed Fisheries Sampling data. Based on relative bay area percentages, the suitability of MinQ and MaxH predicted flows for producing the observed, peak density zones was evaluated.

Results. Figures 3.24 to 3.30 compare the Observed Samples salinity gradient for each of the seven target species in relation to MinQ and MaxH modeled salinity gradients. These GIS plots reveal that spatial distributions of observed fisheries salinity zones were generally different for each inflow regime, as would be expected for the unique inflow and tidal circulation patterns occurring in each case. However, the structure of the modeled salinity gradients (in terms of bay area percentages for each of the seven zones) could be expected to resemble the Observed Fisheries Samples cases to some degree. A tabular summary of bay salinity composition (Tables 3.4 - 3.10) provides a direct quantitative comparison of acreage differences between the inflow-dependent salinity zones. Tables 3.4 - 3.10 compare the percentages of bay area for each species falling within the observed samples salinity zones and the MinQ or MaxH salinity zones.

1) White shrimp and blue crab (Tables 3.4 & 3.5) showed the most pronounced positive response, or affinity, for the low mesohaline regions (5 to 9.9 ppt) of the bay. For these two species, MaxH flows produced between 51 to 67 % of bay area within the peak density salinity range compared to the Observed Fisheries Samples case. The reduction in area was smallest for white shrimp (33%), and greatest for blue crab (49%). Min Q flows produced correspondingly less optimal area than MaxH (48 % for both species).

2) Brown shrimp, Atlantic croaker and Gulf menhaden (Tables 3.6 - 3.8) showed distinct affinities for higher mesohaline salinity areas (10 - 19.9 ppt) in the bay, but their density was also high in the low mesohaline zone (5 - 9.9 ppt). For these species, MaxH flows produced substantially less peak density salinity zone area than the Observed Fisheries samples case (range: 46% less for menhaden; 56% less for croaker; and 60% less for brown shrimp). Under MinQ, the reduced optimal habitat zone area was up to 65 % less for brown shrimp.

Table 3.4. Blue Crab GIS statistics comparing observed samples case area with MinQ case and MaxH case areas. Data represent average conditions over the January - June period. Peak density area for 5 – 14.9 ppt zones is indicated in italics.

Salinity Zone (ppt)	Observed Samples Case (% Bay Area)	MinQ Case (% Bay Area)	MaxH Case (% Bay Area)
0 - 4.99	1.5	3.02	3.08
5 - 9.99	***11.38***	***5.95***	***6.92***
10 - 14.99	***17.28***	***7.89***	***7.82***
15 - 19.99	32.52	11.93	12.54
20 - 24.99	27.03	32.11	31.32
25 - 29.99	10.3	8.01	7.80
>30	0.00	31.10	30.51

Total Bay Area = 60,912 ha

Table 3.5. White Shrimp GIS statistics comparing observed samples case area with MinQ case and MaxH case areas. Data represent average conditions over the July - December period. Peak density area for 5 – 9.9 ppt zone is indicated in italics.

Salinity Zone (ppt)	Observed Samples Case (% Bay Area)	MinQ Case (% Bay Area)	MaxH Case (% Bay Area)
0 - 4.99	2.04	1.97	2.49
5 - 9.99	***6.78***	***3.27***	***4.56***
10 - 14.99	12.54	5.85	7.68
15 - 19.99	13.91	9.16	11.27
20 - 24.99	37.78	33.52	34.45
25 - 29.99	26.95	13.37	9.09
>30	0.00	32.87	30.46

Total Bay Area = 60,912 ha

Table 3.6. **Brown Shrimp** GIS statistics comparing observed samples case area with MinQ case and MaxH case areas. Data represent average conditions over the April - September period. Peak density zone areas for 10 – 19.9 ppt zones are indicated in italics.

Salinity Zone (ppt)	Observed Samples Case (% Bay Area)	MinQ Case (% Bay Area)	MaxH Case (% Bay Area)
0 - 4.99	5.12	2.50	2.98
5 - 9.99	7.72	3.90	6.27
10 - 14.99	*19.93*	*7.39*	*7.84*
15 - 19.99	*27.26*	*8.98*	*10.95*
20 - 24.99	34.63	32.82	33.34
25 - 29.99	5.33	11.61	7.72
>30	0.00	32.78	30.91

Total Bay Area = 60,912 ha

Table 3.7. **Gulf Menhaden** GIS statistics comparing observed samples case area with MinQ case and MaxH case areas. Data represent average conditions over the January - December period. Peak density zone areas for 5 – 9.9 ppt and 15 – 19.9 zones are indicated in italics.

Salinity Zone (ppt)	Observed Samples Case (% Bay Area)	MinQ Case (% Bay Area)	MaxH Case (% Bay Area)
0 - 4.99	3.19	2.50	2.78
5 - 9.99	*7.6*	*4.14*	*5.45*
10 - 14.99	14.41	7.50	8.09
15 - 19.99	*25.07*	*9.65*	*12.06*
20 - 24.99	32.22	35.00	32.64
25 - 29.99	17.51	9.25	8.49
>30	0.00	31.95	30.49

Total Bay Area = 60,912 ha

Table 3.8. **Atlantic Croaker GIS statistics comparing observed samples case area with MinQ case and MaxH case areas. Data represent average conditions over the February - July period. Peak density zone areas for 5 – 19.9 ppt zones are indicated in italics.**

Salinity Zone (ppt)	Observed Samples Case (% Bay Area)	MinQ Case (% Bay Area)	MaxH Case (% Bay Area)
0 – 4.99	3.29	2.94	3.25
5 - 9.99	*10.65*	*6.00*	*7.46*
10 - 14.99	*17.99*	*7.81*	*7.82*
15 - 19.99	*34.33*	*10.86*	*12.31*
20 – 24.99	27.66	33.76	32.45
25 – 29.99	6.07	7.65	6.88
>30	0.00	30.98	29.83

Total Bay Area = 60,912 ha

Table 3.9. **Bay Anchovy GIS statistics comparing observed samples case area with MinQ case and MaxH case areas. Data represent average conditions over the January - December period. Peak density zone areas for 20 – 24.9 ppt zone are indicated in italics.**

Salinity Zone (ppt)	Observed Samples Case (% Bay Area)	MinQ Case (% Bay Area)	MaxH Case (% Bay Area)
0 - 4.99	3.19	2.50	2.78
5 - 9.99	7.6	4.14	5.45
10 - 14.99	14.41	7.50	8.09
15 - 19.99	25.07	9.65	12.06
20 - 24.99	*32.22*	*35.00*	*32.64*
25 - 29.99	17.51	9.25	8.49
>30	0.00	31.95	30.49

Total Bay Area = 60,912 ha

Table 3.10. Pinfish GIS statistics comparing observed samples case area with MinQ case and MaxH case areas. Data represent average conditions over the June - November period. Peak density zone areas for 25 – 29.9 ppt zone are indicated in italics.

Salinity Zone (ppt)	Observed Samples Case (% Bay Area)	MinQ Case (% Bay Area)	MaxH Case (% Bay Area)
0 - 4.99	2.48	2.12	2.75
5 - 9.99	7.41	3.54	5.30
10 - 14.99	13.2	6.46	8.05
15 - 19.99	13.07	9.09	11.46
20 - 24.99	43.04	30.17	33.87
25 - 29.99	***20.8***	***16.05***	***8.50***
>30	0.00	32.57	30.07

Total Bay Area = 60,912 ha

3) Bay anchovy and pinfish (Tables 3.9 & 3.10) were species with highest densities in higher salinity zones of the bay around 20 - 29.9 ppt (polyhaline region). Interestingly, bay anchovy revealed good correspondence in bay area within the 20 - 24.9 ppt zone for both MaxH and MinQ case flows (slightly more area for both cases). These results suggest that habitat for these salinity-tolerant species is adequately protected by the modeled freshwater inflows.

Interpretation of Results. Table 3.11 summarizes these quantitative comparisons between Observed Fisheries Samples peak density and corresponding predicted MinQ and MaxH peak density zones. The major implication of these data (Table 3.11) is that, even under MaxH inflows, the area of the mesohaline salinity zones (*ca* 5- 20 ppt) may be reduced compared to the Observed Fisheries samples cases. For all seven species, the percentage correspondence between MaxH and observed fisheries density zones ranged from a low of 40% (brown shrimp) to a high of 101% (bay anchovy). In terms of habitat quantity, this could be a critical limitation for species requiring these lower salinity zones. Because of variable functions supported by low salinity habitats (food, protection from predators, bottom substrate, etc.), MaxH flows appear to offer better protection to the needs of these brackishwater species than MinQ flows. MaxH flows alone may result in some mesohaline zone reductions in the mid to lower bay areas compared to the Observed Fisheries samples case. Thus continuous MaxH flows without occasional flood events could lead to reduced production of these species even though the MaxH flow pattern achieves the maximum harvest on an annual basis.

These GIS overlay analyses document the complexities of FWI contributions to the relative abundance and distribution of bay populations of these target species. Species, which spawn in the nearshore Gulf and migrate back to the bay as larvae (*viz.* shrimp, blue crabs, Gulf menhaden, Atlantic croaker), had a stronger affinity for lower salinity bay areas. In these cases, FWI effects could act directly through salinity preferences and secondarily through other factors such as food or habitat requirements as shown by Zimmerman and Minello (1984) and Zimmerman et al. (1990). Conversely, bay anchovies and pinfish appear tolerant to bay salinities over a broader range. Because their maximum estuarine densities were supported by moderately high salinities, FWI effects appear indirect (perhaps through food supply or habitat), rather than directly through salinity.

Table 3.11. Peak Density Salinity Zone Area of San Antonio Bay System under Three Inflow Regimes.

Target Species	*Peak Density Salinity Zone (ppt)*	*Observed Fisheries Samples Case (% Bay Area)*	*Min Q Case (% Bay Area)*	*Max H Case (% Bay Area)*
White Shrimp	5 - 10	6.8	3.3	4.6
Blue Crab	5 - 15	28.7	13.8	14.7
Brown Shrimp	10 - 20	47.2	16.4	18.8
Gulf Menhaden	5-10, 15-20	32.7	13.8	17.5
Atlantic Croaker	5 - 20	63.0	24.7	27.6
Bay Anchovy	20 - 25	32.2	35.0	32.6
Pinfish	25 - 30	20.8	16.0	8.5

SECTION 4: TARGET INFLOW RECOMMENDATION

Based on these results, TPWD staff recommends that the MaxH inflow (1.15 million ac-ft per yr) be used as the lowest FWI target value which fulfills the biological needs of the Guadalupe Estuary System on a seasonal basis.

The following key biological results are summarized to support the TPWD inflow recommendation:

1) Correlations between target species' 12-year average densities and the low to moderate salinity zones of the bay. Densities of five species (white and brown shrimp, blue crab, Atlantic croaker, and Gulf menhaden) showed significant positive correlations with low or moderate salinity areas (ie. between 5 to 20 ppt). Using salinity as a proxy for freshwater inflows, this is evidence that inflows at least as great as MaxH are needed to provide an optimal salinity gradient for key target species during May through October.

2) GIS overlays and time series analyses of salinity regimes at upper bay sites. These results suggest that MinQ salinities at critical times of the year are on the borderline compared to MaxH salinity regimes for sensitive wetland plant species in upper San Antonio Bay and oyster communities in the middle bay. Salinity zone conditions in Upper and Middle Bay areas are better maintained under MaxH flows than under MinQ flows during the critical period, June through September.

3) Comparison of total fisheries harvest predicted from the optimization model (Table 2.2). The optimization procedure in fact predicts significantly higher (15%) fisheries harvest for the bay under MaxH inflows compared to MinQ levels. The species composition of both the MaxH and MinQ harvests are close to the historical 24-year median harvest, but MaxH supports more blue crab, Eastern oyster, red drum, and brown shrimp harvest. Juvenile crabs, shrimp, and oysters are also ecologically important as food for many other estuarine species.

4) The GIS results from observed fisheries samples vs. modeled salinity zones clearly establish that salinity gradients correlating with peak densities of some target species would be best provided by FWI regimes at least equal to the MaxH case. These GIS results allow us to identify a number of sensitive species (both plants and animals) whose distribution and abundance correlates strongly and positively with the lower salinities (oligohaline and mesohaline) and moderately high nutrient conditions produced where FWI enters the bay.

An inherent weakness with the "probability" approach used in the optimization procedure is also a factor in developing our FWI recommendation. Because salinities are related to freshwater inflow through stochastic regression equations (Matsumoto 1994), the statistical error in the model equations should be recognized and considered. At the 50% probability level used in this analysis, there is only a 50-50 probability that inflows (whether MinQ or MaxH values) will achieve or maintain a certain salinity. Because of this uncertainty associated with salinity-inflow relationships, modeling results based on them should be treated conservatively. Since MinQ is by definition at the lowest allowable part of the performance curve for inflows, this value should be interpreted with caution in any management application. TPWD recommends the more conservative value of MaxH, which has been shown to produce conditions closer to many of the salinity preferences of the target species and wetlands examined in this analysis.

Because timing of FWI is critical to the biological communities and individual species' life cycles, the FWI amount is recommended as a series of seasonal (monthly) inflows. The distribution of flows approximating the historical monthly median pattern provides the most adequate salinity conditions during critical months. A variety of organisms need high flows during the spring months of May and June, while dryer conditions during summer months (July and August) may be expected naturally and can be tolerated if the estuary is prepared by earlier inflows. Although it is not readily evident from the optimization model output, the historical hydrologic record often exhibits higher flows during September and October. This is due to the occurrence of early fall rains, tropical storms, and hurricanes. Accordingly, these higher fall flows will occasionally occur and should be given due consideration in all management scenarios.

Although the recommended target inflow is 1.15 million acre-feet per year, it is important to realize that inflow to the Guadalupe Estuary, like most Texas estuaries, is highly variable. Examination of the hydrologic record (Figure 4.1) reveals that, during the past 47 year record, the Guadalupe Estuary has received greater than the median annual inflows of 2.1 million acre-feet at least 50% of the years. Only 23% of these years had less than the 1.15 million acre-feet target amount for MaxH, which is substantially lower than the median inflow of 2.1 million acre-feet. When considered in this perspective, the MinQ flow of 1.03 million-acre feet can be judged as being significantly more infrequent, occurring in less than about 15 % of years. The higher MaxH flows, which only occur in about 23% of years, would be particularly important in loading the system with nutrient and sediment reserves needed during lower-flow years. **Thus, TPWD strongly recommends that water management programs retain these occasional higher inflows, particularly above the target level, because they are critical to maintaining the biological productivity and ecological health of this Estuary.**

SECTION 5: IMPLEMENTATION OF TARGET FRESHWATER INFLOWS FOR MANAGEMENT PURPOSES

5.1. Philosophy for Shared Use of Water at Low Flow Levels

The long term, annual FWI amount estimated to adequately meet the biological needs of the Guadalupe Estuary system is 1.15 million ac-ft per year (MaxH). However, during drought conditions, inflows would be much lower than the minimum threshold level of 1.03 million ac-ft per year (MinQ) (Fig. 4.1). At these lower subsistence inflows, biological productivity and fisheries harvest would be expected to greatly decrease. During the drought of the 1950s, oyster and white shrimp production crashed and other estuarine species suffered physical trauma as a result of widespread, chronically high salinities caused by drastically reduced inflows (Copeland 1966).

Management of river flows to supply target inflows to the estuary would obviously be dependent upon the availability of river inflows and return flows. When available flows in the river are lower than the recommended threshold amount due to hydrologic drought, flows to the estuary would decrease correspondingly. Under these reduced riverflow management conditions, however, the <u>frequency of reduced bay inflow levels</u> should not be increased beyond historical occurences. The main concept implied in these biological "target" definitions is that when sufficient river flows do occur, then the estuary should receive the full recommended amount prior to any new diversion being approved. The challenge is to develop watershed management programs that provide target and lower flows at almost the same frequency at which they occurred in the past and retain as much historical variability at higher flows as possible. Drought contingency measures should be formulated to ensure that environmental needs are balanced with human needs when water supplies become limited.

5.2. Biological Effects during Critical Inflow Shortage

There have been, and will continue to occasionally be, times when nature does not provide the water to meet the recommended MinQ or MaxH inflows to San Antonio Bay. The biological effects of these reduced inflows on the Guadalupe Estuary fisheries productivity and biodiversity are examined here. Maintenance of productivity of economically important and ecologically characteristic sport or commercial fish and shellfish species and the food webs that support them are goals identified in Texas Water Code Section 11.147(a). The freshwater inflow targets presented in this document are designed to meet the requirements for beneficial inflows as described in Texas Water Code Section 11.147(a). A major concern of TPWD is that an increase in severity, frequency, or duration of drought flows will alter the ecosystem structure by either reducing overall fisheries production or by favoring one fisheries species production at the expense of others, thereby reducing biodiversity.

We examined the effect of reduced inflows on productivity by reducing the harvest target input for the TxEMP optimization model from the standard 80 percent of the mean historical harvest gradually down to 75, 70, 60, and 50 % of the mean historical harvest, while also removing the preset biomass ratio constraints. The biomass ratio constraints were implemented to maintain the relative composition of species making up the total harvest. The optimization results with reduced harvest targets of 75, 70, 60, and 50 % predicted annual inflow targets of 0.86, 0.82, 0.79 and 0.76 million acre-feet per year, respectively. The latter value, 0.76 million acre-feet per year, is also equivalent to the 10th percentile annual inflow to the Guadalupe Estuary (Figure 4.1). For the period 1941 - 1987, there were only 5 years with less flow than 0.76 million acre-feet: 1954, 1955, 1956, 1963 and 1984.

While the TxEMP model results examining the effect of reduced inflows on productivity suggest that differences in total productivity are small, changes in species composition and production are significantly different than the accepted MinQ case. This is expected since the biomass ratio constraints are designed to preserve the relative composition of species making up the total harvest. For example, the scenario that assumes a 75% mean historic harvest target with the biomass ratio constraints removed (MinQ75H), violates the accepted biomass ratio constraints (Fig. 5.2A) and results in a significant increase in oyster production at the expense of red drum, spotted seatrout, blue crab, brown shrimp and white shrimp (Fig. 5.2B).

Examination of time-series output from the TxBLEND hydrodynamic model provides some explanation for the increases in predicted oyster harvest and concomitant reductions in other species predicted for inflows less than MinQ. In the reduced inflow cases mid-bay salinities are violated by 1.4 to 2.5 ppt between 60 and 80 days during the critical summer period in which young-of-the-year are developing (Fig 5.3). Oysters which are most prevalent in this area of the bay have relatively high salinity tolerances and would be expected to do well initially under these conditions. However, prolonged periods of high salinity would tend to be stressful to other species that depend on the oysters and would be conducive to parasites (*P. marinus*) and oyster drills (*Thais hemastoma*) that prey on oysters (Powell et al. 1994), eventually resulting in reductions in oyster productivity. In addition *P. marinus* will spread more rapidly at high oyster population densities (Powell et al. 1994), whereas low population densities reduce the rate of infection and subsequently reduce large variations in abundance due to disease. Prolonged periods of high salinity would also tend to be stressful to other species such as blue crab and white shrimp. In contrast, under the MinQ (Fig. 5.4B) oyster production was maintained in mid-bay, yet salinity constraints for other important fisheries that use oysters and associated macrofauna as food resources are not violated.

In the reduced inflow cases, upper bay salinities are as much as 10 ppt greater during critical summer periods than would have occurred under MinQ conditions (compare Fig 5.4B and 5.5) although the magnitude of the salinity constraint exceedance is small (0.4 to 1.3 ppt.). These waters are contiguous with the brackish marsh surrounding Lucas Lake, where bulrush, common reed, and marsh cordgrass vegetation occur which could be impacted at this high end.

Total fishery productivity will remain about the same under reduced inflow but the productivity of some important species will be reduced. These sensitive fisheries will be impacted by increased salinities during critical summer periods in which young-of-the-year are being recruited into the bay fisheries populations.

5.3. Implementation Strategies

Drought, especially long term severe drought, and its effects on the environment, cannot be completely avoided. What can be and should be avoided are the adverse environmental effects due to human-induced increases in the magnitude and duration of naturally occurring droughts. Threats to fish and wildlife resources are compounded by multiple factors. Reduced streamflows due to reduced runoff and reservoir releases coupled with the full diversion of authorized water in fully or overappropriated basins, likely to occur during times of drought, would stress fish and wildlife resources in State waters.

The TNRCC lists portions of the following river basins that are fully appropriated: Colorado (all); Rio Grande (all): Canadian; Red; Cypress; Sabine; Neches; Trinity; Brazos; Guadalupe; and Nueces River Basins. Clearly, there is a need to develop an equitable system for maintaining water for the environment while allowing other beneficial uses to occur and economic activity to continue.

Management of freshwater inflow requirements should be an integrated basin-wide effort. The establishment of estuarine advisory councils for each principal bay and estuary is supported by Texas Water Code Section 11.1491 subsection (b). Representatives of TNRCC, TPWD and TWDB as well as from the Texas Department of Health, General Land Office, commercial fishing groups, conservation groups, and water suppliers are to make up each advisory council. The advisory councils may develop recommendations regarding alternative water management methods that may be used in maintaining the sound environment of the bays and estuaries.

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Appendix

Values and Constraints for the TXEMP Model

Used in the Freshwater Inflow Analysis

of the Guadalupe Estuary

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

Values and constraints for the TXEMP mathematical programming model were included for salinity conditions in the estuary, historical harvest (productivity) values, freshwater inflows, ratios of biomasses of individual species, nutrient loading, sediment loading, salinity-inflow equations, and harvest-inflow equations. All of the values and constraints were based upon historical data collected in the estuary or in the rivers flowing to the estuary and are consistent with requirements in TEXAS WATER CODE 11.147, for maintenance of beneficial inflows to maintain the productivity of fish and shellfish and the estuarine life on which they depend. Use of the values and constraints in the TXEMP mathematical programming model generally follows the procedures described in sections 8.1 and 8.2 of Longley (ed.) (1994).

SALINITY

Salinity zones. Three salinity zones (Solis 1994, page 35) were defined for the model. They included an area in upper San Antonio Bay adjacent to Seadrift, an area in lower mid San Antonio Bay southeast of the Intracoastal Waterway, and an area in mid Espiritu Santo Bay.

Data. Salinity data were taken from the Texas Water Development Board (TWDB) Coastal Data System and Bay and Estuary Datasonde programs, Texas Parks and Wildlife Department (TPWD) Fishery Resource Monitoring Program, Texas Natural Resource Conservation Commission (TNRCC) Statewide Monitoring Network, and Texas Department of Health Shellfish Sanitation Monitoring Program. Data were reported in parts per thousand (ppt). All data before November 1986 and some data after that date came from single measurements taken at various times throughout the year. Beginning in late 1986, ambient water quality data were collected *in situ* with automated instruments (Hydrolab Datasondes) that were left in the bay for a period of approximately one month. The Datasondes took measurements every 1 to 1.5 hours while they were deployed. To keep Datasonde data from overly influencing the less-frequently collected historical single-measurement data, Datasonde data for seven-day periods were summed to provide a single value for each period. The period of record for data used to determine salinity zone bounds was 1967 until 1994 and included a large number of data points: Seadrift (n = 549), lower San Antonio Bay (n = 266), and Espiritu Santo Bay (n = 345).

Salinity bounds. Several approaches were taken in selecting the salinity bounds. Monthly frequency distributions of the salinity measurements were examined for each zone. They provided information about historical ranges of salinities in each month. Of particular interest were the monthly 25th and 75th percentiles since salinities between these values represent half of the measurements that fall in the middle range of salinity values for the zone. Biotic salinity limits for major estuarine plant and animal species from scientific literature and reports were also reviewed. A recent compilation of this information is contained in tables 5.2.2 and 6.7.3 of Longley (1994). Information about salinity bounds that were set for the Nueces Estuary by the Nueces Estuary Advisory Council was also evaluated. Using the aforementioned information, the bounds for this analysis were selected by staff of the TWDB and TPWD, and are presented in the tables below. In most instances, the lower bounds were set below the 25th percentile of the historical salinity. Where the lower bound was above the 25th percentile, the differences in salinity between the bound and the 25th percentile were less than 3 ppt. In general, the upper bounds were set above the 75th percentile of the historical salinity.

Upper San Antonio Bay:

Month	Lower Salinity Bound	Upper Salinity Bound
Jan	5.0	20.0
Feb	5.0	20.0
Mar	5.0	20.0
Apr	5.0	20.0
May	1.0	15.0
Jun	1.0	15.0
Jul	1.0	15.0
Aug	1.0	15.0
Sep	5.0	20.0
Oct	5.0	20.0
Nov	5.0	20.0
Dec	5.0	20.0

Lower Mid San Antonio Bay:

Month	Lower Salinity Bound	Upper Salinity Bound
Jan	5.0	25.0
Feb	5.0	25.0
Mar	5.0	25.0
Apr	5.0	25.0
May	5.0	25.0
Jun	5.0	25.0
July	5.0	25.0
Aug	5.0	25.0
Sep	5.0	25.0
Oct	5.0	25.0
Nov	5.0	25.0
Dec	5.0	25.0

Espiritu Santo Bay:

Month	Lower Salinity Bound	Upper Salinity Bound
Jan	10.0	40.0
Feb	10.0	40.0
Mar	10.0	40.0
Apr	10.0	40.0
May	10.0	40.0
Jun	10.0	40.0
July	10.0	40.0
Aug	10.0	40.0
Sep	10.0	40.0
Oct	10.0	40.0
Nov	10.0	40.0
Dec	10.0	40.0

<u>Salinity chance constraint bounds.</u> 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 the analysis, the salinity chance constraints for the lower and upper salinity bounds were set to 50% at all three sites.

HARVEST

Data. Data for blue crab, eastern oyster, red drum, black drum, and spotted seatrout were taken from *Texas Landings*, a cooperative publication of TPWD and the U.S. Department of the Interior (USDOI) for the years 1963 to 1969 and 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. The data on brown and white shrimp comes from *Gulf Coast Shrimp Data*, published by the USDOI for 1960 to 1969 and by the USDOC for 1970 to 1978. Thereafter, the brown and white shrimp data were taken from the National Marine Fisheries Service Gulf Coast Shrimp Data Base.

Harvest targets and historical values. Periods for calculation of mean harvests and harvest targets were: 1962 to 1980 for red drum and spotted seatrout; 1962 to 1987 for black drum, blue crab, and eastern oyster; and 1959 to 1987 for brown and white shrimp. In the table below the harvest of blue crab and oysters are meats only; for blue crab, meats were estimated to be 15% of the whole animal weight reported in the harvest records. The Harvest Targets, used in the TXEMP model, were set to no less than 80% of the mean historical harvests for each species harvested.

Species	Thousand pounds of harvest			
	Minimum	Maximum	Mean	Target (80% of mean)
Blue crab	41.4	716.4	240.2	192.2
Eastern oyster	53.9	1937.2	433.2	346.5
Red drum	24.4	179.2	77.0	61.6
Black drum	0.4	131.0	40.5	32.4
Spotted seatrout	12.2	114.8	56.7	45.4
Brown shrimp	67.1	1830.2	572.0	457.6
White shrimp	241.8	1415.0	780.6	624.5

Harvest chance constraint bounds. The harvest chance constraint is the minimum probability that the calculated harvest equals or exceeds the harvest target. For the analysis, the harvest chance constraint was set to 50%.

INFLOWS

Data. The inflow bounds in the analysis represent statistical measures of the combined flow of all runoff from the land to the estuary for the period 01/1941 to 12/1987. Combined flow is the sum of the gaged and ungaged flow. Gaged flow is the measured flow at the last U.S. Geological Survey (USGS) stream gage on a river that flows toward the estuary. For the Guadalupe Estuary, the records of four gages contributed to the gaged record: San Antonio River at Goliad (USGS Station No. 8188500, 01/1941 to 12/1987); Guadalupe River at Victoria (USGS Station No. 8176500, 01/1941 to 12/1987); Coleto Creek near Schroeder (USGS Station No. 8177000, 10/1952 to 6/1978); and Coleto Creek near Victoria (USGS Station No. 8177500, 01/1941 to 09/1952 and 07/1978 to 12/1987).

Ungaged flow is the runoff from the land that occurs below USGS stream gages and is not measured by the gages. It is determined from three hydrologic components: modeled runoff for the areas below the gages (simulated using TXRR, a calibrated rainfall-runoff model); return flow from discharges below the gages to rivers, streams, or estuaries; and diversions of freshwater below the gages from rivers and streams. The data used to simulate modeled flows were daily precipitation data from the National Weather Service and other precipitation stations operated by the TWDB. Precipitation was distributed on a watershed basis through use of a Thiessen network for allocating precipitation to specific watershed areas. The return flow and diversion values came from records of measured and estimated flows for the Self-reporting Wastewater Discharge and Water Use data bases that are managed by the Texas Natural Resource Conservation Commission (TNRCC). Ungaged flow was calculated by adding the modeled runoff and the return flow, and subtracting the diversions. Gaged and modeled flows are in units of acre-ft/day while diversions and return flows are in units of acre-ft/month. Combined flows are in units of acre-ft/day and include daily diversions and return flows as monthly values divided by the number of days in each month.

Three different sets of flow bounds were defined to constrain the solution. Monthly flow bounds limited the flow in any monthly period. Seasonal bounds were based on 2-month seasons, to correspond to the 2-month seasonal periods used with the harvest equations. Annual bounds were used to limit flows on an annual basis. All bounds were based on combined (gaged plus ungaged) inflow statistics for the 47-year period 1941 to 1987.

Monthly upper and lower inflow bounds. The lower bound for monthly inflow was set to the 10th percentile flows for the month. The upper bound was set to the median inflow for the month. Thus, in no month would the inflow requirements calculated by the TXEMP model exceed the median inflow for that month, based on 1941-1987 historical data.

Month	Thousands of acre-ft/month Lower monthly inflow bound	Upper monthly inflow bound
Jan	33.9	111.2
Feb	46.2	124.2
Mar	43.0	117.5
Apr	42.2	110.5
May	61.0	222.6
Jun	36.2	162.7
Jul	22.3	95.2
Aug	18.5	94.9
Sep	38.5	139.4
Oct	42.7	138.4
Nov	33.1	116.1
Dec	38.5	104.1

Seasonal (2-month) upper and lower inflow bounds. The bounds for the bimonthly flows, on which the harvest regressions are based, were set to values close to the sum of the monthly flow bounds for any pair of months. In the table below, the sum of the January and February lower bounds totaled 80.1 thousand acre-ft; the sum of the upper bounds totaled 235.4 thousand acre-ft. The January-February seasonal lower bound was set to a value slightly lower than the sum of the monthly bounds (75 thousand acre-ft); the January-February seasonal upper bound was set to a value slightly higher than the sum of the monthly upper bounds (300 thousand acre-ft). The reason for extending the seasonal bounds slightly outside the range of the two-month sums was to allow the TXEMP model to have plenty of maneuvering room to search for an optimal solution.

Month	Thousands of acre-ft/month Sum of monthly lower bounds	Sum of monthly upper bounds	Seasonal lower bound	Seasonal upper bound
Jan-Feb	80.1	235.4	75.0	300.0
Mar-Apr	85.2	228.0	80.0	300.0
May-Jun	97.2	385.3	90.0	400.0
Jul-Aug	40.8	190.1	36.0	200.0
Sep-Oct	81.2	277.8	75.0	300.0
Nov-Dec	71.6	220.2	70.0	300.0

Annual (12-month) upper and lower inflow bounds. Annual lower and upper flow bounds were used in an operational manner to calculate performance curves over a wide range of flows. Calculation of local maxima is a problem in optimization analysis that can result in false estimates of the true maximum harvests. This problem can be avoided by bounding the annual flow solutions to narrow ranges and then performing a number of optimization runs that incrementally span the flow range of interest. The smallest annual lower bound used was 200,000 acre-ft per year while the largest upper bound used 2.2 million acre-ft. For any particular run of the model, the annual upper bound was usually set to the annual lower bound plus 200,000 acre-ft. The model was run 10 or more times, incrementing the lower and upper bounds on each run. The results of the individual runs were then combined into a single performance curve.

BIOMASS RATIOS

The original TXEMP model permitted harvest equations to be weighted for individual species in the calculation of the objective function. This allowed control of the relative importance of any individual harvest equation in the optimization routine. If the weighting for an equation were set to zero, the equation would not contribute to the harvest included in the objective function and the optimization results would be independent of that species' contribution to harvest. Likewise, a species' harvest equation could be weighted so it contributed more to the harvest of the objective function than another species' equation. It was originally thought this would be a convenient way to allow different management options to be tried. However, the nonlinear nature of the equations occasionally resulted in harvest amounts for some species beyond levels historically observed. To counteract this unrealistic tendency with low inflows, a new constraint was added as a refinement to the optimization routine to ensure that the harvest of any species compared to the total harvest of all species fell within the bounds of a defined range. This constraint was called the biomass or harvest ratio and was based upon historical biomass or harvest data from the estuary. In essence, this constraint assured that the relative harvests of species from the optimization model fell within ranges that have been observed for the estuary. The constraint avoids the problem of having the model calculate a solution that provides exceptionally abundant harvest for one or two species to the detriment of all the others.

Data. Two sources of data were used to calculate biomass or harvest ratios. Bag seine data from TPWD (Coastal Fisheries Monitoring Program) provided annual biomass estimates of the target species for the period 1977 to 1990 for biomass ratios. Commercial harvest data for 1962 to 1981 (excluding 1968) provided harvest data for all species for harvest ratios. There is a conceptual difference between biomass and harvest ratios. Biomass ratio is an estimate of the average proportion of the standing crop of the target species in the estuary that is attributable to any one of the species. Harvest ratio is an estimate of the average proportion of the harvest or production of one species compared to the total harvest, where harvest is the amount of biomass harvested per unit of time. The two ratios are only comparable if the rates of secondary production, mortality, and harvest per mass of the individual are approximately equal among the species

Sampling for the TPWD Fisheries Monitoring Program was carried out according to a random, stratified, sampling methodology; statistical measures of biomass from this sampling procedure are thought to be unbiased estimates of the standing crop of the target species in the estuary. Harvest values come from commercial landings data and lack the statistical rigor of the Fisheries Monitoring Program data base. Of the two types of ratios, harvest is the more appropriate for a constraint since the optimization model calculates harvest (biomass collected per unit time) rather than standing crop (biomass). A comparison of the mean biomass and harvest ratios is presented below.

Species	Biomass ratio	Harvest ratio
Blue crab (meat)	0.16	0.11
Eastern oyster (meat)	0.14	0.15
Red drum	0.06	0.04
Black drum	0.02	0.03
Spotted seatrout	0.04	0.03
Brown shrimp	0.26	0.20
White shrimp	0.32	0.44

Even though biomass and harvest ratios differ conceptually, the table shows that the calculated values for the ratios are very similar. Because the values of the ratios were so similar, the decision was made to use the biomass ratio values in the constraints since there was high confidence that the sampling methods produced accurate ratio values for the estuary.

__Biomass ratio bounds.__ Several different methods were considered in setting upper and lower bounds including use of minimum and maximum ratios actually measured over the period of record, and a statistical ratio. A decision was made to base the lower and upper bounds on the mean biomass plus or minus three standard errors since the period of record extended only 14 years and the statistical characteristics of standard errors are well known. One problem encountered using this formulation was that the lower bound for the three fish species—red drum, black drum, and spotted seatrout—resulted in biomass ratios less than 0. For these species, the lower bounds were set to 0.

Species	Biomass Ratio Lower bound	Upper bound
Blue crab	0.06	0.26
Eastern oyster	0.04	0.24
Red drum	0.00	0.16
Black drum	0.00	0.11
Spotted seatrout	0.00	0.14
Brown shrimp	0.16	0.36
White shrimp	0.22	0.42

Since the decision was made to use biomass ratios to assure realistic results, the weights for all seven harvest equations were set to 1.

NUTRIENT CONSTRAINT

The nutrient constraint is based on the requirements of the estuary for nutrient loading. Whitledge (1989) determined that nitrogen is the macronutrient most likely to potentially limit primary production in the Guadalupe Estuary. From an analysis of nutrient budgets, Brock (1994) was able to relate the total nitrogen budget for the estuary to freshwater inflows in a wet year and a dry year. His preliminary analysis revealed that an annual inflow of at least 286,000 acre-ft per year was needed to provide an input of nutrients that balanced the losses to adjacent estuaries.

This analysis assumed that current nutrient loading rates would continue into the future. In a further analysis, Brock (1995) refined the nutrient budget and assessed the inflow requirements for nitrogen for the case of the nutrient constraint reflecting premodern stream nitrogen concentrations. He noted that modern flow-weighted nitrogen loading is 2.33 mg/l N as the result of upstream anthropogenic activities while premodern levels are on the order of 0.9 mg/l N. Using this reduced loading rate and making some additional adjustments allowed preparation of a nutrient budget with stream loadings consistent with water quality improvements. A nutrient constraint reflecting more natural levels of nutrient loading would require 860,000 acre-ft of combined inflow each year. This amount of inflow would be needed to offset the nutrient losses from export to the Gulf and adjacent estuaries, denitrification, burial in the sediment, and fisheries migration and harvest. An arbitrarily high upper bound was set for the calculation since only the lower bound was of interest in TXEMP model operation.

SEDIMENT CONSTRAINT

The sediment constraint is based on the requirements for sediment to maintain deltaic and shallow-water habitats in the upper areas of the Guadalupe Estuary. The Guadalupe River transports suspended sediment from the Guadalupe and San Antonio river basins to the estuary. A portion of the suspended sediment is deposited in the habitats around the Guadalupe Delta, although most is transported by river flow and estuarine circulation to other areas of the bay, or to the Gulf. Due to world-wide (eustatic) sea level rise and local compaction of recently deposited sediment, there is a slow sea-level rise in the coastal region of the state. The rate of relative sea-level rise has been measured at the Colorado River Delta (80 km east of the Guadalupe Delta) at 8 mm/yr.

Using that value for annual sea-level rise, Longley and Malstaff (1994) determined the quantity of sediment required to be deposited in the lower Guadalupe Delta to offset the effects of relative sea-level rise. With measured values of gaged flow and sediment load collected by the TWDB over the period 1935 through 1965, and information on the change in depth of Mission Lake, they were able to determine that 21% of the sediment transported to Mission Lake by the Guadalupe River was deposited there. This information, along with data about bulk density of the delta sediment and area of Mission Lake, allowed them to determine that an annual gaged inflow of 355,235 acre-ft/yr was needed to provide enough suspended sediment to offset the effects of relative sea-level rise and maintain the elevation of habitats of the Traylor Cut delta and Mission Lake bay bottom. On average, 80.85% of the combined inflow to the estuary is from gaged flow, so the lower bound of this sediment constraint is 439,375 acre-ft/yr of combined inflow. Only the lower bound is of interest in the analysis so the upper bound was set arbitrarily high.

SALINITY-INFLOW EQUATIONS

Salinity data for the period 1967 through 1987 were used to prepare the salinity-inflow equations. Salinity data after 1987 were not used since hydrology data for the Guadalupe Estuary were unavailable after 1987. The salinity and hydrology data sets were filtered to remove some values associated with very high flows, and final data sets were used to create salinity regression equations based on a substantial number of points: Seadrift ($n = 263$), lower mid San Antonio Bay ($n = 168$), and Espiritu Santo Bay ($n = 219$). In the equations below, S is salinity in ppt, Q is the monthly combined inflow in acre-ft, and ln is the natural logarithm function.

Upper San Antonio Bay: $S = 47.14764 - 7.82469 * \ln(Q)$

Lower mid San Antonio Bay: $S = 53.83083 - 7.28188 * \ln(Q)$

Espiritu Santo Bay: $S = 42.28531 - 3.45241 * \ln(Q)$

HARVEST-INFLOW EQUATIONS

Harvest and inflow data described above were used to prepare the harvest-inflow equations. In the equations below, H is annual harvest in thousands of pounds per year, Q_P is the sum of inflows for a two-month period in acre-ft (P = JF for January-February, MA for March-April, MJ for May-June, JA for July-August, SO for September-October, and ND for November-December), and ln is the natural logarithm function.

Blue crab: $H = 110.64 - 145.3 * \ln(Q_{JF}) + 332.5 * \ln(Q_{JA}) - 141.4 * \ln(Q_{SO})$

Eastern oyster: $H = 3000.7 + 180.4 * \ln(Q_{MA}) - 963.3 * \ln(Q_{MJ}) + 710.0 * \ln(Q_{JA}) - 231.5 * \ln(Q_{SO})$

Red drum: $H = 32.786 + 0.0797 * Q_{MJ} + 0.2750 * Q_{JA} - 0.2010 * Q_{ND}$

Black drum: $H = -18.087 + 0.2411 * Q_{JF} - 0.1734 * Q_{MA} + 0.0850 * Q_{ND}$

Spotted seatrout: $\ln(H) = 2.6915 - 0.7185 * \ln(Q_{MA}) + 1.860 * \ln(Q_{MJ}) - 1.086 * \ln(Q_{ND})$

Brown shrimp: $\ln(H) = 6.5679 + 0.6707 * \ln(Q_{JA}) - 0.7486 * \ln(Q_{SO})$

White shrimp: $H = 545.59 + 160.9 * \ln(Q_{JF}) + 279.1 * \ln(Q_{MJ}) - 155.1 * \ln(Q_{JA}) - 277.9 * \ln(Q_{ND})$

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FIGURES

Figure 2.1. TxEMP MODEL SOLUTIONS FOR GUADALUPE ESTUARY

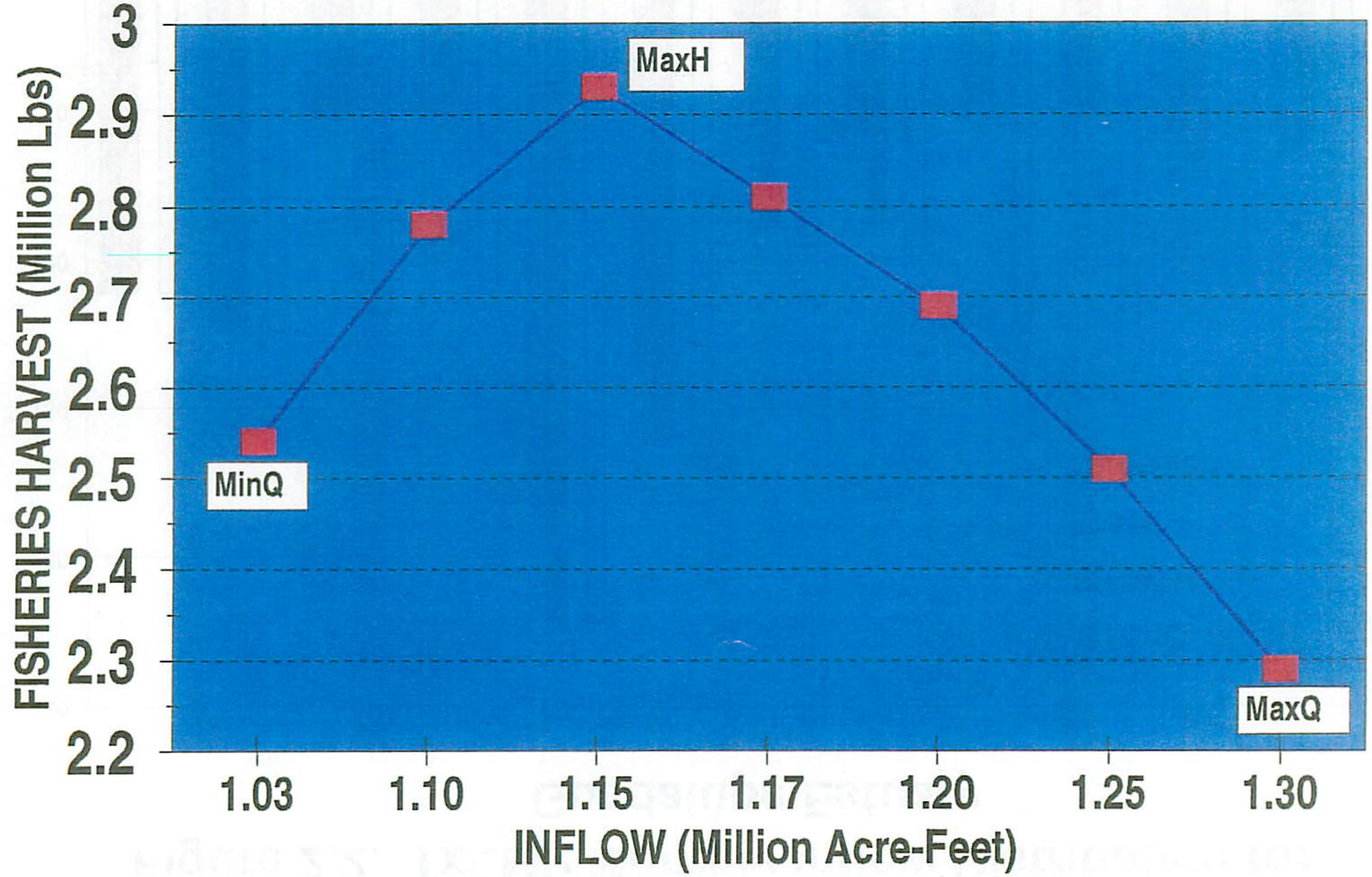
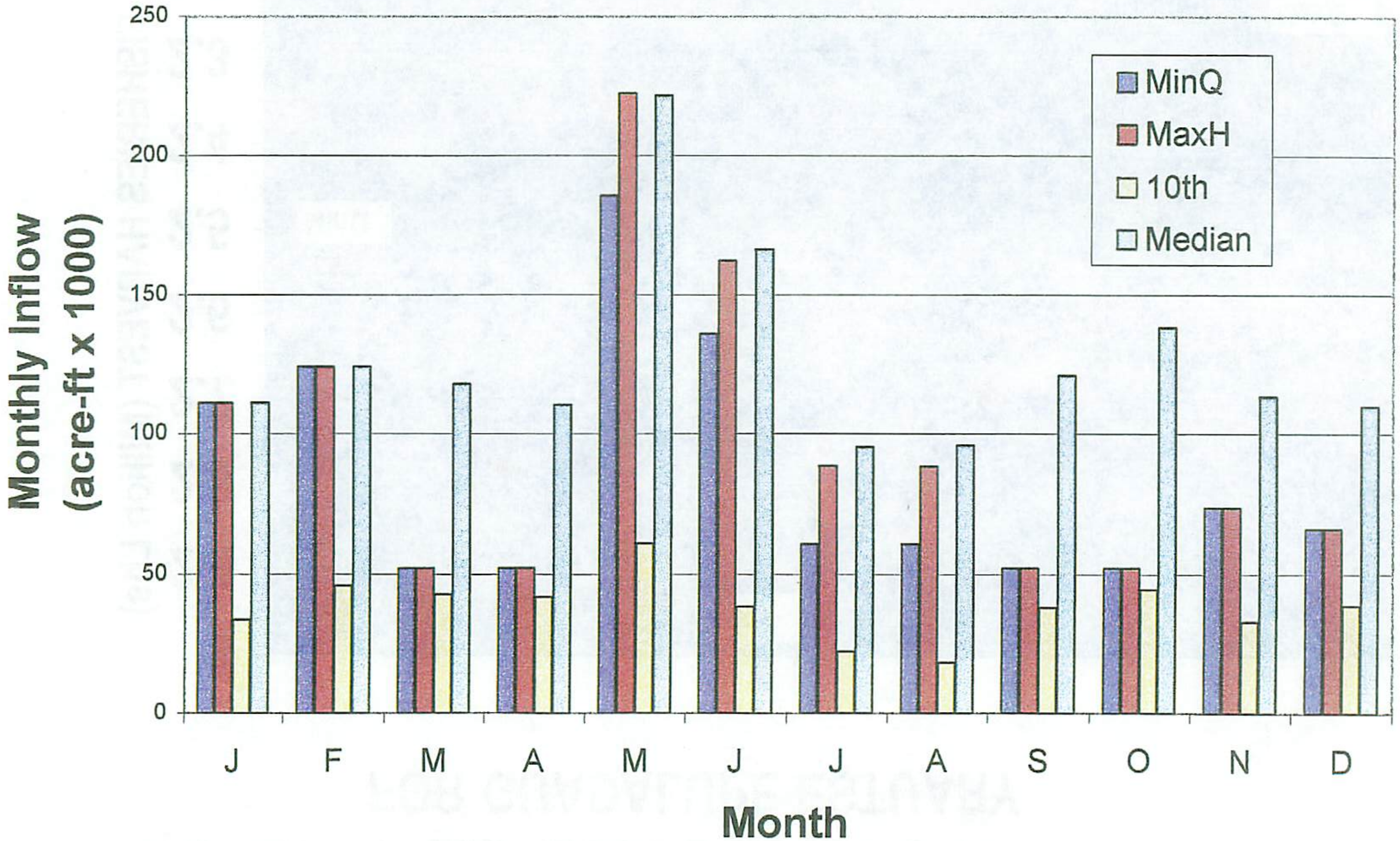


Figure 2.2. TxEMP Monthly Inflow Distribution for Guadalupe Estuary



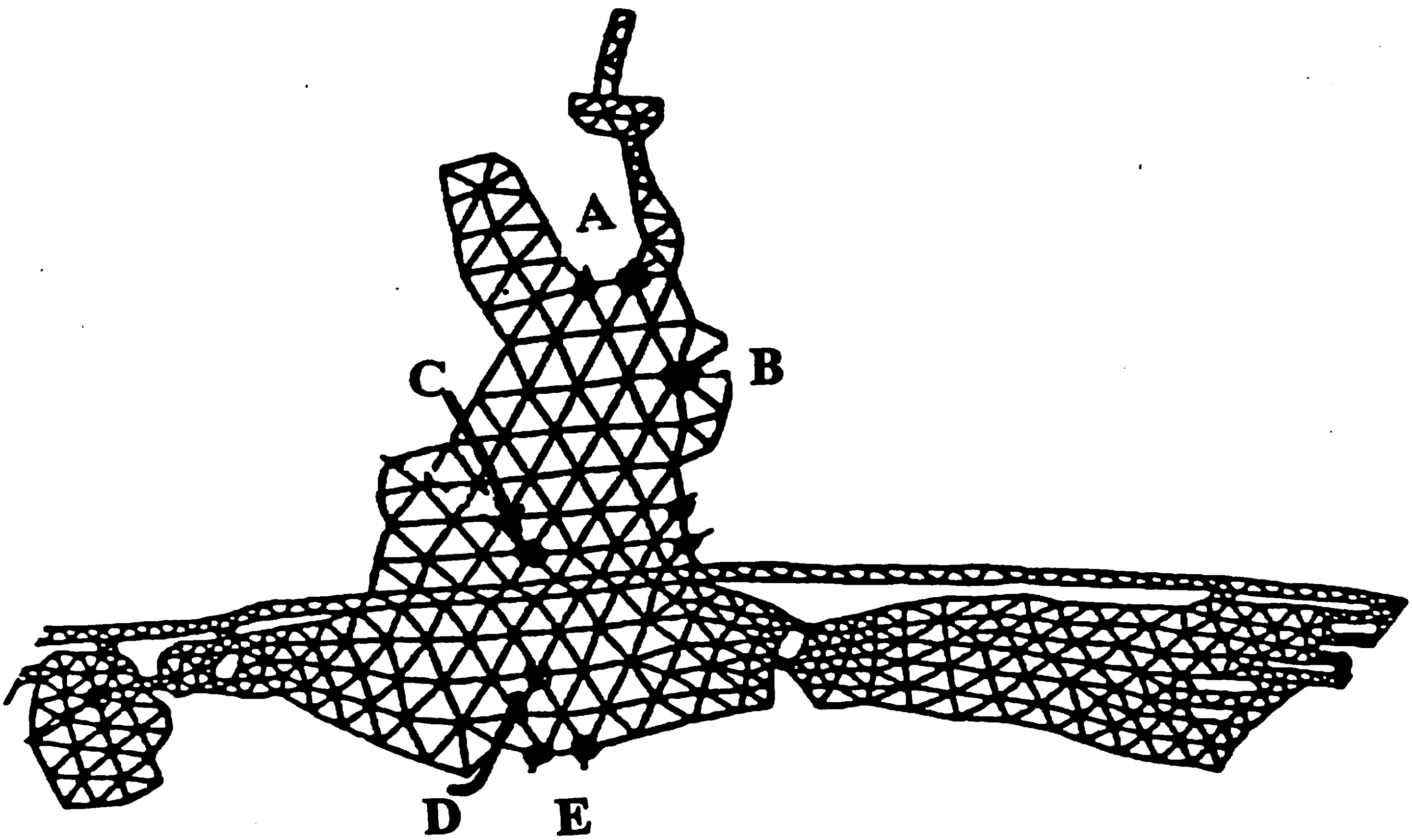


Figure 2.3. San Antonio Bay System grid from circulation model (TXBLEND), showing locations of five time-series sites for salinity data analysis.

A. Shoreline near Lucas Lake (double node).
B. Upper Bay node.
C. Mid Bay node.
D. Lower Bay node.
E. Shoreline near Panther Point (double node).

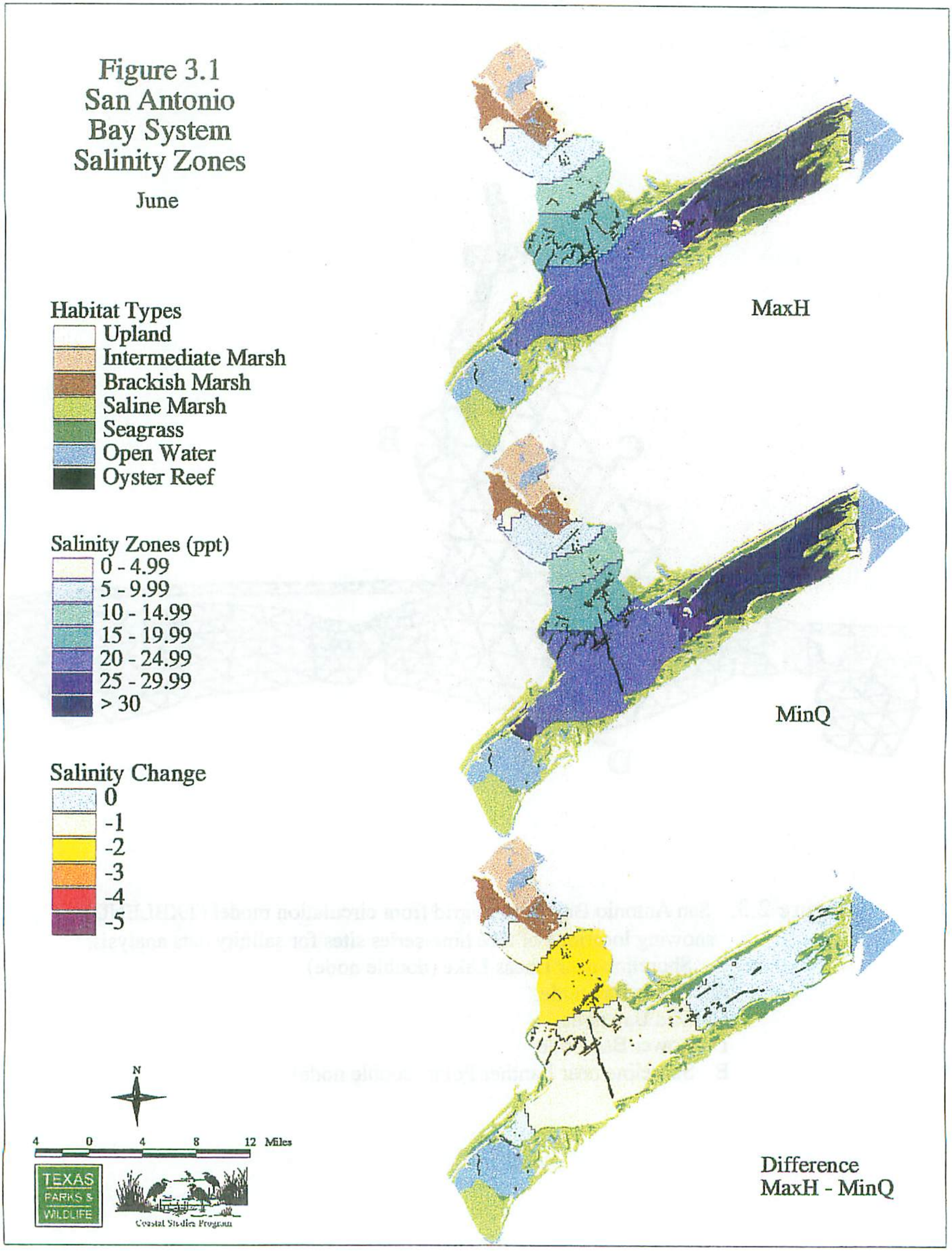


Figure 3.1
San Antonio
Bay System
Salinity Zones
June
Habitat Types
Upland
Intermediate Marsh
Brackish Marsh
Saline Marsh
Seagrass
Open Water
Oyster Reef
Salinity Zones (ppt)
0 - 4.99
5 - 9.99
10 - 14.99
15 - 19.99
20 - 24.99
25 - 29.99
> 30
Salinity Change
0
-1
-2
-3
-4
-5
N
4 0 4 8 12 Miles
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Coastal Studies Program
MaxH
MinQ
Difference
MaxH - MinQ

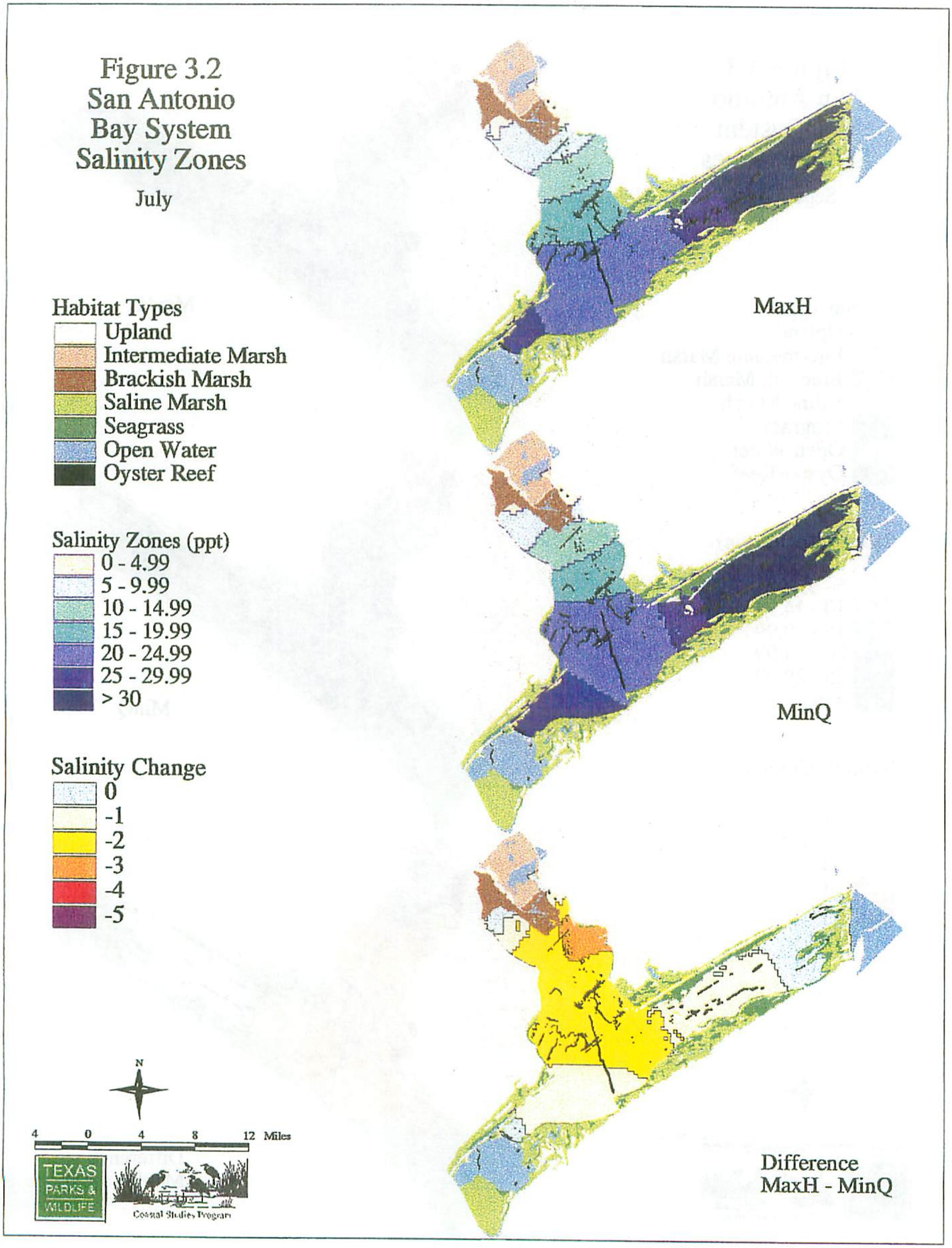
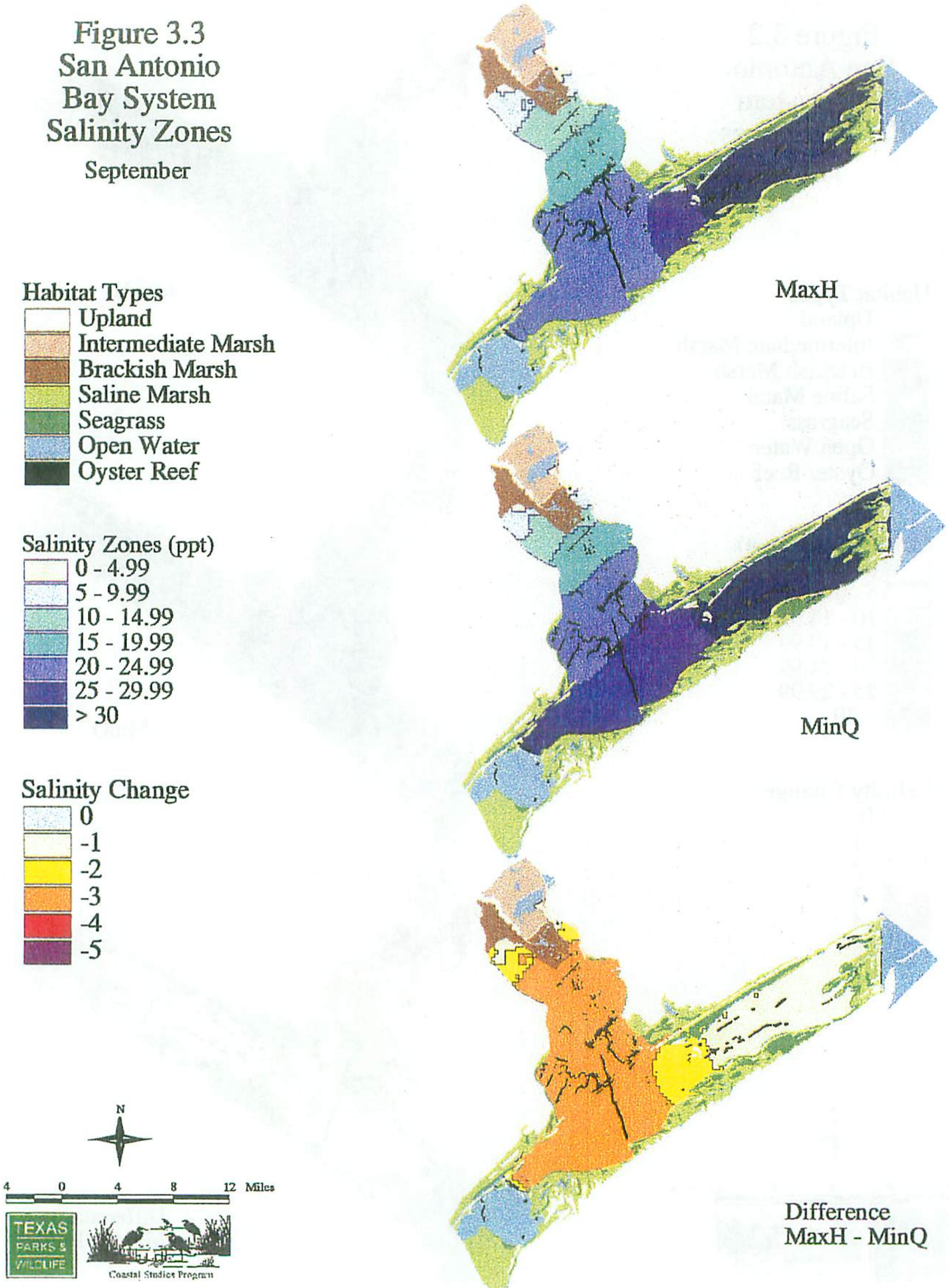


Figure 3.2
San Antonio
Bay System
Salinity Zones
July
Habitat Types
Upland
Intermediate Marsh
Brackish Marsh
Saline Marsh
Seagrass
Open Water
Oyster Reef
Salinity Zones (ppt)
0 - 4.99
5 - 9.99
10 - 14.99
15 - 19.99
20 - 24.99
25 - 29.99
> 30
Salinity Change
0
-1
-2
-3
-4
-5
N
4 0 4 8 12 Miles
TEXAS PARKS & WILDLIFE
Coastal Studies Program
MaxH
MinQ
Difference
MaxH - MinQ

Figure 3.3
San Antonio Bay System Salinity Zones
September



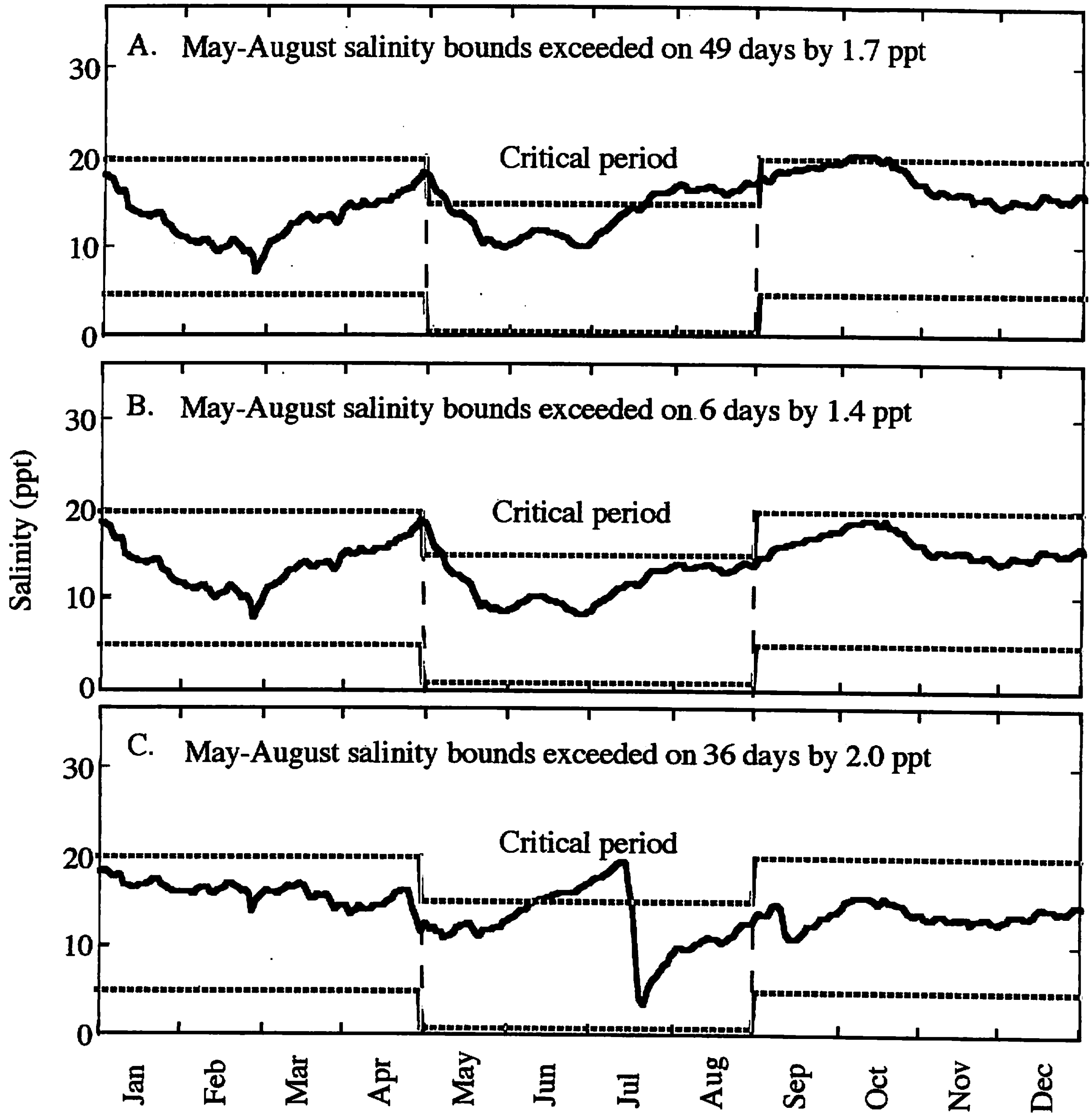


Figure 3.4. Annual salinity time series for Upper San Antonio Bay node. Solid lines show simulated salinities from hydrodynamic model for the cases: A. MinQ-50%, B. MaxH-50%, and C. 1990 inflow case. Dashed lines show lower and upper salinity bounds used for the Upper Bay constraints in the optimization model. Number of days and the mean difference for which salinity constraints are exceeded are shown for the May-August period critical to the life cycle of several bay species.

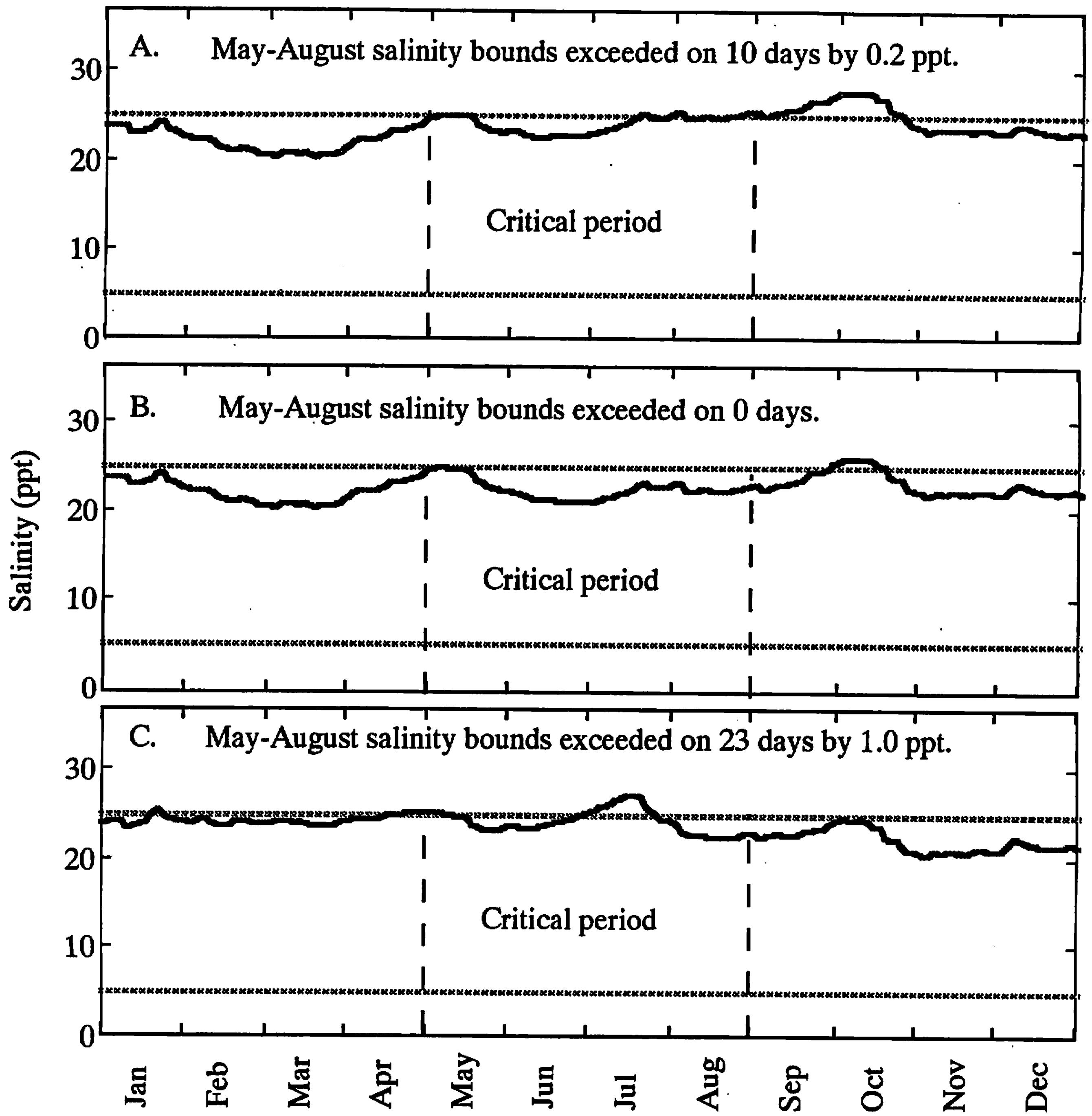


Figure 3.5. Annual salinity time series for Lower San Antonio Bay. Solid lines show simulated salinities from hydrodynamic model for the cases: A. MinQ-50%, B. MaxH-50%, and C. 1990 inflow case. Dashed lines show lower and upper salinity bounds used for the Lower Bay constraints in the optimization model. Number of days and the mean difference for which salinity constraints are exceeded are shown for the May-August period critical to the life cycle of several bay species.

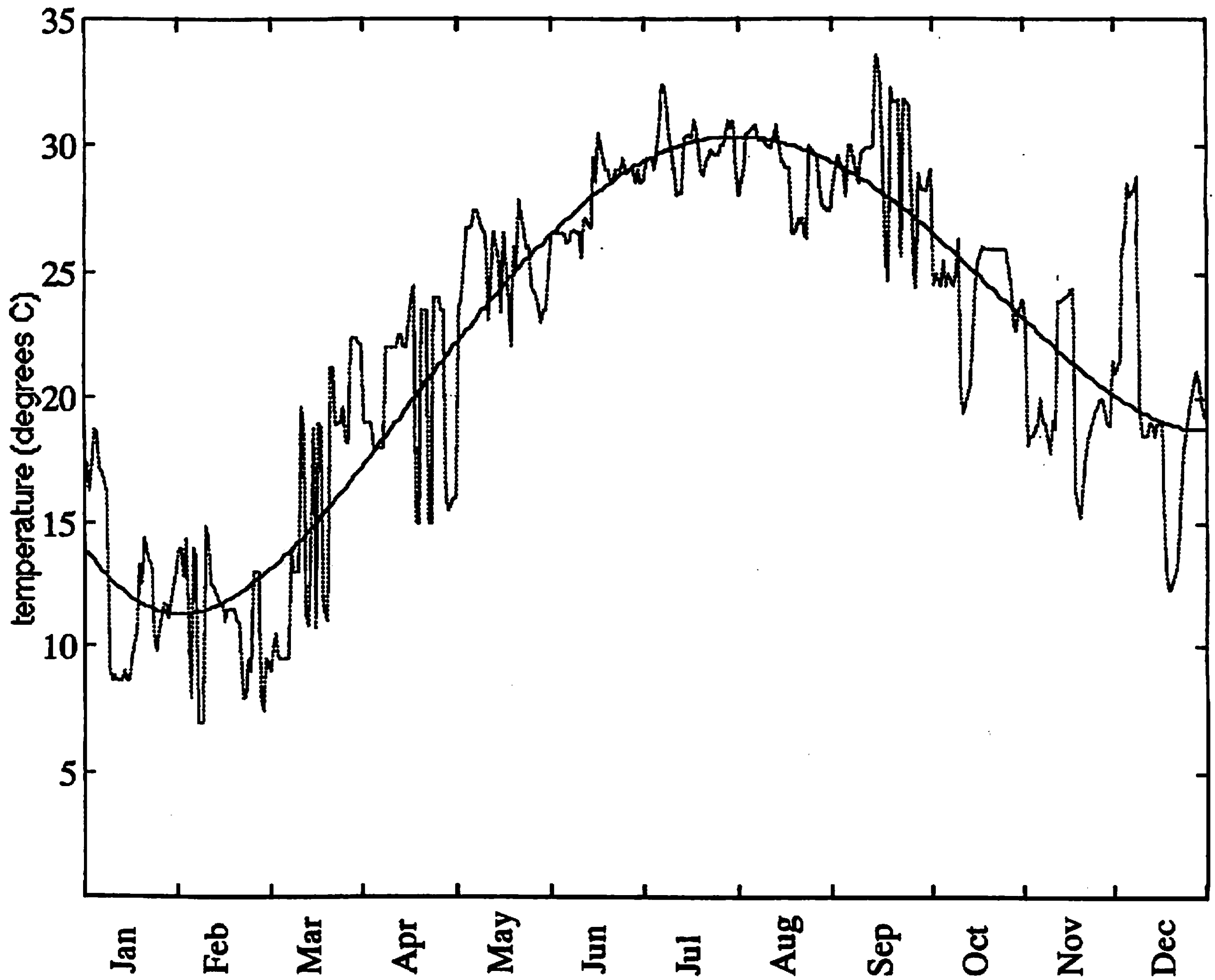


Figure 3.6. Fourth degree polynomial fit of TWDB temperature data from 1977-1991.

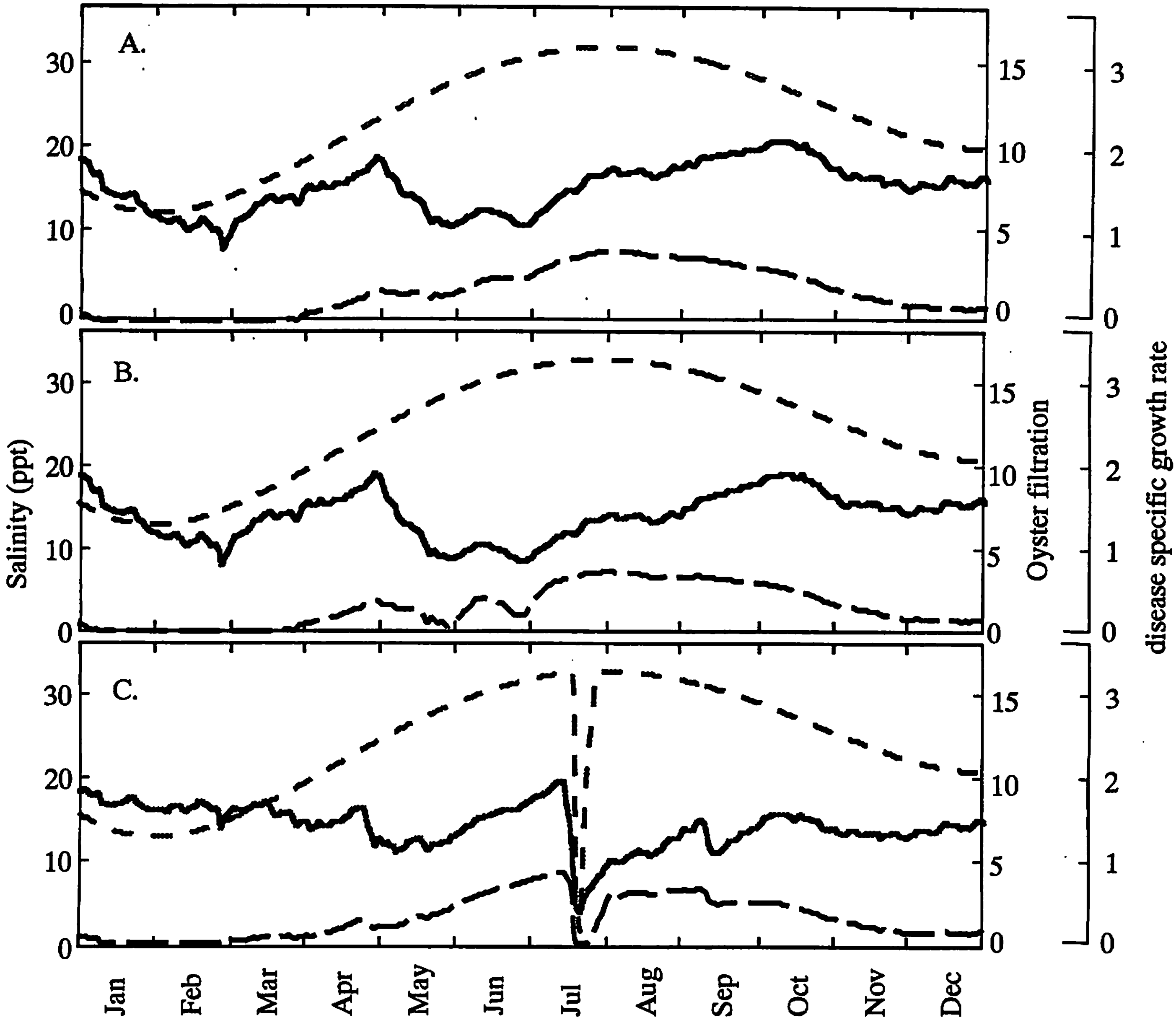


Figure 3.7. Annual salinity time series for Upper San Antonio Bay. Solid lines show simulated salinities from hydrodynamic model for the cases: A. MinQ-50%, B. MaxH-50%, and C. 1990 inflow case. Short dashed lines show oyster filtration rate (ml. filtered ind.$^{-1}$ min^{-1} when uneffected by disease. Long dashed lines show net specific growth rate (day^{-1}) of the oyster disease P. marinus..

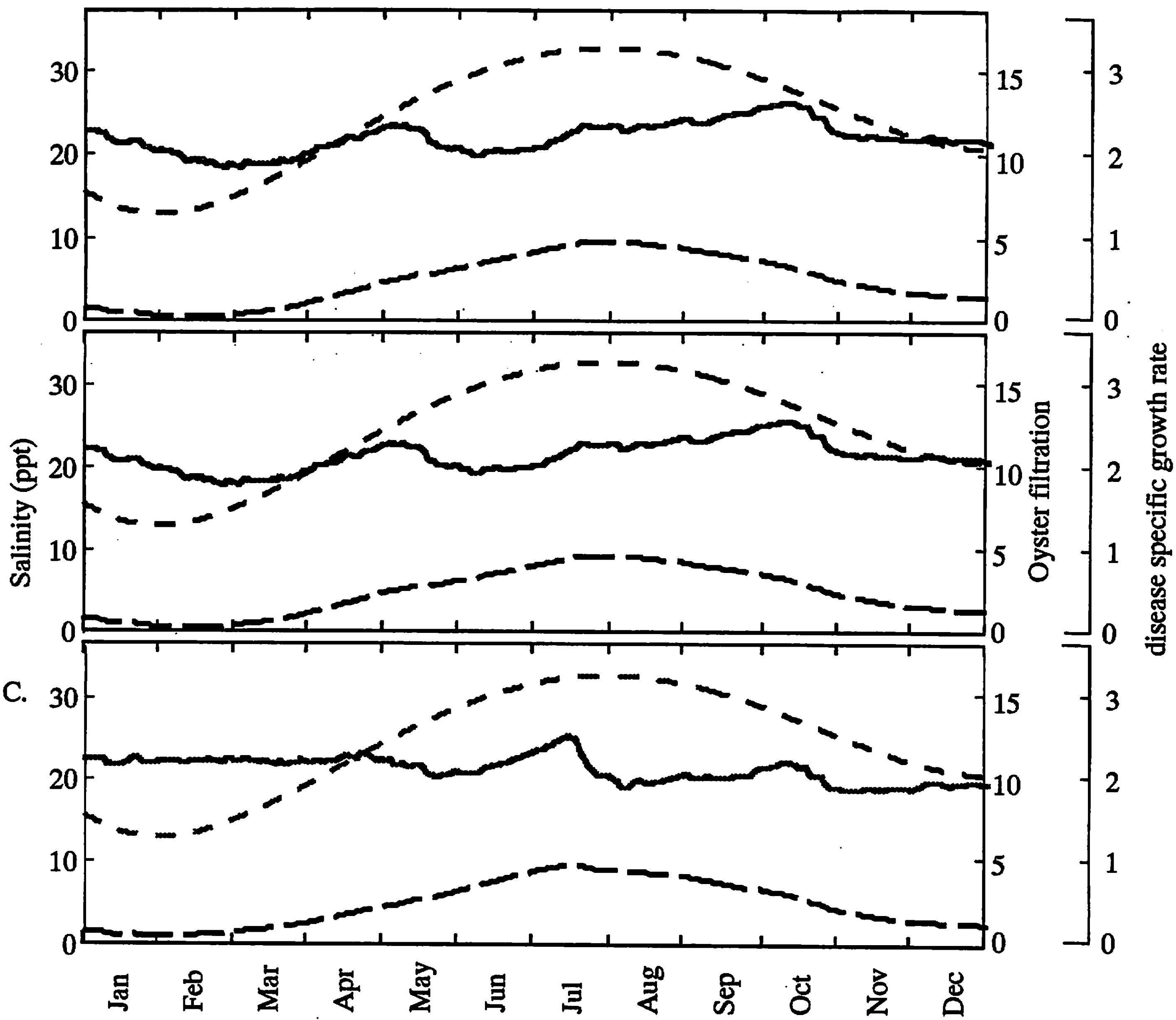


Figure 3.8. Annual salinity time series for Mid San Antonio Bay. Solid lines show simulated salinities from hydrodynamic model for the cases: A. MinQ-50%, B. MaxH-50%, and C. 1990 inflow case. Short dashed lines show oyster filtration rate (ml. filtered ind.$^{-1}$ min^{-1} when uneffected by disease. Long dashed lines show net specific growth rate (day^{-1}) of the oyster disease P. marinus.

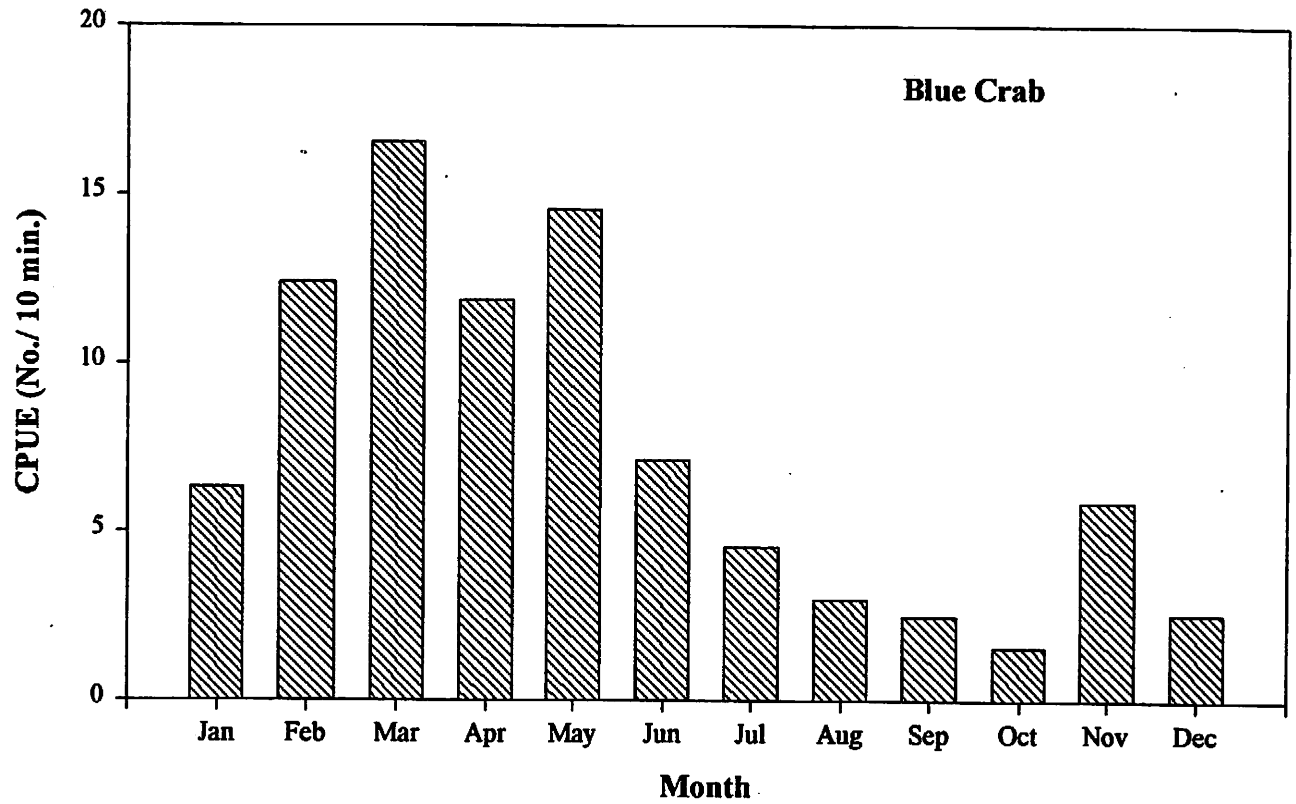
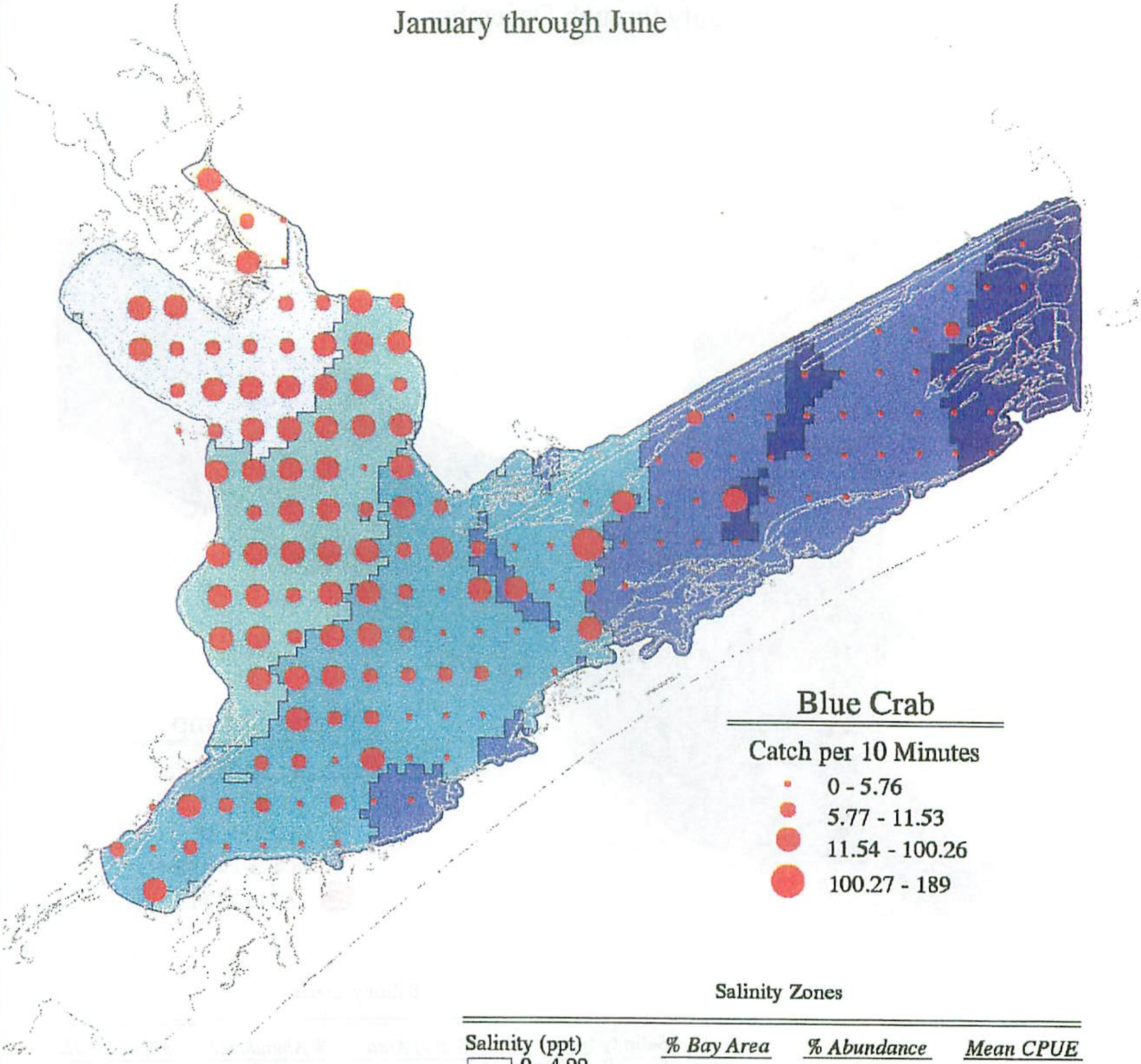


Fig. 3.9. Seasonal abundance of blue crab caught by trawl in the San Antonio Bay system. Data were pooled from 1982 - 1993.

Figure 3.10

Spatial Distribution of Blue Crab in the Guadalupe Estuary

January through June



Salinity Zones

Salinity (ppt)	*% Bay Area*	*% Abundance*	*Mean CPUE*
0 - 4.99	1.50	1.20	7.70
5 - 9.99	11.38	20.30	17.06
10 - 14.99	17.28	32.82	18.16
15 - 19.99	32.52	33.82	9.95
20 - 24.99	27.03	9.10	3.22
25 - 29.99	10.30	2.76	2.56
> 30	0.00	0.00	No Data

4 0 4 8 Miles

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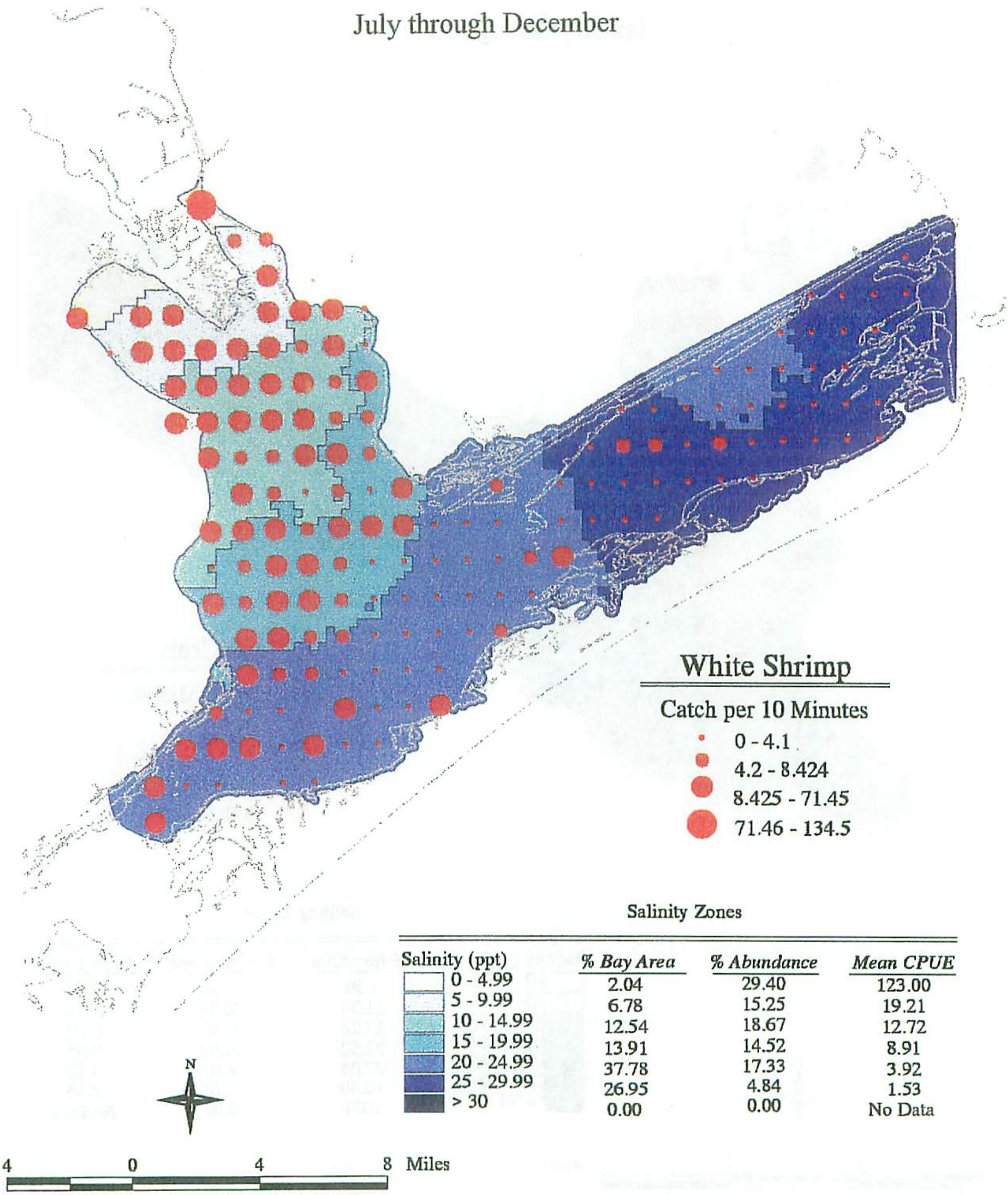
Figure 3.11

Spatial Distribution of White Shrimp in the Guadalupe Estuary

July through December



Salinity Zones

Salinity (ppt)	*% Bay Area*	*% Abundance*	*Mean CPUE*
0 - 4.99	2.04	29.40	123.00
5 - 9.99	6.78	15.25	19.21
10 - 14.99	12.54	18.67	12.72
15 - 19.99	13.91	14.52	8.91
20 - 24.99	37.78	17.33	3.92
25 - 29.99	26.95	4.84	1.53
> 30	0.00	0.00	No Data

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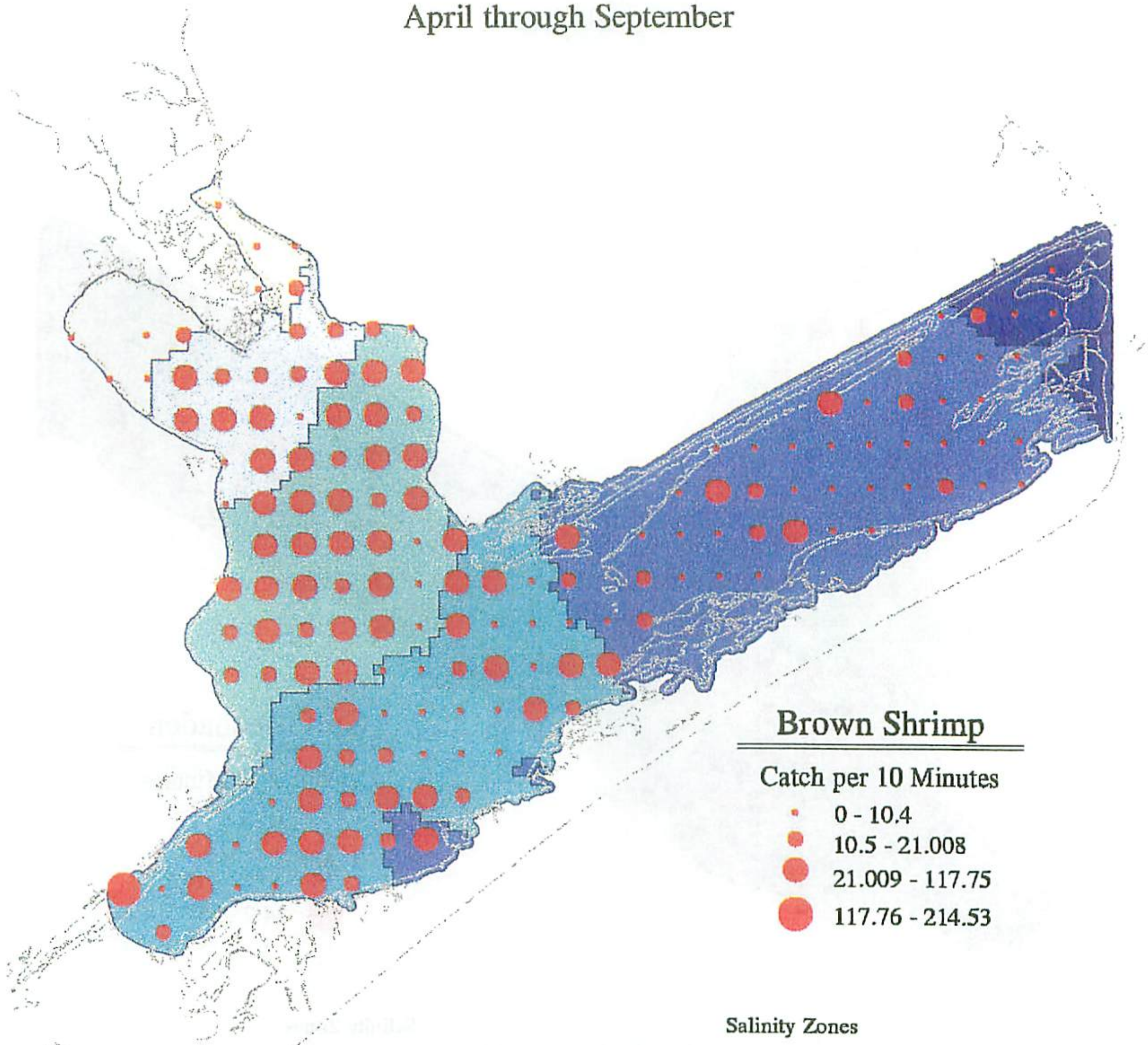
Figure 3.12

Spatial Distribution of Brown Shrimp in the Guadalupe Estuary

April through September



Salinity Zones

Salinity (ppt)	% Bay Area	% Abundance	Mean CPUE
0 - 4.99	5.12	2.58	9.49
5 - 9.99	7.72	10.24	25.01
10 - 14.99	19.93	30.20	28.56
15 - 19.99	27.26	36.22	25.04
20 - 24.99	34.63	19.64	10.69
25 - 29.99	5.33	1.22	3.96
> 30	0.00	0.00	No Data

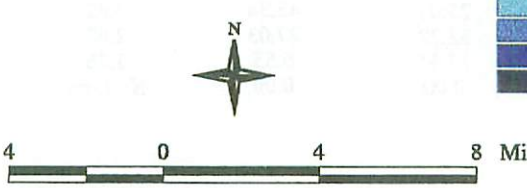


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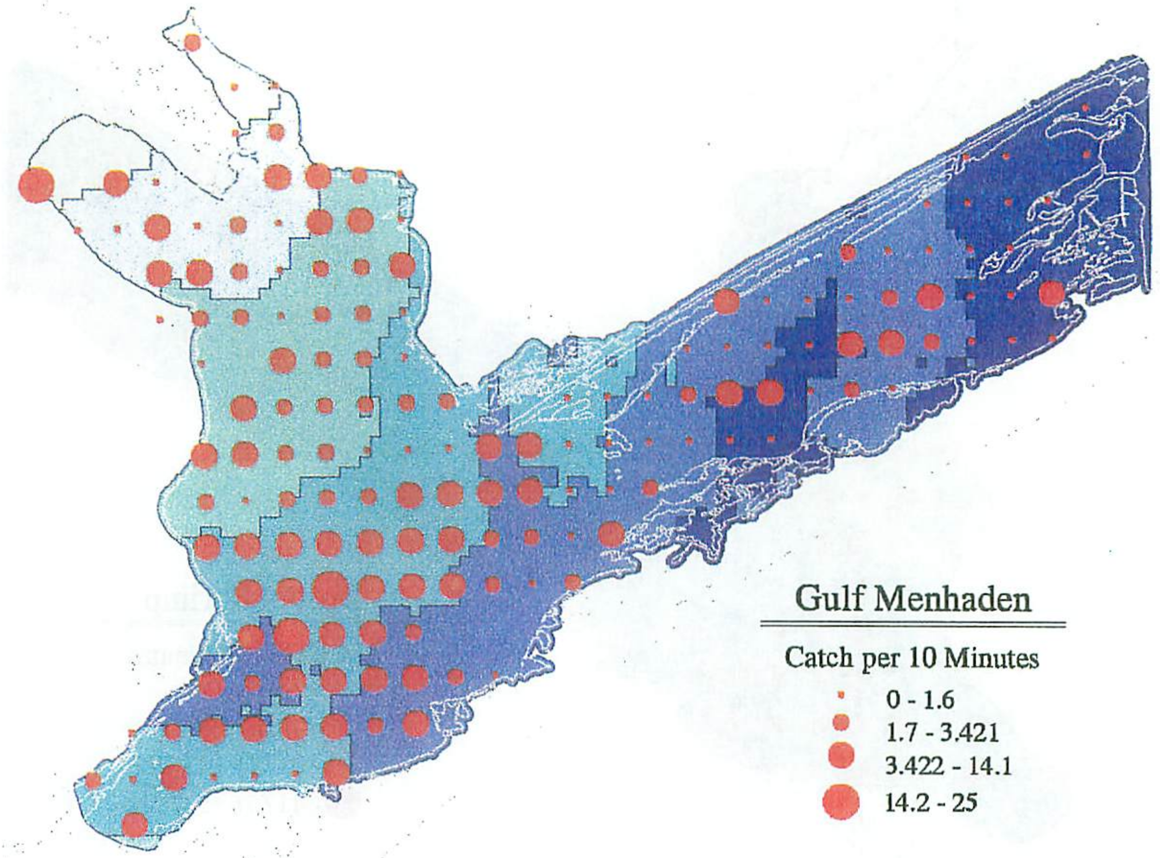
Figure 3.13

Spatial Distribution of Gulf Menhaden in the Guadalupe Estuary

All Year



Salinity Zones

Salinity (ppt)	*% Bay Area*	*% Abundance*	*Mean CPUE*
0 - 4.99	3.19	2.46	2.6
5 - 9.99	7.60	8.73	3.86
10 - 14.99	14.41	11.89	2.78
15 - 19.99	25.07	43.34	5.82
20 - 24.99	32.22	27.03	2.82
25 - 29.99	17.51	6.55	1.26
> 30	0.00	0.00	No Data

N

4 0 4 8 Miles

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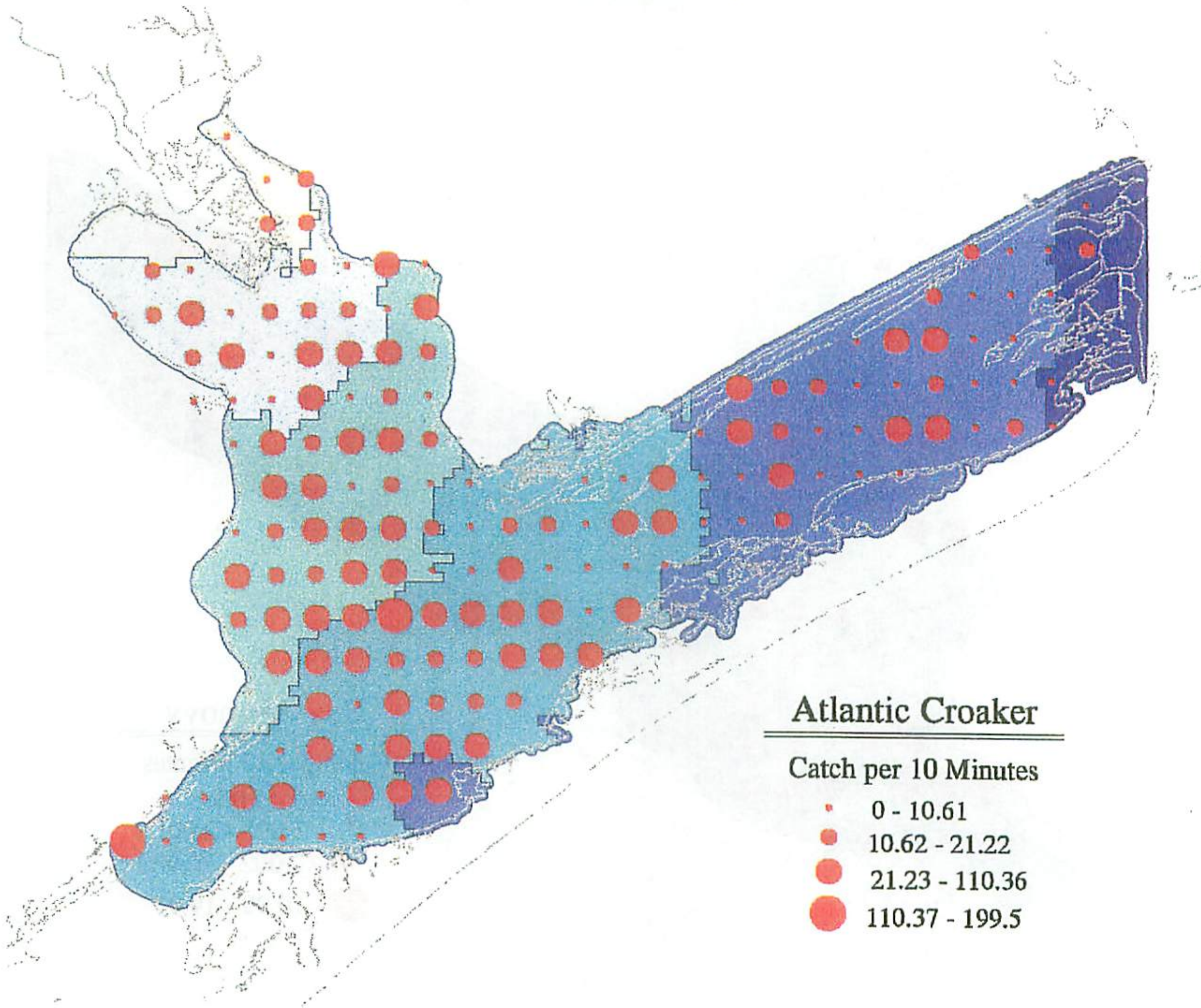
Coastal Studies Program

Figure 3.14

Spatial Distribution of Atlantic Croaker in the Guadalupe Estuary

February through July



Salinity Zones

Salinity (ppt)	% Bay Area	% Abundance	Mean CPUE
0 - 4.99	3.29	1.79	11.45
5 - 9.99	10.65	9.15	18.08
10 - 14.99	17.99	19.00	22.23
15 - 19.99	34.33	51.01	31.28
20 - 24.99	27.66	17.09	13.01
25 - 29.99	6.07	1.97	6.81
> 30	0.00	0.00	No Data

N

4 0 4 8 Miles

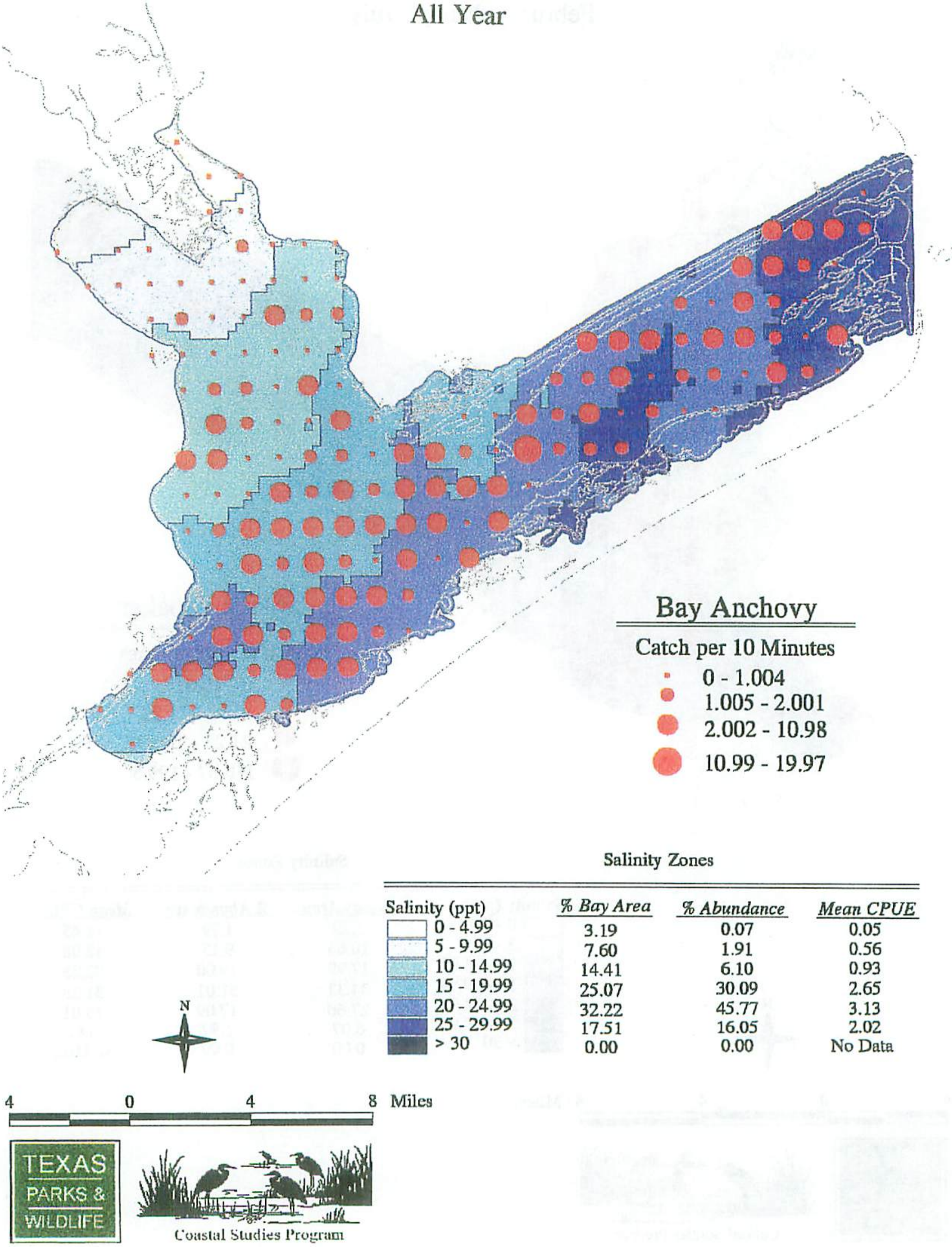
TEXAS PARKS & WILDLIFE

Coastal Studies Program

Figure 3.15

Spatial Distribution of Bay Anchovy in the Guadalupe Estuary

All Year



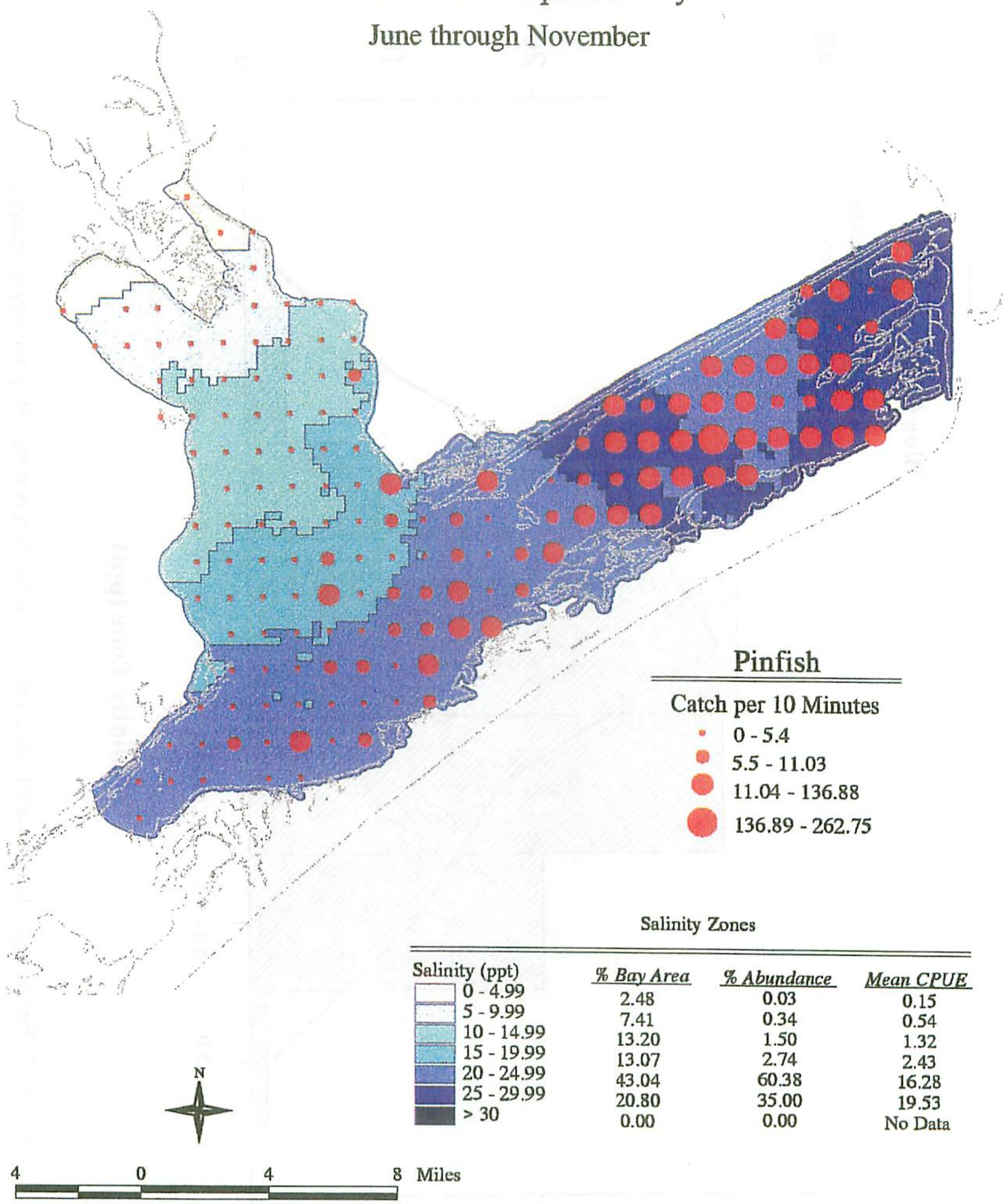
Salinity Zones

Salinity (ppt)	% Bay Area	% Abundance	Mean CPUE
0 - 4.99	3.19	0.07	0.05
5 - 9.99	7.60	1.91	0.56
10 - 14.99	14.41	6.10	0.93
15 - 19.99	25.07	30.09	2.65
20 - 24.99	32.22	45.77	3.13
25 - 29.99	17.51	16.05	2.02
> 30	0.00	0.00	No Data

Figure 3.16

Spatial Distribution of Pinfish in the Guadalupe Estuary

June through November



Salinity Zones

Salinity (ppt)	% Bay Area	% Abundance	Mean CPUE
0 - 4.99	2.48	0.03	0.15
5 - 9.99	7.41	0.34	0.54
10 - 14.99	13.20	1.50	1.32
15 - 19.99	13.07	2.74	2.43
20 - 24.99	43.04	60.38	16.28
25 - 29.99	20.80	35.00	19.53
> 30	0.00	0.00	No Data

TEXAS PARKS & WILDLIFE

Coastal Studies Program

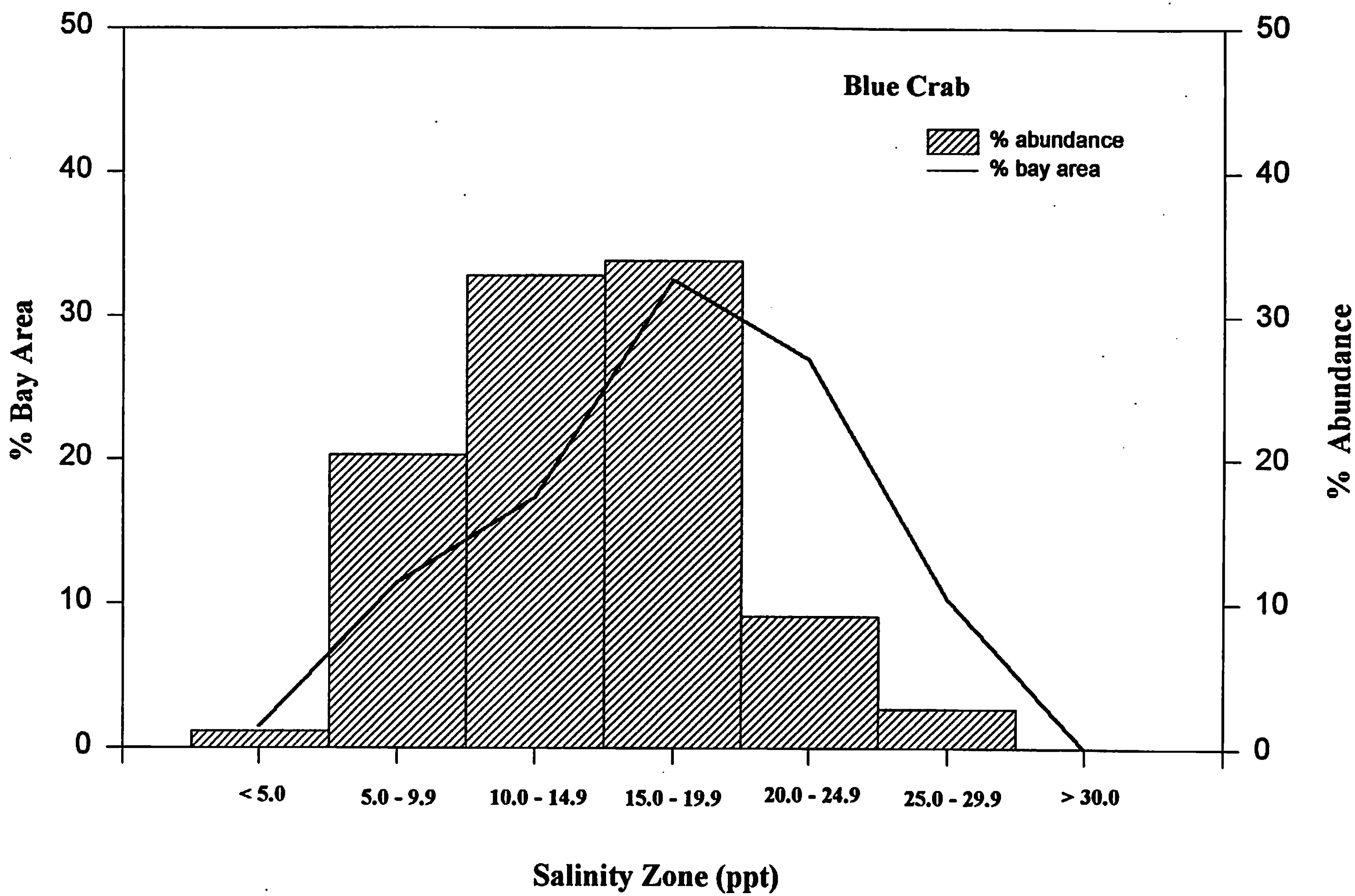


Fig. 3.17. Percentage abundance of blue crab along the San Antonio Bay salinity gradients.

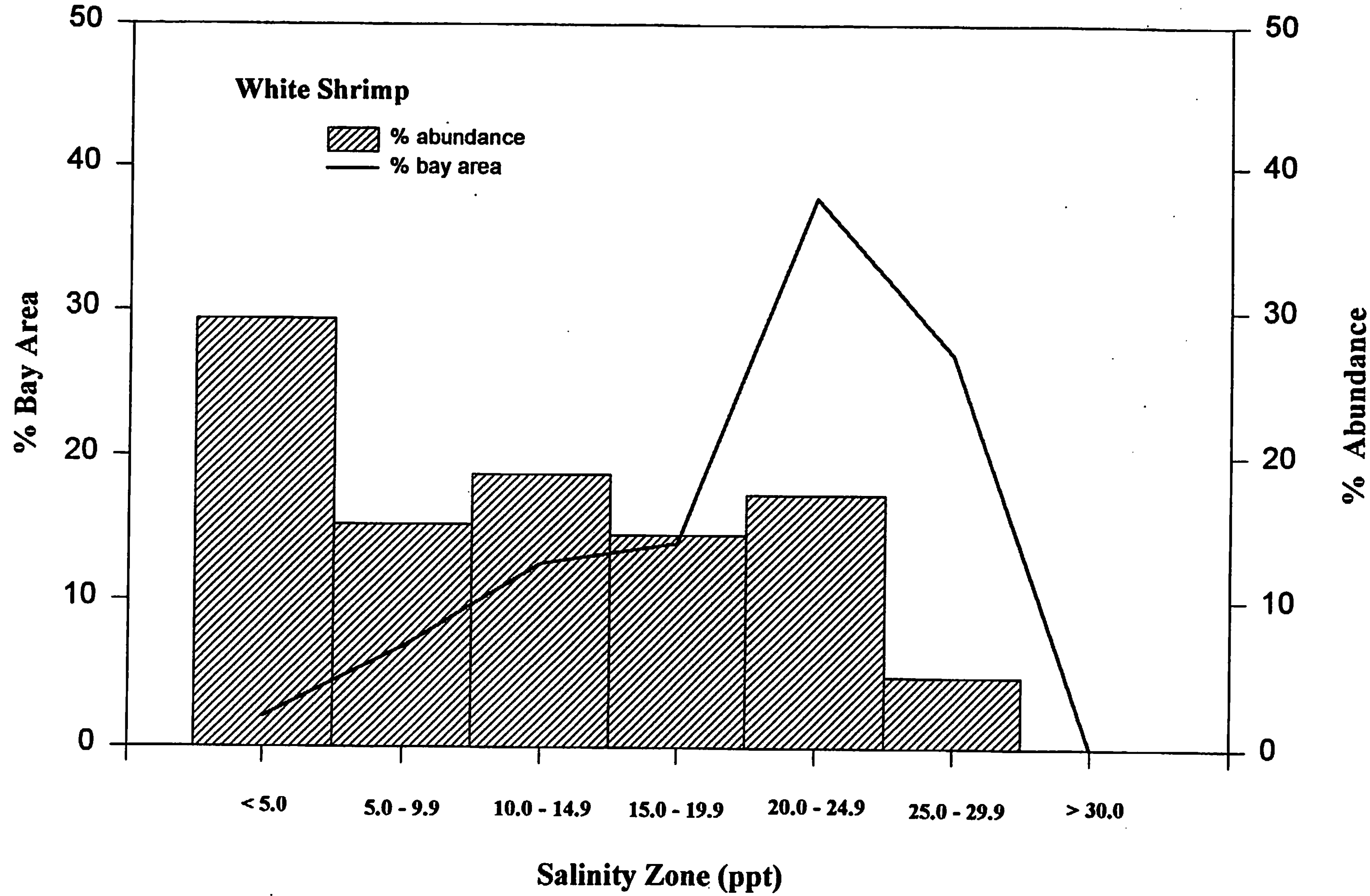


Fig. 3.18. Percentage abundance of white shrimp along the San Antonio Bay salinity gradients.

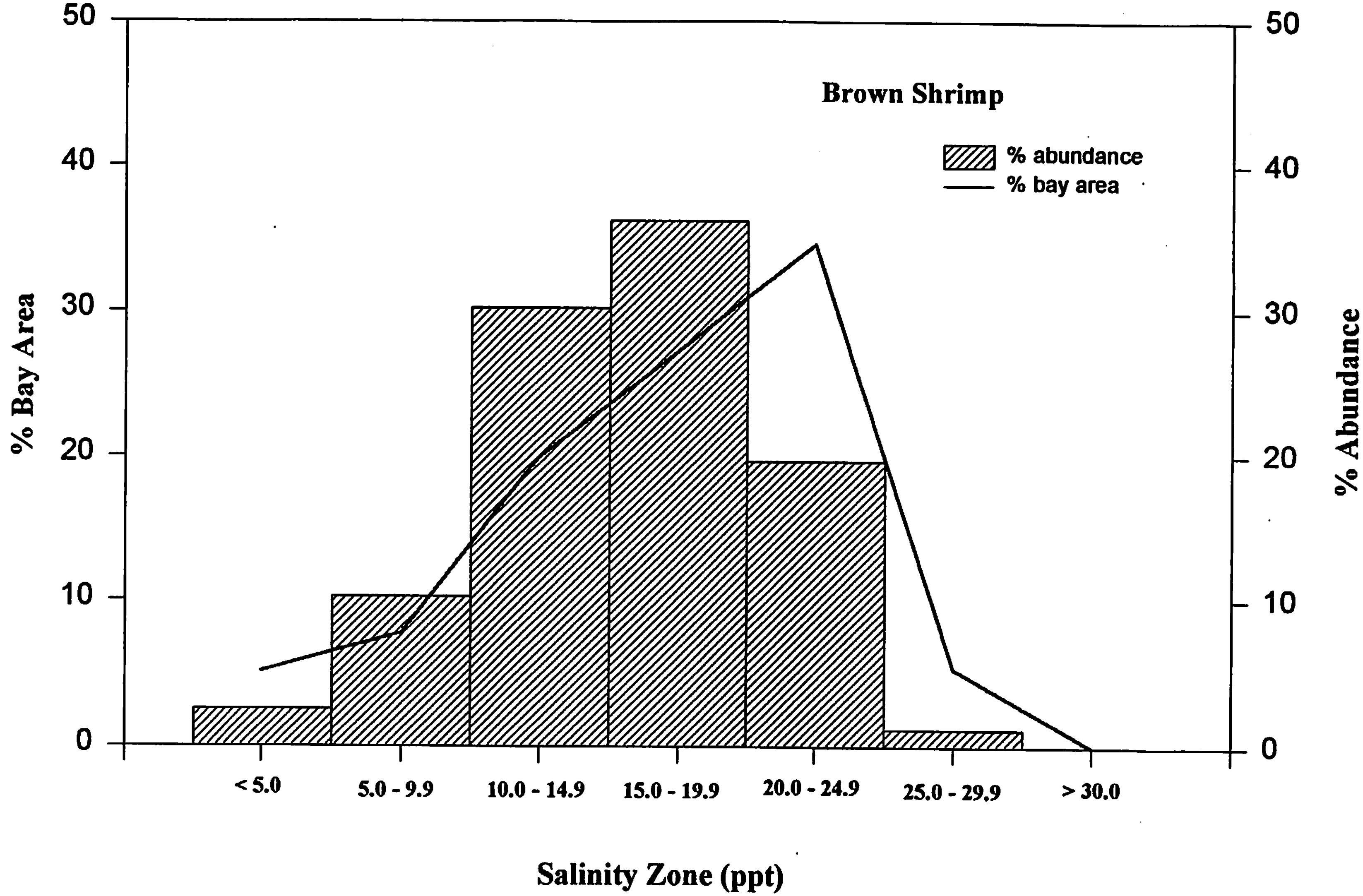


Fig. 3.19. Percentage abundance of brown shrimp along the San Antonio Bay salinity gradients.

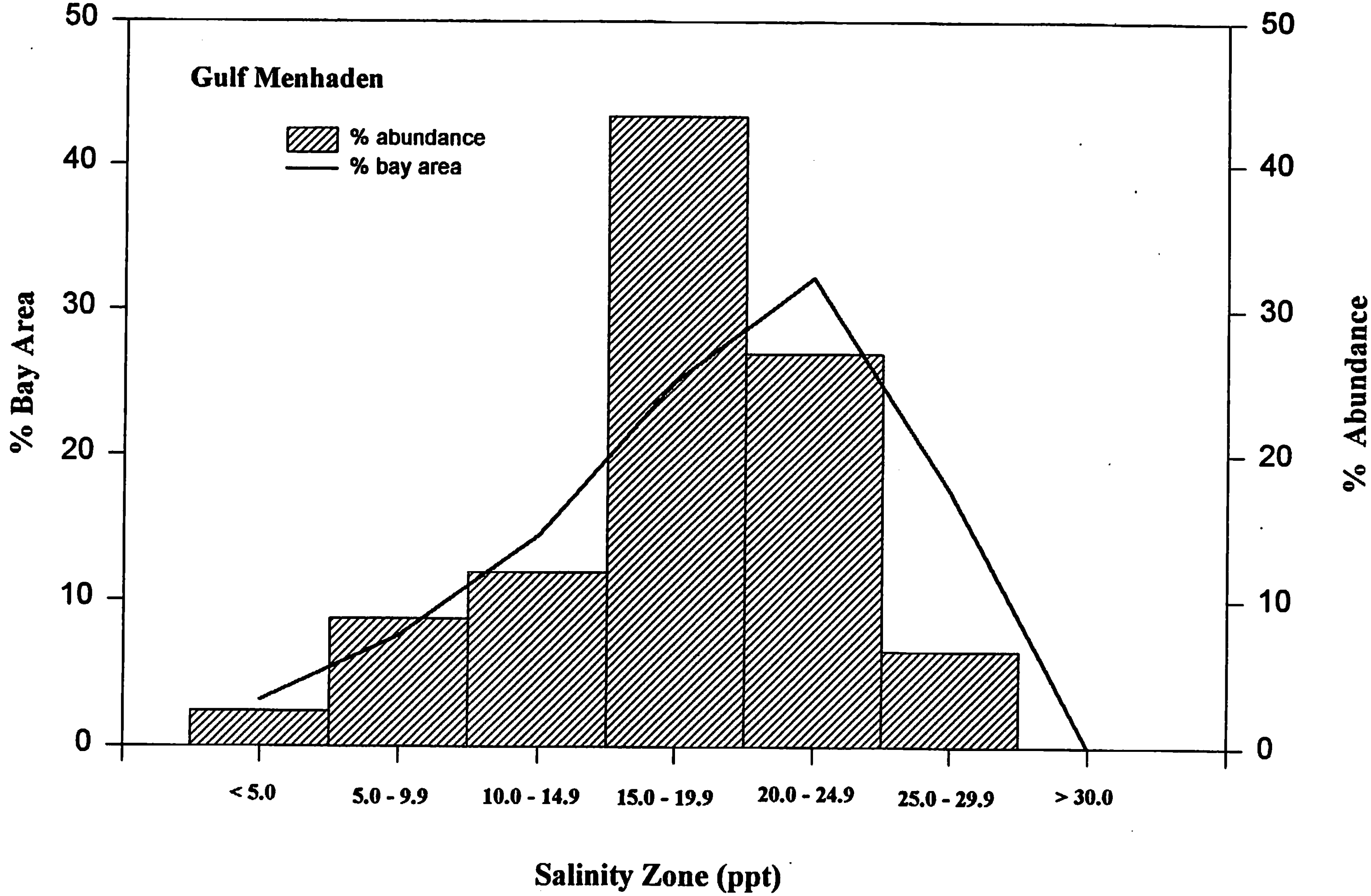


Fig. 3.20. Percentage anbundance of Gulf menhaden along the San Antonio Bay salinity gradients.

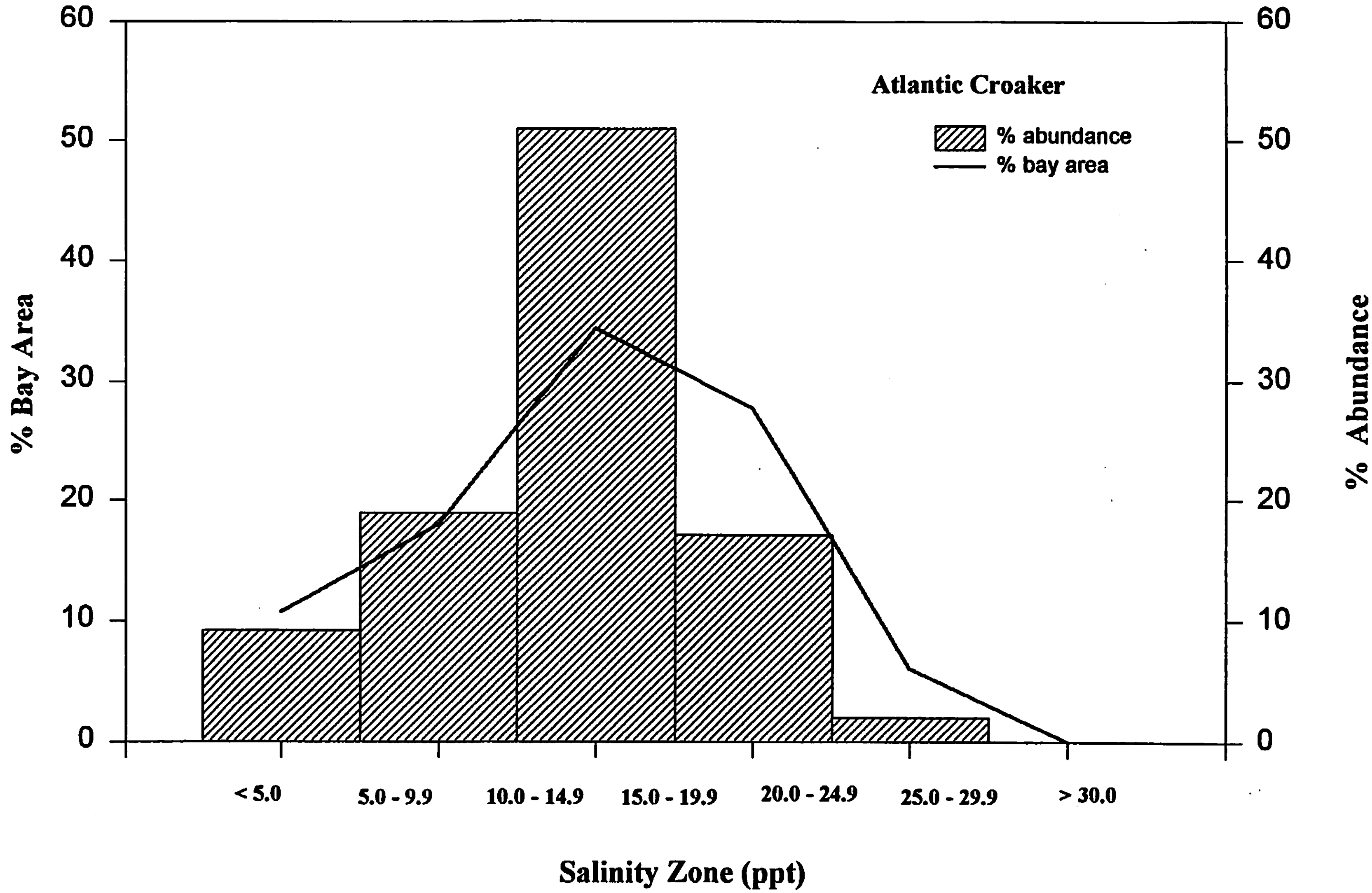


Fig. 3.21. Percentage abundance of Atlantic croaker along the San Antonio Bay salinity gradients.

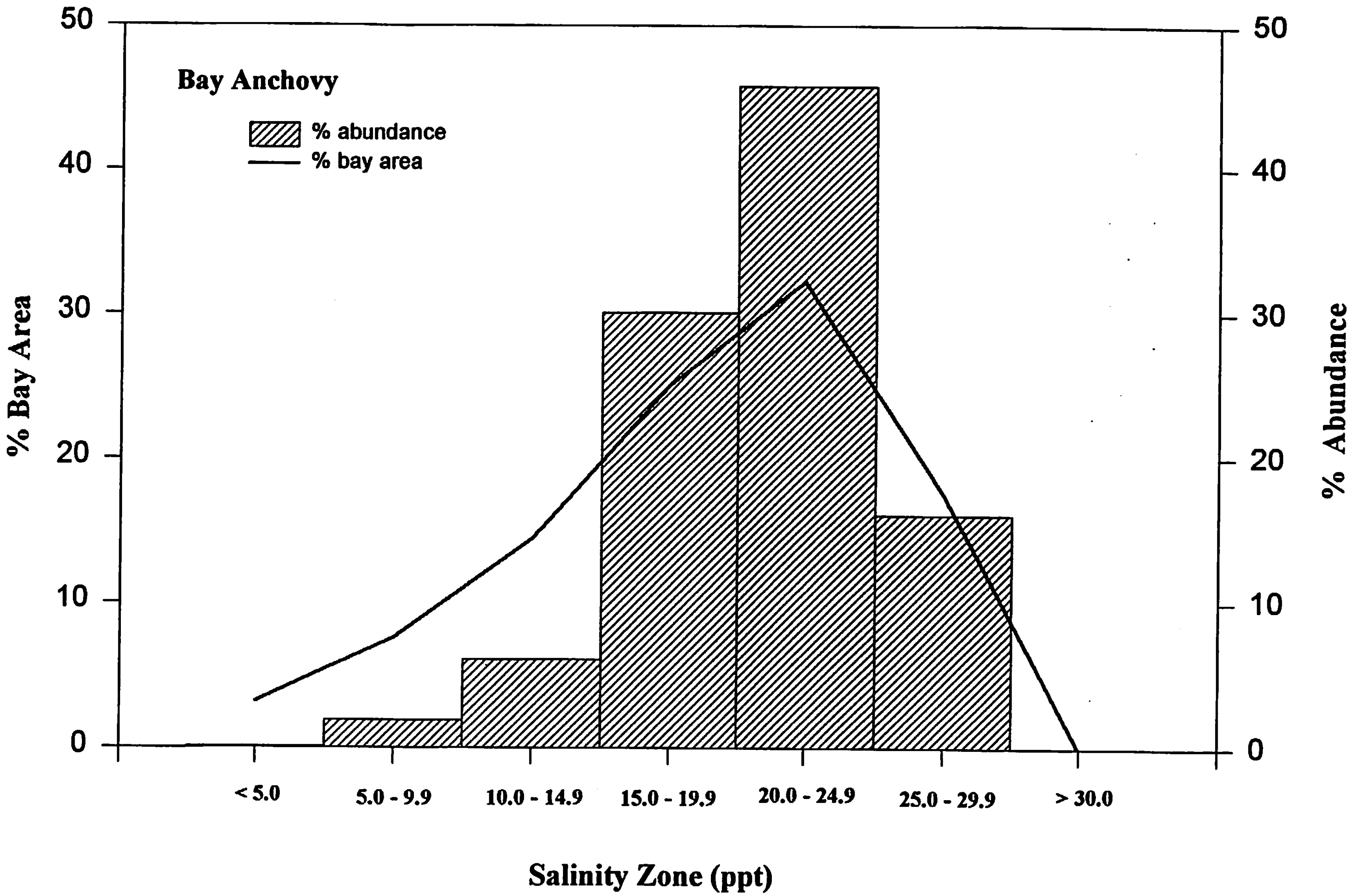


Fig. 3.22. Percentage abundance of bay anchovy along the San Antonio Bay salinity gradients.

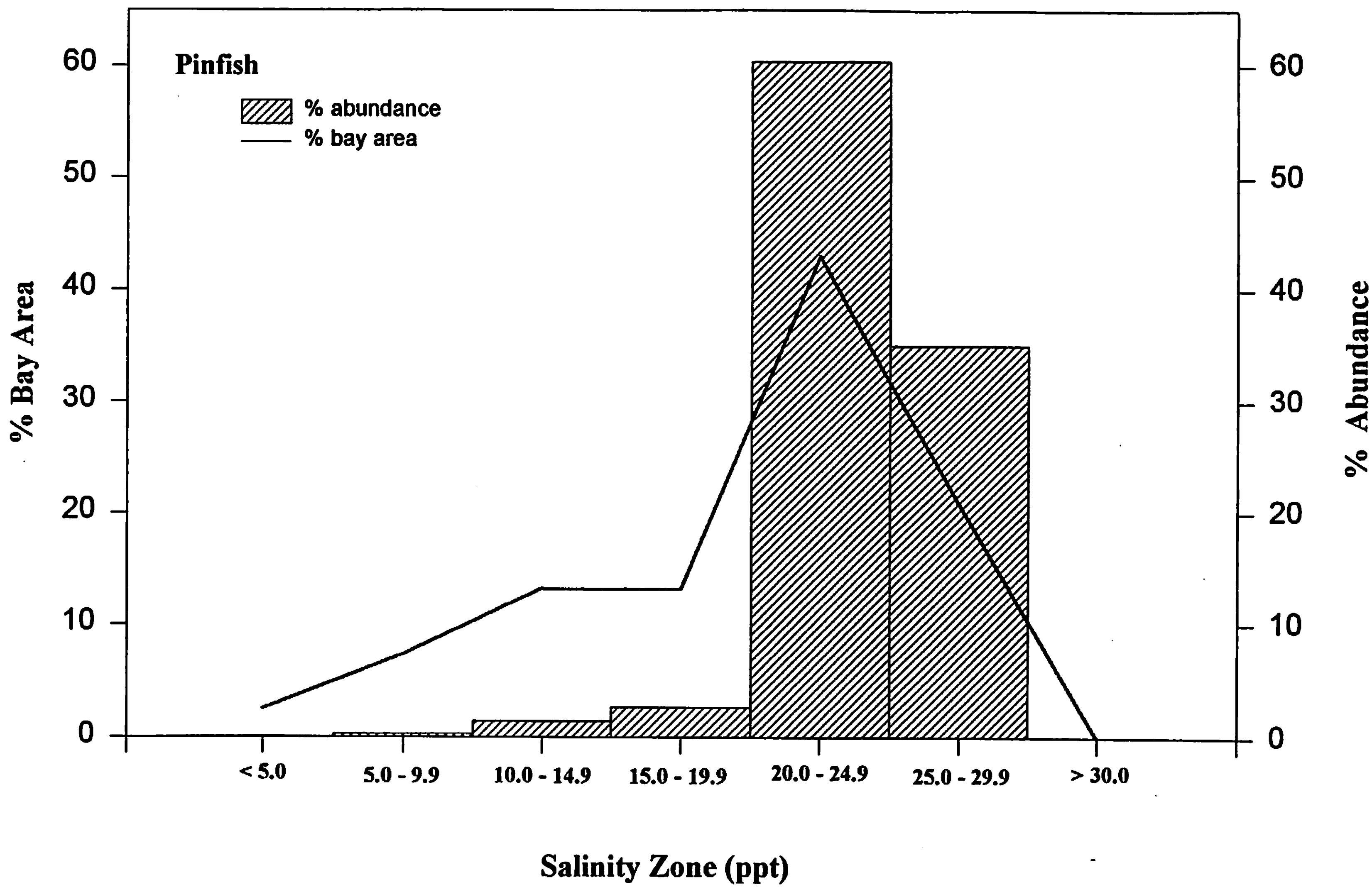


Fig. 3.23. Percentage abundance of pinfish along the San Antonio Bay salinity gradients.

Figure 3.24
Blue Crab
Observed Salinity Gradient
vs.
MinQ and MaxH Salinity Patterns
January through June

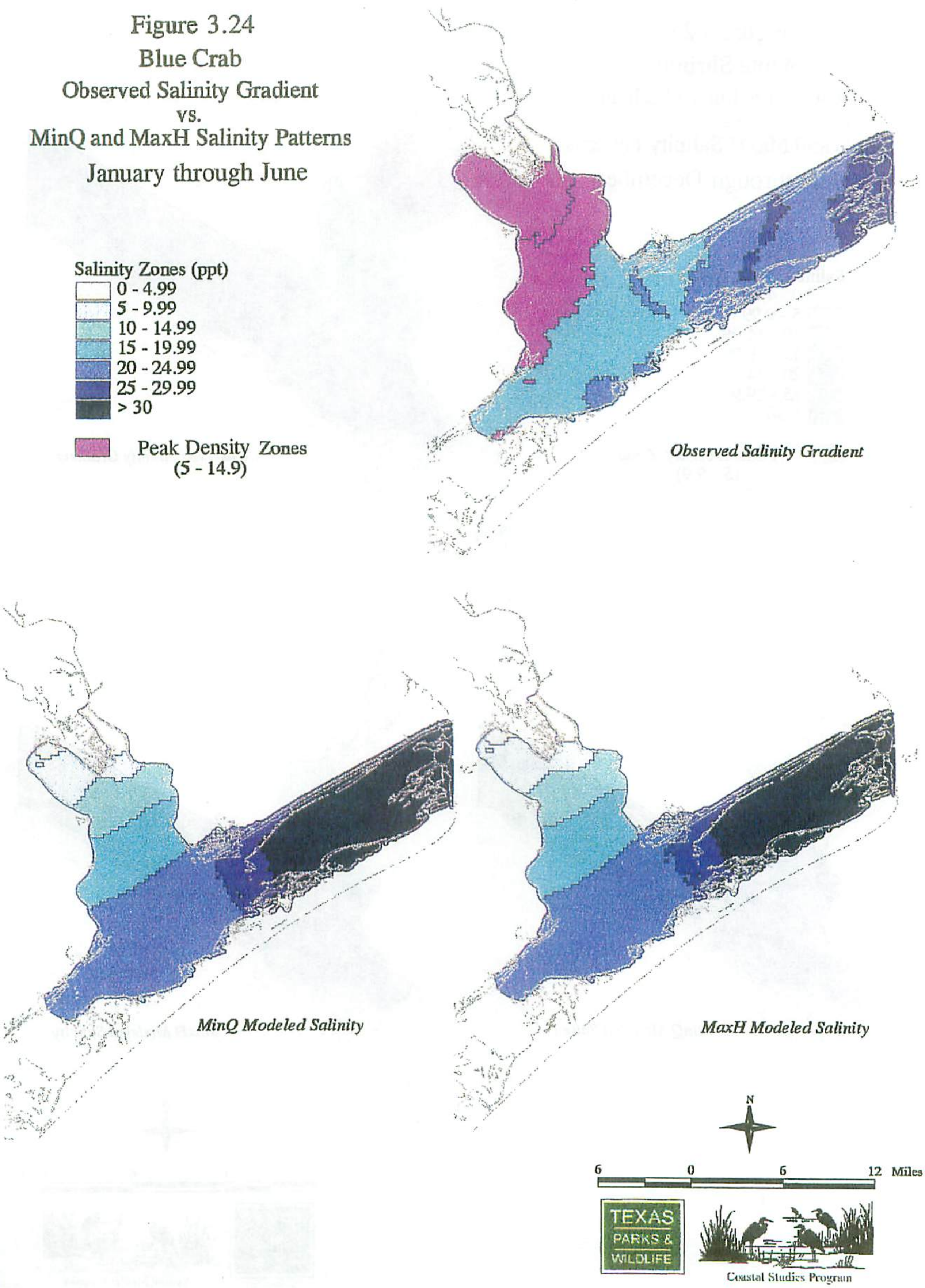


Figure 3.25
White Shrimp
Observed Salinity Gradient
vs.
MinQ and MaxH Salinity Patterns
July through December

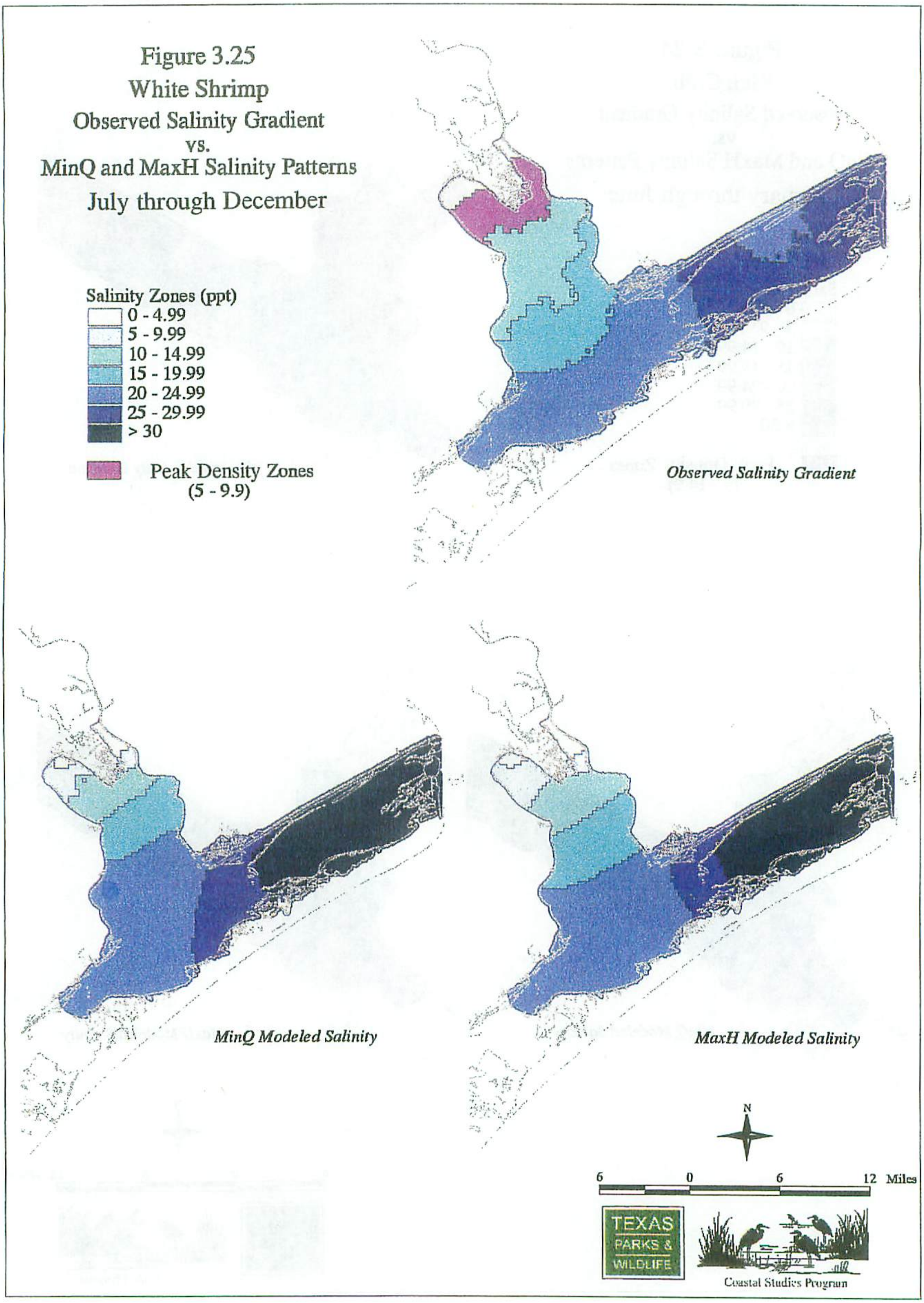


Figure 3.26
Brown Shrimp
Observed Salinity Gradient vs. MinQ and MaxH Salinity Patterns
April through September

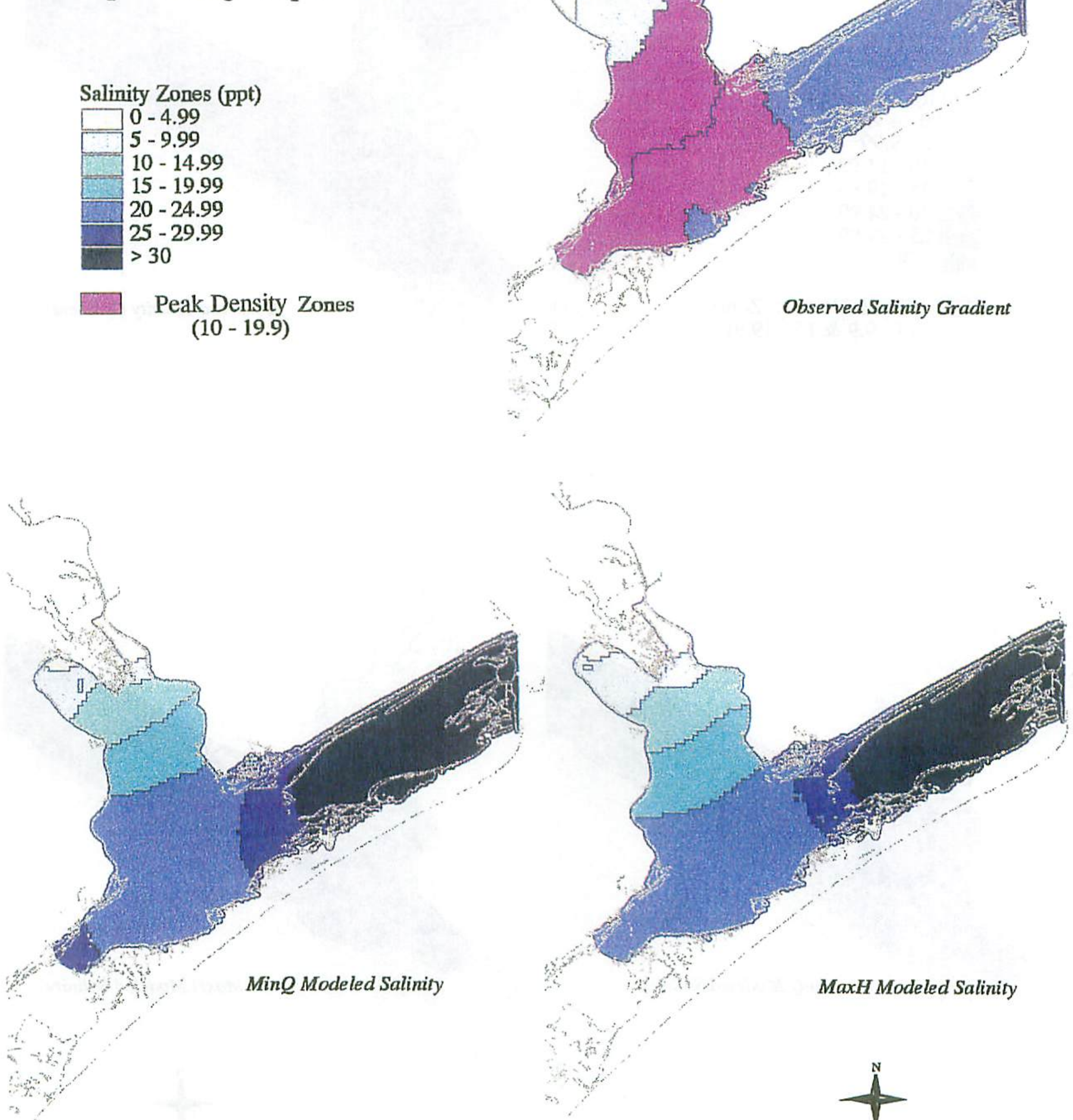


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Figure 3.27
Gulf Menhaden
Observed Salinity Gradient
vs.
MinQ and MaxH Salinity Patterns
All Year

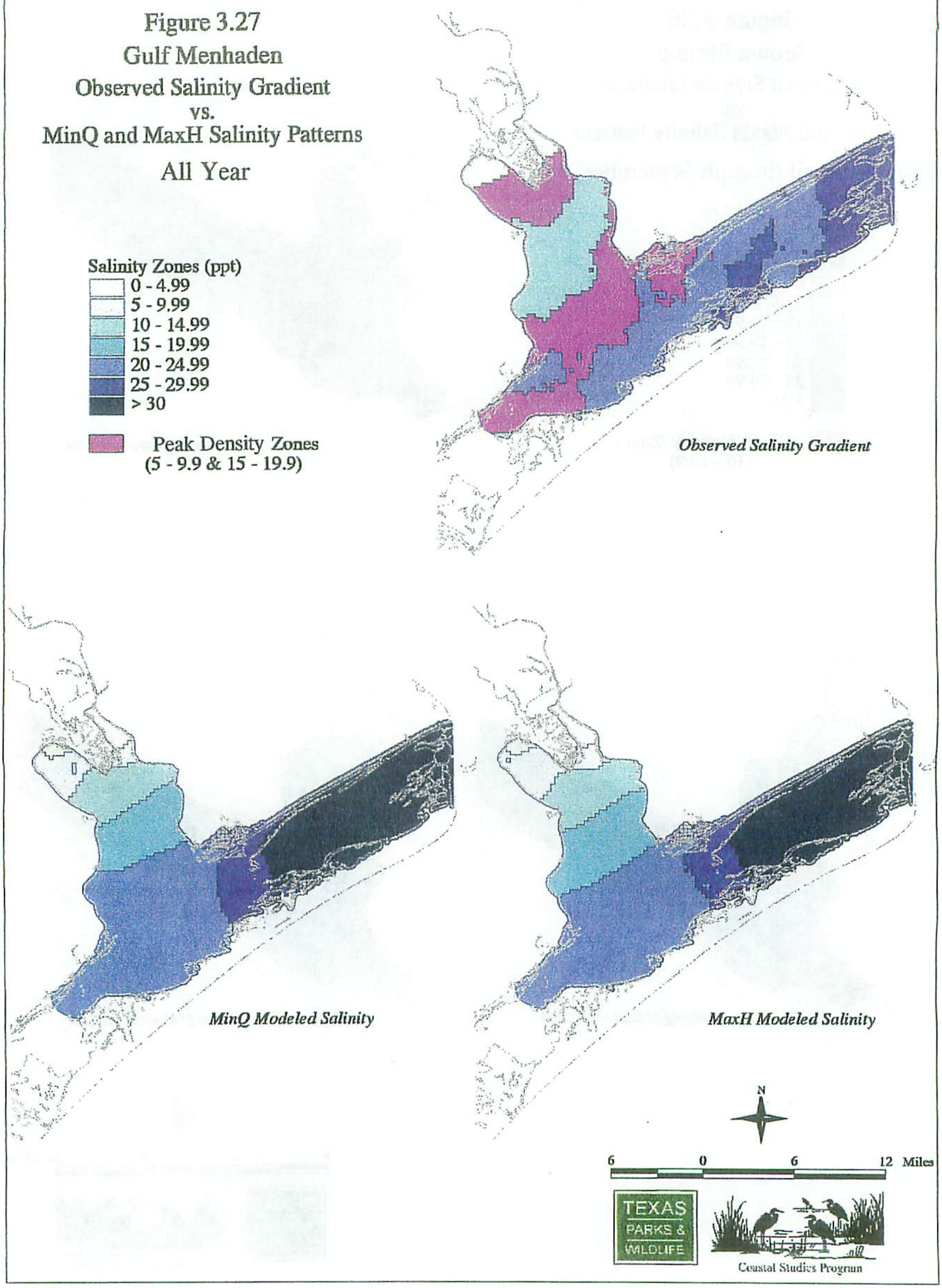


Figure 3.28
Atlantic Croaker
Observed Salinity Gradient
vs.
MinQ and MaxH Salinity Patterns
February through July

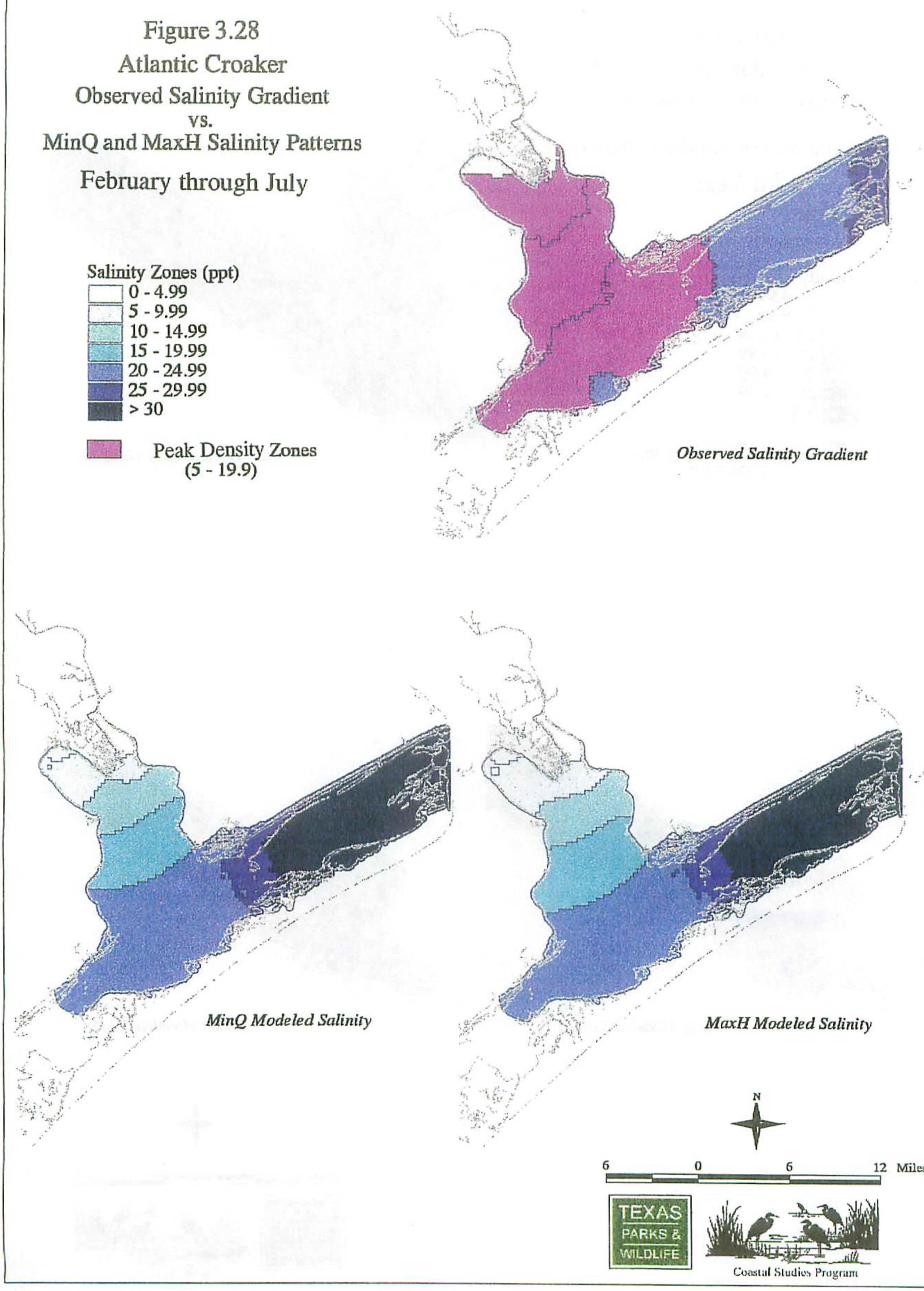
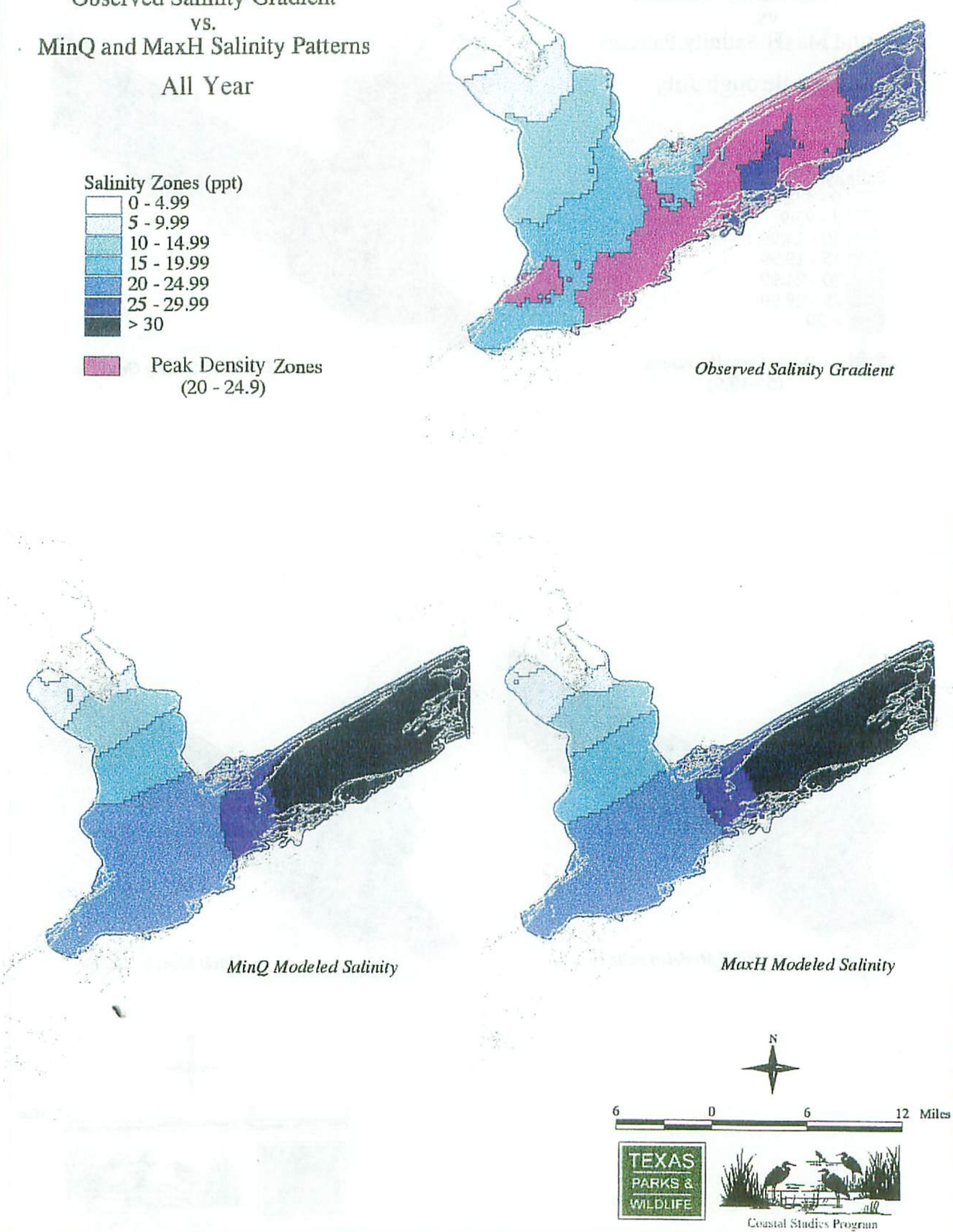


Figure 3.29
Bay Anchovy
Observed Salinity Gradient
vs.
MinQ and MaxH Salinity Patterns
All Year



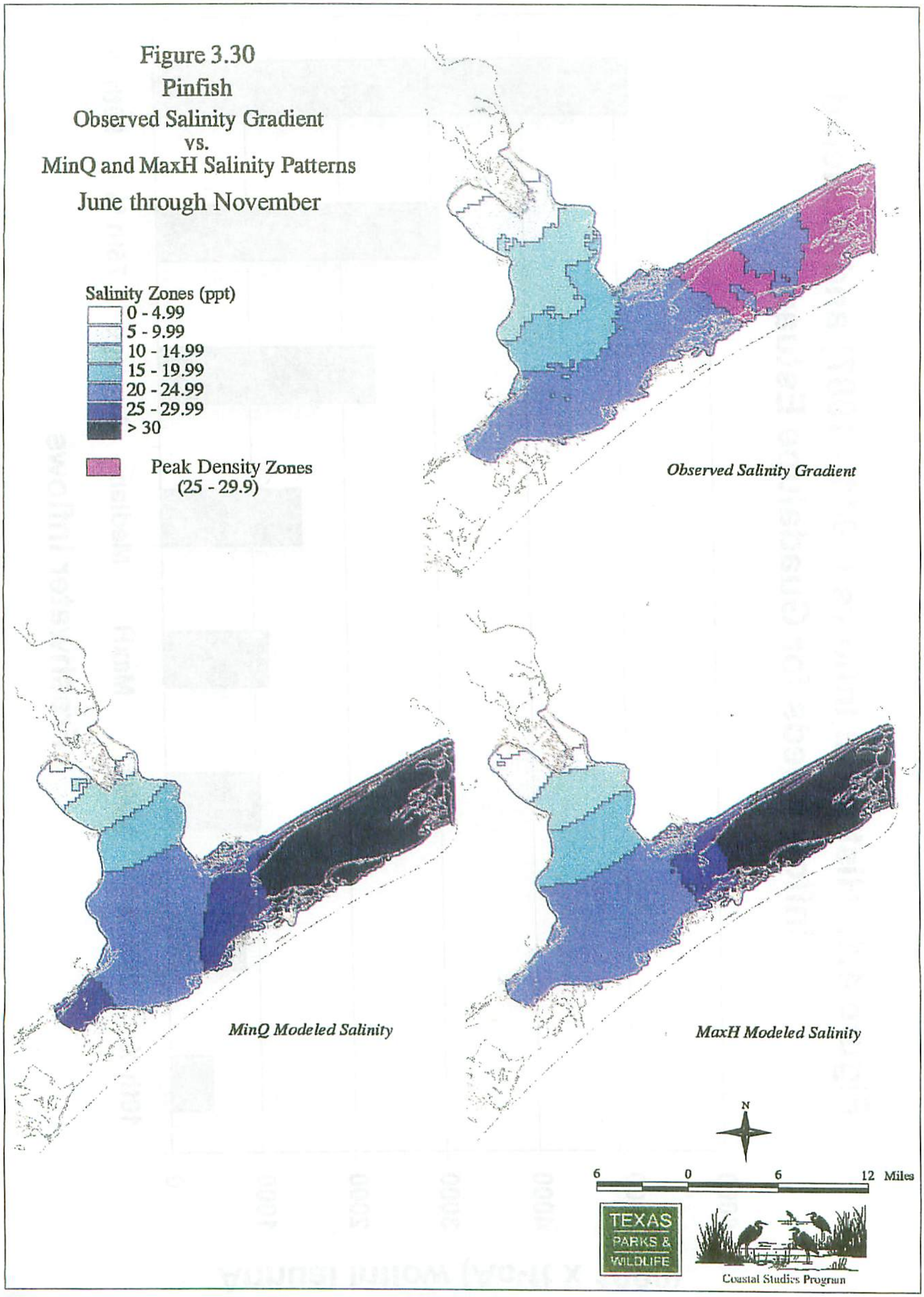


Figure 3.30
Pinfish
Observed Salinity Gradient
vs.
MinQ and MaxH Salinity Patterns
June through November
Salinity Zones (ppt)
0 - 4.99
5 - 9.99
10 - 14.99
15 - 19.99
20 - 24.99
25 - 29.99
> 30
Peak Density Zones
(25 - 29.9)
Observed Salinity Gradient
MinQ Modeled Salinity
MaxH Modeled Salinity
N
6
0
6
12 Miles
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Figure 4.1. Historical Inflows (1941 - 1987) and Modeled Inflow Needs for Guadalupe Estuary

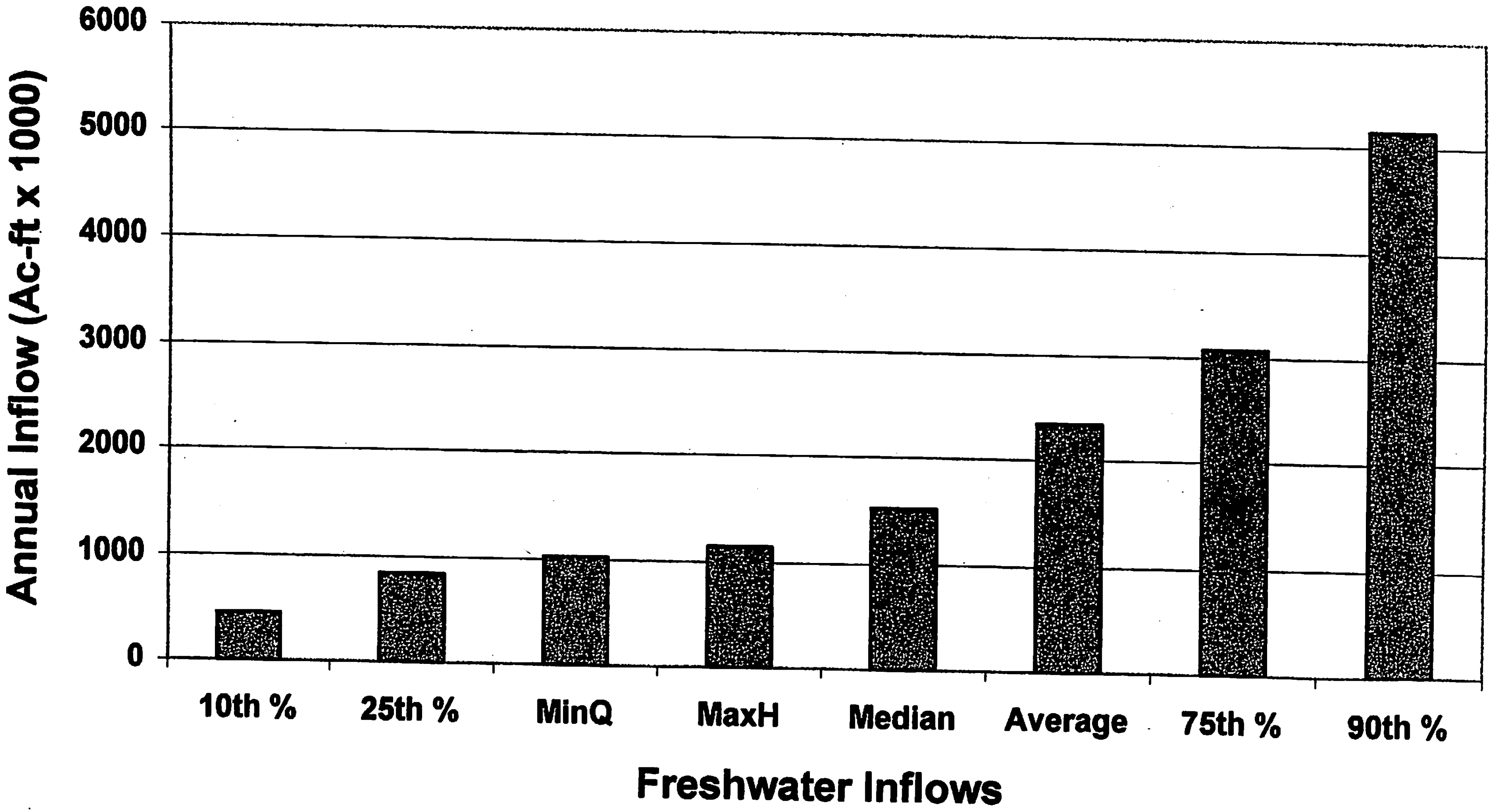


Figure 5.2A Biomass Ratio Constraints

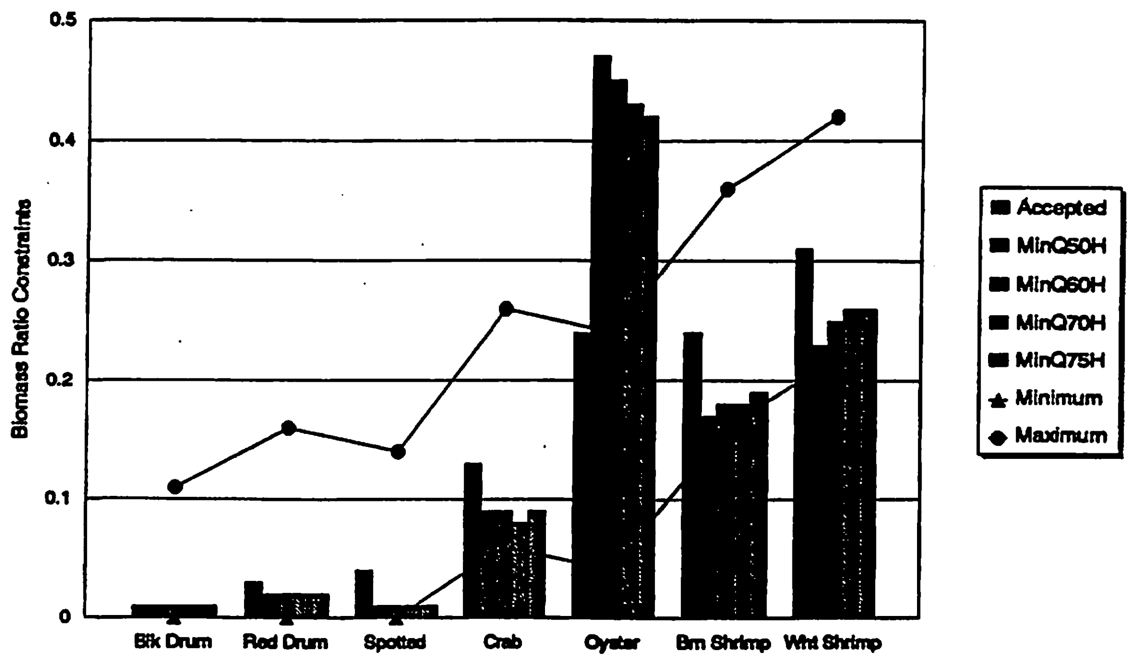
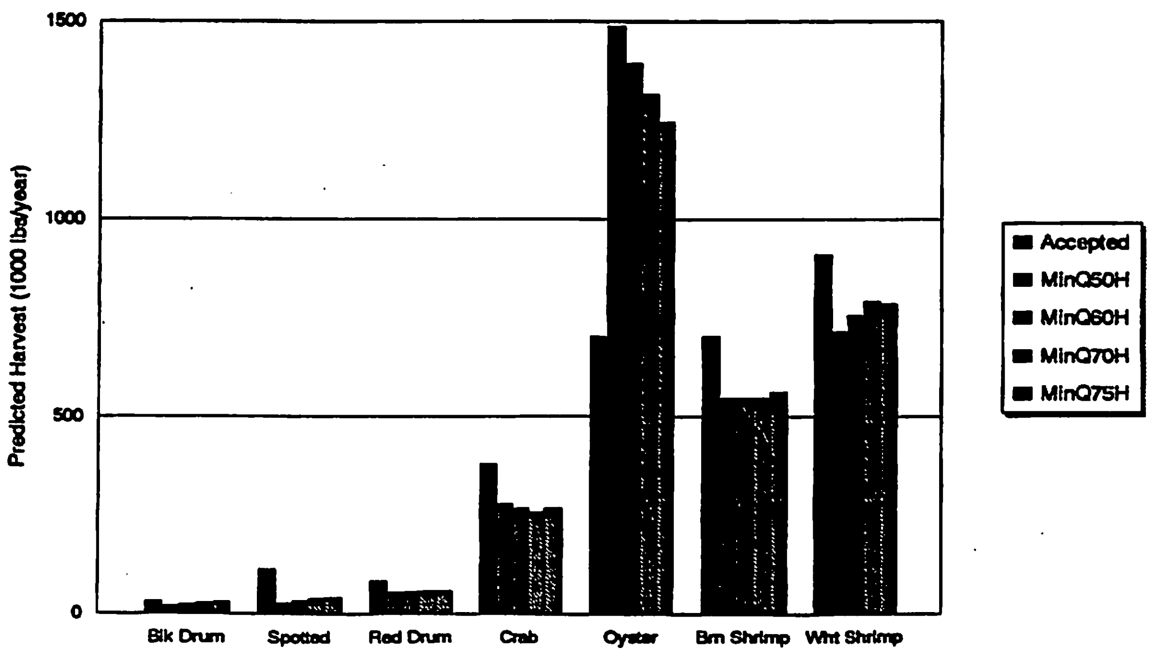


Figure 5.2B Predicted Harvest (1000 lbs)



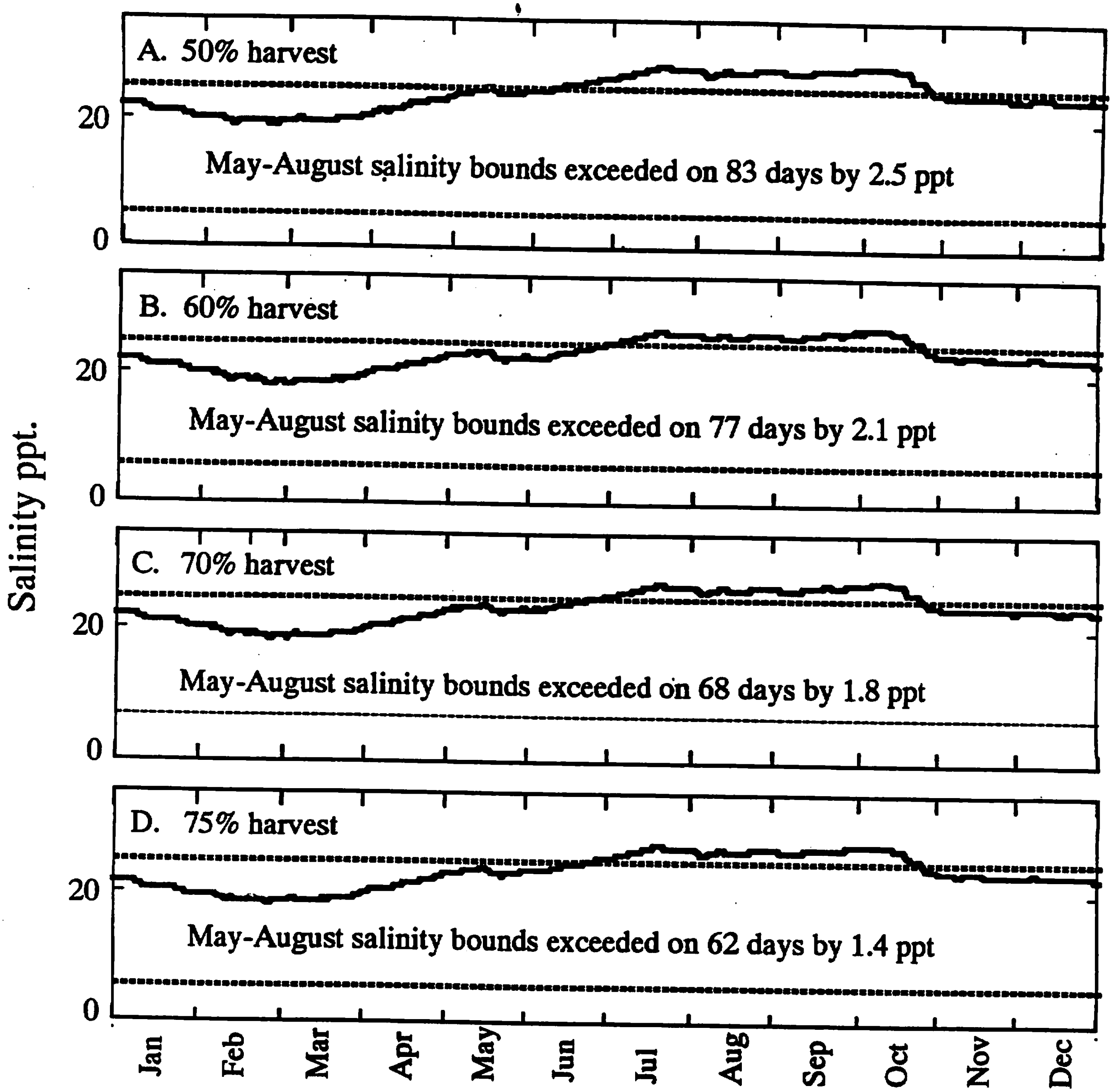


Figure 5.3. Annual salinity time series for San Antonio Bay Mid Bay node. Solid lines show MinQ simulated salinities from hydrodynamic model for the cases: A. 50% Harvest, B. 60% Harvest, C. 70% Harvest, and D. 75% Harvest. Dashed lines show lower and upper salinity bounds used for the Upper Bay constraints in the optimization model. Number of days and the mean difference for which salinity constraints are exceeded are shown for the May-August period critical to the life cycle of several bay species.

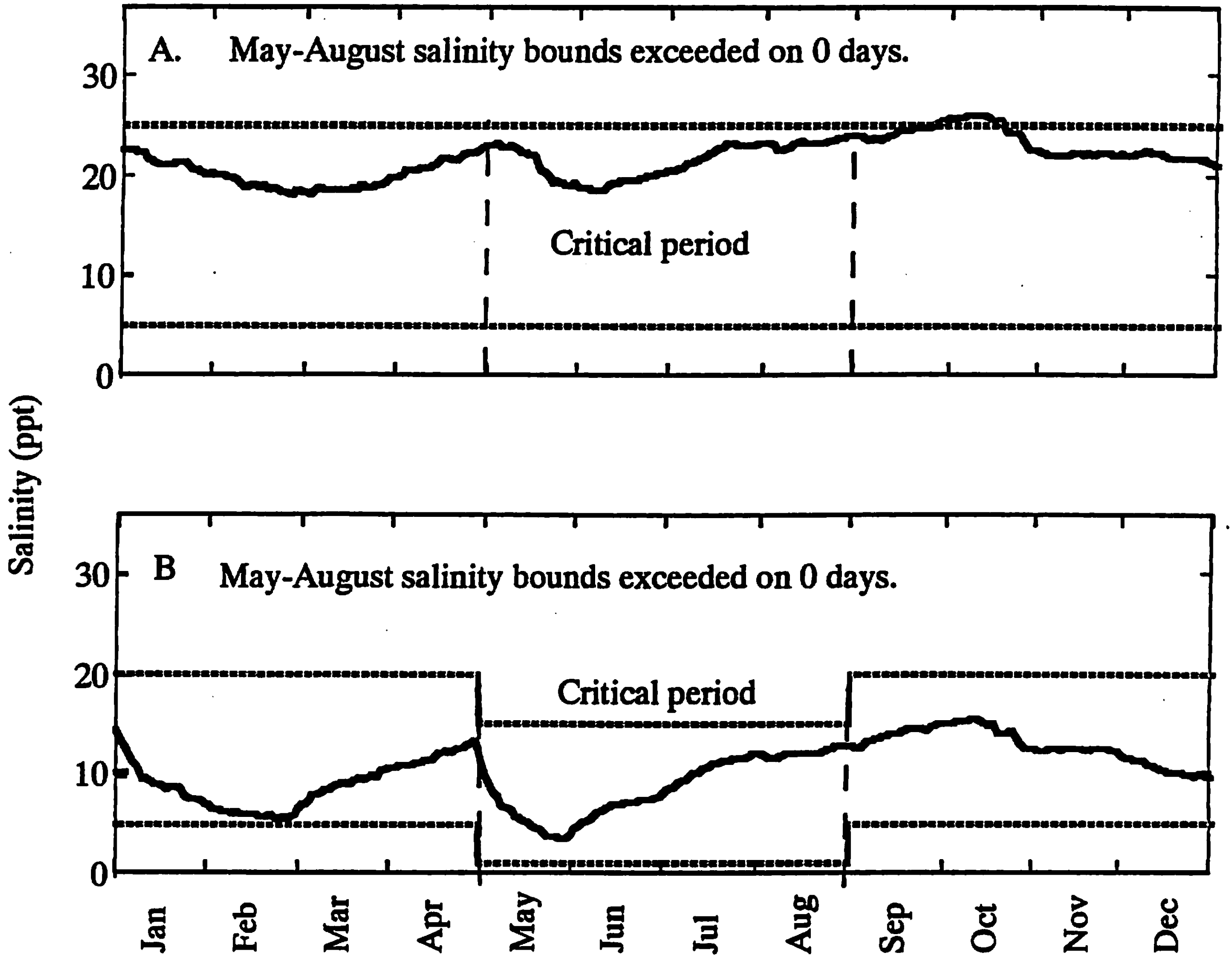


Figure 5.4. Annual salinity time series for A. Mid San Antonio Bay and B. San Antonio Bay shoreline near Lucas Lake. Solid lines show simulated salinities from hydrodynamic model for the MinQ case. Dashed lines show lower and upper salinity bounds used for the Lower Bay constraints in the optimization model. Number of days and the mean difference for which salinity constraints are exceeded are shown for the May-August period critical to the life cycle of several bay species.

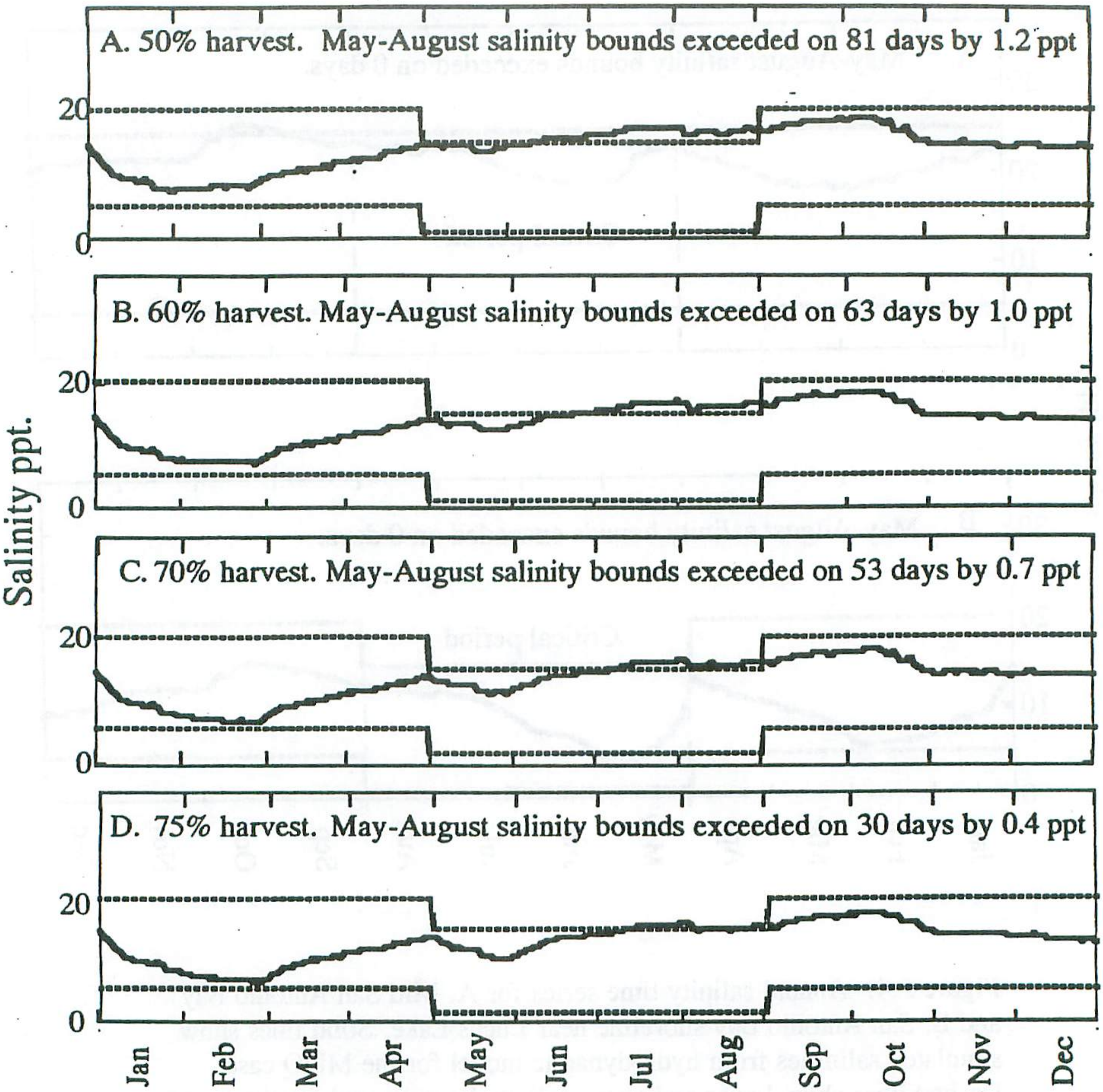


Figure 5.5. Annual salinity time series for San Antonio shoreline near Lucas Lake. Solid lines show MinQ simulated salinities from hydrodynamic model for the cases: A. 50% Harvest, B. 60% Harvest, C. 70% Harvest, and D. 75% Harvest. Dashed lines show lower and upper salinity bounds used for the Upper Bay constraints in the optimization model. Number of days and the mean difference for which salinity constraints are exceeded are shown for the May-August period critical to the life cycle of several bay species.