Freshwater Inflow Recommendation for the Trinity-San Jacinto Estuary of Texas

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Executive Summary

Freshwater inflows from rivers, streams and local runoff maintain the salinity gradients, nutrient loadings and sediment inputs necessary to support a healthy and productive estuary. The Texas Water Development Board (TWDB) and Texas Parks and Wildlife Department (TPWD) have been legislatively mandated to determine the effects of and needs for freshwater inflows to estuaries by House Bill 2 (1985) and Senate Bill (1987). Section 11.147 of the Texas Water Code guides freshwater inflow studies by the two agencies which are intended to ensure "a salinity, nutrient, and sediment loading regime adequate to maintain an ecologically sound environment..."

Working cooperatively with mathematical models, the TWDB and TPWD have estimated that the Trinity-San Jacinto estuary requires 5.22 million acre-ft/year of freshwater inflows in order to maximize harvest of oysters, white and brown shrimp, blue crabs, red and black drum, spotted sea trout, and flounder. Annual freshwater inflow of about 4.16 million acre-ft/year is estimated to allow acceptable levels of harvest. These flows, 4.16 and 5.22 million acre-ft/year, lie between the 10^{th} and 50^{th} percentile flow for the system (as determined from flow records over the period of 1941-1990). Both inflow regimes are similar for most months of the year except for March through June when higher inflows appear to support larger harvests over the year.

The estimated annual harvest at an inflow of 5.22 million acre-ft/year is 11.7 million pounds. Annual harvest is calculated to approximate 10.7 million pounds at 4.16 million acre-ft/year.

TPWD biologists analyzed historical fish community data collected by the TPWD Coastal Fisheries biologists as part of a long-term, probabilistically-based sampling design. These data were evaluated to determine whether the mathematical model estimates were reasonable. TPWD considered fisheries independent data collected for oysters, white and brown shrimp, blue crabs, Atlantic Croaker, bay anchovy and pinfish.

Analysis revealed that blue crab, white shrimp, Gulf menhaden, and pinfish would tend to inhabit a larger portion of the system at 5.22 million acre-ft/year inflow while brown shrimp and bay anchovies would occur in higher numbers at inflows of about 4.16 million acre-ft/year.

The two inflow amounts evaluated would allow important oyster reefs to generally be protected from the oyster parasite, Perkinsus marinus, which tends to thrive in higher salinities.

Results of TPWD analysis suggest that a freshwater inflow between 4.16 to 5.22 million acre-ft/year with an appropriate seasonal distribution would allow the ecological health and productivity of the bay to be protected in the future.

Section 1. Introduction

This report summarizes the protocol and analyses used to determine the target freshwater inflow (FWI) needed to support the biological productivity of the Trinity - San Jacinto Estuary. Each Texas estuary requires FWI in order to maintain the proper salinity gradients, nutrient concentrations and sediment loading, which in turn support the abundance and distribution of fauna and flora in these systems. Freshwater inflow from rivers and the local ungaged runoff thus acts as a critical mechanism to regulate the coastal factors and processes that produce an "ecologically sound and healthy estuary".

Estuaries require a range of freshwater inflows that satisfy both the ecological and physical requirements of the system. However, there is also a minimum threshold at the low end of the FWI range where one of the ecological functions of FWI becomes limiting, whether it is maintenance of salinities or supplying nutrients, particulate organic matter, or sediments. It is important to realize that below this critical minimum FWI, ecological health and productivity will suffer, perhaps drastically. In order that water resources in Texas may be developed with minimal biological damage to the State's estuaries, Texas Parks and Wildlife Department (TPWD) seeks to identify for management purposes the amounts of FWI needed to sustain the historical average productivity and typical biodiversity of each estuarine system.

The overall objectives, research design, reference data, and analytical methods for the freshwater inflow studies were previously detailed in the published report – "Freshwater inflows to Texas bays and estuaries: ecological relationships and methods for determination of needs" (Longley, 1994). This previous work was a joint interagency project, in which Texas Water Development Board (TWDB) developed hydrologic modeling techniques and assessed trends in hydrologic conditions of Texas estuaries, while TPWD reviewed trends in coastal biological data and provided ecological data synthesis for the systems.

The models and procedures developed during this earlier effort (Longley, 1994) were further tested, refined, and applied to the Galveston Bay system. The current study has led to a prediction of a range of flows including two target flows to the estuary, the MinQ and the MaxH FWI. The optimal FWI (MaxH) constitutes a target flow to the estuary which would maximize biological productivity (as measured by fisheries landings). This MaxH inflow is distinct from the MinQ inflow level which represents a minimal inflow to maintain both the historical salinity gradients and biological productivity. Maintenance inflows are those occurring between MinQ and the higher optimal MaxH level.

Two other inflow levels, MinQ-Sal and MaxQ, are also important to know in order to be able to manage the system properly. MinQ-Sal is the flow at which only the salinity constraints of the estuary are met and it is in general lower than the MinQ. On the other hand, MaxQ is the maximum level of inflow at which both the salinity requirements and biological productivity in the system are met but the productivity may not necessarily be maximized. MaxH lies between MinQ and MaxQ, and is generally considerably higher than the MinQ-Sal.

The objective of this report is to find a monthly flow pattern and an annual inflow, which may lead to a sound and healthy environment for the biota. The predicted MaxH seems a reasonable inflow level compared to the historical pattern and also maximizes fishery production. It may be selected and recommended for management purposes. Conversely, MinQ may be recommended under low inflow or drought conditions. This report presents the description of the protocol and the analyses performed to assess and validate the two target inflow levels, MinQ and MaxH.

Section 2. Analytical Protocol

Sound decisions concerning FWI management must be based on accurate scientific facts and a consistent analytical protocol. For this purpose, the general protocol guiding the FWI determination process is outlined in the attached diagrams (Fig. 2.0 A & B). Figure 2.0A shows the relationships between compiled scientific information and the logical sequence of analyses used by TWDB and TPWD to jointly produce the inflow target as predicted by optimization modeling. Subsequent procedures and analyses performed by TPWD to independently verify the predicted FWI target and develop a FWI recommendation for the Galveston Estuary are the subject of this report (Fig. 2.0B). The final step of the protocol requires that TNRCC, TPWD, TWDB and interested stakeholders develop a strategy and implementation plan to insure that the needed FWI is delivered to the estuary.

2.1 TxEMP Model Results

The protocol for this report begins with evaluation of the output from optimization and hydrodynamic modeling which is in the form of a predicted, theoretical optimal FWI range. These models depend heavily on estuarine monitoring data as the basis for assumptions and input constraints. The Estuarine Mathematical Programming or Optimization Model (TxEMP), which uses multi-objective functions and incorporates statistical uncertainty in the inflow solution, produces a range of solutions that simultaneously predict optimal annual inflows and corresponding estuarine fishery harvests. Another important result of the optimization process is the delineation of an optimum inflow pattern characteristic of the historical, monthly pattern for the estuary. The output from the TxEMP model is then used in the hydrodynamic circulation model (TxBLEND) to evaluate effects on salinity distributions and bay circulation.

The TxEMP model generates a performance curve (see Longley, 1994) that graphically describes how varying amounts of annual inflow affect fishery harvest. The performance curve (Fig.2.1A) is generated by first finding its endpoints, the minimum annual inflow (MinQ) and maximum annual inflow (MaxQ), that satisfy the constraint sets (see Appendix). From this analysis, MinQ was found to be 4.16 million acre-ft/year and MaxQ was 6.18 million acre-ft/year. These flows were between the 25th percentile and the median of the historical inflows (1941-1990) (Fig. 2.2). The monthly distribution of inflows was found by allowing TxEMP to optimize for the maximum possible harvest while limiting annual inflow to the minimum annual inflow (the MinQ case). Even though annual inflow is limited to only the minimum amount necessary to satisfy the constraint sets, monthly inflows are distributed in the seasonal pattern most beneficial to the biota in the system.

Finally, TxEMP was executed to optimize for fishery harvest (MaxH) within the range of annual 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 the maximum harvest. For the Galveston Bay system, MaxH was estimated to be 5.22 million acre-ft/year with the corresponding fishery harvest of 11.67 million pounds. Figure 2.1B shows the monthly inflows under the MinQ and MaxH conditions. Table 2.1 also lists the monthly flow levels along with inflow bounds developed for the model. Salinity bounds set in the TxEMP model were formulated by TWDB and TPWD for three regions in the Galveston estuary. These constraints were developed based on historical salinity data and salinity tolerances of the key biota in these particular regions.

Table 2.1. Monthly inflow bounds (as percentile of historical inflows) and the predicted inflows for MinQ and MaxH (in thousands of acre-feet).

Month	Flow Bounds 10th	50th	MinQ	MaxH
Jan	150.5	699.6	150.5	150.5
Feb	155.2	946.5	216.7	155.2
Mar	164.4	652.8	363.9	652.8
Apr	193.9	632.5	352.6	632.5
May	260.0	1273.7	679.7	1273.7
Jun	190.3	838.7	448.1	839.7
Jul	107.7	340.4	232.7	211.5
Aug	78.0	225.3	153.9	139.9
Sep	93.3	330.2	330.3	102.9
Oct	49.9	251.9	251.9	78.5
Nov	89.5	351.5	351.5	351.5
Dec	93.9	626.8	626.8	626.8
Total			4158.6	5215.5

Fishery harvest predicted by TxEMP under the different inflow levels ranged from 10.7 million pounds at MinQ to 11.7 million pounds at MaxH. Fishery harvest at MaxQ was the lowest among the three inflows (~10.6 million pounds). In both the MaxH and MinQ cases, eastern oyster and white shrimp dominated the harvest (Table 2.2).

Table 2.2 . Minimum and maximum historical harvest and the predicted harvest (in thousands of pounds) under MinQ and MaxH inflow conditions.

Species	Historical (min)	Harvest (max)	MinQ	MaxH
Blue crab	311.3	3018.6	1359.7	1867.0
Oyster	43.1	6949.1	3779.7	4150.5
Red drum	1.3	97.5	24.9	29.8
Black drum	7.9	269.0	74.5	98.3
Spotted seatrout	17.0	344.2	344.2	344.2
Brown shrimp	8.6	3261.4	1551.8	1409.9
White shrimp	82.0	4700.7	3522.2	3731.6
Flounder	4.2	222.7	45.8	45.8
Total harvest			10702.6	11677.0

2.2 TxBLEND

The effect of annual and seasonal inflows estimated by TxEMP was assessed using TxBLEND, a two-dimensional, finite element hydrodynamic model which simulates circulation and predicts salinity patterns of the system under the varying freshwater inflow regimes. In this study, the input variables included both the seasonal and annual inflows from the TxEMP runs together with the tidal and climate conditions measured during a historically dry year.

The TxBLEND model computes salinity values at a 2-hour time interval over 1600 nodes in the Galveston Bay. The simulated salinity values resulting from each inflow scenario were then illustrated by output in two formats:

1. Isohalines by month for the entire bay system, and
2. Daily salinity variation (for 365 days) at selected locations in the upper and lower Galveston Bay.

Section 3. Analysis of Biological Responses to Historical Freshwater Inflows

Although estuarine productivity can be assessed by a large variety of criteria, fisheries species' occurrence and abundance were analyzed to gage FWI effects. If salinity or other FWI-related factors provide for the growth requirements of sensitive indicator species, then we may conclude that a particular FWI regime is adequate for maintaining estuarine health. Two major types of biological analyses were performed: 1) verifying the biotic suitability of salinity zones produced from the hydrodynamic model runs, and 2) demonstrating dependent relationships between representative biota and FWI (especially salinity) regimes from actual field data.

3.1 Evaluation of Biological Responses

This part of the report presents the spatial and statistical analyses of long-term biological survey data collected by TPWD in order to verify and assess the model predictions. These historical hydrographic and biological monitoring data produce a picture of the typical ecosystems and environmental conditions for the Galveston Bay system. This step in the protocol offers a 'reality check' on results from the prior theoretical modeling exercises. Galveston Bay has a diversity of habitat types that need to be considered in a biological assessment (Fig. 2.3). The abundance of typical fishery species and their known salinity or habitat requirements in the estuary are the basis for evaluating the true impact of FWI regimes. By comparing predicted results with actual field data for the bay system under known inflow conditions, we can infer whether or not the model results are reasonable and appropriate. In effect this provides an independent check on effects from the proposed FWI management scenarios. Based on this biological assessment of impact, a final FWI recommendation can be proposed.

Biological monitoring information consisted of sampling data on estuarine fish species and their wetland habitats obtained from literature sources, TPWD databases and field surveys by departmental staff. For purposes of this discussion, seven target species, their growth requirements and environmental tolerance limits were used to assess the adequacy of different FWI amounts. The source of fish and shellfish data was the TPWD Coastal Fisheries Resource Monitoring Program which started bay trawl and bag seine fish surveys in the late 1970's (Kana et al., 1993). This survey program collects random trawl and bag seine samples from all Texas bays on a monthly basis. Along with the abundance of organisms, hydrographic data (e.g. salinity) are also collected at all sample sites. This Coastal Fisheries database and its use to describe species distribution and productivity are thoroughly discussed in the original Bays and Estuaries report (Boyd and Green, 1994; Lee, 1994).

3.2 Effects of MinQ vs MaxH on Salinity Regimes

TWDB and TPWD have used the hydrodynamic model to predict salinity gradients in Galveston Bay. These salinity distributions are then superimposed on fishery distributions to assess the effects freshwater flows have on sensitive fishery species. The results of this model validation analysis are presented and summarized here.

Because output from TxBLEND consists basically of a grid map of salinity at nodes throughout the bay, GIS (geographic information system) techniques were used to compare these salinity maps for critical FWI conditions. 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 over 1600 grid nodes were subjected to contouring to produce salinity zones in 5–ppt increments, using the kriging module from ARC/INFO. These salinity contour plots are displayed on a monthly basis (e.g. Figs 3.1 – 3.3). To contrast the inflow cases, these figures show both the MaxH and MinQ cases and an image representing the difference between the two cases.

Examination of the plots indicates that salinity zones for the two cases were essentially identical in January (Fig. 3.1). Salinity zones were also similar with a gradual increasing difference in the two scenarios from April through June (Fig. 3.2). This trend reversed with the difference between MaxH and MinQ becoming minimal in October and remaining so until the end of the year (Fig. 3.3). The greatest differences occurred in lower Galveston Bay and West Bay. In summary, observed differences in seasonal salinity zones between MinQ and MaxH cases never exceeded 5 ppt.

3.3 Time Series Analysis of Salinity at Critical Bay Sites

Time series analyses were performed on the salinity data from the circulation model (TxBLEND) at selected sites in the bay. The objective was to evaluate the effect of the annual inflow predictions from the optimization model (TxEMP) and hence, salinity on the biota. Mean daily salinity computed from TxBLEND was compared to salinity bounds (Table 3.1), and the number of days at which salinity constraints were exceeded was then summed up for the individual site.

Table 3.1. Salinity bounds used in Galveston Bay optimization model. Trinity, Red Bluff, and Dollar sites correspond to model nodes 104, 560 and 636 (for details see Fig. 3.4).

Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Trinity Bay	5	5	5	5	1	1	1	5	5	5	5	5
	20	20	15	15	15	15	15	15	20	20	20	20
Red Bluff	5	5	5	5	5	2	5	5	5	5	5	5
	20	20	20	20	20	15	15	20	25	25	20	20
Dollar Bay	10	10	10	10	10	10	10	10	10	10	10	10
	30	30	25	25	20	20	25	30	30	30	30	30

In the upper bay, the time series sites (e.g. nodes 104 and 283) showed small variations in salinity with season (Fig. 3.5). The lowest salinity occurred most notably in summer with MaxH. The simulated daily salinity at these sites, however, never exceeded their salinity bounds at any time during the year at ether MinQ or MaxH. In the middle of Galveston Bay (e.g. nodes 530 and 353), the lower salinity bound was exceeded for about 80 to 100 days for MaxH case, but were within the constraints under the MinQ inflow (Fig. 3.6). A similar salinity trend was observed for sites in the lower bay such as nodes 503 (Fig. 3.7), 507 and 636. Only in West Bay at a considerable distance from Dollar Bay (e.g. node 1333), were salinity bounds exceeded at both MinQ and MaxH cases during the spring. This area is separated from the main bay area by a causeway and would be expected to have salinity similar to that of coastal ocean waters.

3.4 Analysis of Species Spatial Distribution and Determination of Peak Density Zones

The seven target species analyzed include both shellfish (white and brown shrimp, and blue crab) and finfish (Atlantic croaker, Gulf menhaden, bay anchovy and pinfish), and the seven salinity zones encompassed the salinity range from near freshwater to coastal sea water (>30 ppt). The same analytical approach as used for the Guadalupe estuary study (see Pulich et al., 1998) was applied to this Galveston Bay system analysis. Briefly, the seasonal abundance of the seven target species was displayed using historical data (12 years pooled) to establish a time frame when species were abundant. By performing GIS overlays between species abundance and contoured salinity zones derived by kriging, species spatial distributions and associations with salinity were identified.

GIS plots depict species' general distribution patterns in the bay system and their relative abundance within each individual salinity zone. Figures. 3.8 to 3.14 display the spatial distributions along the salinity gradients in the Galveston Bay system. The salinity distribution patterns were different among the seven species of interest because of the difference in species' seasonal abundance patterns and consequently the time frame selected for analysis as described earlier. A species' spatial abundance was then statistically compared to locate its peak density zone along the salinity gradient. Peak density zone was here defined as a salinity zone where species mean catch per unit effort (CPUE) was significantly higher than any other salinity zones in the system. Table 3.2 shows the results of one-way ANOVA and the Dunn's multiple comparison test of the data set, and Table 3.3 summarizes peak density zones for the study species.

Table 3.2. Spatial distribution of selected fish and shellfish along the salinity gradients in the Galveston Bay system. Mean species CPUEs decline from left to right and are grouped by Dunn's multiple comparison procedure. Salinity zones underscored by different segments differ statistically ($p < 0.05$) in their mean CPUEs. Salinity zones are designated as 0: 0 - 4.9 ppt, 5: 5 - 9.9 ppt, 10: 10-14.9 ppt, 15: 15-19.9 ppt, 20: 20-24.9 ppt, and 25: 25-29.9 ppt.

Species	Salinity zone	Salinity zones exempted*	Salinity zones excluded **
White Shrimp	10 15 5 20 25	-	0, 30
Brown Shrimp	15 10 5 20	0, 25	30
Blue Crab	5 0 10 15 20	25	30
Atlantic Croaker	5 10 0 15 20	25	30
Gulf Menhaden	10 5 15 20	25	0, 30
Bay Anchovy	10 15 5 20	25	0, 30
Pinfish	20 15 5 10	25	0, 30

* Salinity zones exempted - insufficient sample size (< 1/month).
** Salinity zones excluded- salinity zones which were absent when species was seasonally abundant.

Table 3.3. Peak density zones for target species in the Galveston Bay System.

Species	Peak Density Zones
Blue crab	0 – 14.9 ppt
White shrimp	10 – 14.9
Gulf menhaden	10 – 14.9
Brown shrimp	10 – 19.9
Bay anchovy	10 – 19.9
Pinfish	20 – 24.9
Atlantic croaker	none

White shrimp (Fig.3.8): This species was collected in trawls throughout the year in the Galveston Bay system. However, significant numbers were not observed until mid-summer and its seasonal peak usually occurred in November. White shrimp were known to prefer low to moderate salinity, generally < 10 ppt salinity (Gunter et al., 1964). In Galveston Bay, peak density of white shrimp was found in regions with salinity of 10 to 15 ppt. This particular region covered about 32.2% of the bay area and accounted for >50% of white shrimp population in the bay. Compared with San Antonio Bay, white shrimp in Galveston Bay not only resided in waters of higher salinity but also were in higher abundance in terms of CPUEs.

Brown shrimp (Fig. 3.9): This species occurred in Galveston Bay from April through December, with its seasonal peak recorded in either May, June or July during the year. After July, brown shrimp were low in number, and in general, were less than 2 per 10 minute tow. Their spatial distribution in the bay was similar to that of white shrimp, except that they aggregated in a wider area. The peak density of brown shrimp was observed in areas of 10 to 19.9 ppt salinity. This special zone was 44.3% of the bay area and accounted for 53% of brown shrimp population in the bay system.

Blue crab (Fig.3.10): In the Gulf of Mexico, juvenile blue crab were reported in waters of 2 to 21 ppt salinity, while adult males were found in waters < 10 ppt and gravid females were abundant in waters of > 20 ppt (More and Moffett, 1965; Pattillo et al., 1997). In Galveston Bay, peak abundance of juvenile crab was seasonally recorded in April, May and June, and mainly in regions of 0 to 14.9 ppt salinity. The peak density zone estimated was 60.8% of the bay area and contained about 80% of blue crab population in the bay system.

Gulf menhaden (Fig. 3.11): Although this species has been reported from freshwater to hypersaline zones, high abundance was generally observed in waters from low to moderate salinity (Pattillo et al., 1997). In Galveston Bay, its spatial distribution conformed to this previous finding. Its abundance declined as salinity increased seaward. The peak density zone of Gulf menhaden in the estuary was observed in regions of 10 to 14.9 ppt salinity, which covered 37% of the bay area and embraced about 58.4% of the menhaden in the system.

Atlantic croaker (Fig. 3.12): This species is considered one of the most abundant bottom-dwelling fish in estuaries along the Gulf of Mexico coast (Hoese and Moore, 1977). Juveniles were estuarine to riverine, and preferred oligohaline to mesohaline zones (Parker, 1971). In Galveston Bay, seasonal peak abundance of Atlantic croaker was recorded in April and May. Mean CPUE in the system ranged from 8.35 in the area of 20 to 24.9 ppt salinity to 13.0 in area of 5 to 9.9 ppt salinity. Owing to the higher variability in catch per unit effort, no peak density zone was statistically and spatially defined for this species based on the data collected from 1983 to 1993.

Bay anchovy (Fig. 3.13): This species is small in size but probably constitutes the greatest biomass of any fish in the bays and estuaries along the U.S. Gulf of Mexico coast. Ward and Armstrong (1980) reported that salinity alone may have little impact on juvenile anchovy distribution and abundance in the Matagorda Bay, Texas. On the contrary, a well-defined peak density zone was observed for this species in Galveston Bay. Anchovy were found most abundant in the area of 10 to 19.9 ppt salinity. This peak density zone covered 50.1% of the bay area and comprised 61.8% of its total abundance in the bay.

Pinfish (Fig. 3.14): This species is euryhaline and is able to survive in salinities from 0 to 45 ppt (Pineda, 1975). In Galveston Bay, it occurred year around but was most abundant from June to November. Of the seven species discussed, this is the only one that was significantly more abundant in the lower reaches than in the upper reaches of the bay system. The mean CPUE at the lower polyhaline zone (20 to 24.9 ppt) was 2.1, compared with 0 in the oligohaline zone (0 to 4.99 ppt) or 0.1 in the mesohaline zone (5 to 18 ppt). The peak density zone averaged 26.8% of the bay, but accounted for over two-third of the pinfish population in the bay.

In addition, eastern **oysters** (Crassostrea virginica) are abundant in Galveston Bay. Figure 2.3 shows the distribution of oyster reefs in the bay. Based on TPWD monitoring data, high spat sets were recorded when spring salinity ranged between 17–24 ppt, while adult oysters are euryhaline and grow well in salinities of 14-30 ppt. However, oysters often suffer high mortality due to oyster drill (Thais haemostoma) and the parasite, Perkinsus marinus, especially when salinity is above 15 ppt and temperatures exceed 25C (Castagna and Chanley, 1973; Hofstetter, 1983). A range of salinities between 5 –15 ppt would thus be ideal for oyster populations. Under either MaxH or MinQ, the salinity time series indicate that salinities at the reef sites (Figs.3.6 and 3.7) are well within the optimum range of 5-15 ppt., and the two flows are protective of oyster populations in the bay.

3.5 Comparison of Species Peak Density Zones to Predicted MinQ or MaxH Target Inflow

This analysis was substantially the same as that done for the San Antonio Bay system freshwater inflow report (Pulich et al., 1998) and mainly focused on spatial correlation between salinity gradient and species abundance (CPUE) in the Galveston Bay system. GIS analyses show the salinity distribution at the three inflows, namely MinQ, MaxH and the average historical flows. The particular salinity zone where species peak abundance occurred was estimated and then compared among the three inflow regimes. Fig 3.15 shows an example of this GIS analysis for blue crab in the system.

Compared with that of MinQ, the MaxH inflow provided more habitat area in the peak density zones for four target species (Table 3.4), including blue crab, white shrimp, Gulf menhaden and pinfish. The higher salinity preferences of the brown shrimp and bay anchovy resulted in greater habitat area in their peak density zones under the MinQ inflow condition. Note that the two species have the same salinity range for their peak density, but they are temporally separated in their seasonal distribution in the system. Because of the slightly higher salinity in the winter for observed MinQ and MaxH cases, more habitat was available for bay anchovy than the brown shrimp. The blue crab had the greatest amount of habitat as a result of the timing of its occurrence in the bay and its salinity preference. Even though the peak densities for white shrimp and Gulf menhaden were recorded in the same areas in the bay, they tended to be present at least through part of the spring and summer while blue crab was most abundant. Figs 3.8 to 3.14 present spatial distribution for the target species and information on species' percent abundance along the salinity gradient in the bay system.

Table 3.4. Peak density zone under MinQ and MaxH freshwater inflows.

Target Species	Salinity at Peak Density Zone (ppt)	Seasons (month)	Observed Bay Area (%)	MinQ Bay Area (%)	MaxH Bay Area (%)
Blue crab	0 – 14.99	Mar - Aug	60.76	48.08	60.54
White shrimp	10 – 14.99	Jul – Dec	32.16	21.88	23.67
Gulf menhaden	10 – 14.99	Jan – Dec	37.00	21.27	22.53
Brown shrimp	10 – 19.99	May – Sep	44.29	37.38	30.43
Bay anchovy	10 – 19.99	Jan – Dec	50.14	39.34	35.80
Pinfish	20 – 24.99	Jun – Nov	26.79	13.85	15.68
Atlantic croaker	*	Mar – Aug	-	-	-

* Peak density zone: not detected

Section 4. Summary and Inflow Recommendations

The preceding analyses indicate that both the MinQ and MaxH inflows from Table 2.1 provide adequate flows to maintain the seven target species. Under these cases, a broad salinity gradient, ranging from riverine waters in Trinity Bay to the coastal ocean in the passes or West Galveston Bay, should be maintained and would provide substantial habitat for those species. Variation in salinity at nodes in Trinity, Red Bluff, and Dollar Bay were well within the salinity constraints set to be protective of Galveston Bay fishery species and habitats. The salinity gradient is not substantially compressed or expanded from that found historically in Galveston Bay. Peak density zones for most target species did not differ significantly between MinQ and MaxH inflows. Blue crab harvest, however, could be substantially enhanced at MaxH compared to MinQ. MaxH and MinQ also provide reasonable protection to oyster populations from Dermo, a protozoan parasite, which is responsible for the majority of disease-related oyster mortalities in the Galveston Bay and which tends to thrive in higher salinities. Accordingly, TPWD recommends a target inflow within the range from MinQ to MaxH for the freshwater management plan for Galveston Bay. The reasons are summarized and discussed below.

1. The MinQ and MaxH are not unusual inflows, both are well within the 25^{th} and 50^{th} percentile historical inflows from 1941 to 1990 (see Fig. 2.2). Although the salinity gradient under the MaxH is more favorable to four of the seven target species (white shrimp, blue crab, Gulf menhaden and pinfish), the difference in peak density zone under the MinQ and MaxH conditions is actually very small and generally <2% of the bay area. Blue crab is the species which benefits most by the MaxH inflow (see Table 3.4), showing abundance in 12% more bay area from MinQ to MaxH. Brown shrimp, on the other hand, may benefit by the MinQ inflow, showing peak abundance in 7% more bay area when compared to peak area at the MaxH.

2. Seasonal salinity distribution for the two cases, MinQ and MaxH, was generally the same for most of the months during the year. The maximum difference was detected in spring from April to June in lower Galveston Bay and West Bay (see Fig. 3.2), where the difference amounts to 4 to 5 ppt. For other months, the difference was small (see Figs. 3.1 and 3.3) and insignificant (<1 ppt salinity).

3. It is known that the oyster pathogen, Perkinsus marinus, prefers high salinity waters (> 15 ppt). Infection from this parasite usually occurs in the warmer months between an oyster's first and second year, then intensifies during the second year, killing the oyster before it reaches market size. In the Galveston Bay system, oyster reefs prevail in the middle bay, where salinity under either the MinQ or MaxH cases seldom exceeds 15 ppt in the late spring and during the summer (see Fig. 3.6). Therefore, loss of oyster resources to disease at either the MinQ or MaxH inflows would not appear to be a serious threat in the middle Galveston Bay.

Section 5. References

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Figure 2.0A. Determining freshwater inflows for a healthy estuary.

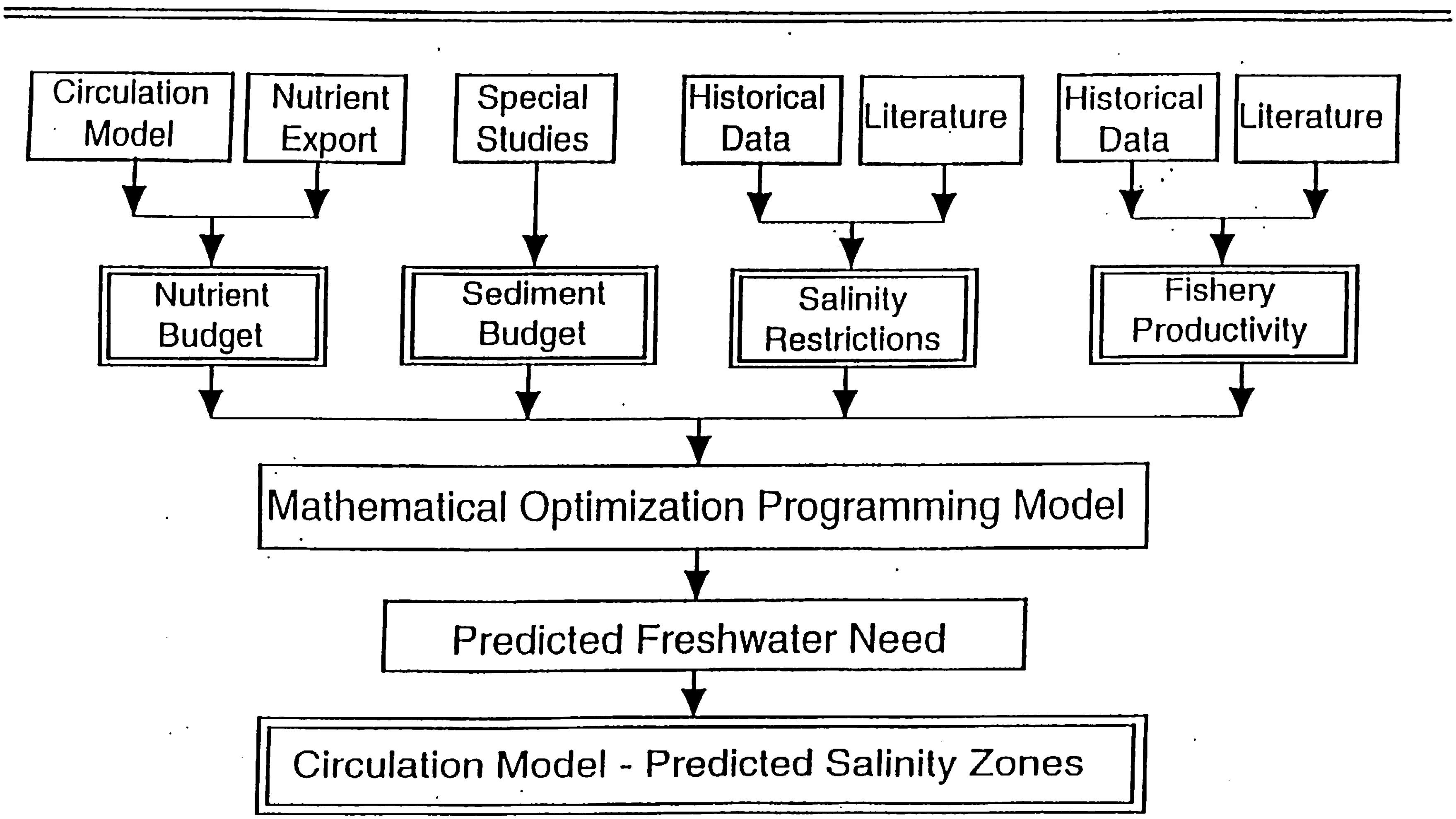
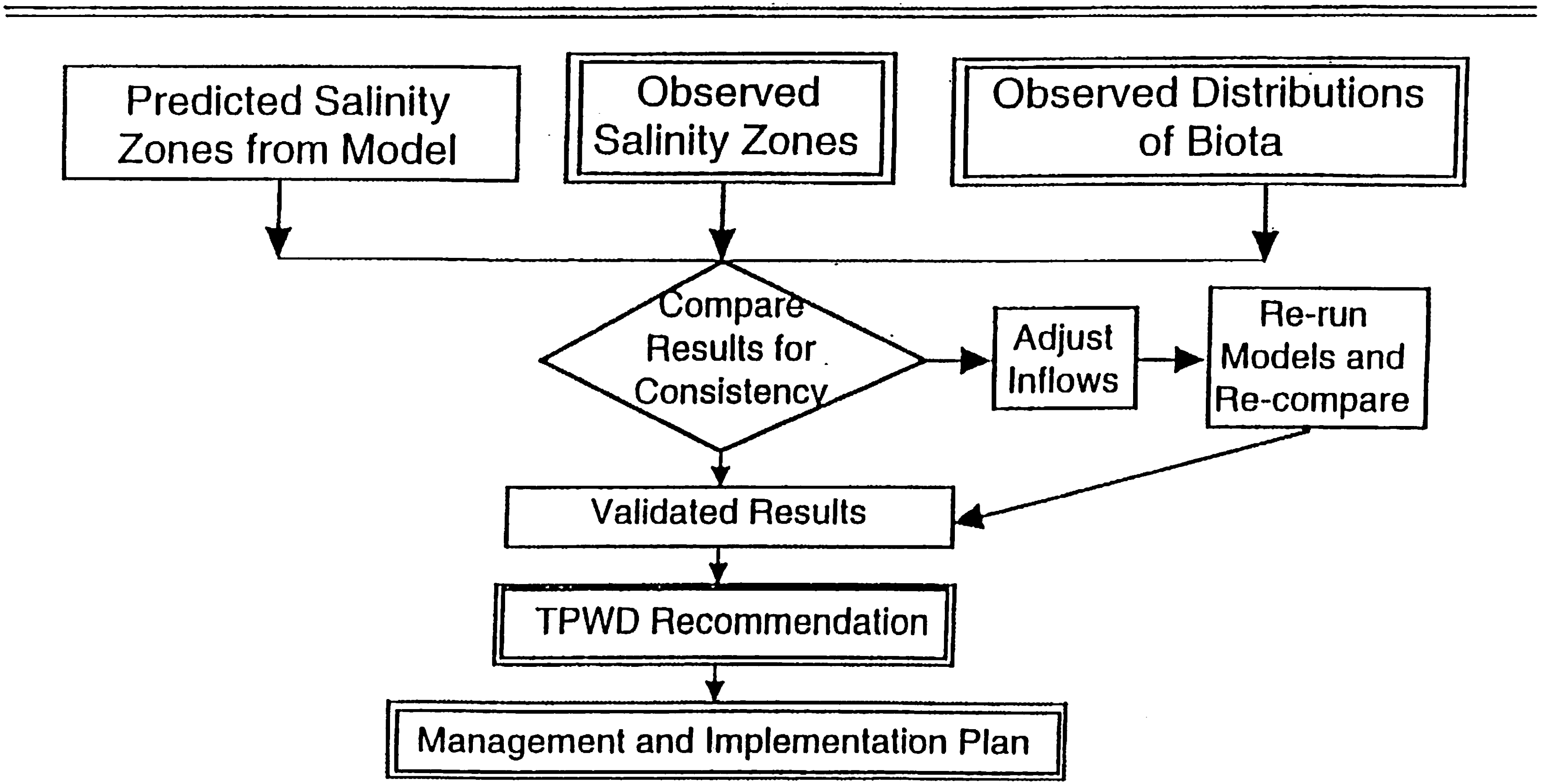
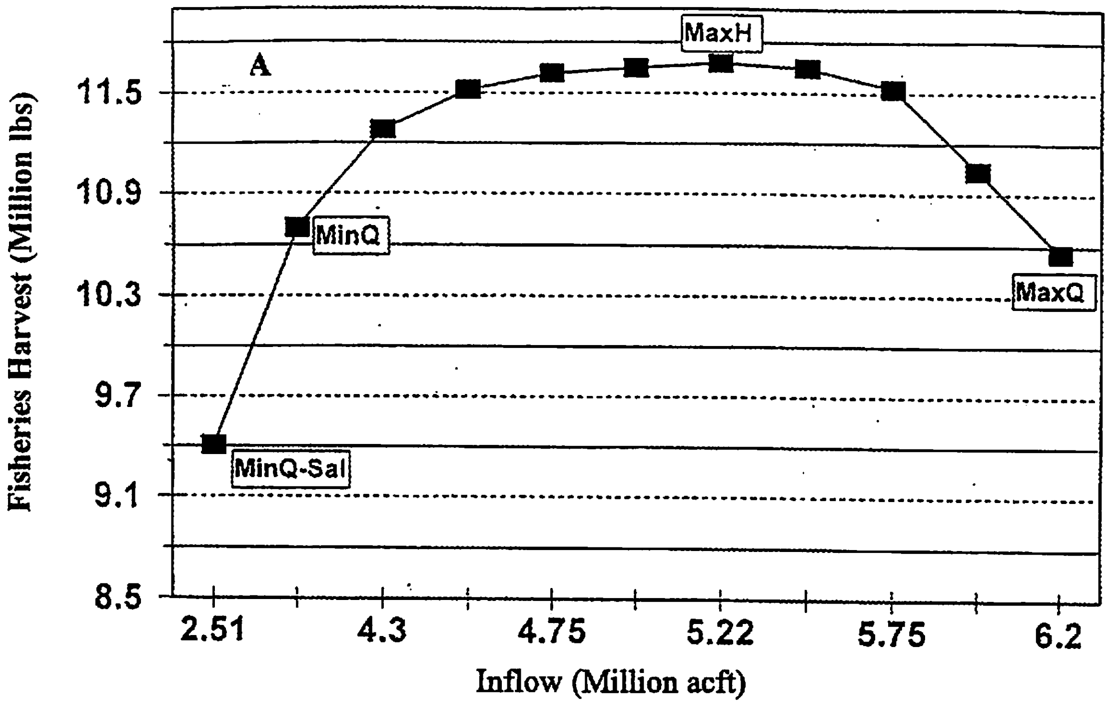


Figure 2.0B. Recommending freshwater inflows for a healthy estuary.





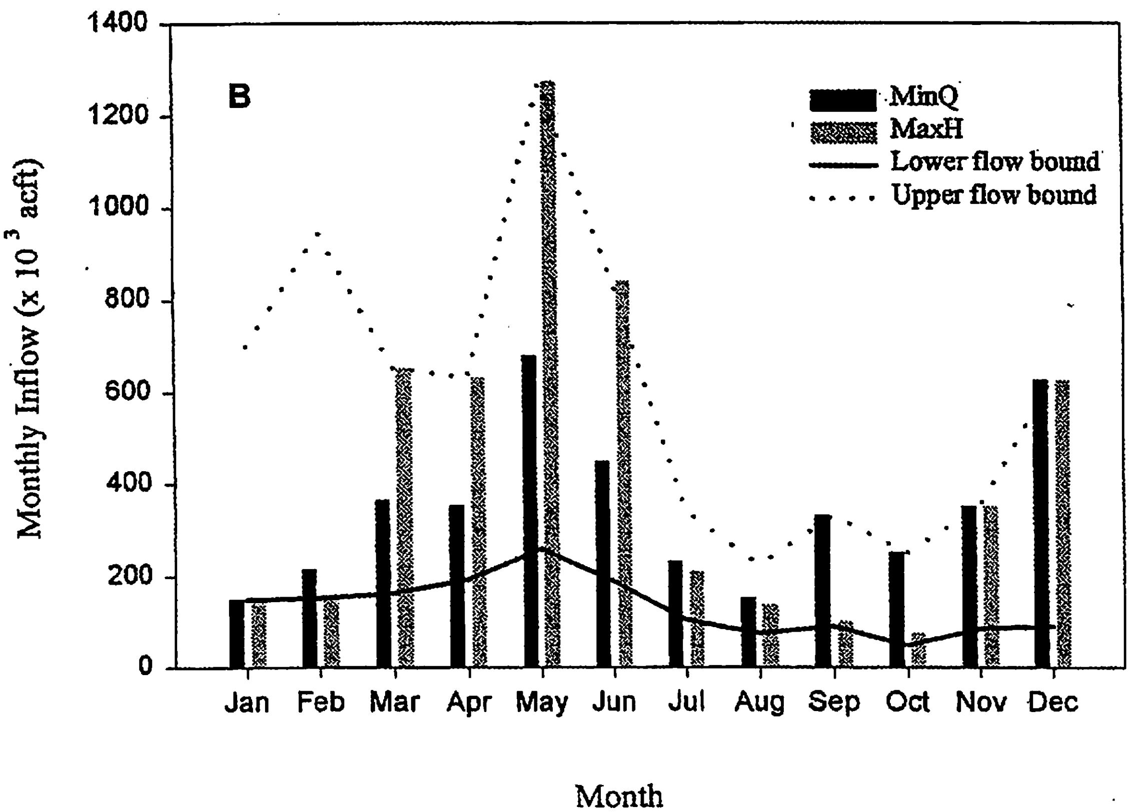
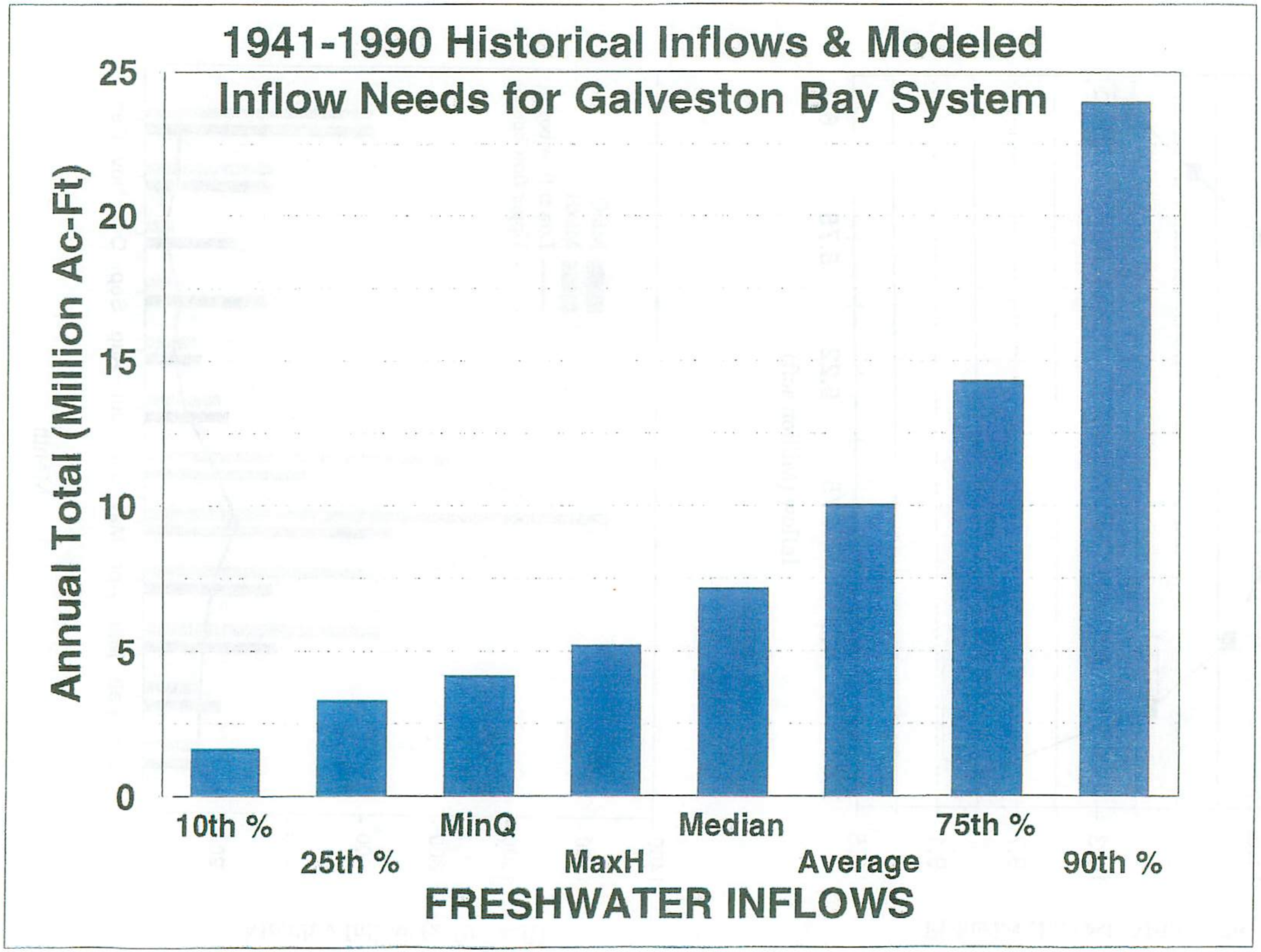


Figure 2.1. MaxH and MinQ inflow cases: Performance curve and monthly inflows.

Figure 2.2


1941-1990 Historical Inflows & Modeled Inflow Needs for Galveston Bay System
Annual Total (Million Ac-Ft)
25
20
15
10
5
0
10th %
25th %
MinQ
MaxH
Median
Average
75th %
90th %
FRESHWATER INFLOWS

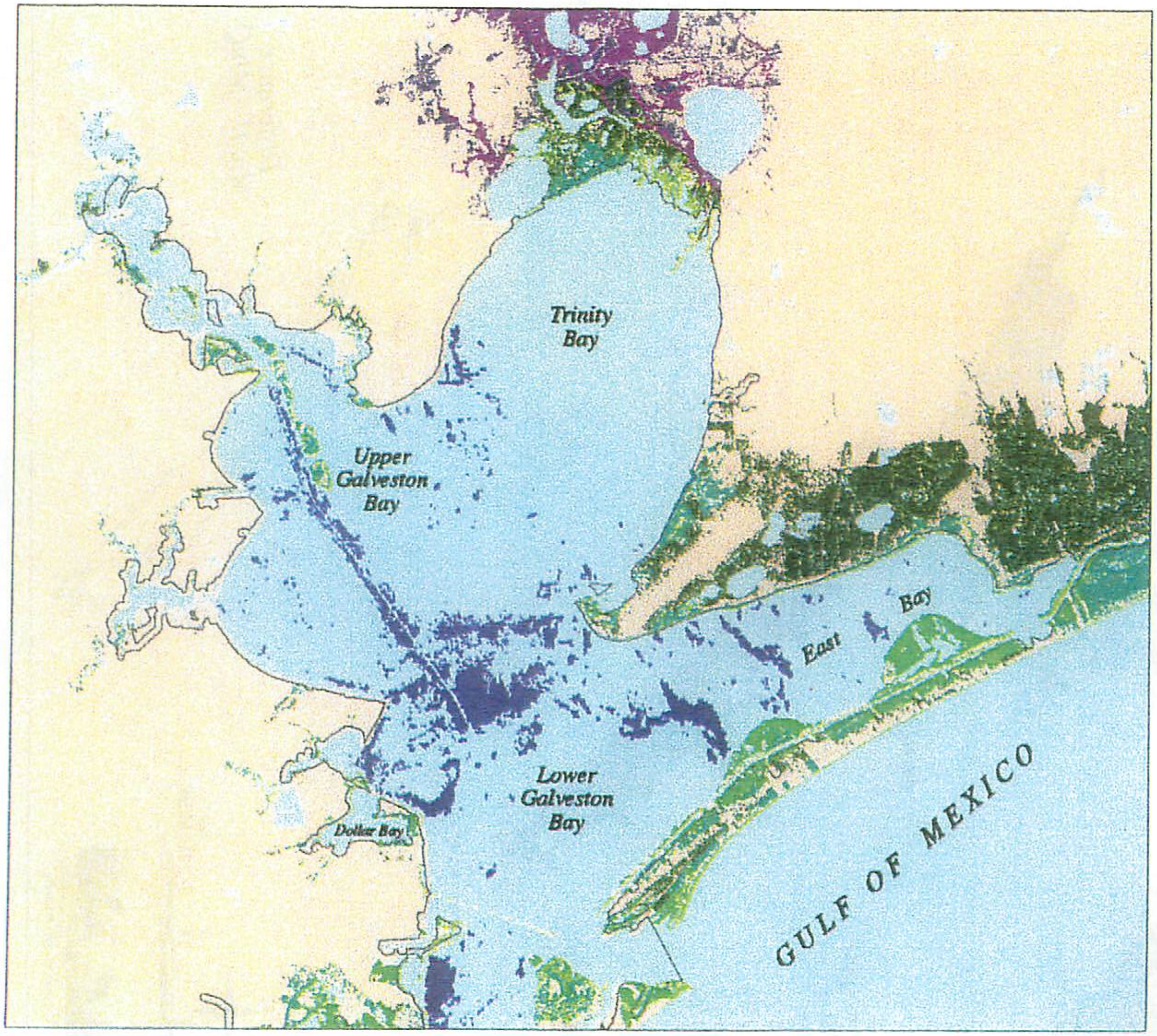


Figure 2.3
Galveston Bay System Habitat
Classified Landsat TM Imagery
1992

Habitat Types

- Upland
- Delta Brackish Marsh
- Salt Marsh
- Brackish Marsh
- Intermediate Marsh
- Palustrine Emergent Wetland
- Palustrine Woody Wetland
- Oysters
- Water

N

4 0 4 8 Miles

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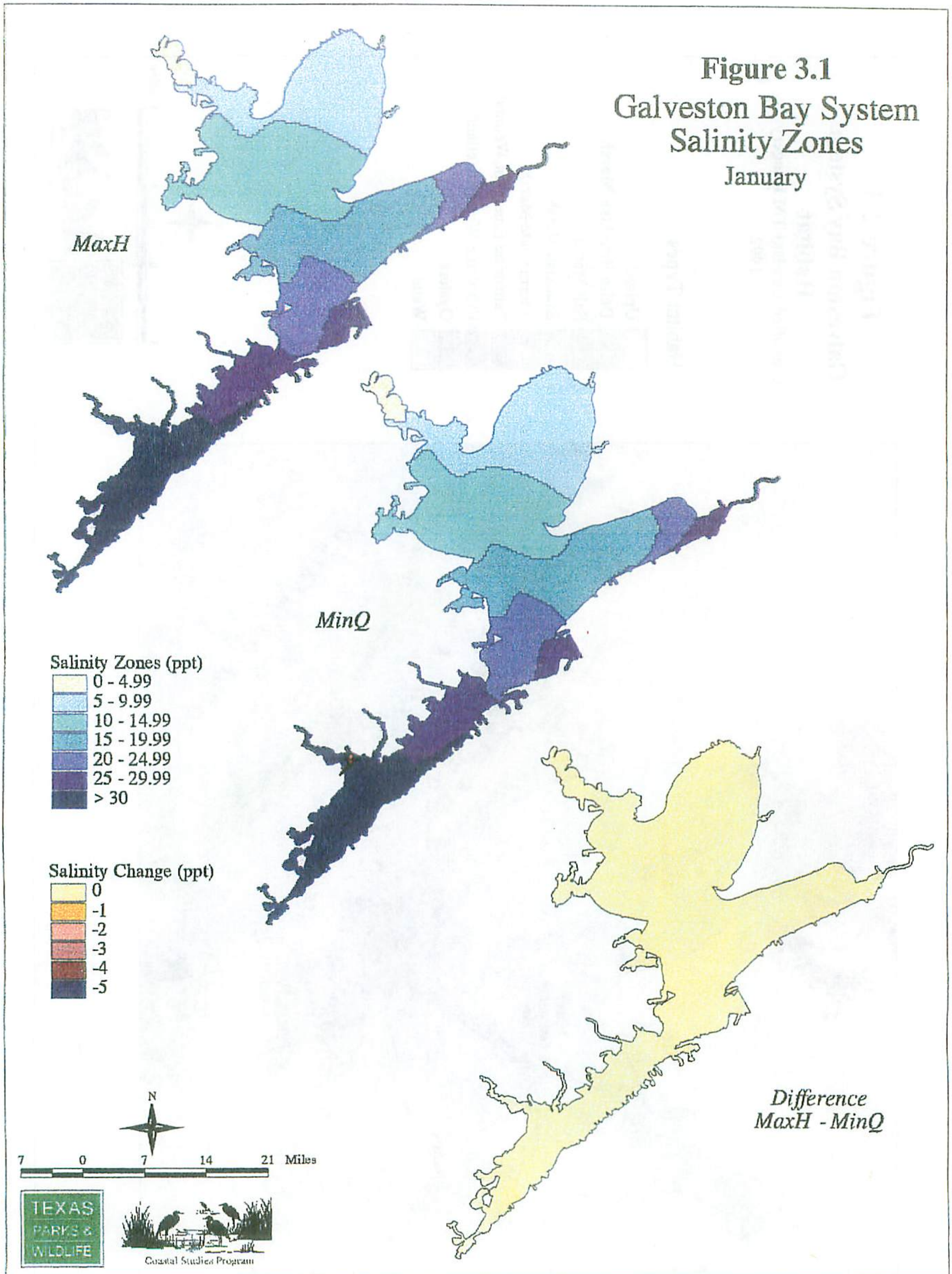
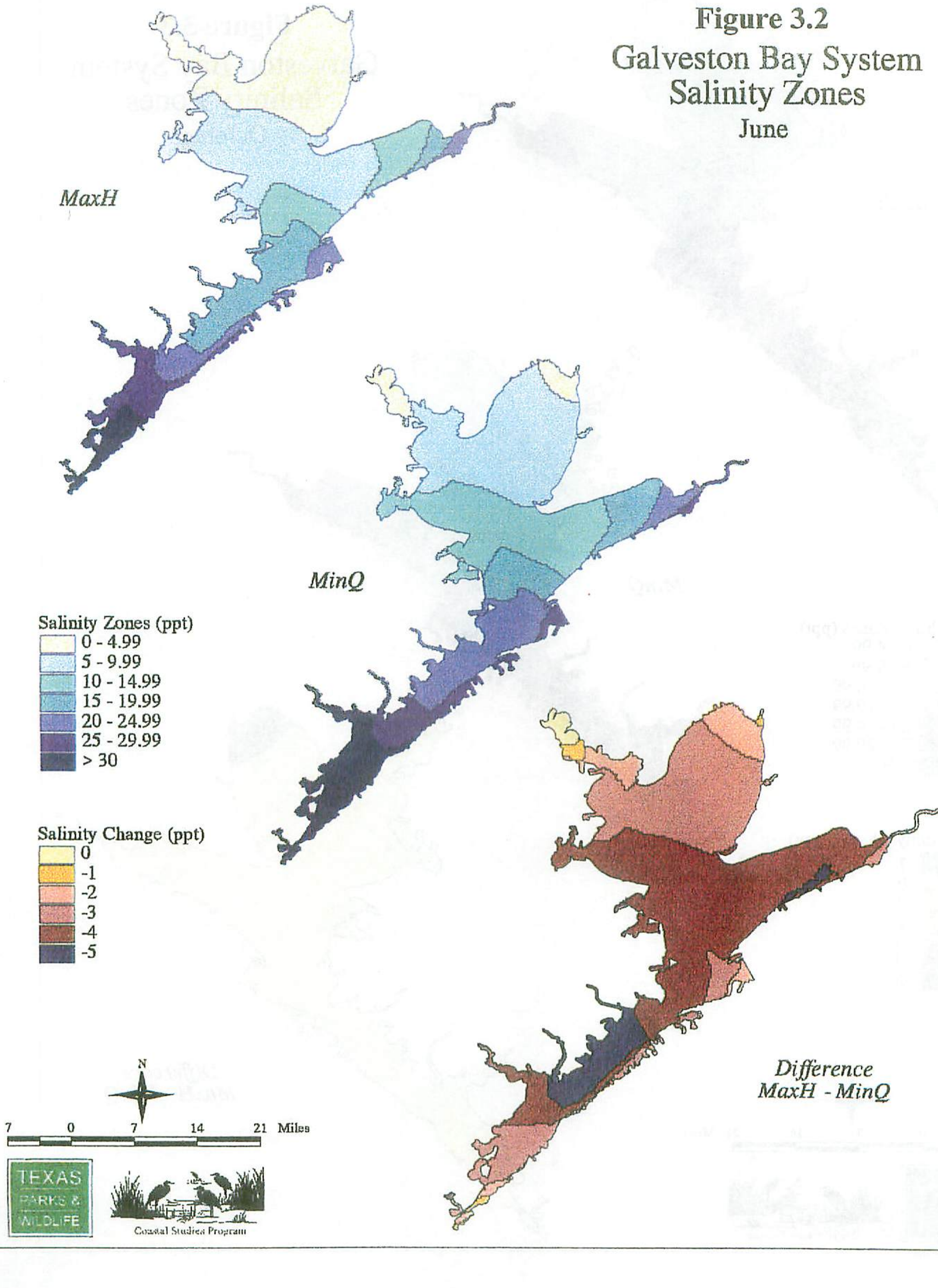


Figure 3.1
Galveston Bay System
Salinity Zones
January

Figure 3.2
Galveston Bay System Salinity Zones
June



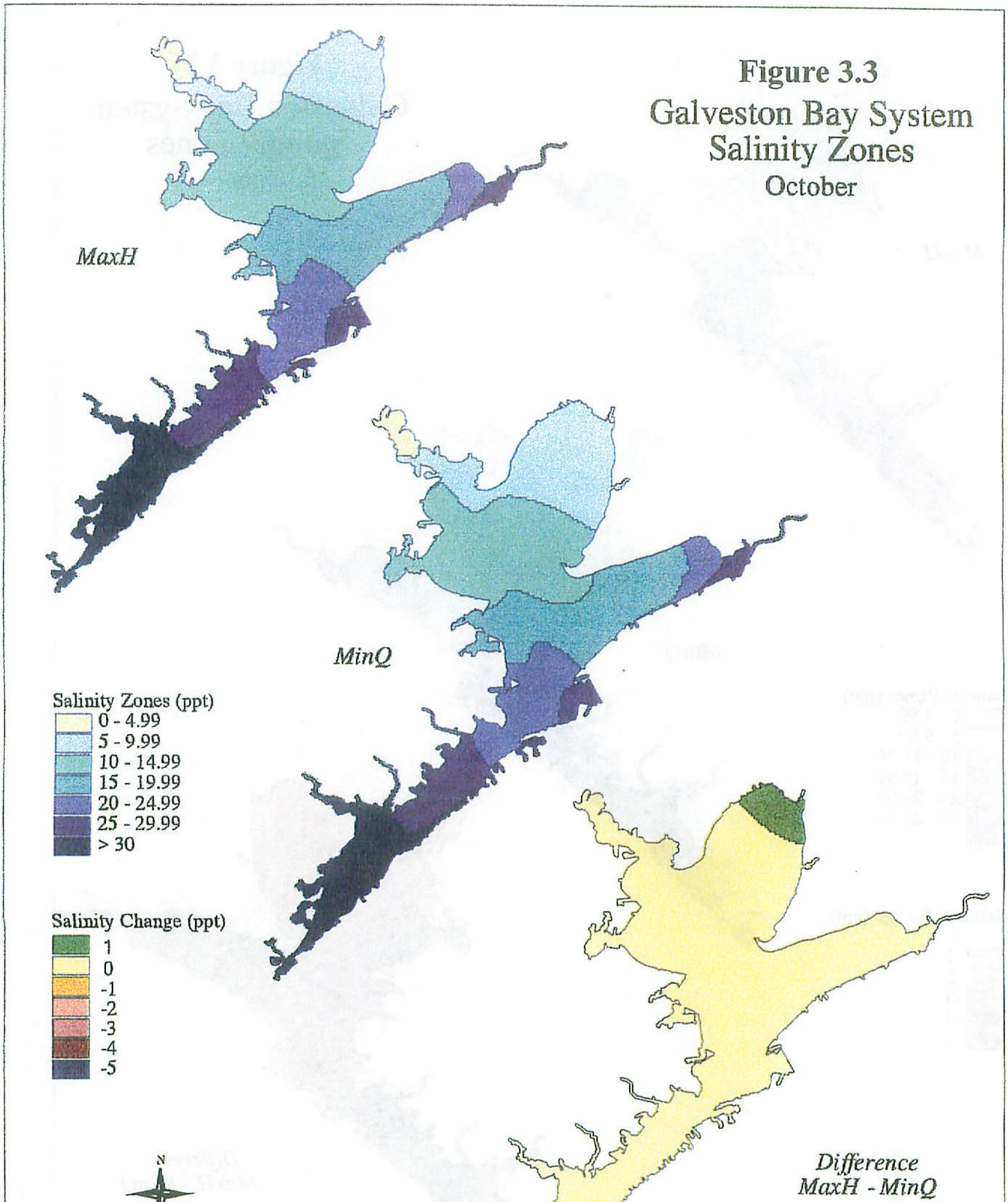
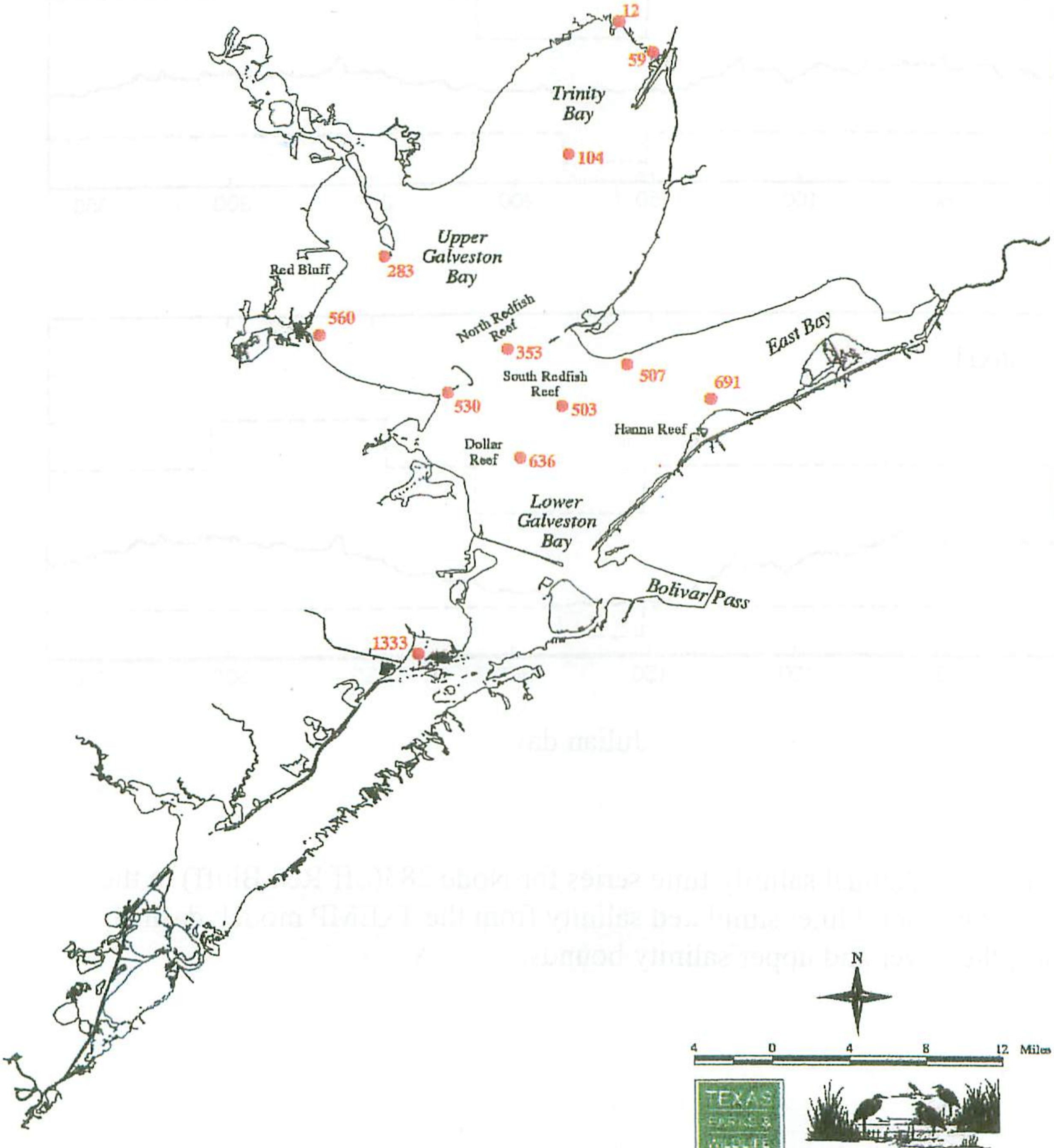


Figure 3.3
Galveston Bay System Salinity Zones
October

Figure 3.4
Time Series Analysis Nodes
in the
Galveston Bay System



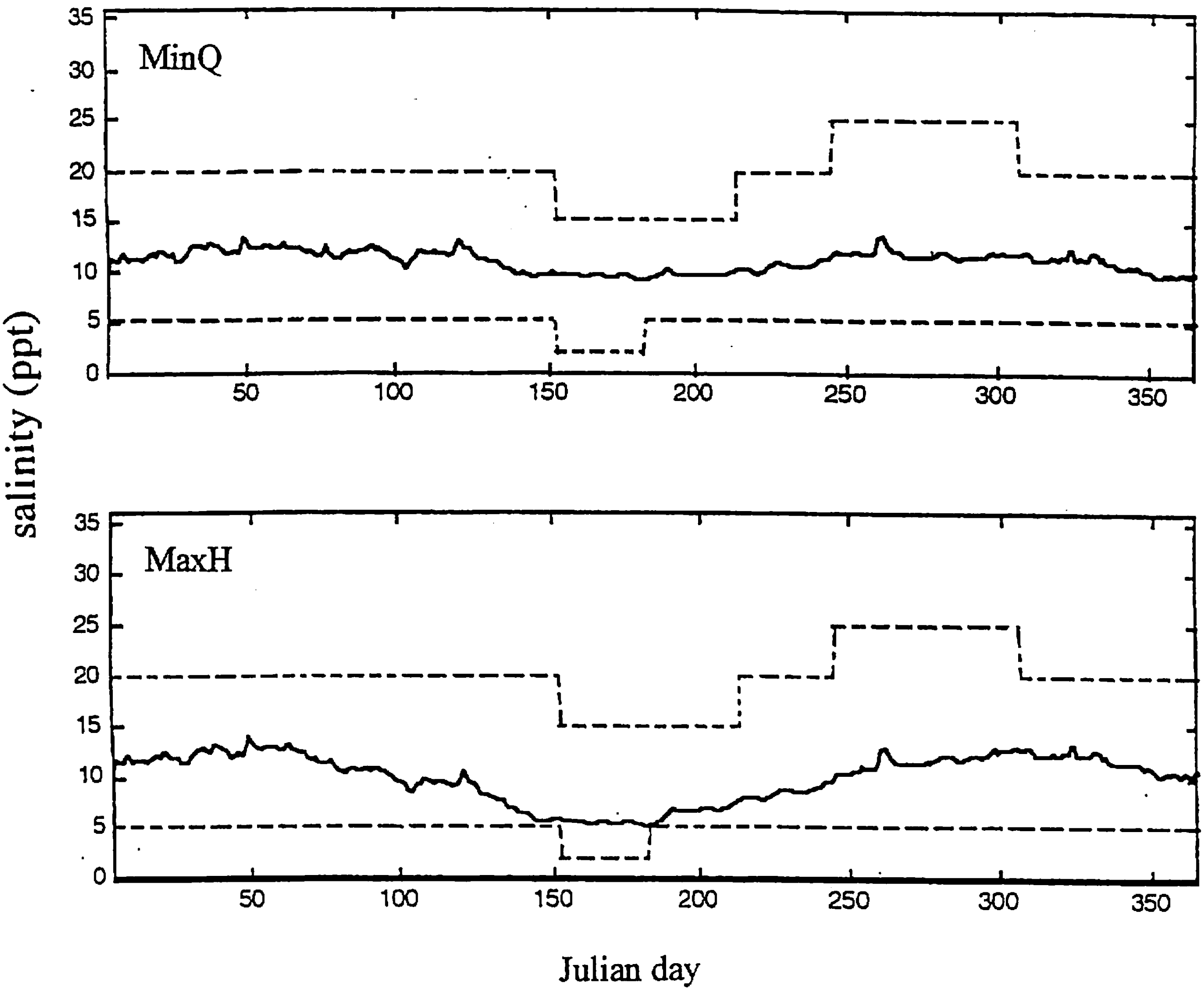


Figure 3.5. Annual salinity time series for Node 283(off Red Bluff) in the upper bay. Solid line: simulated salinity from the TxEMP model; dashed lines: the lower and upper salinity bounds.

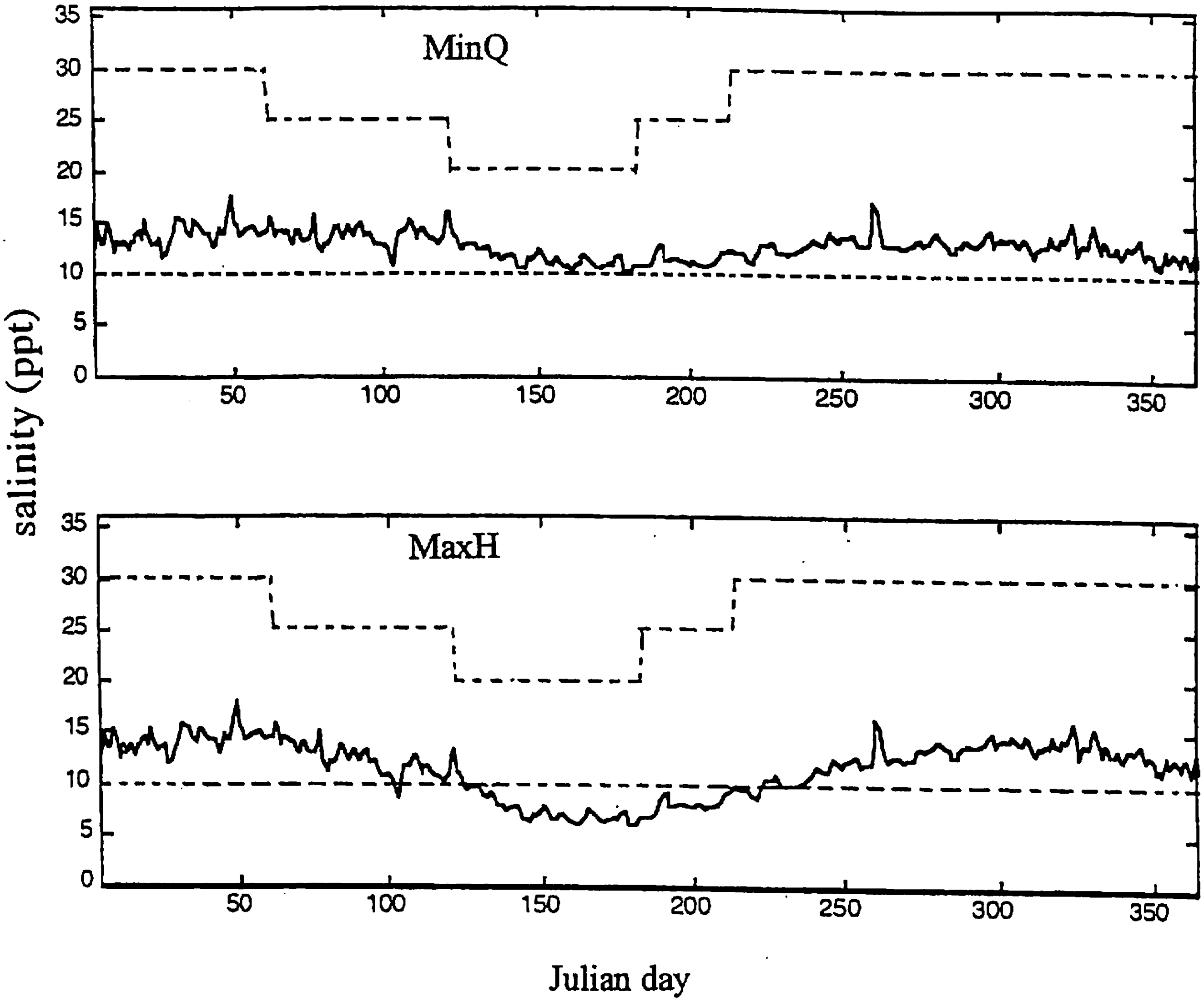


Figure 3.6. Annual salinity time series for Node 353(north Redfish Reef) in the middle bay. Solid line: simulated salinity from the TxEMP model; dashed lines: the lower and upper salinity bounds.

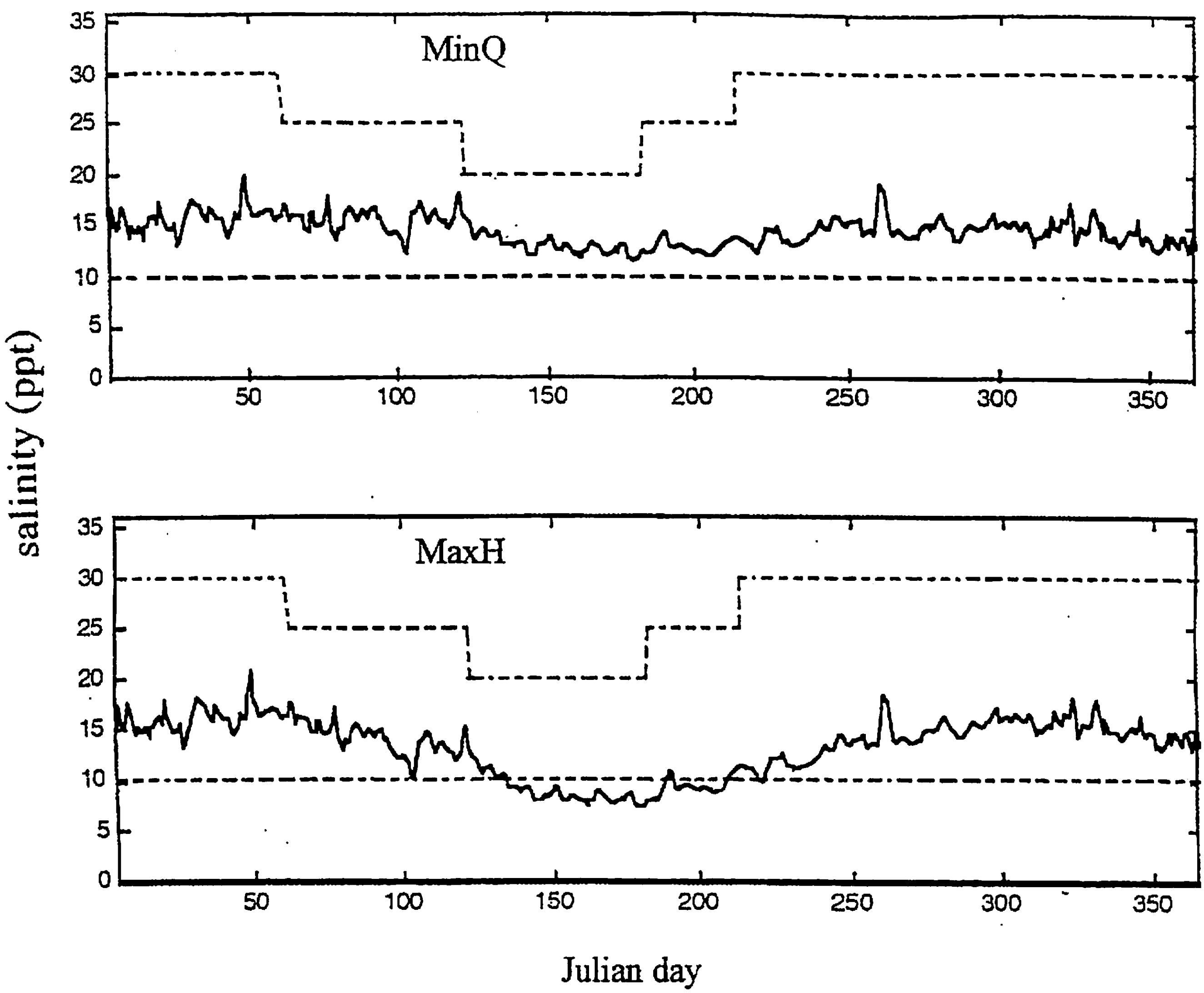
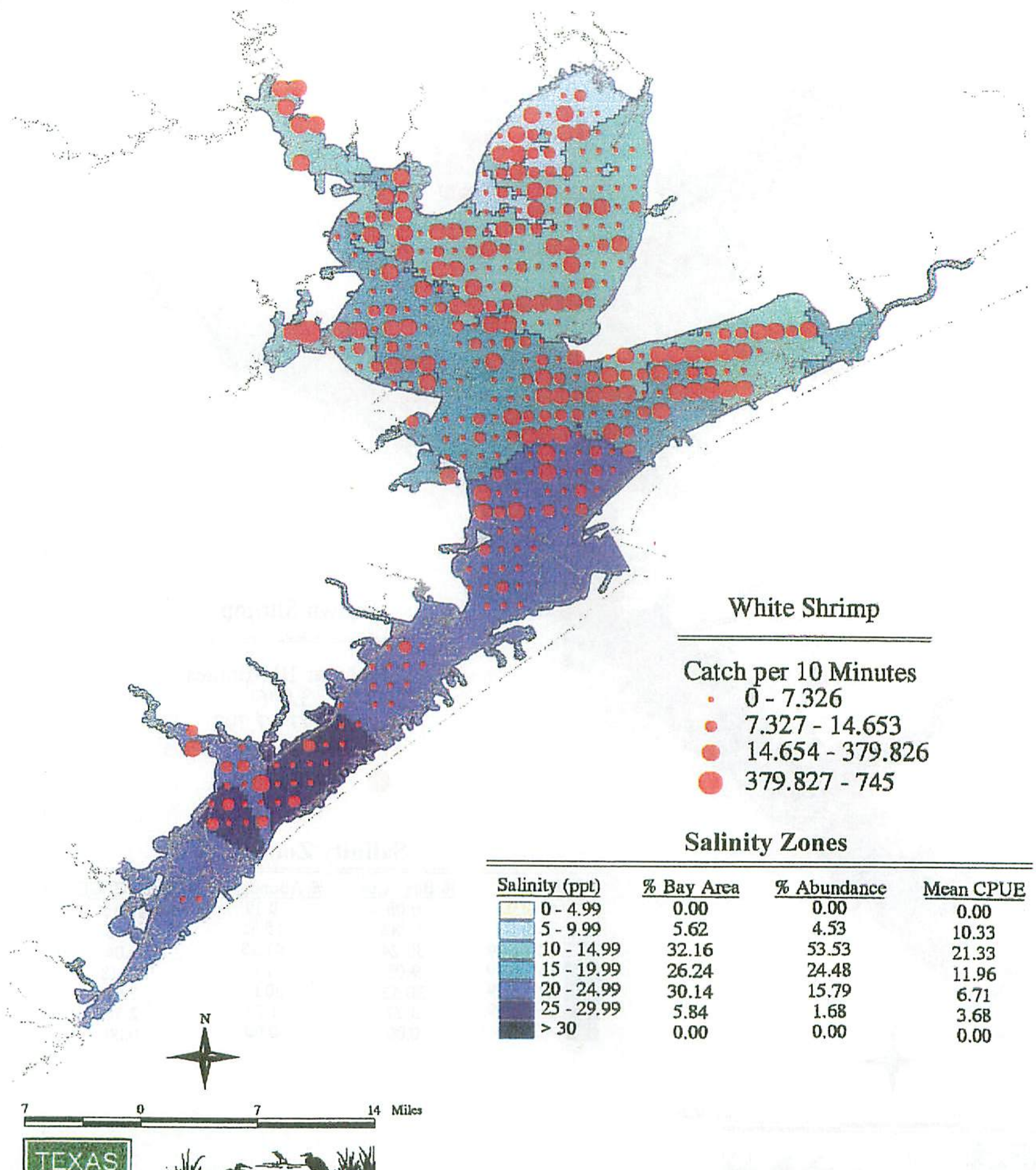


Figure 3.7. Annual salinity time series for Node 503(south Redfish Reef) in the lower bay. Solid line: simulated salinity from the TxEMP model; dashed lines: the lower and upper salinity bounds.

Figure 3.8
Spatial Distribution of White Shrimp in the Galveston Bay System
July through December



Salinity Zones

Salinity (ppt)	% Bay Area	% Abundance	Mean CPUE
0 - 4.99	0.00	0.00	0.00
5 - 9.99	5.62	4.53	10.33
10 - 14.99	32.16	53.53	21.33
15 - 19.99	26.24	24.48	11.96
20 - 24.99	30.14	15.79	6.71
25 - 29.99	5.84	1.68	3.68
> 30	0.00	0.00	0.00

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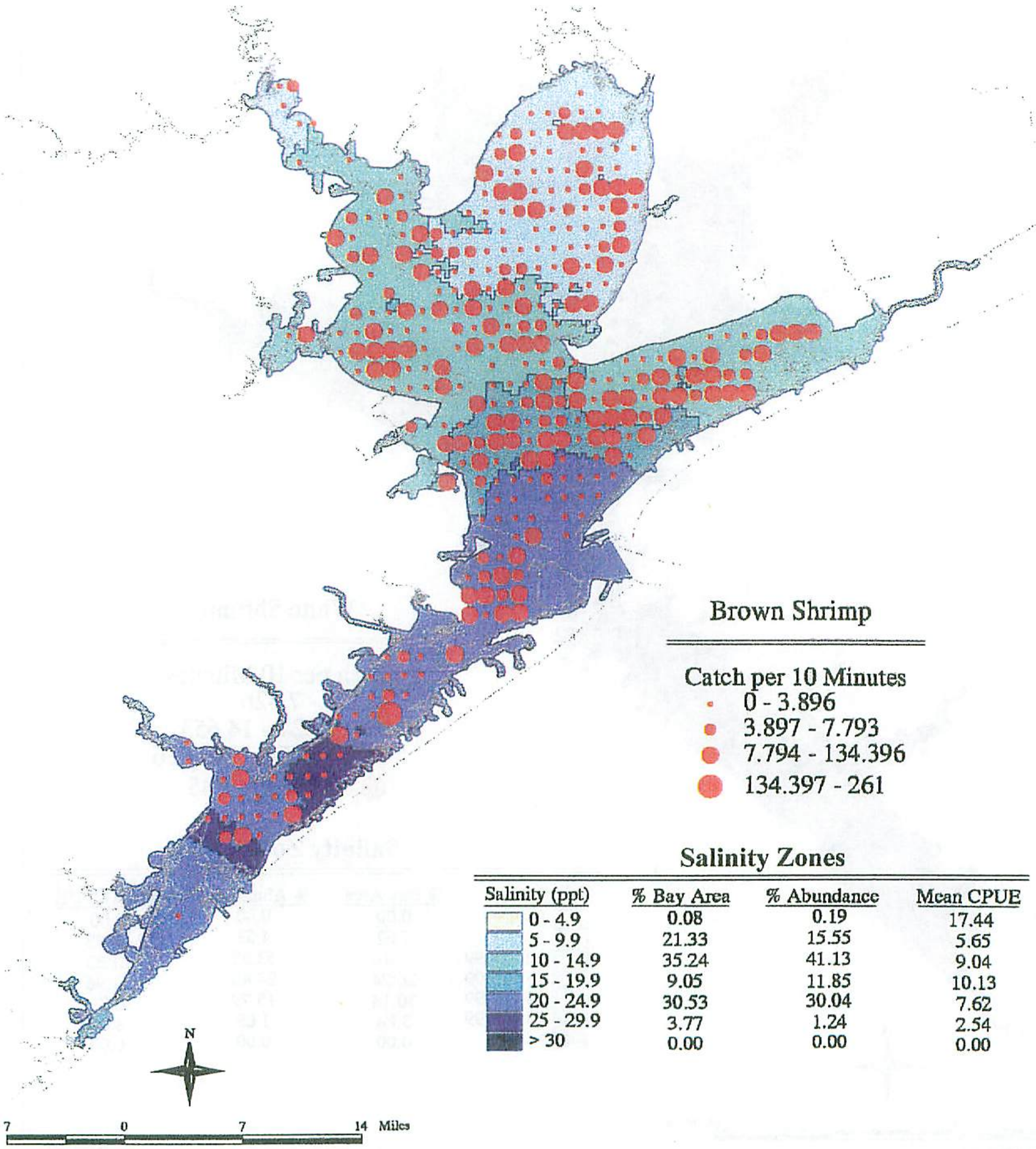
Figure 3.9
Spatial Distribution of Brown Shrimp in the Galveston Bay System
May through September



Salinity Zones

Salinity (ppt)	% Bay Area	% Abundance	Mean CPUE
0 - 4.9	0.08	0.19	17.44
5 - 9.9	21.33	15.55	5.65
10 - 14.9	35.24	41.13	9.04
15 - 19.9	9.05	11.85	10.13
20 - 24.9	30.53	30.04	7.62
25 - 29.9	3.77	1.24	2.54
> 30	0.00	0.00	0.00

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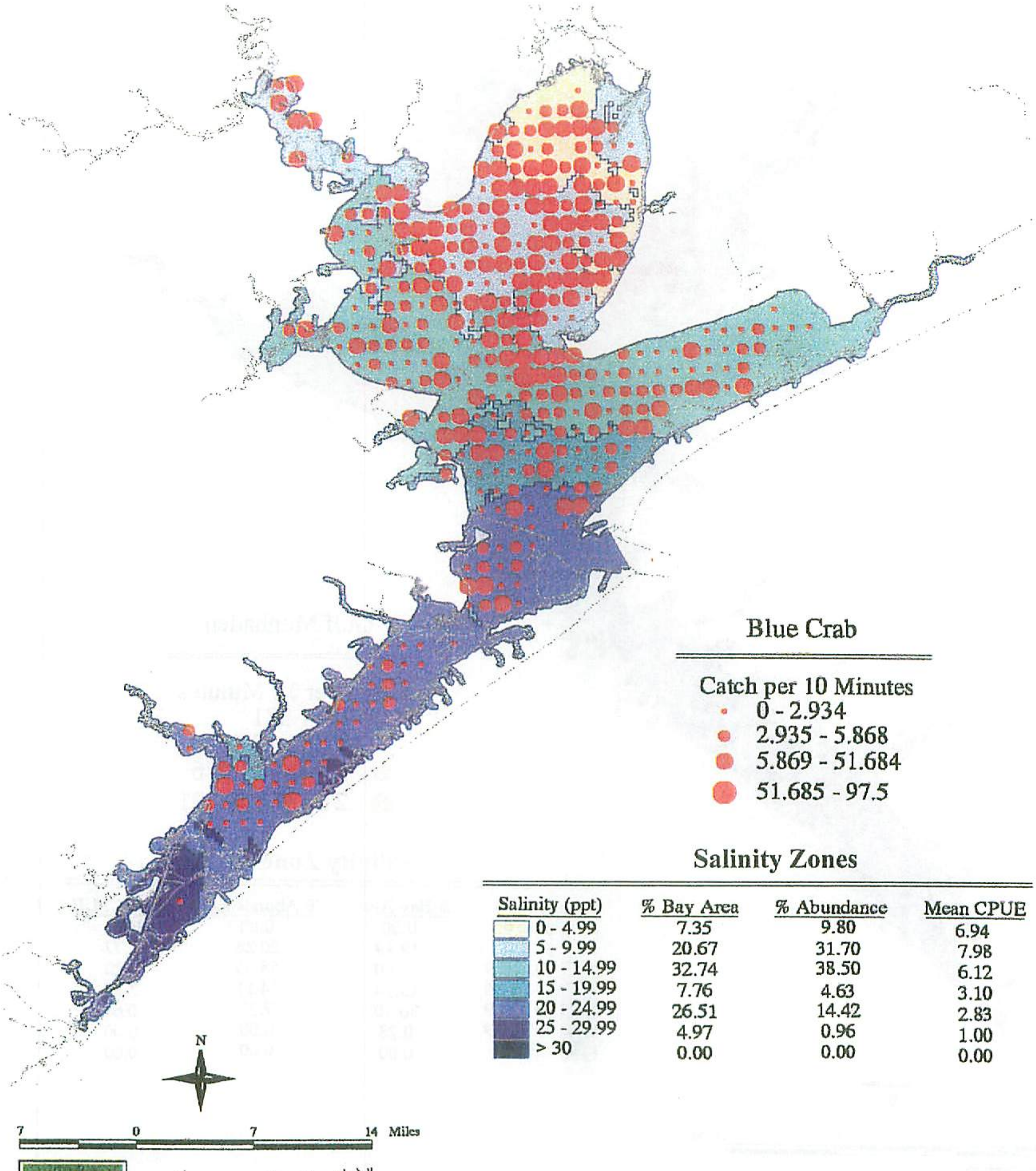
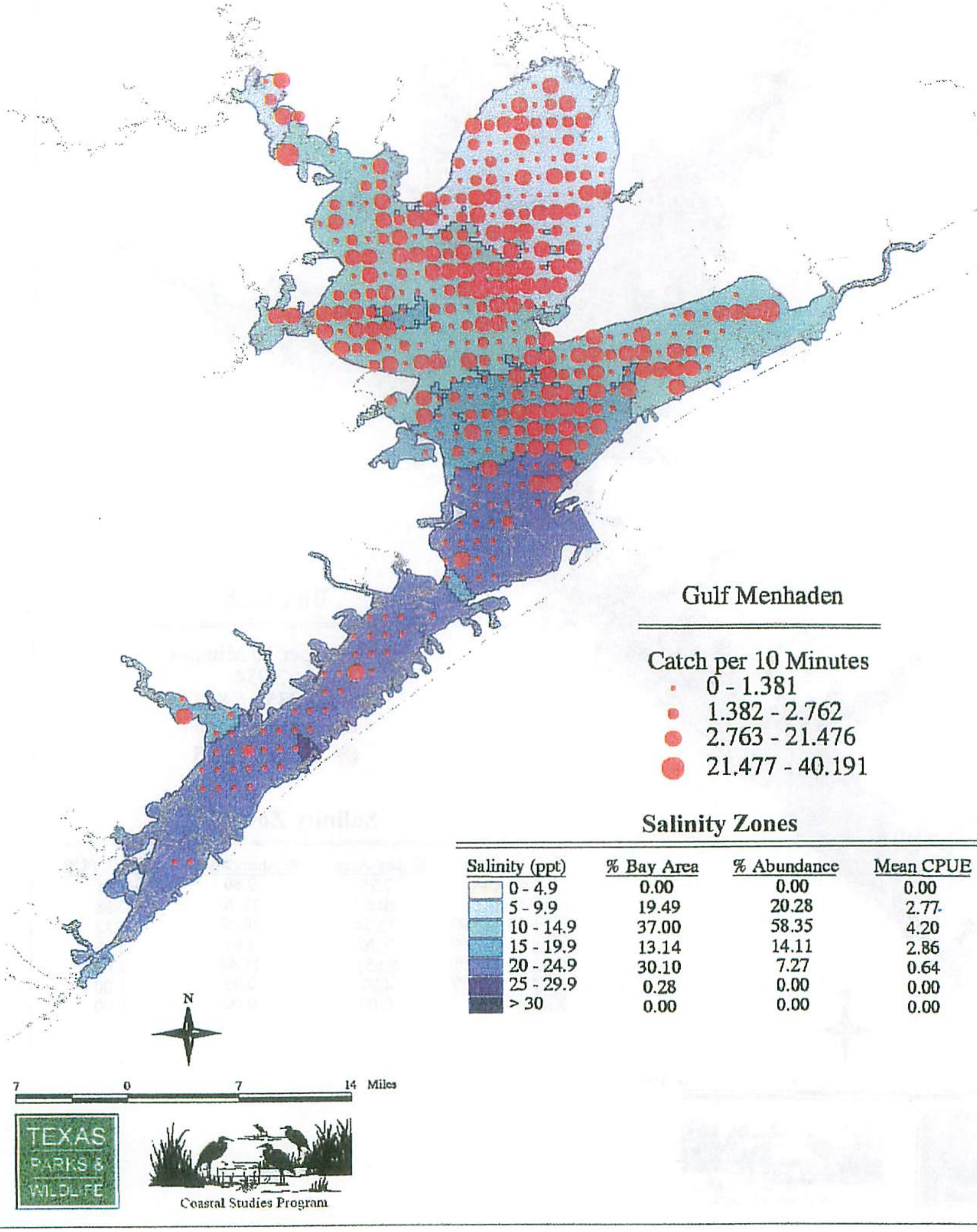
Figure 3.10
Spatial Distribution of Blue Crab in the Galveston Bay System
March through August



Salinity Zones

Salinity (ppt)	% Bay Area	% Abundance	Mean CPUE
0 - 4.99	7.35	9.80	6.94
5 - 9.99	20.67	31.70	7.98
10 - 14.99	32.74	38.50	6.12
15 - 19.99	7.76	4.63	3.10
20 - 24.99	26.51	14.42	2.83
25 - 29.99	4.97	0.96	1.00
> 30	0.00	0.00	0.00

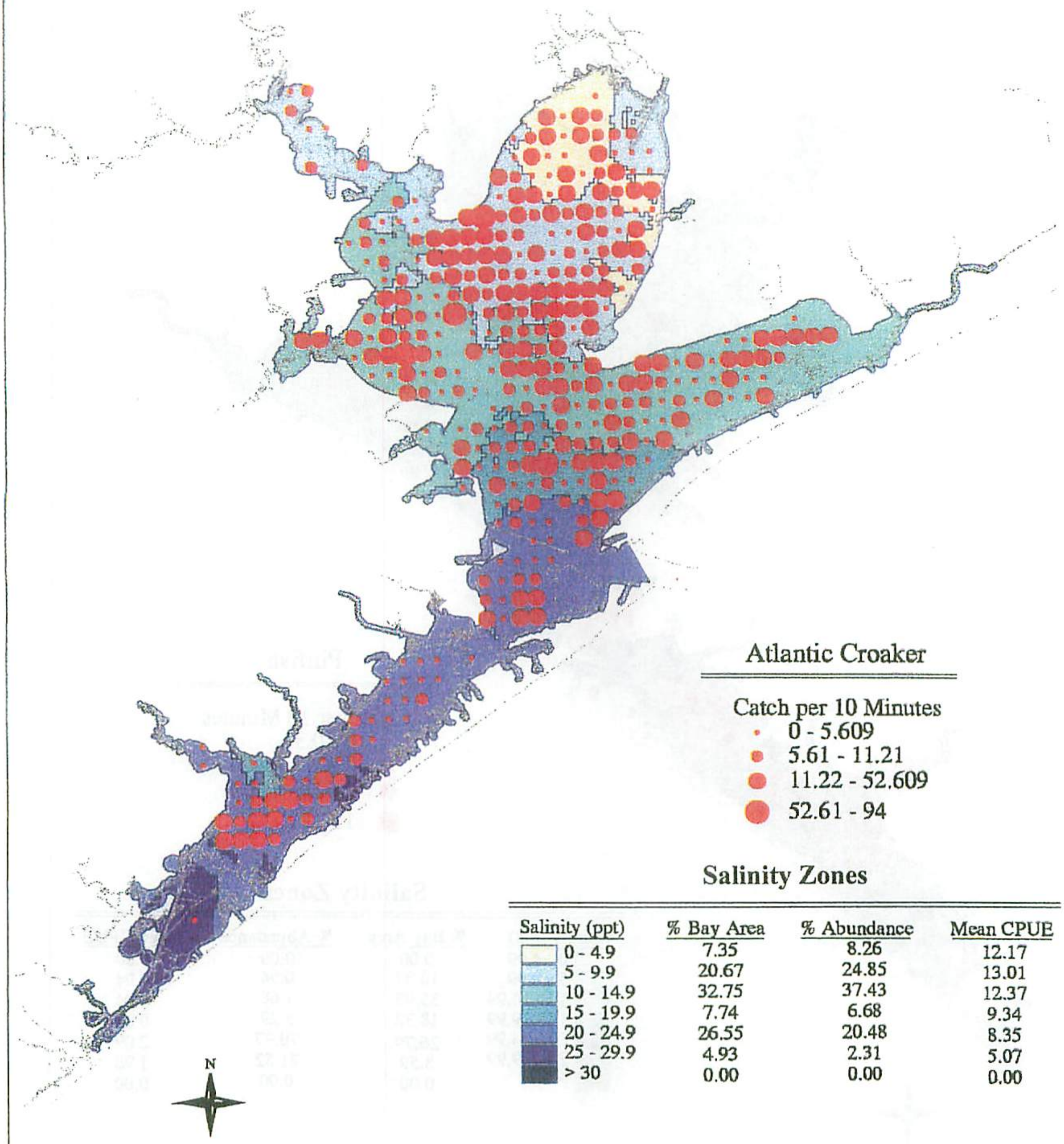
Figure 3.11
Spatial Distribution of Gulf Menhaden in the Galveston Bay System
January through December



Salinity Zones

Salinity (ppt)	% Bay Area	% Abundance	Mean CPUE
0 - 4.9	0.00	0.00	0.00
5 - 9.9	19.49	20.28	2.77
10 - 14.9	37.00	58.35	4.20
15 - 19.9	13.14	14.11	2.86
20 - 24.9	30.10	7.27	0.64
25 - 29.9	0.28	0.00	0.00
> 30	0.00	0.00	0.00

Figure 3.12
Spatial Distribution of Atlantic Croaker in the Galveston Bay System
March through August



Salinity Zones

Salinity (ppt)	% Bay Area	% Abundance	Mean CPUE
0 - 4.9	7.35	8.26	12.17
5 - 9.9	20.67	24.85	13.01
10 - 14.9	32.75	37.43	12.37
15 - 19.9	7.74	6.68	9.34
20 - 24.9	26.55	20.48	8.35
25 - 29.9	4.93	2.31	5.07
> 30	0.00	0.00	0.00

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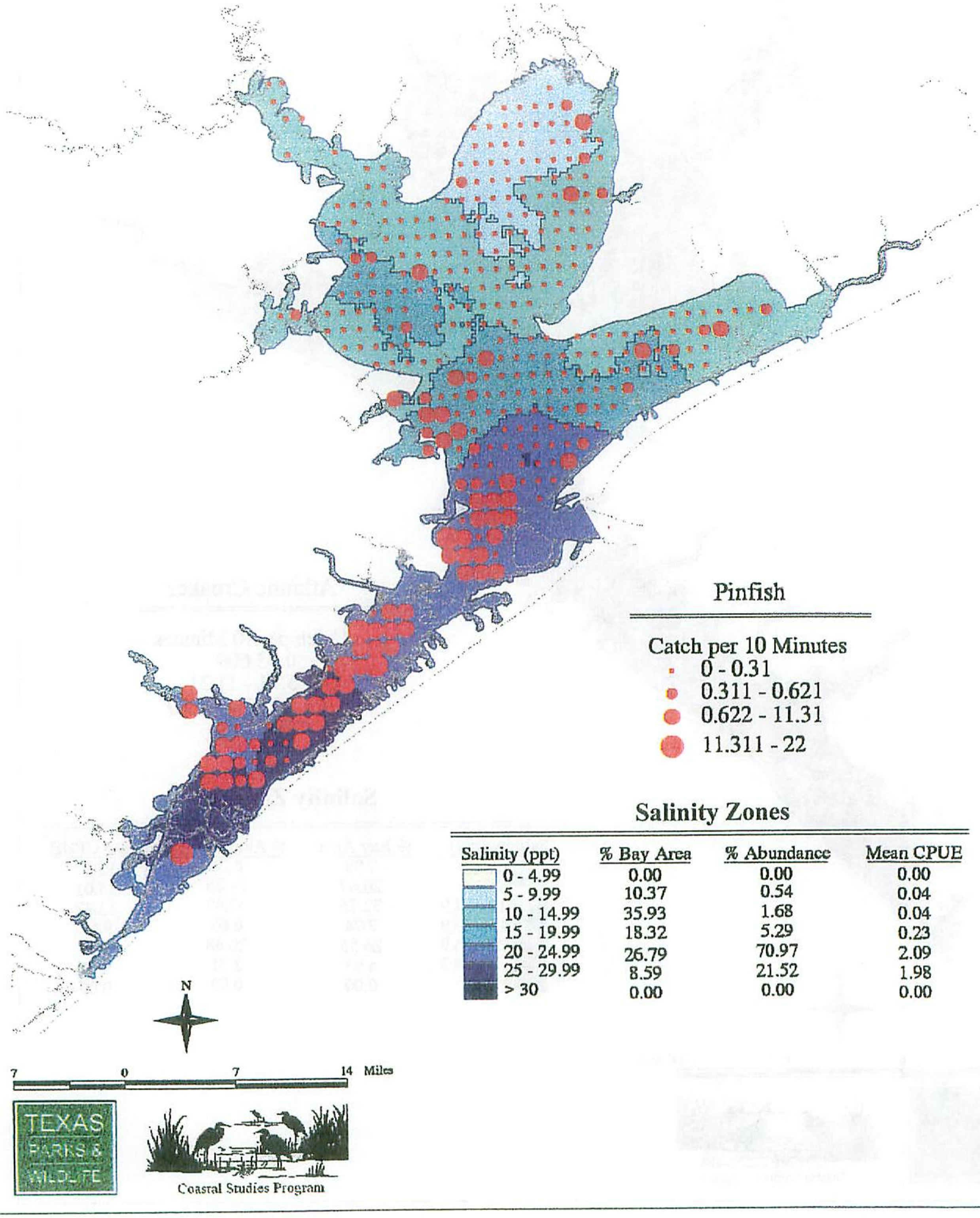
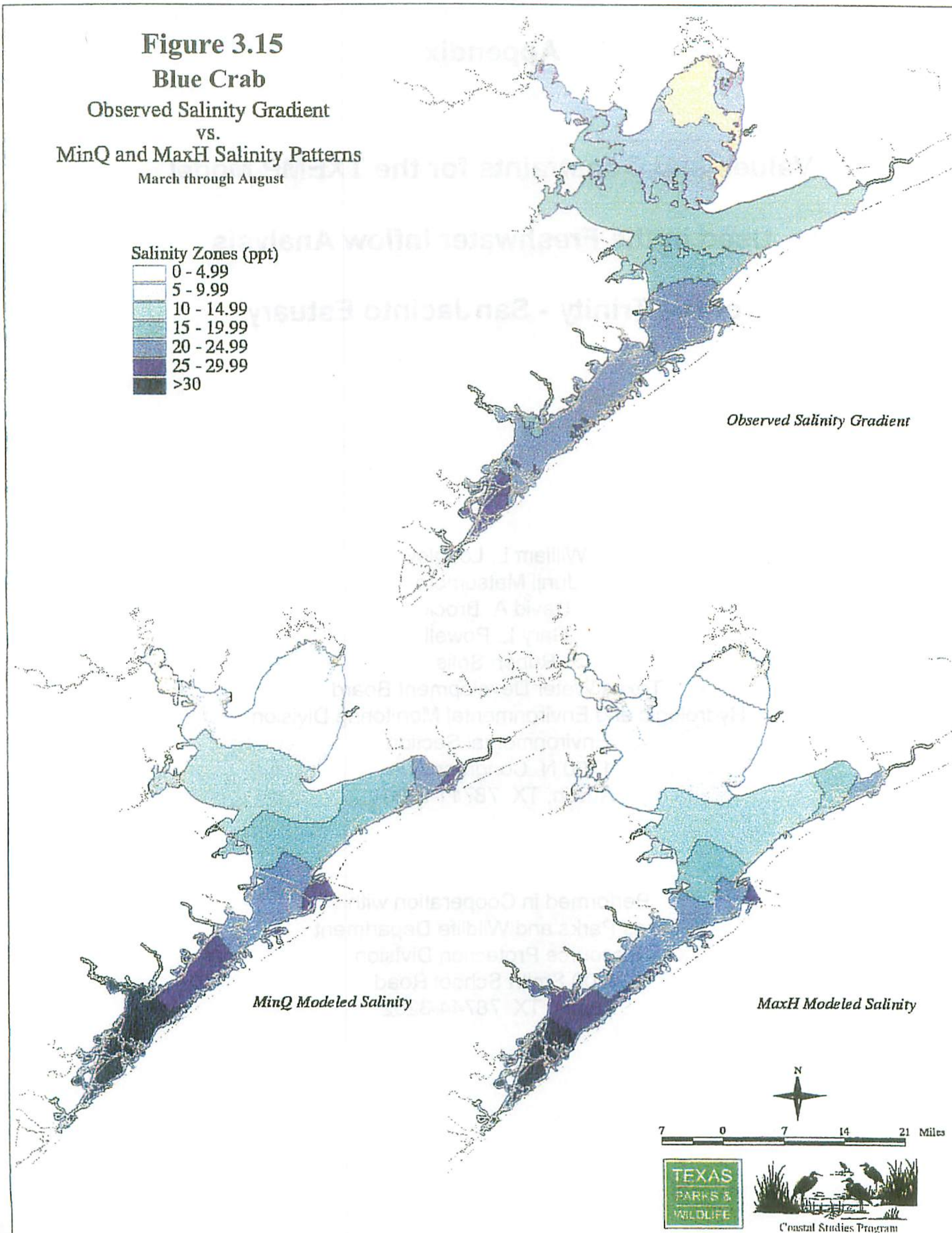
Figure 3.14
Spatial Distribution of Pinfish in the Galveston Bay System
June through November



Salinity Zones

Salinity (ppt)	% Bay Area	% Abundance	Mean CPUE
0 - 4.99	0.00	0.00	0.00
5 - 9.99	10.37	0.54	0.04
10 - 14.99	35.93	1.68	0.04
15 - 19.99	18.32	5.29	0.23
20 - 24.99	26.79	70.97	2.09
25 - 29.99	8.59	21.52	1.98
> 30	0.00	0.00	0.00

Figure 3.15
Blue Crab
Observed Salinity Gradient
vs.
MinQ and MaxH Salinity Patterns
March through August



Appendix

Values and Constraints for the TXEMP Model Used in the Freshwater Inflow Analysis of the Trinity - San Jacinto Estuary

By

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Values and Constraints for the TXEMP Model Used in the Freshwater Inflow Analysis of the Trinity-San Jacinto 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 harvests 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 (1994).

SALINITY

Salinity zones. Six areas with a substantial amount of salinity data were defined for the Trinity-San Jacinto Estuary. Four of the zones, Trinity Bay, Red Bluff-Clear Lake, Mid Galveston Bay, and East Bay, are shown in Solis (1994, page 35). Two additional zones, Dollar Point and Bolivar, were located closer to the mouth of the estuary to the Gulf. From these six areas, three were selected to represent the longitudinal salinity gradient from the river inflow points to the sea: Trinity Bay, Red Bluff-Clear Lake, and Dollar Point.

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 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 December 1986 and some data after that date came from single measurements made 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 2 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 1964 until 1996 and included a large number of data points. Mean, range, standard deviation, and number of data points for each zone were: Trinity Bay (mean = 7.84 ppt, range = 0 to 32.27 ppt, s.d. = 6.44 ppt, n = 548); Red Bluff-Clear Lake (mean = 12.32 ppt, range = 0 to 47.8 ppt, s.d. = 6.68 ppt, n = 552); and Dollar Point (mean = 16.02 ppt, range = 1.2 to 62.26 ppt, s.d. = 7.03 ppt, n = 614).

Salinity bounds. Several sources of information were used in selecting the salinity bounds for the estuary. Frequency distributions of the salinity measurements for each month were examined for each zone to provide information about historical monthly ranges of salinity. The 25th and 75th percentiles were of greatest interest since salinity values in this interval represent half of all measurements, and fall in the middle range of salinity values for the zone. Biotic salinity limits from scientific literature and reports for major estuarine plant and animal species, compiled in tables 5.2.2 and 6.7.3 of Longley (1994), were used in the evaluation. In addition, information about salinity bounds for representative organisms, prepared by the Nueces Estuary Advisory Council, was also considered. With this information, the salinity bounds for the analysis were selected by staff of the TWDB and TPWD, and are presented in the tables below. In all cases the upper salinity bounds were set above the 75th percentile of the historical salinity. In the majority of cases, the lower bounds were set below the 25th percentile of the historical salinity. The lower bound was set above the 25th percentile for Trinity Bay when the 25th percentile was very low, less than 5 ppt in some cases less than 1 ppt. In the few cases for Dollar Point where the lower bound was greater than the 25th percentile, the differences in salinity between the bound and the 25th percentile were less than 3 ppt. For the Red Bluff/Clear Lake zone the lower bound was always set lower than the 25th percentile.

Trinity Bay:

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

Red Bluff/Clear Lake:

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	5.0	20.0
Jun	2.0	15.0
July	5.0	15.0
Aug	5.0	20.0
Sep	5.0	25.0
Oct	5.0	25.0
Nov	5.0	20.0
Dec	5.0	20.0

Dollar Point:

Month	Lower salinity bound	Upper salinity bound
Jan	10.0	30.0
Feb	10.0	30.0
Mar	10.0	25.0
Apr	10.0	25.0
May	10.0	20.0
Jun	10.0	20.0
July	10.0	25.0
Aug	10.0	30.0
Sep	10.0	30.0
Oct	10.0	30.0
Nov	10.0	30.0
Dec	10.0	30.0

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

HARVEST TARGET

Data. Data for blue crab, eastern oyster, red drum, black drum, spotted seatrout, and flounder 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.

	Thousand pounds of harvest			
Species	Minimum	Maximum	Mean	Target (80% of mean)
Blue crab	311.3	3018.6	1699.6	1,359.7
Eastern oyster	43.1	6967.1	2636.4	2,109.1
Red drum	1.3	97.5	31.1	24.9
Black drum	7.9	269.0	67.2	53.8
Spotted seatrout	17.0	344.2	167.4	133.9
Brown shrimp	8.6	3261.4	1317.3	1053.8
White shrimp	982.0	4700.7	2897.4	2317.9
Flounder	4.2	222.7	57.2	45.8

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%.

INFLOW

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 12/1990. 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 Trinity-San Jacinto Estuary, the records of 17 different gages contributed to the gaged record for the period 1941-1976 and are described in Texas Department Of Water Resources (1981). For the period 01/01/1977 through 12/31/1990, 13 gages contributed to the gaged record for the estuary: Cedar Bayou near Crosby (USGS Station No. 8067500); Brays Bayou at Houston (USGS Station No. 8075000); Sims Bayou at Houston (USGS Station No. 8075500); Greens Bayou near Houston (USGS Station No. 8076000); Halls Bayou at Houston (USGS Station No. 8076500); Hunting Bayou at IH 610 (USGS Station No. 8075770); Vince Bayou at Pasadena (USGS Station No. 8075730); Whiteoak Bayou at Houston (USGS Station No. 8074500); Buffalo Bayou at West Belt Drive (USGS Station No. 8073600); Clear Creek near Pearland (USGS Station No. 8077000); Chocolate Bayou near Alvin (USGS Station No. 8078000); Trinity River at Romayor (USGS Station No. 8066500); and Lake Houston near Sheldon (USGS Station No. 8072000, reservoir contents gage).

Ungaged flow is the water reaching the estuary whose source is below the farthest downstream flow gage and therefore is not measured by the gages. Ungaged flow consists of three hydrologic components: modeled runoff from land areas below the farthest downstream gage (simulated using TXRR, a calibrated rainfall-runoff model); return flow from discharges to rivers, streams, or estuaries that occurs below the farthest downstream gage; and diversions of freshwater from rivers and streams that occurs below the last downstream gage. The data used in simulating modeled flows were daily precipitation data from the National Weather Service and other precipitation stations operated by the TWDB. Ungaged watersheds may contain none to several precipitation stations. To provide full precipitation information over the ungaged area, precipitation was distributed on a watershed basis through use of a Thiessen network to allocate precipitation to specific watershed areas. Return flow values came from records of measured and estimated flows for Self-reporting Wastewater Discharges from the Texas Natural Resource Conservation Commission (TNRCC). Diversion values come from the Water Use data bases that are managed by TNRCC as part of the Water Rights Permitting Program.

Ungaged flow was calculated by adding the modeled runoff and the return flow, and subtracting the diversions. The data sources for gaged and modeled flows provide daily data so the flow amounts can be calculated in units of acre-ft/day. The data for return flows and diversions, however, are reported to the TNRCC as monthly totals. Combined flow is calculated as the sum of the gaged and ungaged flows. For some modeling purposes the monthly combined flows are used. For hydrodynamic modeling and some other analyses, daily estimates of combined flow are needed in units of acre-ft/day. To calculate daily combined flows, estimates of the daily return and diversion flows are made by dividing the monthly values 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, based on 2-month seasons, corresponded with 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 inflow statistics for the 47-year period 1941 to 1990.

Monthly upper and lower inflow bounds. The lower bound for monthly inflow was set to the 10th percentile flows for the month for the period 1941-1990. The upper bound was set to the median inflow for the month for the same period. Consequently, the inflow requirements calculated by the TXEMP model would not exceed the median inflow for any month, based on 1941-1990 historical data.

	Thousands of acre-ft/month	
Month	Lower monthly inflow bound	Upper monthly inflow bound
Jan	150.49	699.49
Feb	155.19	946.48
Mar	164.40	652.80
Apr	193.50	632.50
May	260.00	1273.70
Jun	190.32	839.70
Jul	107.71	340.38
Aug	77.98	225.27
Sep	93.33	330.25
Oct	49.89	251.90
Nov	89.48	351.50
Dec	93.87	626.80

Seasonal (2-month) upper and lower inflow bounds. The bounds for the bimonthly flows constitute a separate set of constraints from the monthly flow bounds. Both constraints must be satisfied for an optimum solution. The seasonal bounds were set to values close to the sum of the monthly flow bounds for any pair of months. The sum of the January and February lower bounds totaled 305.7 thousand acre-ft; the sum of the upper bounds for the same period totaled 1646 thousand acre-ft. In the table below, the January-February seasonal lower bound was set to a value slightly lower than the sum of the monthly bounds (300 thousand acre-ft) while the January-February seasonal upper bound was set to a value slightly higher than the sum of the monthly upper bounds (1800 thousand acre-ft). The seasonal bounds are slightly wider than the sum of the monthly to allow the TXEMP optimization model to have plenty of maneuvering room to search for an optimal solution.

	Thousands of acre-ft/month	
Month	Seasonal lower bounds	Seasonal upper bounds
Jan-Feb	300.0	1800.0
Mar-Apr	350.0	1300.0
May-Jun	440.0	2200.0
Jul-Aug	180.0	600.0
Sep-Oct	140.0	600.0
Nov-Dec	180.0	1000.0

Annual upper and lower inflow bounds. Annual lower and upper flow bounds are a third separate set of hydrology constraints to be satisfied. They were used operationally to calculate performance curves over a wide range of flows. The smallest annual lower bound used was 3 million acre-ft per year; the largest upper bound used 6.2 million acre-ft. The model was run a dozen or more times, incrementing the lower and upper bounds on each run, in a series of small steps between the above bounds. The results of the individual runs were then combined into a single performance curve.

HARVEST RATIO

Originally, the TXEMP model permitted harvest equations to be weighted for individual species in the calculation of the objective function. The purpose of this weighting was to allow control of the relative importance of individual harvest equations in the optimization routine. If the weight of an equation were set to zero, that equation would not contribute to the total of the harvest included in the objective function. Consequently, the optimization results would be independent of that species' contribution to harvest. TXEMP calculated the harvest of that species, but would not include the contribution of that species in the optimization. In the same manner, the harvest equation of a species could be weighted so it contributed more to the harvest total of the objective function than the equation of another species. Originally, this was considered to be a convenient way to allow different management options to be tried. Unfortunately, the nonlinear nature of the equations occasionally resulted in calculated harvests for some species greater than levels that were historically observed. To remedy this unrealistic tendency, which typically occurred at extremes of inflows, a new constraint was added as a refinement to the optimization routine. The new constraint was designed to ensure that the harvest of any species compared to the total harvest of all species in the analysis remained within the bounds of a defined range. This constraint was called the harvest or biomass ratio and was based upon historical harvest or biomass data from the estuary. The constraint guaranteed that the relative harvests of species from the optimization model remained within ranges that have been observed for the estuary. As a result, the constraint avoids the problem of the model calculating a solution that provides exceptionally abundant harvest for one or two species to the detriment of all the others.

Data. The harvest data which was previously discussed in the Harvest Target section was the source of information for the harvest ratios. However, differences in the periods for which harvest data was available was a complication. Red drum and spotted seatrout harvest data was available only through 1981; all species had harvest data beginning in 1962 although brown and white shrimp data was available back to 1959. Since the harvest ratio required data from all species for total harvest, it was decided that only years for which harvest data was available for all species should be used, 1962-1981. For that period, white shrimp had the largest proportion of the harvest (35.5%) followed by oyster (27.9%), blue crab (19.0%), brown shrimp (14.1%), spotted seatrout (2.0%), black drum (0.7%), red drum (0.4%), and southern flounder (0.3%).

Harvest ratio bounds. A variety of methods were considered in defining the upper and lower bounds including use of minimum and maximum ratios actually measured over the period of record, and a statistical ratio. Consideration was given to using the mean plus or minus three standard errors The attraction of standard error was that the statistical characteristics of standard errors are well known. However, the range of values for the bounds was too narrow so several other bounding conditions were tried. The condition that worked well and allowed feasible solutions to be computed was plus or minus 1.15 standard deviations about the mean. This bounding condition would include approximately 75% of the harvests during the period of record since 1.15 standard deviations includes 75% of the area under a normal distribution curve.

Species	Harvest ratio	
	Lower bound	Upper bound
Blue crab	0.116	0.266
Eastern oyster	0.095	0.462
Red drum	0.000	0.007
Black drum	0.002	0.012
Spotted seatrout	0.007	0.033
Brown shrimp	0.066	0.217
White shrimp	0.233	0.478
Flounder	0.001	0.005

Since the harvest ratios above were used to assure realistic results, weights for all eight harvest equations were set to 1.

NUTRIENT CONSTRAINT

Also considered in formation of an inflow requirement was the minimum freshwater inflow supplying a nitrogen load consistent with a healthy and productive estuary. In many estuaries, nitrogen is considered the nutrient element most likely to control productivity, and is suspected to limit production in Galveston Bay as well (Armstrong and Hinson, 1973). The bounds on a requirement for nitrogen could be stated as an amount great enough to promote production supporting commercial and recreational harvest, great enough to maintain the community characteristic of the estuary, but an amount not so large as would promote symptoms of eutrophication, nor promote an uncharacteristic ecological community.

Studies for the Galveston Bay National Estuary Program documented sources and trends of nitrogen loadings to the estuary system. Since the 1970's, there has been a trend of decreasing bay nutrient concentrations, probably due to reductions in wastewater discharges (GBNEP, 1994). However, there is still uncertainty over the question of supply relative to the demand of biological production.

Nitrogen budgets for the Trinity-San Jacinto Estuary were developed for three years spanning a range of inflows. Results from this effort are presented in Brock, et al, (1996), and summarized here.

Annual total nitrogen budget for the Galveston Bay system, 10^6 g /y TN.

	1988	*1989*	*1990*
Inputs from Freshwater Inflows			
Gaged streamflow	8360	25900	35090
Ungaged runoff	3320	9590	5890
Wastewater	7250	7290	7570
Direct rain	570	760	700
Total	19500	43550	49250
Nitrogen Fixation	560	560	560
Inputs from Entrained Tides	2330	2440	2240
Total Inputs	22390	46550	52050
Outflows			
Net water balance outflow	-3090	-14610	-14530
Entrainment outward	-22320	-27770	-24060
Total Outflows	-25420	-42380	-38590
Transport Balance	-3590	3610	12900
Denitrification	-3680	-3680	-3680
Sediment Burial	-690	-2280	-2620
Fisheries, Fish migration	-770	-1070	-1430
Total Losses	-30560	-49410	-46320
Water Column Storage	170	270	-360
Remainder	-8000	-2590	5370

Unfortunately, for critical elements of the budget, burial and denitrification especially, there is insufficient data on variation of losses with inflows. Therefore, while the budget exercise puts contribution of all sources and sinks in perspective, the sensitivity of the system to freshwater inflows is not clear. Therefore, the recommendation for a beneficial nutrient loading level was developed from other considerations.

With the exception of Sabine Lake, Galveston Bay receives the highest nitrogen loading per volume of all Texas major estuaries. (Longley, 1994). Therefore, the present rate of nitrogen supply may not be a useful starting point for development of a nitrogen loading requirement. An assessment of minimal nitrogen needs for a productive estuary could start with an estimate of the pre-development nitrogen loading to the productive system. In concept, prior to urbanization and extensive agricultural development in the basin, inflows to the estuary would have provided nitrogen at rates related to concentrations found in streams not impacted by man's activities. There are complications in the application of this concept, because the estuary differed in other ways prior to regional development from its current state. However, we can infer that the estuary was healthy and productive under those pre-modern conditions.

Loading of nitrogen to Galveston Bay characteristic of pre-modern conditions is based on stream concentrations of 1.2 mg/l N, after Jensen et al (1991) and median inflows, assuming the median of present gaged + modeled inflows ($10.4x10^6$acre-feet/y) can represent pre-modern inflows. This concentration times median inflow rate gives a loading of $15,268x10^6$ g N/y. This pre-development median stream-flow load is proposed as a present minimal nitrogen load. From this load can be calculated a nitrogen-based lower bound on required freshwater inflows. To deliver $15,268x10^6$ g N/y at present average stream concentrations (median 2.9 mg/l), a target median 4,270,000 ac-ft annual surface inflow (gaged+ungaged-diversions+returns) would be needed.

A nutrient-based inflow requirement for Galveston Bay is 4,270,000 ac-ft/y. This annual inflow target is near the 12% quartile of the distribution of annual drainage basin inflows. This inflow quantity could be used as an inflow constraint in the TWDB TxEMP optimization model used to reconcile various aspects of estuary inflow requirements and water resource demands. Establishment of an inflow constraint based on nutrient delivery assumes that tributary nitrogen concentrations will remain substantially as at present. Any change in tributary loadings should signal a need for re-evaluation.

SEDIMENT CONSTRAINT

A sediment constraint for the analysis was investigated by attempting to relate the rate of deposition of sediment in the Trinity Delta with Trinity River flood flows. Cores were taken at sites in the delta and strata were dated using naturally occurring lead isotopes (White and Morton 1993). Amounts of sediment deposited were compared with cumulative river flood flows for each period in which the deposition occurred. Various flooding levels were used to try to focus on flows large enough to reach the sample sites. Of the sites investigated, only one showed a weak correlation between flood flows and deposition; this site was close to the river levee. None of the other sites showed any positive relationship between flood flows and sediment deposition. Attempts to relate deposition with sediment load from the river were also unproductive.

Consequently, we were unable to define any sediment constraint based on inflow for the TXEMP analysis.

SALINITY-INFLOW EQUATIONS

Salinity data for the period 1977 through 1990 were used to prepare the salinity-inflow equations. Salinity is a function of two values, the total of the inflows in the previous 30-day period before the salinity measurement (Q_1) and the total of the inflow in the period 30 to 60 days before the salinity measurement (Q_2). 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.

Trinity Bay: $S = 49.109 - 3.221 * \ln(Q_1) - 3.039 * \ln(Q_2)$

Red Bluff $S = 42.438 - 3.567 * \ln(Q_1) - 1.179 * \ln(Q_2)$

Dollar Point $S = 48.803 - 4.316 * \ln(Q_1) - 0.757 * \ln(Q_2)$

Equation	n	S.E.	F	adj-r^2
Trinity Bay	266	3.25	338.3	0.72
Red Bluff	260	3.70	141.7	0.52
Dollar Point	277	4.29	156.8	0.53

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: $H = 751.23 - 0.2756 * Q_{JF} + 0.8464 * Q_{MA} - 0.1839 * Q_{MJ} - 0.4747 * Q_{SO} + 0.6001 * Q_{ND}$

Eastern oyster: $H = 4169.8 - 0.9397 * Q_{JF} + 0.2838 * Q_{MJ} - 0.9445 * Q_{JA}$

Red drum: $\ln(H) = 3.1548 + 0.0003926 * Q_{MJ} - 0.002043 * Q_{JA} + 0.0006981 * Q_{SO}$

Black drum: $H = 50.225 - 0.02985 * Q_{JF} + 0.1040 * Q_{JA} - 0.06391 * Q_{SO} + 0.03292 * Q_{ND}$

Spotted seatrout: $\ln(H) = 8.2764 - 1.8241 * \ln(Q_{JF}) + 1.4248 * \ln(Q_{ND})$

Brown shrimp: $H = 1019.8 - 0.5779 * Q_{JF} + 0.4192 * Q_{JA} + 0.4060 * Q_{SO} + 0.3533 * Q_{ND}$

White shrimp: $H = 3212 - 0.6905 * Q_{JF} + 0.2734 * Q_{MA} - 0.3254 * Q_{JA} + 0.5046 * Q_{ND}$

Flounder: $H = -12.122 - 0.03094 * Q_{JF} + 0.05408 * Q_{JA} + 0.04940 * Q_{ND}$

Species	r^2	adj-r^2	S.E.	N-used	N-deleted	P
Blue crab	0.82	0.76	413.29	23	3	< 0.0001
Oyster	0.53	0.46	914.01	25	1	0.0011
Red drum	0.66	0.59	0.536	19	1	0.0009
Black drum	0.51	0.41	42.12	25	1	0.0053
Seatrout	0.57	0.52	0.494	20	0	0.0007
Brown shrimp	0.57	0.49	582.75	27	2	0.0005
White shrimp	0.64	0.57	584.3	27	2	0.0001
Flounder	0.60	0.54	42.49	25	1	0.0002

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