FRESHWATER INFLOW RECOMMENDATIONS FOR THE MISSION – ARANSAS ESTUARINE SYSTEM

By

Texas Parks and Wildlife Department
Coastal Fisheries Division
Austin, TX 78744

APPENDIX

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Texas Water Development Board
Surface Water Resources Division
Bays and Estuaries Program
Austin, TX 78711

September 2010

TEXAS PARKS & WILDLIFE

TEXAS WATER DEVELOPMENT BOARD

SPORT FISH & WILDLIFE RESTORATION

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FRESHWATER INFLOW RECOMMENDATION FOR THE MISSION-ARANSAS ESTUARINE SYSTEM

By

Grace F. Chen
Texas Parks and Wildlife Department
Ecosystem Resources Program
Coastal Fisheries Division
Austin, Texas 78744

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Austin, Texas 78711

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EXECUTIVE SUMMARY

As a result of severe droughts in the 1950s, the Texas legislature tasked the Texas Water Development Board (TWDB) and the Texas Parks and Wildlife Department (TPWD) "to determine the bay conditions (i.e., sediments, nutrients, and salinity gradients) necessary to support a sound ecological environment." Since freshwater inflows (FWI) are a main driver of bay conditions in Texas, TPWD and TWDB sought to determine the amount of FWI that was needed to maintain the ecological integrity of the estuary. This report summarizes studies that were used to formulate TPWD's freshwater inflow recommendation for the Mission-Aransas (M-A) system.

TARGET INFLOWS

Monthly FWIs needed to maintain bay productivity were predicted using the Texas Estuarine Mathematical Programming (TxEMP) Optimization Model. This model was also used to predict three target annual inflow amounts (MinQ, MaxH, and MaxQ), which are evaluated in later analyses. MinQ and MaxQ are the minimum and maximum annual inflow amounts that satisfy model input constraints. MaxH is the annual inflow amount that maximizes fishery productivity (commercial fishery harvest) and satisfies model constraints. MaxH is always between MinQ and MaxQ.

The TxEMP analysis, which estimated the inflows necessary for the M-A system, utilized commercial harvest data as input for the model. TPWD acknowledges the known shortcomings of this data type. However, at the time TxEMP analysis was conducted for this ecosystem, commercial harvest data were chosen as input because they covered a longer period of record relative to the TPWD fisheries independent dataset. Subsequent to the TxEMP analysis for this ecosystem, TWDB began to employ TPWD coastal fisheries (CF) independent data for their analyses of other bay systems. It is recommended that any and all future analysis for the M-A system using this methodology use the fisheries independent data rather than commercial harvest data. In addition, it is recommended that the reader be aware of this data shortcoming when considering the inflows evaluated by the TPWD assessment.

ASSESSMENT OF BIOLOGICAL RESPONSES TO TARGET INFLOWS

Based on Browder and Moore's conceptual model of spatial overlap and production area, the freshwater inflow recommendation for the M-A Estuary was made by comparing the spatial extent and distribution a favorable salinity zone (modeled using a hydrodynamic model, TxBLEND) resulting from predicted MaxH (86,000 ac-ft/year) and MinQ (58,000 ac-ft/year) inflows against those contained in the baseline patterns of observed salinity data during a period critical to key fish/shellfish inhabiting the bay area.

Five procedures that combine GIS techniques and standard statistical analyses were implemented to determine the common temporal and spatial components of salinity patterns. The temporal component refers to a biologically critical period for the majority of the key fishery community, while the spatial component refers to salinity zones favored by the majority of the key fishery community. Both observed and modeled salinity patterns used data obtained during the same time period and focused on the size and distribution of the same favorable salinity zones. These five procedures were:

Step 1: Identify fisheries species characteristic to the M-A Estuary. Eight key fish/shellfish, including Atlantic croaker (*Micropogonias undulatus*), spot (*Leiostomus xanthurus*), sand seatrout (*Cynoscion arenarius*), silver perch (*Bairdiella chrysoura*), pinfish (*Lagodon rhomboides*), white shrimp (*Litopenaeus setiferus*), blue crab (*Callinectes sapidus*), and brown shrimp (*Farfantepenaeus aztecus*), captured with both bag seines and trawls, were chosen for this study.

Step 2: Determine season of peak abundance for each gear-species combination based on the median of mean monthly log-transformed catch per unit effort (CPUE). Peak abundance seasons for the species analyzed for this study were then aggregated to represent the "biologically critical period" for the fisheries community. Because the majority of key gear-species combinations appear in the bay area simultaneously during May through August, this time period was chosen to serve as the "biologically critical period" for further comparisons.

Step 3: Establish spatial associations between relative abundance (CPUE) and salinity zones. Geographic information system (GIS) techniques, including ordinary kriging and spatial join, were employed to interpolate salinity patterns and append indices of classified salinity zones to each record of log-transformed CPUE. The salinity-CPUE relationships were then analyzed at aggregated levels for visual comparisons and at discrete point levels for statistical tests in Step 4.

Step 4: Favorable salinities for individual species-gear combinations as well as an overall preferred salinity for the group of species studied were evaluated. Analysis of variance (ANOVA) was used to analyze the 16 species-gear combinations, and all but sand seatrout and silver perch captured with bag seines are statistically significant at an alpha = 0.01. Multiple comparisons were used to identify preferred salinity zones for each of the remaining 14 gear-species combinations. Salinities ranging from 10 – 20 ppt was defined as the most "favorable salinity zone" because the majority of key species were relatively abundant in this salinity range.

Step 5: Create baseline salinity patterns for comparisons. Three baseline salinity patterns corresponding to relatively dry, normal, and wet climatic conditions were created to determine variation in the size and location of the favorable salinity zone. Annual surface inflows for the M-A drainage basin, estimated from 1982 – 2004, were sorted in ascending order and divided into four quartiles. Years falling in the first quartile represented dry years, while those falling in the fourth quartile represented wet years. TPWD CF observed salinity data were used to interpolate baseline patterns for the respective dry and wet years. Average salinities were calculated from the 23 year CF database to create the long-term average salinity patterns depicting a normal hydrological condition. The size of the favorable 10-20 ppt salinity zone during the dry, normal, and wet conditions varied (i.e., 1%, 47%, and 67% of bay area, respectively).

COMPARISONS OF OBSERVED VS. MODELED SALINITY PATTERNS

Based on TPWD observed salinity measurements, the favorable salinity zone (10 – 20 ppt) was mainly distributed within the upper bay, to include Port, St. Charles, and Copano Bays. However, the favorable salinity zone shrank to the tip of the mouth of the Aransas River during the dry period, and extended to a larger portion of Aransas Bay during the wet period. This observed pattern suggests that FWI originating from the M-A watershed predominantly influenced salinity in Copano Bay, and its influence on Aransas Bay might be outweighed by FWI from the Guadalupe River through San Antonio Bay.

Three sets of comparisons of observed vs. modeled salinity patterns were conducted for three climatic conditions: relatively normal, dry, and wet. First, comparisons of the long-term observed (1982 – 2004) vs. modeled (1987 – 1992) salinities indicate that both patterns were nearly identical in both size and spatial distribution of the favorable salinity zone.

The second comparison performed on the observed vs. modeled salinity patterns for the relatively dry condition also suggested that MaxH and MinQ inflows (1988 simulation) should be capable of maintaining the historical fisheries production in the M-A Estuary.

The third comparison was performed on the observed vs. modeled salinity patterns created for the relatively wet condition. Although the size of the favorable salinity zone resulting from the modeled wet year (1992) was within the extreme boundary conditions tested (1 – 67% of bay area), the spatial distribution of this zone deviated greatly from the typical pattern. Specifically, the favorable salinity zone of 10-20 ppt shifted from Copano Bay to mid-Aransas Bay, which typically has salinities ranging 20 – 30 ppt. This displacement was mainly caused by the influence of FWI from the Guadalupe River, which received its highest recorded volume of inflows during 1992 (based on a period of record from 1941-1999). This inflow created salinity conditions deemed acceptable to maintain a healthy M-A system.

FRESHWATER INFLOW RECOMMENDATION AND SUGGESTION

Comparisons of the observed vs. modeled salinity patterns indicate that both MaxH and MinQ inflows are capable of maintaining historical fisheries production for the M-A Estuary. Salinity patterns modeled under average conditions are nearly identical to those generated from the long-term observed patterns in terms of size and spatial distribution of the favorable salinity zone. In addition, the sizes of favorable salinity zone (10 -20 ppt) resulting from the model-dry and -wet conditions (25 – 27% of bay area) fit within the calculated test range (1 – 67% of bay area) based on the TPWD CF salinity data.

Accordingly, TPWD recommends a target inflow within the range of MinQ to MaxH for the M-A Estuarine system, while recognizing that the inflows into the M-A Estuary from its upstream drainage area may at times be of less consequence to overall fisheries production than are the inflows entering from the neighboring Guadalupe Estuary system.

SECTION 1: INTRODUCTION

Estuaries, where freshwater meets saltwater, are among the most productive natural ecosystems in the world (Day et al. 1989). The vitality of estuarine ecosystems relies on balanced interactions among physical, chemical, and biological factors. Freshwater inflows (FWI) transport nutrients, detritus, and sediments from upstream areas. They also reduce salinities, mix water masses, and play a critical role in the balance of factors responsible for estuarine production (Browder and Moore 1981). Quantitatively determining optimal environmental flows to sustain productivity of aquatic ecosystems has been advocated and practiced in many places including the State of Texas. The 69th Texas Legislature required the Texas Water Development Board (TWDB) and Texas Parks and Wildlife Department (TPWD) "to determine the bay conditions (i.e., sediments, nutrients, and salinity gradients) necessary to support a sound ecological environment" (Longley 1994). The two agencies jointly worked on an analytical process to determine "target inflows" that maintained favorable conditions as defined by the legislature. The Water Development Board took on the responsibility of estimating the quantity of "target inflows" for each Texas major bay via a mathematical optimization processes, whereas TPWD's responsibility was to recommend an optimal inflow for each bay by assessing the effectiveness of target inflows on maintaining historical productivity. This report documents the background and analytical procedures conducted to assess the biological responses to target inflows prescribed for the Mission-Aransas (M-A) Estuary. An inflow recommendation for the M-A system, as well as a review of the effects of FWIs from the Guadalupe Estuary in the M-A Bay system are discussed.

1.1. Background of Texas's Freshwater Inflow Studies

The need for provisions of FWI to Texas's bays and estuaries has been recognized since the drought of record that lasted from 1948 – 1956 resulted in a drastic decline in the commercial harvests of oyster, white shrimp, and blue crab from Texas bays (Texas Department of Water Resources [TDWR] 1981; Powell et al. 2002). The first legislative effort to address this need was the enactment of the Texas Water Planning Act of 1957, which gave special consideration to the effect of upstream development on estuarine ecosystems (Powell 1994). In order to make decisions about FWIs, scientific data needed to be collected. Therefore, TWDB initiated a cooperative Bays and Estuaries Program in 1967 to facilitate collections of physical, chemical, and biological data required for characterizing major Texas bays. The State Methodology for determining FWI needs was refined in 1985, when the 69th Texas Legislature directed the TWDB and TPWD to jointly establish and maintain a continuous data collection and analytical study program to support ecologically sound estuarine systems (Powell 1994; Powell et al. 2002).

To meet future challenges, the 78th Texas Legislature (2003) passed Senate Bill 1639 that established a Study Commission on Water for Environmental Flows and a Science Advisory Committee to develop technical recommendations on the science and methodology for determining environmental flow needs. This effort was expanded in 2005 with Senate Bill 3 which established a stakeholder process to recommend environmental flows to maintain the viability of the state's streams, rivers, bays, and estuaries (TPWD 2005a). Senate Bill 3 was passed by the 80th Texas Legislature in 2007.

1.2. Conceptual Model for Assessing Biological Responses to Freshwater Inflows

Excessive influxes of freshwater or saltwater resulting from storm events or severe droughts may alter salinity gradients and shift isohalines in an upstream or downstream direction (Sklar and Browder 1998). Shifts of salinity gradients resulting from abnormal weather patterns or alteration of FWI regimes may place favorable salinities out of reach for plants and animals that have adapted to a particular environment and developed their physiological and behavioral patterns accordingly (Day et al. 1989; Sklar and Browder 1998). Although the relationships between FWI and fishery production in estuaries has long been recognized, they are difficult to quantify. Browder and Moore (1981) suggested that potential fishery productivity was a function of the size of "production area", where favorable dynamic habitats spatially overlapped with favorable stationary habitats. Dynamic habitats include favorable salinity ranges or temperatures, while stationary habitats may include salt marshes, oyster reefs, or seagrass beds. Theoretically, the larger the spatial extent of the production area, the higher the productive potential for an estuary (Browder and Moore 1981; Sklar and Browder 1998).

This concept model of production area can be applied to assess the potential impact of changes in FWI on biological communities by measuring changes in spatial patterns of salinity in relation to variations of FWI regimes (Sklar and Browder 1998). Assuming stationary habitats remained the same throughout the research period, this study used the spatial extent and spatial distribution of salinity patterns resulting from TPWD observed data as criteria to evaluate the effectiveness of modeled inflows on sustaining historical estuarine productivity for the M-A Bay.

1.3. Methodology

Texas's approach to freshwater inflow recommendations for bays and estuaries includes both a modeling and biological review (validation) process. As depicted in the schematic of the State Methodology (Figure 1), optimal freshwater inflows required to achieve specific management objectives are estimated using the Texas Estuarine Mathematical Programming (TxEMP) Optimization Model developed by TWDB. This model relies on relationships of historical freshwater inflow to salinity, nutrient loads, sediment loads, and fisheries production (Matsumoto et al. 1994; Powell et al. 2002) to calculate potential target inflows, which can then be modeled to determine the effect of inflow on bay circulation and salinity. The target inflows are referred to as MinQ, MaxH, and MaxQ. MinQ is the minimum inflow that meets all defined salinity and biological constraints set within TxEMP. It's counterpart, MaxQ is the maximum inflow that meets all salinity and biological constraints set within TxEMP. MaxH inflow lies between MinQ and MaxQ and is the flow which maximizes fisheries harvest within the range of possible inflows considered. These target inflows (i.e., MinQ, MaxH, and MaxQ) can be input into TxBLEND, a two dimensional hydrodynamic and salinity transport model, to create simulated bay salinities (Powell et al. 2002).

Texas Parks and Wildlife Department evaluates the effectiveness of the target inflows on maintaining historical fisheries productivity by comparing the size and spatial distribution of favorable salinity zones predicted by the model against those obtained from long-term observations. Favorable salinity zones are areas where catch rates of key fishery species are relatively high. They are determined by overlaying the spatial distribution of each key species and the salinity gradients interpolated from TPWD data during seasons of peak abundance identified for each species. Once the effectiveness of target inflows on maintaining estuarine productivity is validated, TPWD then recommends the FWI amount for the estuarine system under study.

The TxEMP output evaluated in the present analysis was based on commercial harvest data input, rather than TPWD CF independent data. At the time this analysis was conducted, commercial harvest data were chosen over TPWD CF independent data as input for TxEMP because the harvest data covered a longer period of record. Subsequent to that time, TWDB started using TPWD CF independent data for their analyses. For any future analyses conducted using this methodology on the M-A system, it is recommended that TPWD CF independent data be used as input for TxEMP.

1.4. Objectives of Study

The goal of this study was to provide a FWI recommendation for the M-A Estuary through the assessment of biological responses to target inflows generated by TxEMP. Based on the concept of production area, the effectiveness of target inflows on maintaining a sound ecological environment in the M-A Estuary was evaluated by comparing the spatial extent and distribution of a favorable salinity zone resulting from the observed vs. modeled salinities. Specific objectives for this study were to determine:

- Fishery species that are economically and/or ecologically important to the M-A Estuary that would be used for analyses in this report;
- The biologically critical times in the bay for each key fishery species and the fisheries community and to identify how the critical times are defined;

- Favorable salinity zones for each key species and the fisheries community and to identify how the favorable salinity zones are determined;
- The acceptable sizes of production area required for sustaining the estuarine productivity of the bay; and
- How the baseline salinity patterns for comparisons were established.

SECTION 2: FRESHWATER INFLOW MODELING

A comprehensive documentation of the Texas approach to freshwater inflow modeling may be found in Longley (1994), as well as in articles by Matsumoto et al. (1994) and Powell et al. (2002). The Appendix of this report provides details of the TxEMP parameters used to generate target inflow regimes for the M-A Estuarine system. Following a description of the study area, this section briefly reviews key components of TxEMP and TxBLEND, and their applications to this estuarine system.

2.1 Study Area

The M-A Estuarine system encompasses 577 km^2 and is named after the two major rivers, the Mission and Aransas Rivers. In addition to the two major rivers, freshwater inflows enter the bay system through Copano, Cavasso, and Salt Creeks. The study area comprises one tertiary bay, Mission Bay, three secondary bays, Copano, Port, and St. Charles Bays, and three primary bays, Aransas, Mesquite, and the north part of Redfish Bay. These bays are separated from the Gulf of Mexico by San Jose Island but are still hydraulically connected via Aransas Pass and Cedar Bayou (Figure 2). The M-A system is hydraulically connected to San Antonio Bay (Guadalupe Estuary) to the north and Corpus Christi Bay (Nueces Estuary) to the south. Like most other Texas estuaries, the M-A system is shallow, with average depths for Mission, Copano, and Aransas Bays of 0.6, 1.6, and 2.6 m, respectively. A dredged navigation channel, the Gulf Intracoastal Waterway (GIWW), runs along Aransas Bay and spans the entire Texas coast. With a width of 91 m and depth of 4.5 m, the GIWW serves as an important channel for water exchange between neighboring estuarine systems (U.S. Geological Survey [USGS] 2001).

Major processes governing hydrological conditions in the M-A system include climatologic factors, freshwater inflows, and to a lesser extent tidal fluctuations (Smith and Dilworth 1999; University of Texas at Austin Marine Science Institute [UTMSI] 2003). The influence of tides on bay circulation is relatively minor because the bay is shallow and the tidal prism, ranging 0.3 - 0.7 m, is small (Montagna et al. 1998). Prevailing winds exert a much stronger influence on the magnitude and direction of water movement within the bay. Precipitation is another climatologic factor influencing bay hydrology. Direct precipitation to the bay accounts for 44 % of freshwater input to the M-A Estuary (TWDB 2010). The M-A Estuary has the smallest upstream drainage area of all the major Texas bays (Solis 1994).

In addition to the influence of precipitation patterns across the state, timing of peak inflows is strongly associated with the occurrence of hurricanes, tropical storms, and frontal passages that trigger rainfalls in spring and fall (Figure 3). The relatively large differences in the monthly average and median inflows demonstrate the pulsed nature of freshwater inflows in the M-A system (Moore 2000). Isolated freshwater pulses brought by storm systems not only affect monthly hydrographs but also control salinity throughout the bay. Because of the shallowness and restricted connection to the Gulf of Mexico, the impact of freshwater pulses on bay salinity is retained for a long period (Pulich et al. 2002; UTMSI 2003; Johns 2004). In general, the response of bay salinities to an influx of freshwater occurs within a few days to several weeks. In contrast, it requires weeks to months for the salinity to recover as the inflow diminishes (Ward 1997).

2.2. Application of TxEMP to the Mission-Aransas Estuarine System

Through a series of ecological interactions between freshwater inflows, salinity, nutrients, and quality of habitats, fishery species are considered effective integrators of the estuarine environment (TDWR 1981). Accordingly, the State Methodology uses fishery production either measured by the commercial harvests of economically important species or by TPWD Coastal Fisheries (CF) fisheries-independent data collected for ecologically and/or economically important species as indicators of estuarine productivity.

As with some previous applications of the TxEMP model, commercial fisheries harvest data collected by TPWD and the U.S. Department of Interior were used for this analysis. For the M-A study, data collected between 1962 and 1996 on the following species: red drum (*Sciaenops ocellatus*), black drum (*Pogonias cromis*), spotted seatrout (*Cynoscion nebulosus*), southern flounder (*Paralichthys lethostigma*), white shrimp (*Litopeneus setiferus*), brown shrimp (*Farfantepenaeus aztecus*), eastern oyster (*Crassostrea virginica*), and blue crab (*Callinectes sapidus*) were used to establish the fishery-inflow relationship for the M-A system. Because some key species live longer than others or take relatively longer to mature to a legally harvestable size, the impact of freshwater inflows on commercial harvests may vary with species and may involve delayed effects. Also, it is known that freshwater inflows have their greatest effect on the young of fisheries species (Powell et al. 2002). Hence, the fishery-inflow relationships for oyster, red drum, and spotted seatrout were analyzed using mean seasonal inflows taken from two or three years prior to the harvest year (Longley 1994; Powell et al. 2002) to account for the time it takes these species to grow from young to harvestable sizes.

Even though there were periodic closures to commercial oyster harvesting, the robust dataset provided enough data for the following analyses (see Appendix for further details).

Optimization via TxEMP is accomplished by relating freshwater inflows to fishery production and abiotic conditions which can include bay salinities, nutrients, and sediments. These abiotic factors are important to the formation and maintenance of fishery habitats. For example, sediments delivered by rivers from upstream help maintain shallow water and marsh habitats, which provide nursery grounds for juvenile fishery species but may decline with local subsidence and sea-level rise (Powell et al. 2002; Wenner 1998). Ideally, one might estimate the annual minimum sediment required to replenish the shallow water and marsh habitats through sediment budgeting. However, due to the sporadic nature of sediment delivery and the lack of long-term data collection, the sediment-inflow relationship was not integrated into the TxEMP optimization process for this application. Rather, it was assumed that the current sediment regime is sufficient to maintain historical marsh habitats. Likewise, the nutrient constraint that was developed based on the median historical streamflow loading and measured concentrations was not integrated into the optimization process but rather used as an external check on the TxEMP output (see Appendix).

The salinity-inflow regression equations required for the optimization analysis were obtained using salinity data collected between 1968 and 1996 in the M-A Estuary. To capture the longitudinal effect of freshwater inflow on bay salinity and associated fauna and flora, salinity-inflow equations were developed using monthly mean salinities at three locations along a salinity gradient and the sum of monthly surface inflows to the estuary. The three sites representing the longitudinal salinity gradient were Copano-Southwest, Copano-Causeway, and Mid-Aransas Bay (Figure 4).

TxEMP allows for management decisions to be represented as constraints which limit the optimization solution. Constraints may include designation of upper and lower monthly inflows as well as upper and lower bounds for salinity and nutrient or sediment loadings. The analysis for the M-A system only included constraints on inflows and salinity (see Appendix).

The freshwater inflows considered in the TxEMP optimization are combined surface inflows, including gaged and ungaged flows, draining from the landscape upstream of the estuary. This excludes direct precipitation on the bay. USGS gaged streamflows represent a synthesis of climatic and hydrologic processes as well as human influences over time and provide an estimate of gaged river inflows. However, USGS gage stations are traditionally located far enough upstream to avoid tidal influences on flow and water level (Asquith et al. 1997; LCRA et al. 2006). As shown in Figure 5, active gage stations located along the Aransas River (gage no. 8189700), Mission River (8189500) and Copano Creek (8189200) account for approximately 40% of the drainage area of the M-A watershed (excluding areas draining into Mesquite Bay), leaving a significant portion of the watershed ungaged.

Surface inflows from the ungaged watersheds were estimated using a rainfall-runoff model (TxRR) that estimates daily runoff generation based on the Curve Number (CN) method (TDWR 1981). Curve numbers are a function of land use/cover type, soil type, and management practice within the simulation area. The CN approach to runoff estimation assumes the area under simulation is a hydrologically homogeneous unit and uses a single value for each parameter. Theoretically, the more homogeneous the area under simulation, the more accurate the prediction will be (Chen 2001). To obtain the best predictions, TWDB staff divided the M-A watershed into 16 sub-watersheds (Figure 5). A runoff value was generated for each sub-watershed and summed into the modeled runoff from the ungaged drainage area. Modeled runoff was incorporated into the calculation of monthly surface inflow entering the M-A Estuary.

Combined Surface Inflow = (1) Sum over all gaged watersheds (USGS Gaged Flow)

\+ (2) Sum over all ungaged watersheds (Modeled Flow)

\+ (3) Sum over all ungaged watersheds (Returned Flow)

\- (4) Sum over all ungaged watersheds (Diverted Flow).

Because returned and diverted flows provided by TCEQ were presented on a monthly basis, monthly combined surface inflows were calculated. Based on historical hydrological data (1941 – 1996), the relative contributions of each inflow component entering the M-A Estuary are listed in Table 1. Uncertainty associated with the estimation of freshwater inflows for M-A Estuary may be higher compared to the majority of Texas coastal basins because more than half of the drainage basin was ungaged and relied on the TxRR simulation.

Similar to setting salinity bounds, solutions to TxEMP optimization equations may be constrained by lower and upper inflow bounds. Previous TxEMP analyses set inflow bounds at the 10^{th} and 50^{th} percentiles of historic monthly inflows in order to assess flows which are beneficial under normal (non-drought) conditions (Powell et al. 2002). However, the lower monthly inflow bound for this M-A study was set at the 25^{th} percentile of historical inflows (1941 - 1996), because the 10^{th} percentile inflow was too low to obtain a biologically feasible solution (see Appendix).

In addition to the relationships of fisheries and salinities to inflows and the constraints for inflow and salinity, desired levels of fishery production (e.g., maximal or 70^{th} percentile of mean annual fisheries harvest) were also factored into the analysis. Based on these inputs, TxEMP generated a series of optimal solutions that satisfied the varying management objectives on a monthly basis (Figure 6). While the monthly distribution of flows obtained from the TxEMP analysis is essential to achieving the benefits of the target flows, for discussion purposes each monthly output was summed into annual target inflow such that MaxH totaled 86,170 ac-ft/year and MinQ totaled 58,750 ac-ft/year.

A performance curve depicts the relationship between annual modeled inflows and the corresponding annual fisheries harvests (Figure 7). The performance curve reflects the Odum et al. (1979) subsidy-stress model postulating that estuarine productive potential is maximized when an optimal amount of freshwater is received by the bay but diminishes as inflow goes above or below this optimal range. As shown in Figure 8, MaxH and MinQ inflows for the M-A Estuary are relatively low even though they are between the 25th and 50th percentiles of historical inflows (1941-1996). The relatively high mean (vs. median) historical inflow reflects the pulsed nature of inflows in this study area. Sporadic heavy rainfalls brought by hurricanes or tropical storms have placed the historical mean flow above the 75th percentile rather than next to the median inflows.

2.3. Application of TxBLEND to the Mission-Aransas Estuarine System

While TxEMP determines the target inflows best suited to maintain estuarine productivity under set management constraints, TxBLEND simulates the effect of those inflows on salinities within the bay. TxBLEND uses a finite element grid made up of nodes and linear triangular elements across the bay and neighboring bay systems to account for the continuity of water movement and salinity transport between connected bay systems. A computational grid consisting of 5,544 nodes and 8,992 triangular elements extending from Matagorda Bay to the northeast to Nueces Bay to the southwest of the M-A Estuary (Figure 9) was used for this application. Unlike Sabine Lake or the Galveston Bay system, the M-A Estuary is hydraulically connected to other major bay systems, most importantly the San Antonio Bay system. Therefore, TxBLEND used observed surface inflow, bathymetry, tide, salinity, wind, precipitation, and evaporation information for the neighboring systems between 1987 and 1992 (Matsumoto et al. 1997). For the M-A system, modeled inflows (MaxH and MinQ) were used instead of observed flows.

Typically for analysis purposes, the impact of MinQ and MaxH on bay salinities is considered within the context of meteorological and tidal conditions from a known wet and dry year. "Dry" and "wet" years refer to the meteorological and tidal conditions, rather than the inflow amounts used in the report's analyses. In other words, TxBLEND can simulate the effects of wet or dry climatic and tidal conditions on salinity zones created by target inflows (MinQ or MaxH). To verify the effect of the target inflows on salinity in the M-A Estuary, MaxH and MinQ were input to the computational grid through points 11, 12, 13 and 14 (Figure 9) throughout the six years of simulation. These grid points correspond to the Aransas River, Mission River, Copano Creek, and Cavasso Creek, respectively, and the inflows were distributed among the points in proportion to their annual contribution of FWIs to the estuary (e.g., Table 2 shows distribution of MaxH flows). All other input data varied with time and reflected observed conditions for 1988 and 1992. Although all target inflows were simulated, only pertinent analyses or select analyses for demonstration purposes are presented in this report.

Bay salinities resulting from each target inflow were simulated at five-minute intervals beginning January 1, 1987 though December 31, 1992 (J. Matsumoto, Texas Water Development

Board, personal communication). This output was averaged for each month to represent the monthly salinity in the bay. Hydrological conditions of this simulation period appear to be typical of the highly variable and pulsed hydrological cycles observed in the study area (Figure 10). The dry and wet years chosen from the simulation period were 1988 and 1992, respectively. Based on the historical records (1941 – 1996), 1988 ranked as the seventh driest and 1992 ranked as the third wettest year. Modeled salinities resulting from these two years (1988 and 1992) served as indicators denoting how the bay system responded to each target inflow under relatively extreme climatic conditions. The effectiveness of a target inflow on maintaining historical estuarine productivity can be validated if the particular target inflow results in a satisfactory distribution of salinities during abnormally dry and wet periods. Accordingly, the validation process focused on the modeled salinity pattern as generated by MaxH and MinQ flows for 1988 (a representative dry year) and 1992 (a representative wet year).

SECTION 3: ASSESSMENT OF BIOLOGICAL RESPONSES TO TARGET FRESHWATER INFLOWS

3.1. Effects of Target Inflows on Bay Salinities

The effects of TxEMP target inflows on bay salinities were evaluated by employing the hydrodynamic/salinity model, TxBLEND, for the M-A study. The modeled salinities obtained at the 5,544 data nodes were then aggregated into daily and monthly averages for further analyses as discussed in this section.

3.1.1. Behavior of the Models

Monthly modeled salinities simulated for MaxH and MinQ inflows during 1988 (dry year) and 1992 (wet year) were interpolated into continuous salinity patterns using GIS techniques. The modeled salinity patterns were created using ordinary kriging, a geostatistical interpolation technique available in ArcGIS™ software. Varying semivariogram models with different parameters were tested to ensure the best prediction power for the application. Based on the criterion of the sum-of-squares of the residuals (Perez-Castaneda and Defeo 2004), the Gaussian model with a lag size of 1,850 m was selected to interpolate the modeled salinities. This lag size (1,850 m) was chosen to approximate the length of a one-minute meridian, on which the TPWD CF sampling grids are based.

An inspection of four modeled salinity patterns (Figure 11) suggests that climatic conditions (dry vs. wet) exert much stronger influences on bay salinities in the M-A Estuary than the target inflows scenarios (MaxH vs. MinQ). For example, approximately 78% of the bay area was predicted to be at salinities >25 ppt in 1988 under both inflow scenarios, while only 18% of the bay was this saline in 1992 (Table 3). This above observation was confirmed by a two-way ANOVA (Table 4) which showed that the difference in mean salinities between dry and wet years was significant at the $p<0.0001$ level, while the difference between MaxH and MinQ inflows was not statistically significant ($p = 0.18$). The model output (salinity data) used to calculate this ANOVA was based on a grid (1,326 data points) that encompassed the M-A Estuary and includes a 5 km buffer zone (Figure 12).

The behavior of the models was further examined by plotting the monthly mean salinities of the 1,326 data points. As depicted in Figure 13, monthly mean salinities resulting from MaxH and MinQ inflows were very similar in part due to the similarity of the monthly distribution of the target inflows (see Figure 6 and Appendix Table 14). In addition, the small size of the M-A watershed (in addition to local climate) resulted in lower inflows relative to other major Texas bays (Figures 14 & 15). Therefore, it is not surprising that the MaxH and MinQ inflows calculated for this system were the lowest of any major Texas bay system. The primary influence of these inflows on bay salinity is mostly limited to the upper bay (Copano Bay). Neighboring systems, particularly the Guadalupe Estuary, also play an important role in shaping salinity structure of the M-A Estuary (particularly that of Aransas Bay) and in maintaining ecosystem productivity. Although the TxEMP analysis was only based on inflows to the M-A system, TWDB conducted a sensitivity analysis to evaluate the effects of reduced inflows from the Guadalupe River on salinity conditions within Copano and Aransas Bays (see Appendix: Influence of Guadalupe River). Because of the hydraulic connection between bays, changes in Guadalupe River inflows have an affect on salinity in Copano and Aransas Bays.

3.1.2. Time Series Analyses of Modeled Salinity at Critical Bay Sites

As previously described, target inflows aimed at maintaining historical (long-term) biological productivity of the bay were estimated using historical hydrological data. The effectiveness of each target inflow was examined by time series analyses. Daily simulated salinity obtained during differing time periods was plotted against the salinity constraints set as the as the upper and lower bounds at critical sites.

Three sites, including Copano-Southwest, Copano-Causeway, and Mid-Aransas Bay (Figure 4) were chosen to demonstrate the time series analysis. Each of the three sites was progressively further from the sources of freshwater inflow. Their mean salinities throughout the historical records are representatives of the salinity gradients across the M-A Estuary. For instance, the mean monthly upper bounds from May through August for Copano-Southwest, Copano-Causeway and Mid-Aransas Bay were 21, 25, and 32 ppt, respectively (Tables 2-4 in the Appendix).

As depicted in Figures 16 – 18, salinities predicted from the MaxH inflow (data not shown for MinQ) for the driest (1988) and wettest (1992) years during the simulation period were chosen to denote the range of the variability of the simulated salinity. The mean of daily salinities obtained from 1987 – 1992 were used to indicate a long-term average (normal) condition. The percent of exceedance for MinQ and MaxH listed in Table 5 permits comparisons of modeled scenarios between key sites.

The percent exceedance resulting from MaxH and MinQ inflows was very similar at individual sites, except for Copano-Southwest. Due to the proximity of this site to the Aransas River, MaxH resulted in fewer days of exceedance than MinQ during a dry year (1988). The difference, however, diminished as the distance between a site and the mouth of rivers increased.

The effects of both target inflows on the percent of exceedance were nearly identical at the Mid-Aransas site regardless of dry or wet climatic condition. These comparisons reinforced the hypothesis that FWI from the M-A watershed predominantly influences salinity in the upper bay. The influence of target inflows on salinity in Aransas Bay may be outweighed by freshwater from the Guadalupe River. Overall, both target inflows provide salinity conditions which appear to effectively sustain the fisheries productivity in the M-A Estuary, although within the upper part of the estuary, MaxH inflow produced fewer exceedences of salinity constraints versus MinQ inflow under the driest conditions.

3.2. Salinity Affinity of Key Fishery Species

Assessing the effectiveness of TxEMP target inflows on the maintenance of bay productivity was accomplished by comparing the size and spatial distribution of favorable salinity zones resulting from the TxBLEND model outputs against those historically observed. Favorable salinities vary in time and space along with the biotic communities in the estuarine environment. Because salinity tolerances for biotic communities are not fully documented, favorable salinities for an estuarine system must be inferred from data indicating environmental conditions under which key species are most abundant or most frequently found (Boyd and Green 1994).

Data from the previously described analyses and relevant biological data were used to determine if the MinQ or MaxH volumes (from TxEMP) and the resultant salinity zones (from TxBLEND) were biologically feasible for the M-A Estuary. The following five steps describe the process used to compile and analyze observed data so that it could be compared to model output: 1) identify key fishery species in the bay system, 2) determine seasons of peak abundance for each key species individually and for the fishery as a whole 3) establish spatial relationships between salinity zones and relative abundances of key species using spatial overlay, 4) determine preferred salinity zones for each key species individually using ANOVA and for the key species as a whole, and 5) create baseline salinity patterns using TPWD CF data to determine the acceptable size of favorable salinity zones.

The TPWD CF Division initiated a Marine Resources Monitoring Program in 1975 to obtain information on finfish and shellfish using different gear types, including bag seines, trawls, gill nets and oyster dredges (TPWD 2005b). Standardized gear types and deployment procedures, as well as sampling schemes, were implemented in Texas estuaries and the near shore Gulf of Mexico systematically so that trends in species composition, size, and catch rates of fishery communities could be determined (Boyd et al. 1995). As illustrated in Figure 19, bay bag seines are deployed adjacent to shorelines to catch small organisms, trawls are used in open water at depths greater than one meter to catch larger organisms, and oyster dredges are utilized along grids containing oyster reefs in water equal to or greater than one meter deep at mean low tide (Fuls 2002).

To provide random samples of marine resources for scientific studies, the CF Monitoring Program devised a spatial framework to guide the selection of sampling sites. The spatial framework consists of grids that were numbered independently for each estuarine system. As depicted in Figure 19, the bay area of M-A Estuary and adjacent land were divided into grid cells of one minute latitude and one minute longitude. Each cell was further subdivided into 144 five-second gridlets. Sampling grid cells are selected randomly using computer programs prior to monthly field surveys. The ecosystem leaders then choose gridlets within the selected grid cell in the field (Fuls 2002). To ensure trawl samples are distributed throughout the open bay, the trawlable area within the estuary is further partitioned into two zones: areas closer to river mouths and areas closer to the Gulf. Ten random samples are collected from each zone on a monthly basis. In addition to catch rates of fishery species, the CF Monitoring Program also measures salinity, temperature, turbidity, dissolved oxygen, and water depth at each bag seine and trawl sampling sites.

To determine salinity affinities for key species inhabiting the M-A Estuary, this study used salinity data and catch rates of key species collected with bag seines and trawls between January 1982 and December 2004 (Table 6). As previously described, bag seine and trawl sampling were designed to capture estuarine organisms at varying life stages and different habitats (shoreline vs open water). Relative abundance measurements for the same species captured using these two gear types are not directly comparable. Catch rates for bag seines are reported as number per unit area (hectare), whereas catch rates from trawls are reported as number per unit time (hour). The CPUE data were analyzed for each species-gear combination separately. In contrast, salinity data collected with each bag seine and trawl are collected with the same equipment in parts per thousand (ppt) and can be merged into a single dataset for further analyses. The sample sizes for salinity, bag seine, and trawl species are summarized in Table 6.

Step 1: Identification of Key Fishery Species

Establishing causal relationships between freshwater inflow and estuary health is difficult because estuarine communities are rich in species that are mobile and heterogeneous in time and space (Ward 2004). The State Methodology assumes fish and shellfish are integrators of environmental conditions and may be used as measures of health of estuarine systems if key species characteristic of the bay under study can be identified (TDWR 1981; Longley et al. 1994; SAC 2004). Similar to the TxEMP optimization process, eight key fishery species were chosen to establish discernible patterns of biological response to freshwater inflows. They were Atlantic croaker (*Micropogonias undulatus*), spot (*Leiostomus xanthurus*), sand seatrout (*Cynoscion arenarius*), silver perch (*Bairdiella chrysoura*), pinfish (*Lagodon rhomboides*), blue crab, white shrimp, and brown shrimp.

This set of key species differs from the one used for the TxEMP analysis mainly because the data availability differed between the time of the analysis and TPWD evaluation. In the 1990s, when these freshwater inflow studies began, the best available data for establishing inflow-fishery relationships (i.e., for use in TxEMP) was from annual commercial harvest data. The eight species listed in Section 2.2 were ecologically and/or economically important to Texas and were selected as key fisheries species for the TxEMP analysis with minor variations in species composition (D. Mosier and J. Tolan, Texas Parks and Wildlife Department, personal communication). The fishery-independent database provides a promising alternative data source for future TxEMP analyses of this system. It also provided the best database for the TPWD evaluation process conducted in this study due to its statistically robust sampling design.

The eight key species chosen for this study were considered economically and/or ecologically important to the M-A Estuarine system because they constituted the vast majority of the biomass collected by trawls as indicated in Table 7 (N. W. Boyd, Texas Parks and Wildlife Department, personal communication). In addition, many of these species are best characterized as forage species that support higher levels of the food web including recreationally and commercially important species. Besides total numbers of catch, relative abundance of each key species was also examined by looking at its frequency of occurrence. This was computed by dividing the number of samples with catch for a particular species by the total number of samples collected by bag seines or trawls over the study period (1982 - 2004). Being estuarine-dependent, most of the key species spend part of their life cycles in the estuary and migrate back to the Gulf for spawning. Their occurrences in the bay typically varied with the time of year. Frequency of occurrence was thus compared on an annual basis and for the season of peak abundance identified for each species.

All key species examined in this report have a peak abundance season (Table 8). Based on Browder and Moore's (1981) theory of spatial overlap, if a species critical life stage (e.g., peak abundance season) overlapped with favorable dynamic and stationary habitats then fishery productivity should be enhanced. Therefore, salinity zone affinity of key fish/shellfish examined in this report were assessed using salinity and CPUE data collected during the season of peak abundance identified below.

Step 2: Determination of Peak Abundance Seasons

Through geological time, many finfish and shellfish have evolved to use estuaries as nursery grounds (Day et al. 1989). It has been estimated that up to 97.5% of commercially harvested fisheries in the Gulf of Mexico rely on estuaries for some portion of their life cycle (UTMSI 2003). To minimize competition for food and maximize the survival and growth of individual species, larvae and juvenile fish and shellfish migrate to different parts of the estuary at different times of the year. Adapted to the hydroclimatic cycles of the natural system, estuarine-dependent species develop unique migration patterns to best utilize available resources. Migration patterns thus constitute an integral part of the life history of estuarine organisms

(TDWR 1981). Knowing peak abundance seasons for each key species and the biologically critical time for the majority of species in the bay system is important for resource management because optimal flow and favorable salinity regimes are most needed during these periods (Browder and Moore 1981; Boyd and Green 1994; Sklar and Browder 1998).

Relative abundance of the key species was measured using catch per unit effort (CPUE) expressed as catch per hectare for bag seines and catch per hour for trawls. Because species abundance data typically violate the assumptions of normality and constant variance that underlie standard parametric statistical analysis (Clarke and Warwick 2001), the CPUE data were log transformed using the formula $\log_{10}(1 + x)$, where x was the CPUE corresponding to each of 4,506 bag seine and 5,520 trawl samples. Once transformed, the mean monthly catch rate for each key species taken with bag seines and trawls over the period of 1982 - 2004 was calculated separately. Using a modification of the National Ocean Service (1999) method, peak seasons were defined as consecutive months with a monthly abundance greater than or equal to the median of mean monthly log transformed CPUEs as depicted by the horizontal lines in Figures 20 and 21 for respective species and gear types. The same definition and procedures were applied to determining peak abundance season for each key species caught by bag seines or by trawls. Comparisons of the results shown in Table 9 reveal that peak season for trawls generally begin later than for bag seines. Such lags in peak seasons are expected because the CF Monitoring Program specifically uses bag seines to catch juveniles and trawls to catch the same organism at older life stages. Peak abundance seasons identified for each species in turn served as the time frames for analyzing species' salinity affinity individually, which is discussed below.

To examine whether a period critical to the 16 species-gear combinations collectively can be discerned, a binary coding that used "1" and "0" to denote above versus below the median of monthly mean CPUEs was applied to translate Table 9 into Table 10 for quantitative comparisons. The weights were then summed up for each month to reveal the collective property of peak abundance seasons for the eight key species (Salt 1979). The summation showed that a majority of key species were most abundant in the months of May through August. These months were accordingly designated as the biologically critical period for maintaining salinity conditions in order to protect the community inhabiting the M-A Estuarine system. Comparisons of observed vs. modeled salinity patterns were conducted based on this biological critical period.

Step 3: Spatial Overlap of Species Relative Abundance and Salinity Zones

As previously discussed, estuarine production potential is a function of the spatial extent and distribution of production area defined as area with favorable dynamic and stationary habitats overlaid at biologically crucial times (Browder and Moore 1981; Sklar and Browder 1998). Assuming stationary habitats remained constant over the study period, this study evaluated the effectiveness of target inflows on sustaining historical fisheries productivity by comparing the size and distribution of favorable salinity zones resulting from TxBLEND outputs against those contained in the baseline salinity patterns created from observed salinity data. Prior to comparisons, however, favorable salinity zones were determined based on observed salinity patterns.

A. Interpolation of Salinity Pattern

Similar to modeled salinity patterns, the observed salinity patterns were interpolated using ordinary kriging based on the 10,026 salinity data points collected by the TPWD CF

Monitoring Program between 1982 and 2004 (Table 6). The mean salinity of the 4,506 data collected around near shore was 19.23 ppt, while the mean for the 5,520 points collected in the open water was 20.66 ppt. Just as for assessing productivity of the eight key fish and shellfish, the salinity data collected with bag seines and trawls complement each other especially in sample size and spatial coverage. As illustrated in Figure 22, the evenly distributed sample points and large sample size permits a better prediction power of geostatistical analysis to interpolate the observed salinity patterns.

To establish spatial associations between salinity and fisheries relative abundance, the merged salinity data was temporally subset into 16 datasets according to peak abundance seasons identified for each species-gear combination using the structured query language provided in ArcGIS™. Sample points included in each temporal subset were then aggregated based on their locations in the CF grid cells. Each grid cell labeled with a unique station number encompasses one minute latitude and one minute longitude. A total of 346 stations (grid cells) comprise the sampling scheme for M-A system, but some stations have never been sampled and some stations are on land (e.g., San Jose Island). All the data points sampled within the same grid cell were averaged to obtain mean salinities for respective stations.

Averaging the values at each sample point within each station reduces variation caused by different sample sizes and approximates the long-term salinity condition. The resulting mean salinities were assigned to the centroids of respective grid cells. The evenly spaced mean salinities were then used for ordinary kriging and delineation of continuous salinity gradients across M-A Bay. Similar to the creation of modeled salinity patterns, the Gaussian model with 12 lags that were 1,850 m apart was used to generate observed salinity patterns based on the

TPWD CF field data. Each continuous salinity surface was in turn divided into seven salinity zones at 5 ppt intervals for subsequent analysis.

B. Analyses of Spatial Relationships between CPUEs and Salinity Zones

Spatial relationships between bay salinity and relative abundance of fishery species was established by spatially overlapping the interpolated observed salinity zones and CPUEs calculated for individual species during its peak abundance season. The CPUE - salinity relationship may be investigated at two analytical levels. One is at the discrete data point and the other is at the aggregated level (Duncan and Davis 1953). The analyses (ANOVAs) discussed in Step 4 were performed at the discrete point level, whereas maps depicting species abundance in relation to salinity were computed at the aggregated level. Both levels of analysis required observed salinity patterns obtained from interpolation of salinity data points as described above.

In addition, all the CPUE - salinity relationships were analyzed based on log-transformed CPUEs performed for each species-gear combination. Normality of the transformed CPUE data contained in each of the 16 temporal subsets was evaluated using Shapiro-Wilk's W-statistic provided by the S-PLUS statistical package. CPUE data are typically right-skewed, and the W-statistics associated with the 16 were all approaching zero and found to be significant (i.e., $p < 0.05$). Log-transformations greatly improved the normality of CPUE distribution for all key species, except for sand seatrout and silver perch caught with bag seine due to low catch rates (Tables 8 and 11).

For analyses conducted at the aggregated level, the station's mean CPUE was computed by averaging all log-transformed CPUEs measured within the same grid cell during the biologically critical period (May through August). Prior to overlaying with salinity zones, mean

CPUEs were back-transformed and divided into four classes using the natural-break approach that separates values into different classes at places where large gaps between adjacent values occur (McGrew and Monroe 2000; Peterson et al. 2000; Clarke and Warwick 2001). Relationships between salinity zones and mean CPUE of each key species-gear combination may be visually compared through map displays. For the purpose of brevity, only maps for pinfish, white shrimp, and blue crab are presented to demonstrate the different CPUE-salinity associations. Mean CPUEs attained from trawls were plotted at the centroids of their respective CF grids and are evenly spaced as illustrated in Figures 23, 25, and 27. Mean CPUEs for bag seines species were plotted at the average location which was computed by taking the simple arithmetic means of the x and y coordinates for each bag seine sample site located within a grid as shown in Figures 24, 26, and 28, because the centroids of bag seine grids may fall outside of the bay area (M. Fisher, Texas Parks and Wildlife Department, personal communication).

Although most estuarine-dependent species are euryhaline and may survive across a wide range of salinities, salinity affinity varies by species and life stage. A comparison of spatial distributions of pinfish and white shrimp indicates that the two species thrive in very different salinity regimes. Specifically, pinfish are most abundant in salinities from 20 to 30 ppt (Figures 24 and 25), while white shrimp are more abundant in salinities that range from 5 to 15 ppt (Figures 26 and 27). Lying between these two extremes are other species, such as blue crab, which are abundant in salinities that range from 10 to 30 ppt (Figures 27 and 28).

As manifested in the six representative maps (Figures 23 thru 28), different organisms that inhabit the estuarine system thrive in different salinity zones. To obtain a better understanding of the salinity affinity for each of the 16 species-gear combination, the association between salinity zones and CPUEs were further analyzed at the point level using an ANOVA followed by pair-wise multiple comparisons.

Step 4: Statistical Analyses for Determining Favorable Salinity Zones

Data for ANOVAs were prepared by appending an index of salinity zone to each CPUE record using GIS functionality "Spatial Join", so both the log-transformed CPUE and corresponding salinity zone collected during respective peak abundance seasons were available on the same dataset for statistical analysis. The null hypothesis for all ANOVAs stated that there was no difference in mean CPUEs among the seven salinity zones.

The resulting F-statistics and *p*-values indicated that all species-gear combinations, except for sand seatrout and silver perch collected with bag seines, were statistically significant at $p < 0.05$ (Table 12). Salinity affinity varies with species and gear types significantly. The results were further assessed with the Tukey's multiple comparison method to pinpoint favorable salinity zones for each species-gear combination.

Similar to the summation performed to learn about the collective property of peak abundance season for the key fishery community, results of preferred salinity zone for individual species were summed up for each salinity zone. As shown in Table 12, salinities between 10 and 20 ppt appeared to be the most favorable salinity zone because a majority of key species were relatively abundant in this salinity range, while salinities between 20 and 30 ppt were regarded as the secondary preferred salinity zone because spot and pinfish were relatively abundant in this range. In contrast, salinities below 5 ppt and above 30 ppt may be less preferable for the estuarine-dependent fishery organisms examined in this estuary. Based on the collective property of salinity affinity for the eight key fish/shellfish, the 10 – 20 ppt salinity range was designated as a favorable salinity zone and thus served as the common factor for comparisons of observed vs. modeled salinity patterns.

Step 5: Creation of Baseline Salinity Patterns for Comparisons

As for the modeling process, TWDB simulated target inflows for the period of 1987 – 1992, which included verification on modeled salinities simulated for 1988 and 1992 in order to learn about how the prescribed inflows behave during relatively dry and wet periods. Likewise, to learn about the acceptable size and distribution of a favorable salinity zone for the fishery community inhabiting the M-A Estuary, three baseline salinity patterns were created using TPWD CF salinity data to measure the change in salinity patterns under relatively normal, dry, and wet climatic conditions.

The size and distribution of the pre-determined favorable salinity zone (10-20 ppt) was compared among the three climatic conditions during the same biologically critical period (May through August). The long-term average pattern was created using average salinities sampled from 1982 to 2004, while the dry and wet patterns were created using data collected in relatively dry or wet years. Observed dry and wet periods were determined by partitioning the 23 years of study into dry, medium, and wet years based on surface inflows calculated by TWDB from 1982 to 2004 (TWDB 2010). The 23 annual surface inflows were sorted in ascending order and divided into four quartiles. Years within the first quartile were defined as dry years (1986, 1988, 1989, 1996, 1999, and 2000)-whereas years in the fourth quartile (1983, 1992, 1993, 1997, 2001, and 2002), were grouped as wet years. Means of salinity data collected during May through August in respective dry and wet periods were computed and used to create observed-dry and observed-wet baseline patterns. The M-A Estuary has not experienced a prolonged dry or wet period during the 23 year period of record from 1982 to 2004. However, based on the dry and wet years defined above, the average range of inflows during the peak abundance season (May – August) for dry years and for wet years range from 14,609 ac-ft/month to 94,478 ac-ft/month. For this study effort, the driest and wettest years during this period were used to delineate the range of salinity tolerance for biological communities in the bay. Summary statistics for the three climatic conditions are compared in Table 13. As expected, the mean salinity increases from wet to normal to dry conditions.

The size of the favorable salinity zone (10-20 ppt) resulting from the long-term average condition occupies 47% of bay area and occurs primarily in Mission, Copano, Port, St. Charles, and upper Mesquite Bays (Figure 29). The long-term observed pattern appears to be typical of the M-A Estuary. It clearly reflects the influence of the Mission River, Aransas River, Copano Creek, Cavasso Creek, Salt Creek, and Guadalupe River through the San Antonio system. Figure 29 clearly depicts the contrast between the three baseline patterns in terms of the size and spatial distribution of the favorable salinity zone. Specifically, the size of the 10 - 20 ppt zone increased from 47% to 67% of bay area and extended into mid-Aransas Bay during the wet period, whereas, the size decreased from 47% to 1% and retreated to the mouth of the Aransas River during the dry period. Such changes in salinity patterns in response to change in hydrological conditions are expected even though the 1% bay area obtained from the dry period was extremely low. The size of the salinity zone (1 – 67% of bay area, in particular the lower bound of 1%) used for this analysis should be considered as an extreme boundary condition for the worst case scenario in this study. Historical estuarine productivity may be jeopardized if only 1% of the bay area contains favorable salinities, particularly if such a pattern persists for a long time. However, this 1% was derived from average salinities of the six non-consecutive driest years during the 23 year study period. Knowing that the favorable salinity zone typically accounts for 47% bay area, the observed dry and wet baseline patterns were created mainly to delineate the extreme acceptable boundary (1 – 67% of bay area) for the favorable salinity zone for the biological community inhabiting the M-A Estuary.

SECTION 4: COMPARISONS OF OBSERVED VS. MODELED SALINITY PATTERNS

According to the conceptual model of spatial overlap and production area, this study evaluated the effectiveness of MaxH and MinQ inflows on maintaining historical fisheries productivity by comparing the size and spatial distribution of the favorable salinity zone (10-20 ppt) in observed vs. modeled salinity patterns. Three sets of comparisons were performed to investigate how the modeled salinity patterns change in response to changes in climatic conditions. Modeled-long-term average, -dry, and –wet salinity patterns created using mean salinities simulated for 1987 – 1992, 1988, and 1992, respectively, were created and paired with observed salinity patterns described previously. All the salinity patterns compared were interpolated based on the same peak abundance season (May through August) and favorable salinity zone derived from preceding analyses. Likewise, the size of the favorable salinity zone was evaluated to determine if it fell within the extreme boundary of 1 - 67% of bay area derived in the previous section. The three sets of comparisons are presented in Figures 30, 31, and 32.

Regardless of the data duration (observed: 1982 – 2004 vs. modeled: 1987 – 1992), the three long-term average salinity patterns created to represent a normal hydrological condition were nearly identical for observed, MaxH, and MinQ inflows (Fig. 30). Their salinity structures are typical of the M-A Estuary and contain a favorable salinity zone (10-20 ppt) accounting for approximately 47% of the bay area. Despite the poor differentiation between the target inflows in their effect on bay salinities, both MaxH and MinQ inflows appear to be capable of sustaining fisheries productivity for the M-A Estuary.

Comparisons of salinity patterns created for the dry and wet periods (Figures 31 and 32) again revealed few differences between the effects of MaxH and MinQ inflow on bay salinity. Both target inflows generated a favorable salinity zone (10 – 20 ppt) accounting for 25 - 26% of bay area under dry conditions (1988) and 27% under wet conditions (1992), though the location of the favorable salinity zone shifted from Copano and St. Charles Bays to Aransas Bay under wetter conditions. Compared to the range of bay area lying within the favorable salinity zone during dry years to wet years (1 – 67%), the salinity patterns obtained from the modeled inflows for MaxH and MinQ were not as drastic and were well within this extreme boundary condition. As noted previously, the lack of difference in the salinity patterns resulting from MinQ and MaxH is attributed in large part, to the similarity in the monthly target inflows resulting from the TxEMP analysis. Additionally, while Guadalupe River inflows are influential to Aransas Bay, the contribution of inflows from the M-A watershed are important to salinity patterns at least within the upper estuary. This is demonstrated in Figure 31, where both MaxH and MinQ provide more favorable salinity conditions to the estuary during a dry period as compared to the observed conditions. Therefore, target inflows mimicing either MinQ or MaxH should be effective in maintaining the M-A Estuary's historical fisheries production, if only judged by the size of favorable salinity zone.

The control of climatic conditions over differences in modeled scenarios is also shown via the salinity patterns interpolated for the dry vs. wet periods. For example, MaxH inflow resulted in 73% of bay area containing salinities higher than 20 ppt in 1988 (dry year), while only 20% of bay area contained salinities greater than 20 ppt in 1992 (wet year). Furthermore, the locations of the favorable salinity zones shifted from the upper to the lower bay in 1992. Based on the conceptual model of spatial overlap and production area, higher production is achieved when preferred dynamic habitats (e.g., preferred salinity zones) overlap with preferred stationary habitats (e.g., marshes, oyster reefs, etc.; Browder and Moore 1981; Sklar and Browder 1998). Thus, if such sub-optimal shifts in salinity conditions persist for a long time, it may reduce or eliminate the spatial overlap of preferred salinities with preferred stationary habitats (e.g., for species traditionally inhabiting the upper bay and those in the lower bay) and alter ecosystem functions.

SECTION 5: FRESHWATER INFLOW RECOMMENDATION

Comparisons of the observed vs. modeled salinity patterns indicate that both MaxH and MinQ inflows are capable of maintaining historical fisheries production for the M-A Estuary for the following reasons. First, the long-term average modeled salinity pattern for MaxH and MinQ inflows are nearly identical to those generated from the long-term observed pattern, in terms of size and spatial distribution of the favorable salinity zone. Second, the sizes of favorable salinity zone in the bay resulting from the model-dry and -wet scenarios (25 – 27% of bay area) are well within the extreme boundary condition as identified by the observed dry and wet extremes which yielded a range of 1 – 67% of bay area.

Accordingly, TPWD recommends a target inflow consistent with the monthly distribution and within the range of MinQ (58,000 ac-ft/year) to MaxH (86,000 ac-ft/year) for the M-A Estuarine system (see Appendix Table 14). TPWD also recommends further exploration into the influence of freshwater inflows and salinity conditions within the Guadalupe Estuary on salinity conditions within the M-A Estuary. This may include conducting a re-analysis of TxEMP to include explicit consideration of salinity and species relationships based on regional freshwater inflows from the Guadalupe and M-A systems. Or, it may include conducting additional TxBLEND simulations to evaluate various inflow scenarios.

SECTION 6: FUTURE DIRECTIONS

The State Methodology uses historical fisheries data to create a fishery-inflow relationship to help determine target inflows. For this study, commercial harvest data were chosen as input for the TxEMP model. Although now there are many recognized limitations with this data source, commercial data were chosen at the time for use in the analysis of the M-A watershed because they covered the longest period of record. However subsequent TxEMP analyses for other Texas estuaries have used the TPWD CF fishery-independent dataset. This dataset has been identified as a superior datasource for TxEMP analyses because it does not suffer from the same limitations as commercial data, and is considered less biased than the commercial harvest dataset used in the preceding analysis. If future analyses are conducted on the M-A system using the State Methodology, it is recommended that TPWD CF fishery independent data be used.

The TxEMP optimization analysis is typically set up to evaluate optimal freshwater inflows for a single bay system based on inflows, species, and other factors specific to that system and surrounding watershed. For the M-A study, the TxEMP analysis focused on the M-A system and did not include inflows or other factors from the neighboring bay systems, despite the established hydraulic connectivity among these mid-coast bays. This study showed that inflows originating within the M-A watershed predominantly influenced salinity in the upper bay (Mission and Copano Bays); whereas, salinities in Aransas Bay are also influenced by inflows from the Guadalupe basin flowing through San Antonio Bay. The impact of inflows from the Guadalupe River on salinity in the M-A Estuary was demonstrated by TxBLEND simulations as evident in the modeled wet salinity pattern. Future research is needed to evaluate the feasibility of incorporating influential neighboring watersheds such as Guadalupe Basin into the calculation of target inflows for this bay system.

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The author would like to thank local biologists, including Karen Meador, Dennis Pridgen (deceased), Kay Jenkins, Michael Weeks, James Tolan, Mark Fisher, and Ed Hegen who contributed their knowledge of the study area and insights into the function of the ecosystem. Their inputs were pivotal to the development of the case study. Special thanks are due to Charles Smith, Brenda Blay, and David Buzan who proofread the first draft, as well as Nathan Kuhn, James Tolan, and Angela Schrift who edited revisions patiently. Many other professionals extended their help in the completion of this study. Among them are Cindy Loeffler, Norman Boyd, Doyle Mosier and Rebecca Hensley with Texas Parks and Wildlife Department; Junji Matsumoto, David Brock, Barney Austin, Ruben Solis, Carla Guthrie, Zhenwen Jia, and Greg Malstaff with Texas Water Development Board; Norman Johns with the National Wildlife Federation; and Angela Rodriguez with Lower Colorado River Authority. Finally, personal thanks to my family in Taiwan as well as church families in Austin, Texas and Iowa City, Iowa for their love and support during my illnesses while conducting this case study.

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TABLES

Table 1. Composition of surface inflow calculated for the Mission-Aransas Bay by TWDB for 1941 through 1996.

Component	Gaged Flow	Modeled Flow	Returned Flow	Diverted Flow
Percent (%)	42.91	45.53	11.73	0.17

Table 2. Surface inflow data used for TxBLEND simulations of MaxH inflows for 1988 (dry year) and 1992 (wet year).

Inflow Point	River	Data Source	Flow88	Flow92	Ratio
1	Colorado River	Combined Inflow	521,530	9,593,100	18.39
2	Lavaca River	Combined Inflow	82,905	2,673,796	32.25
3	Garcitas Creek	Combined Inflow	11,060	572,582	51.77
4	Chocolate Bay	Combined Inflow	4,463	222,427	49.84
5	Powderhorn Lake	Combined Inflow	4,776	247,615	51.85
6	Cox Lake Creek	Combined Inflow	1,491	89,270	59.88
7	Carancahua Creek	Combined Inflow	25,083	608,949	24.28
8	Turtle Creek	Combined Inflow	21,966	214,986	9.79
9	Tres Palacios Creek	Combined Inflow	29,684	414,646	13.97
10	Guadalupe River	Combined Inflow	875,489	7,617,397	8.70
11	Aransas River (37%)	MaxH Inflow	31,883	31,883	1.00
12	Mission River (38%)	MaxH Inflow	32,745	32,745	1.00
13	Copano Creek (9%)	MaxH Inflow	7,755	7,755	1.00
14	Cavasso Creek (16%)	MaxH Inflow	13,787	13,787	1.00
15	Nueces River	Combined Inflow	38,143	946,994	24.83
16	Oso Creek	Combined Inflow	10,821	106,376	9.83

Flow88 and Flow92 are annual flows input from respective inflow points in 1988 and 1992. Ratio = Flow92 / Flow88.

Table 3. Salinity structure resulting from four model scenarios. The numbers represent the percentage of bay area in each salinity range.

Salinity (ppt)	**Dry Year (1988)** MaxH	**Dry Year (1988)** MinQ	**Wet Year (1992)** MaxH	**Wet Year (1992)** MinQ
0 - 5	0.41	0.40	8.65	8.60
5 - 10	0.39	0.37	12.86	12.43
10 - 15	3.78	3.78	14.38	14.53
15 - 20	4.27	3.93	17.55	17.75
20 - 25	13.01	12.72	28.36	28.31
25 - 30	23.31	23.44	11.12	11.20
30 - 35	28.19	28.59	7.08	7.18
> 35	26.62	26.78	0.00	0.00

Note: Based on September's mean simulated salinities for 5,544 model nodes that cross the Mission-Aransas Estuary and neighboring bay systems (as shown in Figure 9).

Table 4. Results of two-way ANOVA conducted on the TxBLEND modeled salinities.

Variable	df	F-Value	P-Value
Weather conditions	1	1,071.52	<0.0001
Target inflows	1	1.84	0.1756
Weather * Inflow	1	3.69	0.0547
Residuals	5,300		

Table 5. Number and percentage of days exceeding the upper or lower salinity bounds.

	Copano-Southwest		Copano-Causeway		Mid-Aransas	
	MaxH	MinQ	MaxH	MinQ	MaxH	MinQ
Above the upper bound in 1988 (dry year)	19 (5.2%)	98. (26.8%)	111 (30.3%)	124 (33.9%)	61 (16.7%)	61 (16.7%)
Below the lower bound in 1992 (wet year)	102 (27.8%)	98 (26.8%)	168 (45.9%)	166 (45.4%)	181 (49.5%)	179 (48.9%)

Table 6. Sample sizes of CPUE and salinity.

Gear Type	**CPUE**	**Salinity**
Bag Seine	4,506	4,506
Trawl	5,520	5,520
Total Data Points	10,026	10,026

Table 7. Numbers and ranks of key species captured with trawls from Mission-Aransas Estuary between 1990 and 2004.

Species	**No. of Catch**	**Rank**
Spot	81,678	1
Atlantic croaker	64,210	2
Pinfish	56,125	3
Brown shrimp	39,123	4
Silver perch	17,521	5
White shrimp	16,253	6
Blue crab	11,640	10
Sand seatrout	2,870	17

Source: TPWD unpublished data, 2005
Note: The rank was rated against a total of 245 species

Table 8. Occurrences of key species in Mission-Aransas Estuary collected between 1982 and 2004.

Bag Seine Species	Year-Round			Peak Seasons		
	Samples	**Occurrence**	**Percent (%)**	**Samples**	**Occurrence**	**Percent (%)**
Atlantic croaker	4,506	769	17	1,876	549	29
Spot	4,506	1,718	38	2,254	1,327	59
Sand seatrout	4,506	29	1	1,504	23	2
Silver perch	4,506	269	6	2,256	245	11
Pinfish	4,506	2,182	48	2,256	1,634	72
White shrimp	4,506	1,149	26	2,256	1,039	46
Blue crab	4,506	2,033	45	2,254	1,153	51
Brown shrimp	4,506	2,184	48	2,256	1,673	74
Trawl Species	Year-Round			Peak Seasons		
	Samples	**Occurrence**	**Percent (%)**	**Samples**	**Occurrence**	**Percent (%)**
Atlantic croaker	5,520	4,043	73	2,760	2,471	90
Spot	5,520	3,872	70	2,300	1,903	83
Sand seatrout	5,520	1,279	23	2,760	916	33
Silver perch	5,520	2,268	41	2,300	1,120	49
Pinfish	5,520	2,806	51	2,760	1,889	68
White shrimp	5,520	2,265	41	2,760	1,508	54
Blue crab	5,520	3,682	66	2,765	2,169	78
Brown shrimp	5,520	2,957	53	1,840	1,455	79

Note: Peak seasons for each species – gear combination were determined according to the procedure described in Step 2.

Table 9. Peak abundance season determined for each key species - gear combination.

Common Name	**Bag Seine**	**Trawl**
Atlantic Croaker	Feb - Jun	Mar - Aug
Spot	Mar - Aug	May - Sep
Sand Seatrout	May - Aug	May - Oct
Silver Perch	May - Oct	Jul - Nov
Pinfish	Apr - Sep	Jun - Nov
White Shrimp	Jun - Nov	Jul - Dec
Blue Crab	Mar - Aug	Feb - Jul
Brown Shrimp	Apr - Sep	Apr - Jul

Table 10. Determination of peak abundance seasons for all species-gear types collectively.

Species (bag seine)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Atlantic Croaker	0	1	1	1	1	1	0	0	0	0	0	0
Spot	0	0	1	1	1	1	1	1	0	0	0	0
Sand Seatrout	0	0	0	0	1	1	1	1	0	0	0	0
Silver Perch	0	0	0	0	1	1	1	1	1	1	0	0
Pinfish	0	0	0	1	1	1	1	1	1	0	0	0
White Shrimp	0	0	0	0	0	1	1	1	1	1	1	0
Blue Crab	0	0	1	1	1	1	1	1	0	0	0	0
Brown Shrimp	0	0	0	1	1	1	1	1	1	0	0	0
Sub Total	*0*	*1*	*3*	*5*	*7*	*8*	*7*	*7*	*4*	*2*	*1*	*0*

Species (trawl)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Atlantic Croaker	0	0	1	1	1	1	1	1	0	0	0	0
Spot	0	0	0	0	1	1	1	1	1	0	0	0
Sand Seatrout	0	0	0	0	1	1	1	1	1	1	0	0
Silver Perch	0	0	0	0	0	0	1	1	1	1	1	0
Pinfish	0	0	0	0	0	1	1	1	1	1	1	0
White Shrimp	0	0	0	0	0	0	1	1	1	1	1	1
Blue Crab	0	1	1	1	1	1	1	0	0	0	0	0
Brown Shrimp	0	0	0	1	1	1	1	0	0	0	0	0
Sub Total	*0*	*1*	*2*	*3*	*5*	*6*	*8*	*6*	*5*	*4*	*3*	*1*
Total	**0**	**2**	**5**	**8**	**12**	**14**	**15**	**13**	**9**	**6**	**4**	**1**

Note: The number “1” denotes the month was identified as part of the peak abundance season for a species-gear combination, while “0” denotes the opposite.

Table 11. Comparison of W-statistic between raw and log-transformed CPUEs.

Species	Bag Seine		Trawl	
	CPUE	Log-CPUE	CPUE	Log-CPUE
Atlantic Croaker	0.2167	0.6439	0.6314	0.9228
Spot	0.4064	0.8393	0.5438	0.9369
Sand Seatrout	0.0682	0.0996	0.4306	0.6837
Silver Perch	0.0974	0.3763	0.4332	0.8040
Pinfish	0.4142	0.8804	0.4869	0.8992
White Shrimp	0.2096	0.7813	0.4245	0.8411
Blue Crab	0.3376	0.7951	0.3968	0.9270
Brown Shrimp	0.3970	0.8759	0.4489	0.9322

Note: the closer the W-statistic is to “1”, the closer the data distribution is to normality.

Table 12. Determination of favorable salinity zone for the 16 species-gear types collectively (based on the results of ANOVAs and multiple comparisons).

Species (bag seine)	**0 - 5**	**5 - 10**	**10 - 15**	**15 - 20**	**20 - 25**	**25 - 30**	**30 - 35**	**F-statistic**	**P-value**
Atlantic croaker	0	0	1	0	0	0	0	15.78	< 0.0001
Spot	0	0	0	0	1	1	0	8.86	< 0.0001
Sand seatrout	0	0	0	0	0	0	0	2.09	0.0800
Silver perch	0	0	0	0	0	0	0	0.88	0.4900
Pinfish	0	0	0	0	1	1	0	39.21	< 0.0001
White shrimp	0	1	1	1	0	0	0	19.45	< 0.0001
Blue crab	0	0	1	1	1	1	0	3.85	0.0018
Brown shrimp)	0	0	1	1	0	0	0	5.58	< 0.0001
Sub Total	*0*	*1*	*4*	*3*	*3*	*3*	*0*		

Species (trawl)	**0 - 5**	**5 - 10**	**10 - 15**	**15 - 20**	**20 - 25**	**25 - 30**	**30 - 35**	**F-statistic**	**P-value**
Atlantic croaker	0	0	1	1	0	0	0	44.73	< 0.0001
Spot	0	0	0	0	1	1	0	27.53	< 0.0001
Sand seatrout	0	0	1	1	0	0	0	10.37	< 0.0001
Silver perch	0	0	1	1	1	0	0	36.70	< 0.0001
Pinfish	0	0	0	0	0	1	0	141.03	< 0.0001
White shrimp	0	0	1	0	0	0	0	59.42	< 0.0001
Blue crab	0	0	1	1	0	0	0	6.49	0.0002
Brown shrimp	0	0	1	1	0	0	0	92.33	< 0.0001
Sub Total	*0*	*0*	*6*	*5*	*2*	*2*	*0*		
Total	**0**	**1**	**10**	**8**	**5**	**5**	**0**		

Note: The number "1" denotes the salinity zone that was preferred by a species-gear combination, while "0" denotes the opposite.

Table 13. Statistics of observed data used to create baseline salinity patterns.

	Long-term Average (23 years)	Dry (6 years)	Wet (6 years)
Count	3574	856	1004
Minimum (ppt)	0	0.7	0
Maximum (ppt)	42	42	40
Mean (ppt)	21.34	26.88	17.30
Standard Deviation	9.68	7.61	9.61

FIGURES

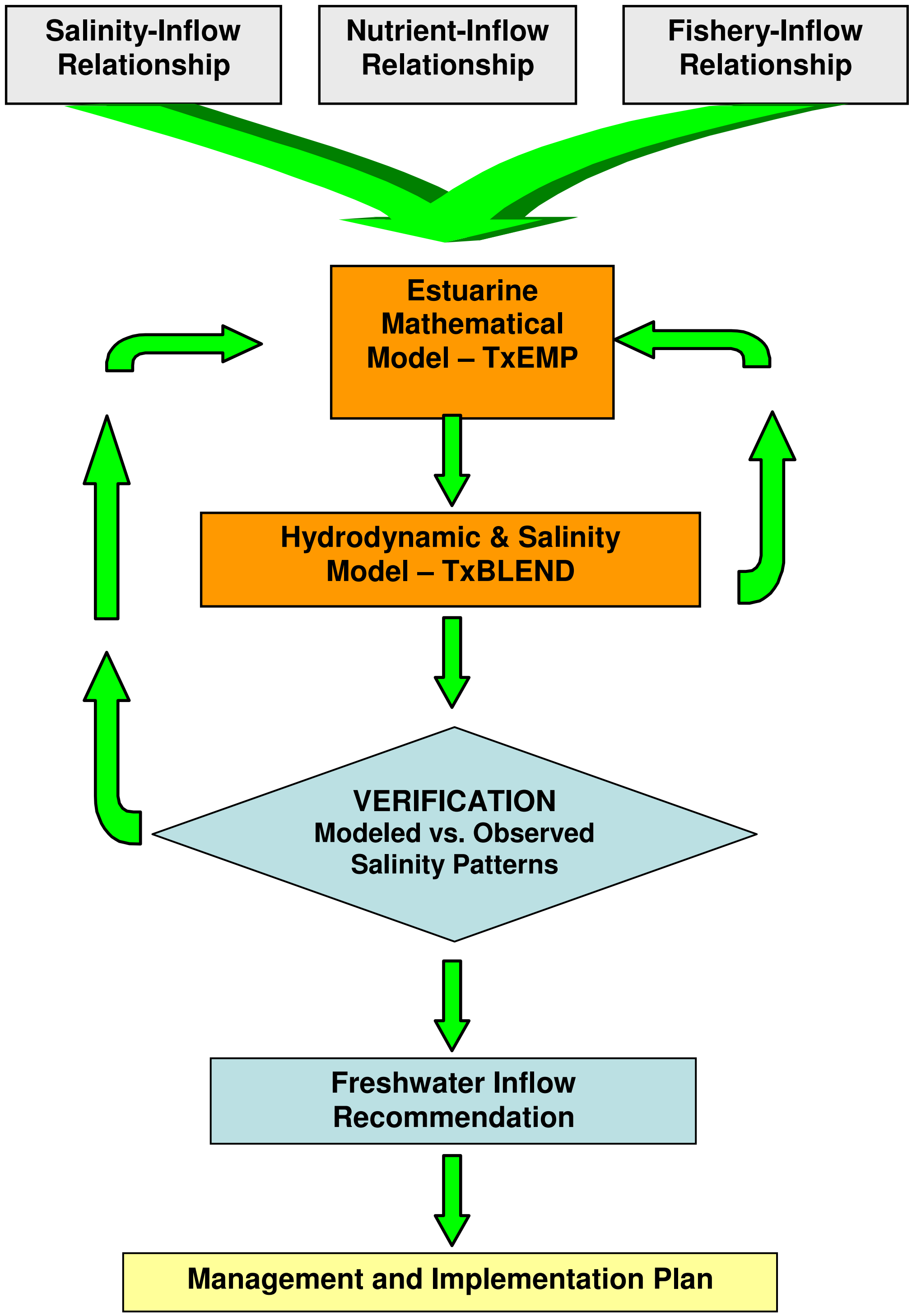


Figure 1. Schematic of state methodology for determining freshwater inflow needs (adapted from LCRA et al. 2006).

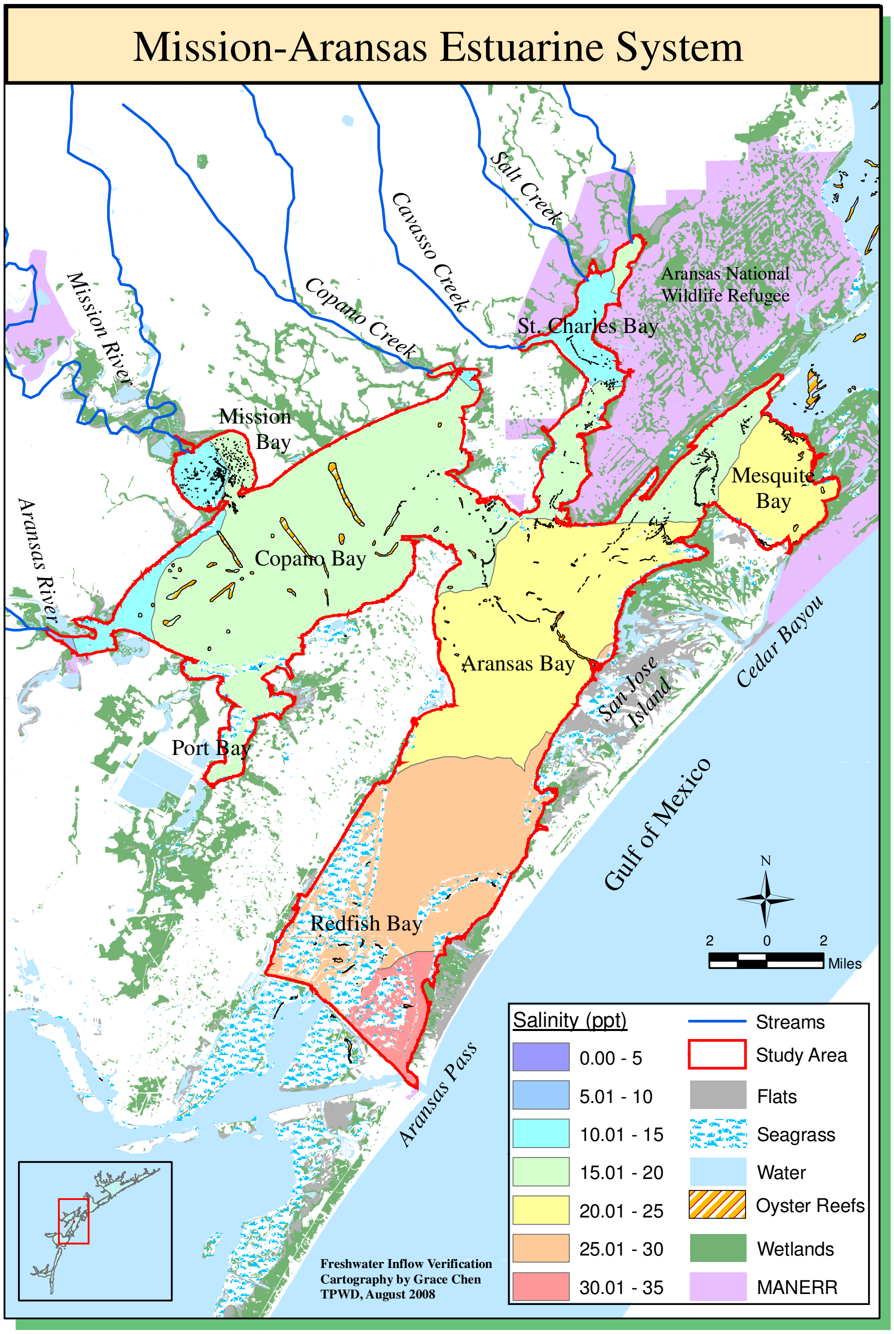


Figure 2. Typical salinity pattern and natural habitats surrounding the study area.

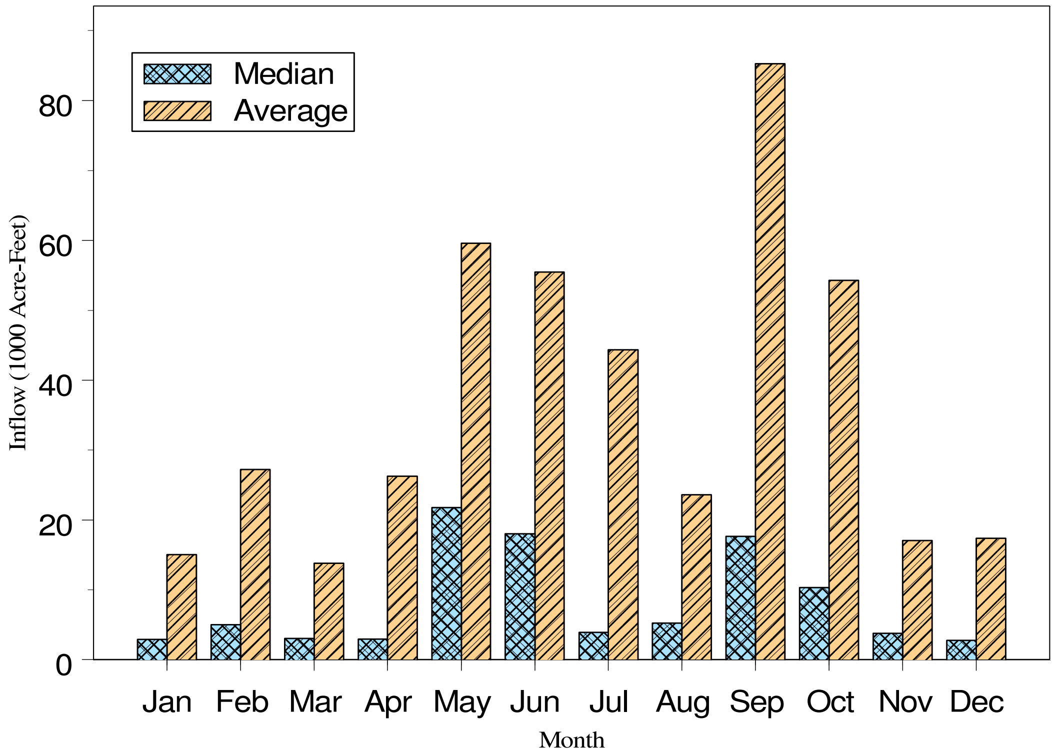


Figure 3. Comparisons of means and medians of monthly surface inflow (1941 - 1996) estimated for the Mission-Aransas Estuary.

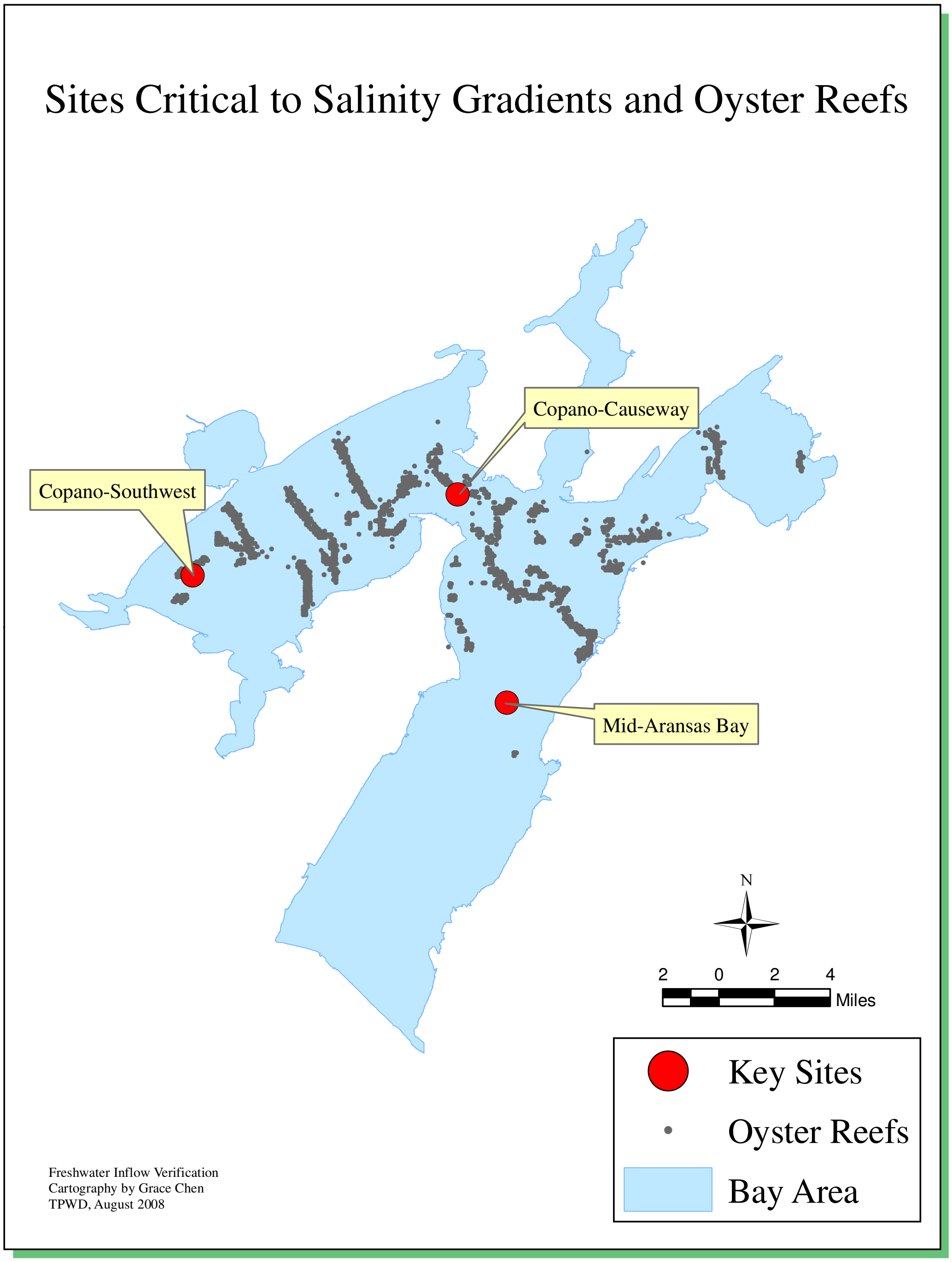


Figure 4. Key sites representing typical salinity gradient across the Mission –Aransas Estuary.

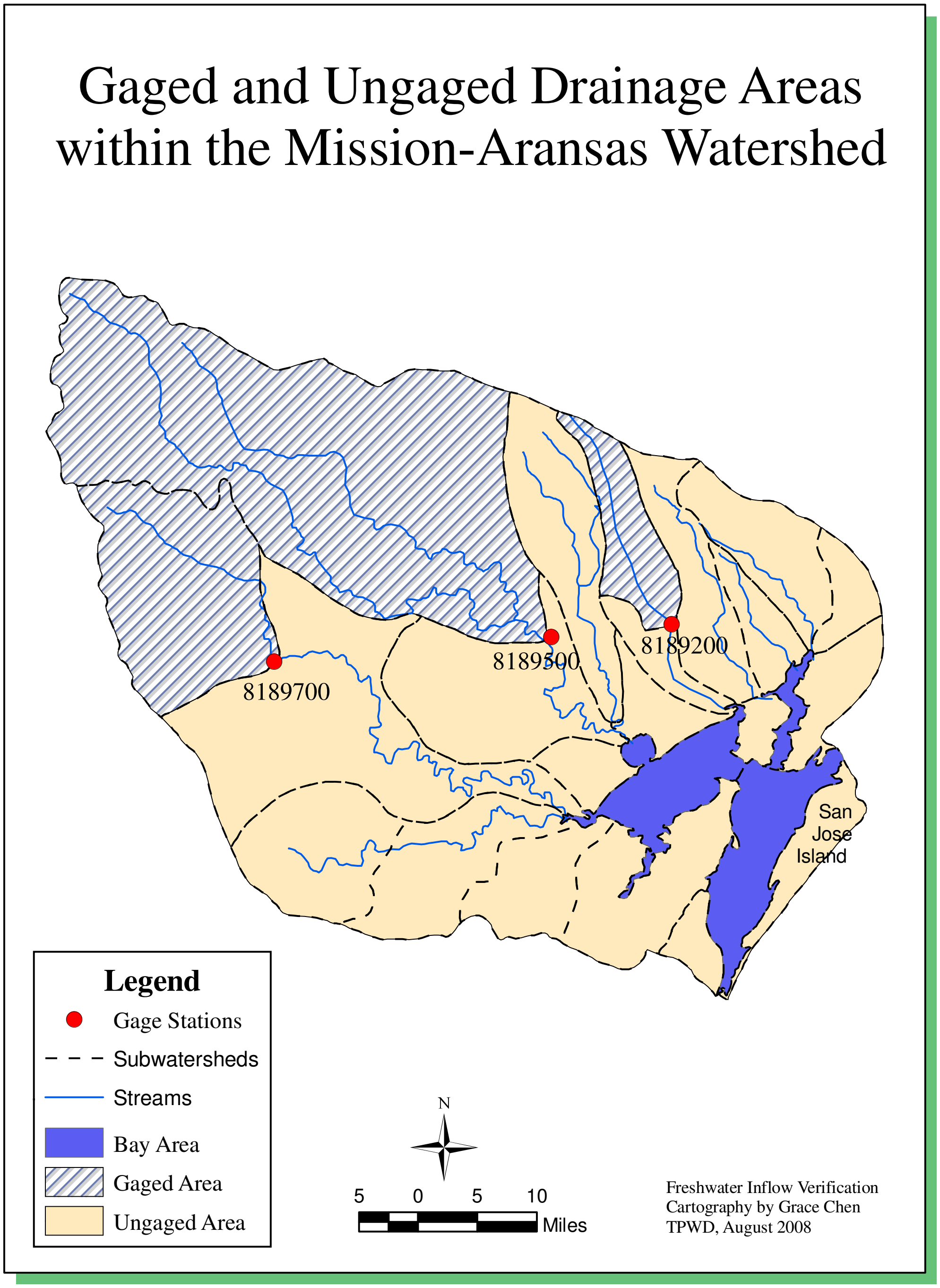


Figure 5. Subwatersheds delineated for the Texas Rainfall-Runoff (TxRR) model for runoff estimation.

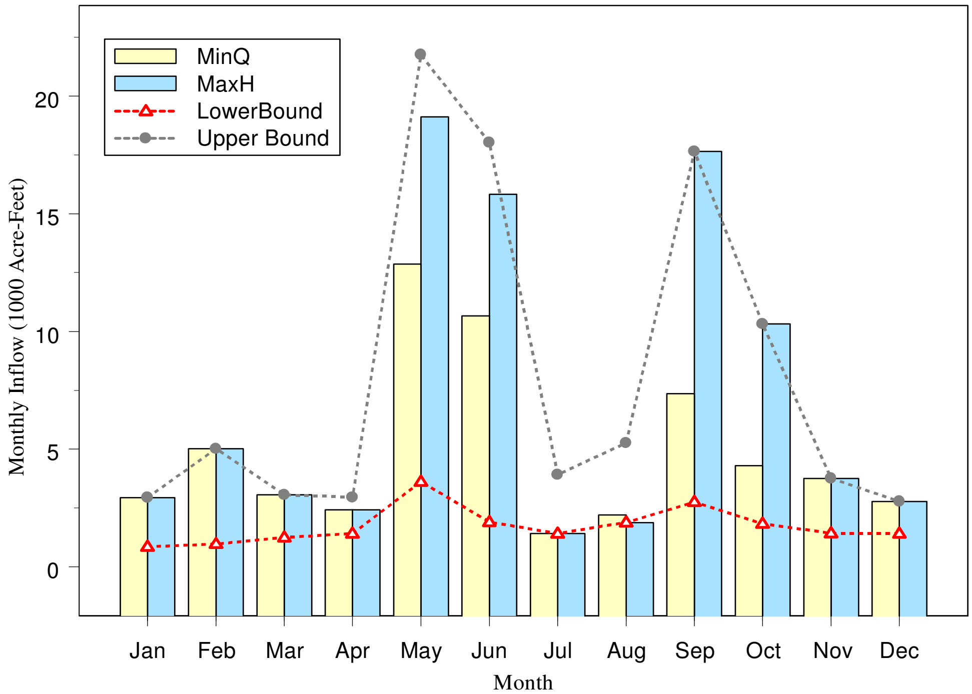


Figure 6. Comparison of monthly target inflows for MaxH and MinQ

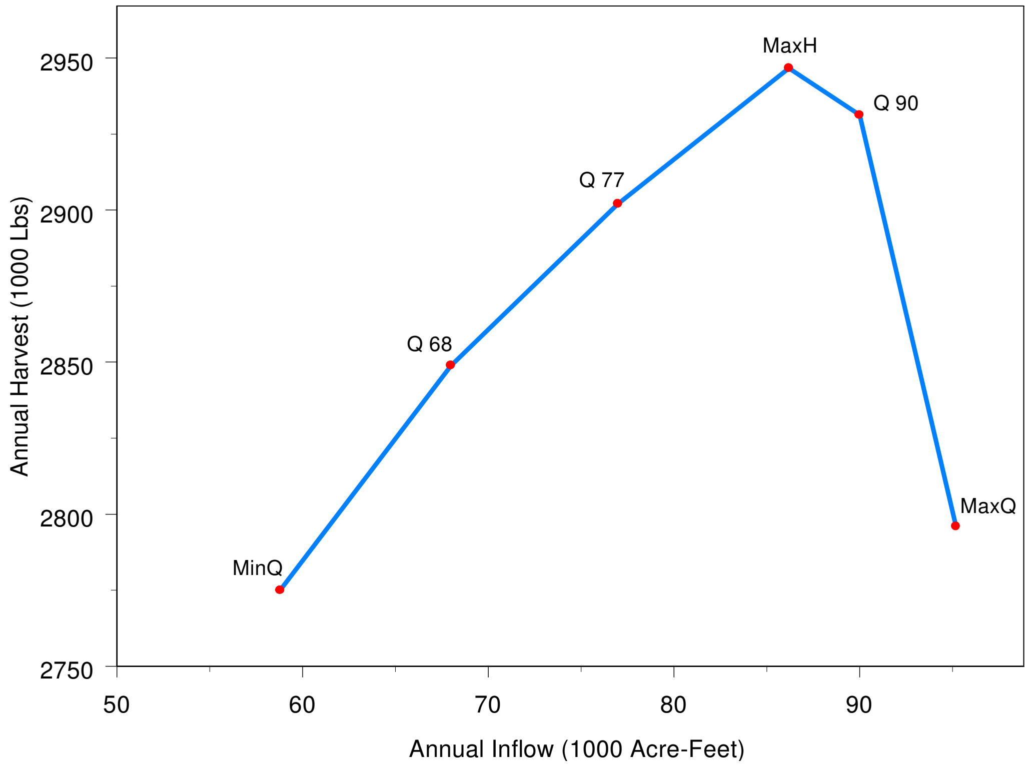


Figure 7. Performance curve of annual fisheries harvest against annual inflow for the Mission-Aransas Estuary.

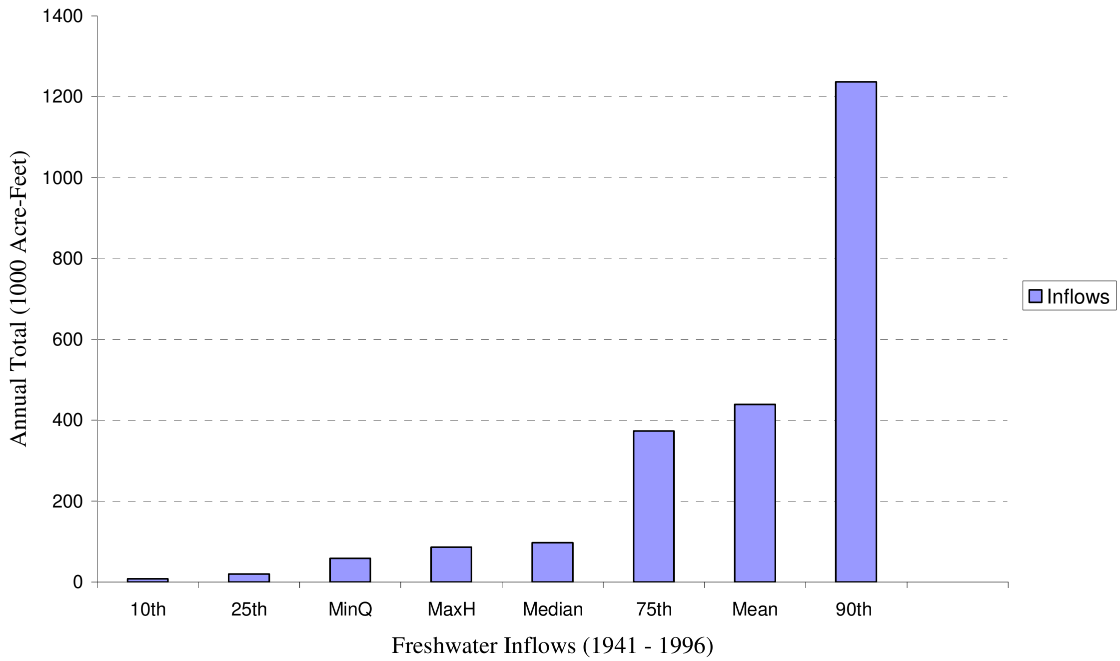


Figure 8. Target inflows (annual MinQ and MaxH) in relation to historical annual total surface inflow (1941-1996).

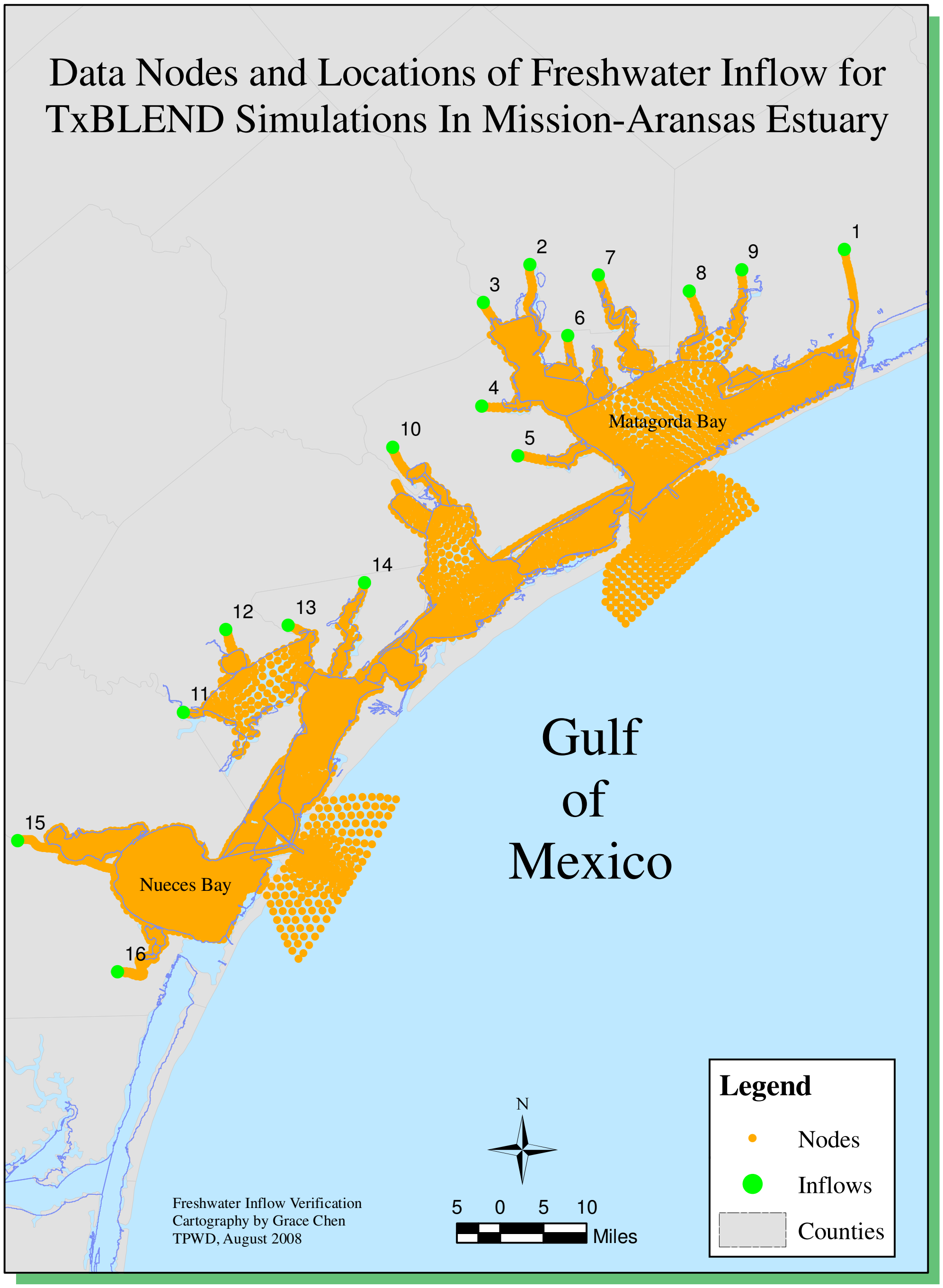


Figure 9. Locations of 5,544 data nodes and 16 inflow points used for the TxBLEND simulation of the Mission-Aransas Estuary.

Note: The inflow point numbers above correspond with the numbers for the waterbodies listed in Table 2.

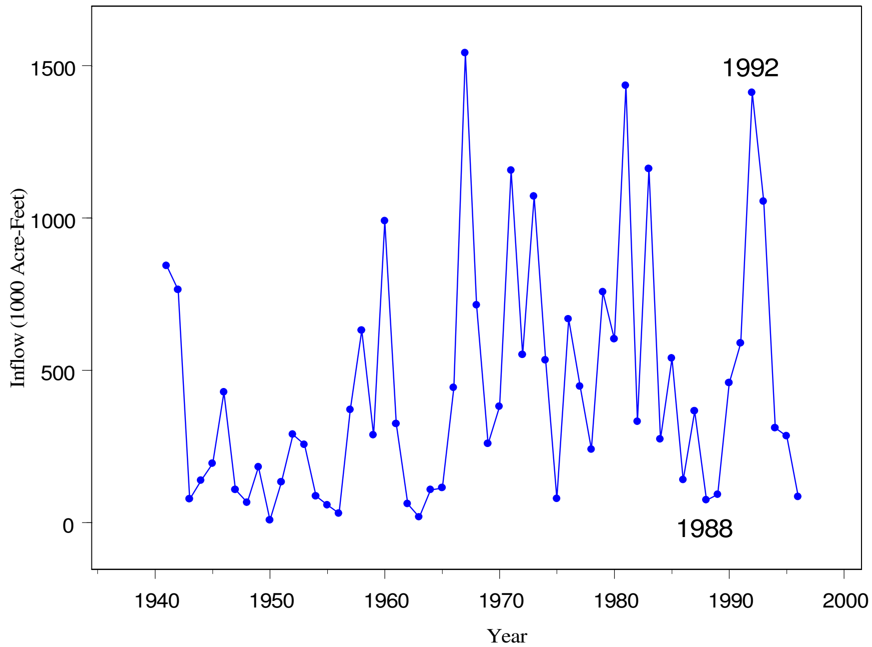


Figure 10. Combined annual surface inflow estimated for the Mission-Aransas Estuary between 1941 – 1996.

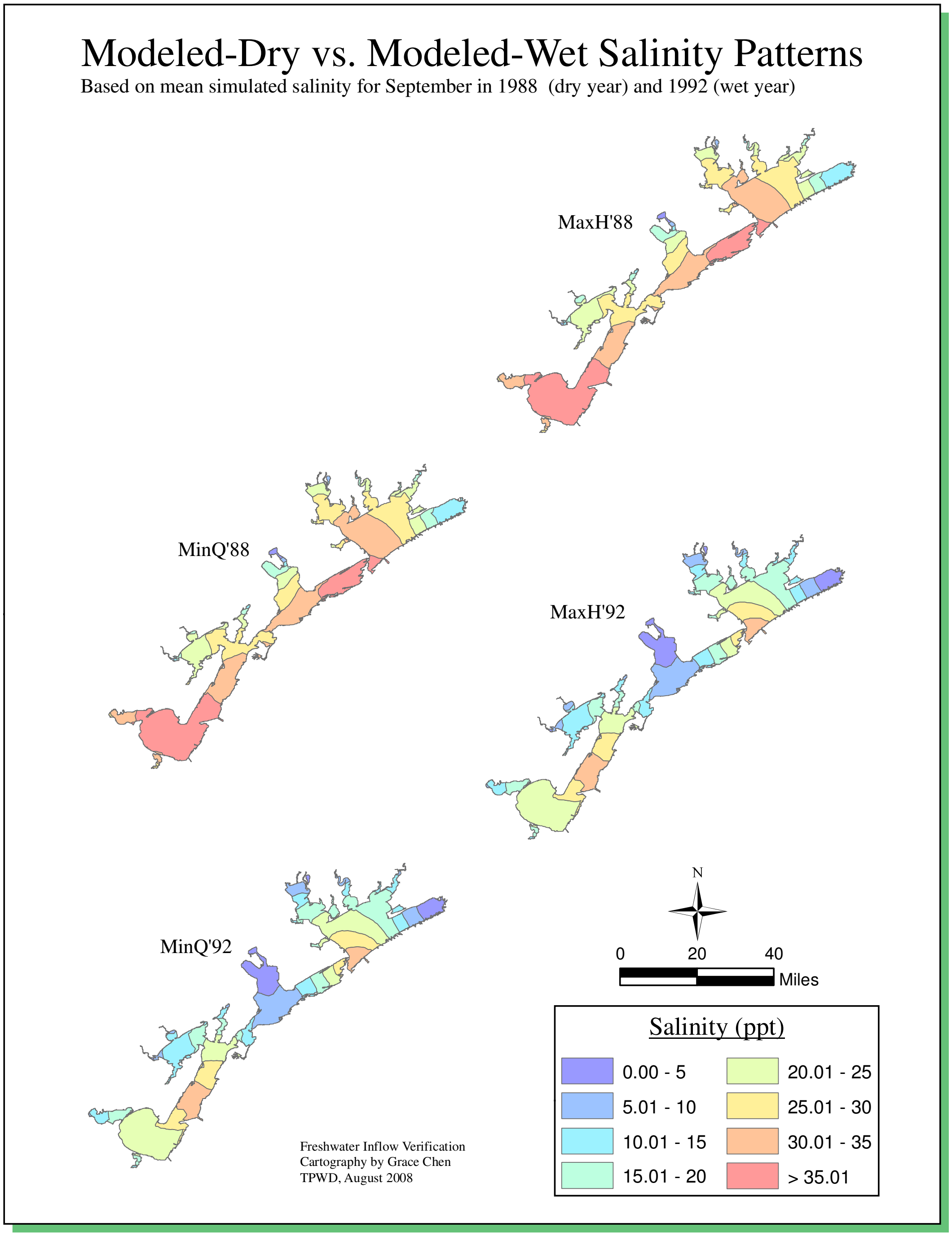


Figure 11. Effects of target inflows (MinQ and MaxH) on salinity in the M-A estuary during dry and wet years. MinQ and MaxH inflows were applied to inflow points within the M-A system, while all other inflows and conditions were consistent with observed data for the respective years. Target inflows were not applied to the neighoring bays.

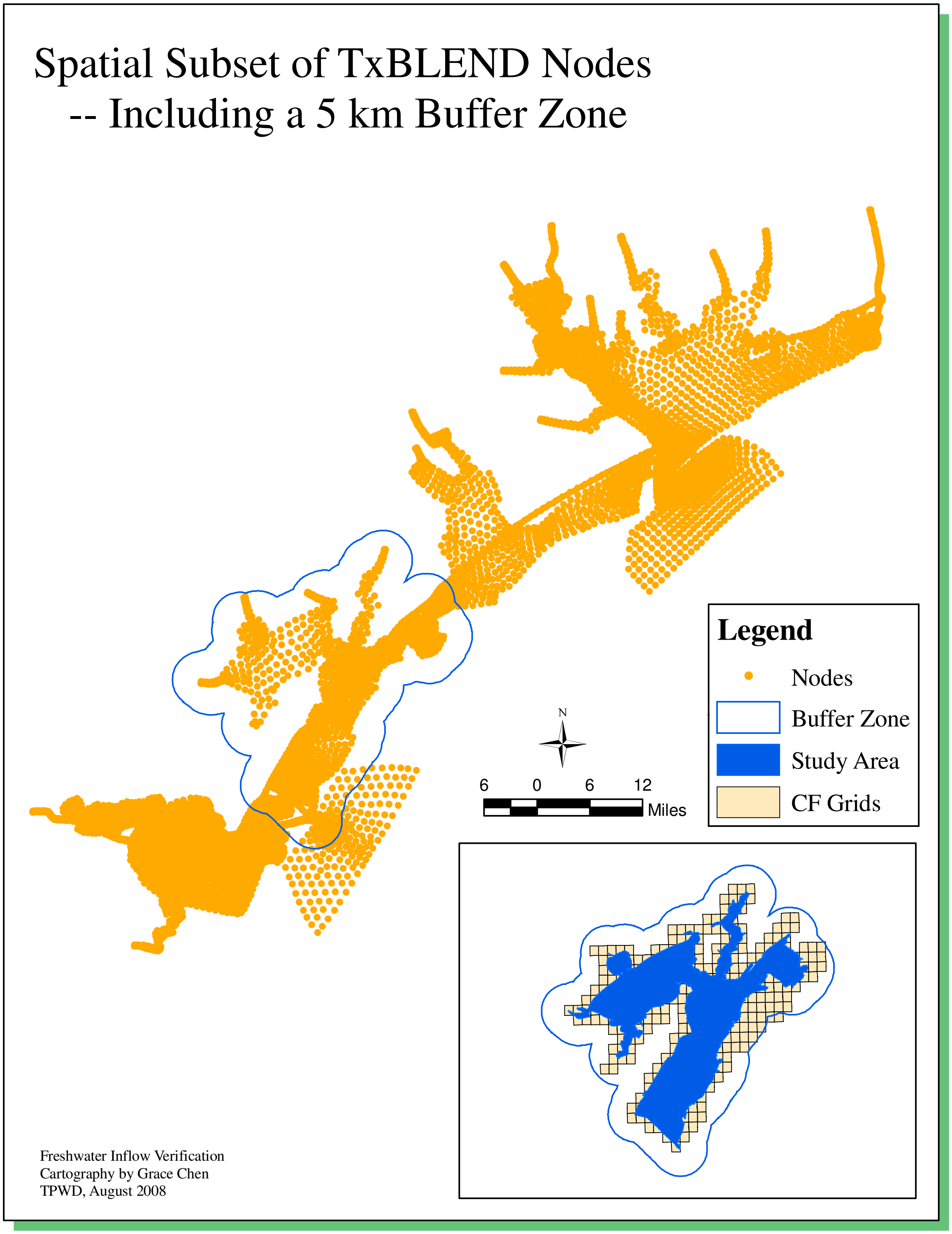


Figure 12. Spatial subset of TxBLEND nodes used to estimate modeled salinity for the M-A system.

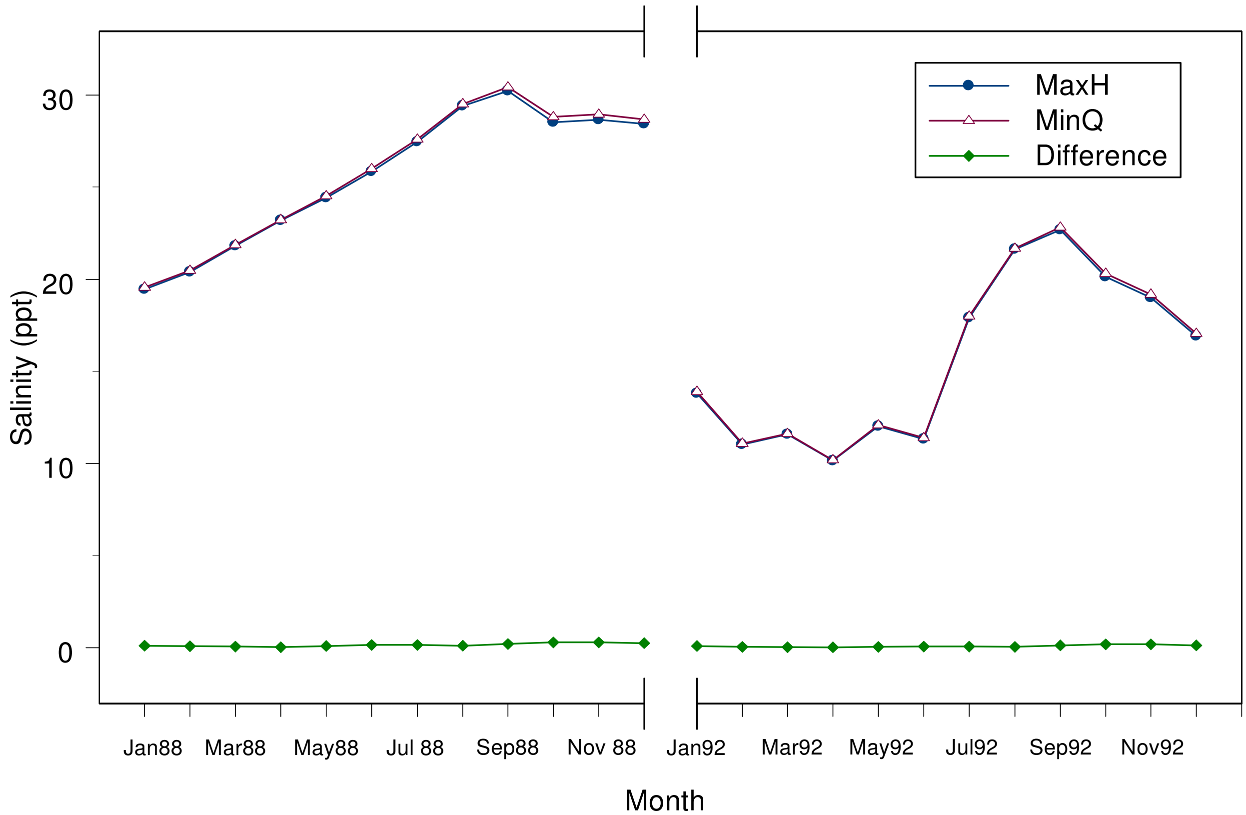


Figure 13. Differences in monthly mean salinities resulting from MaxH and MinQ inflows.

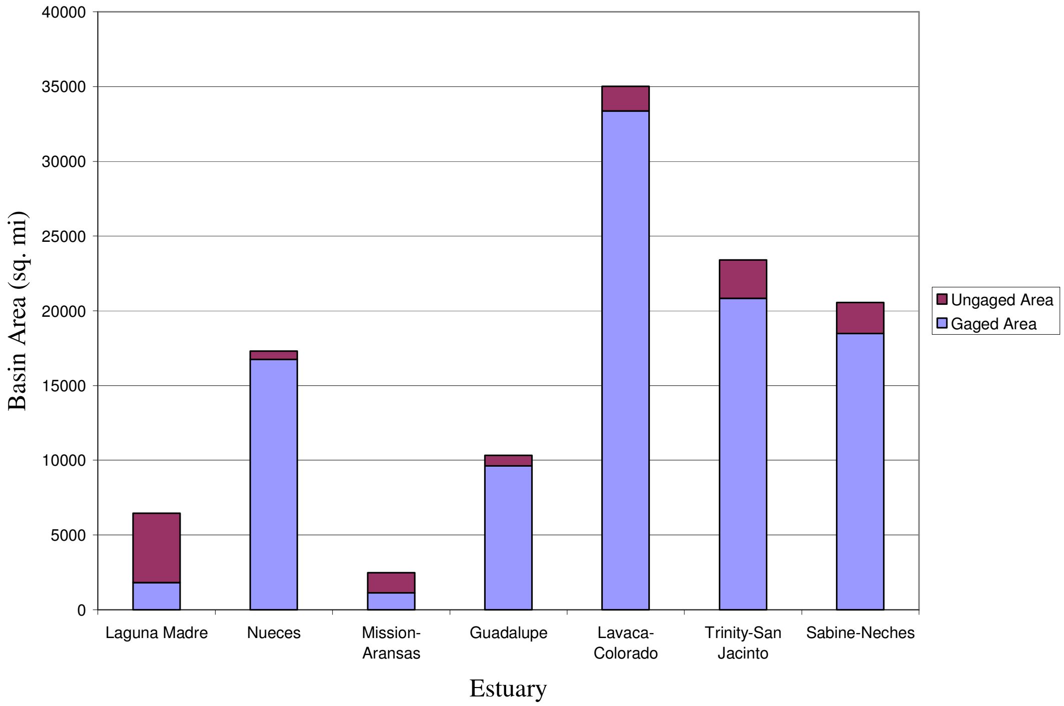


Figure 14. The Mission-Aransas basin is the smallest in size compared to the other six Texas major bays.

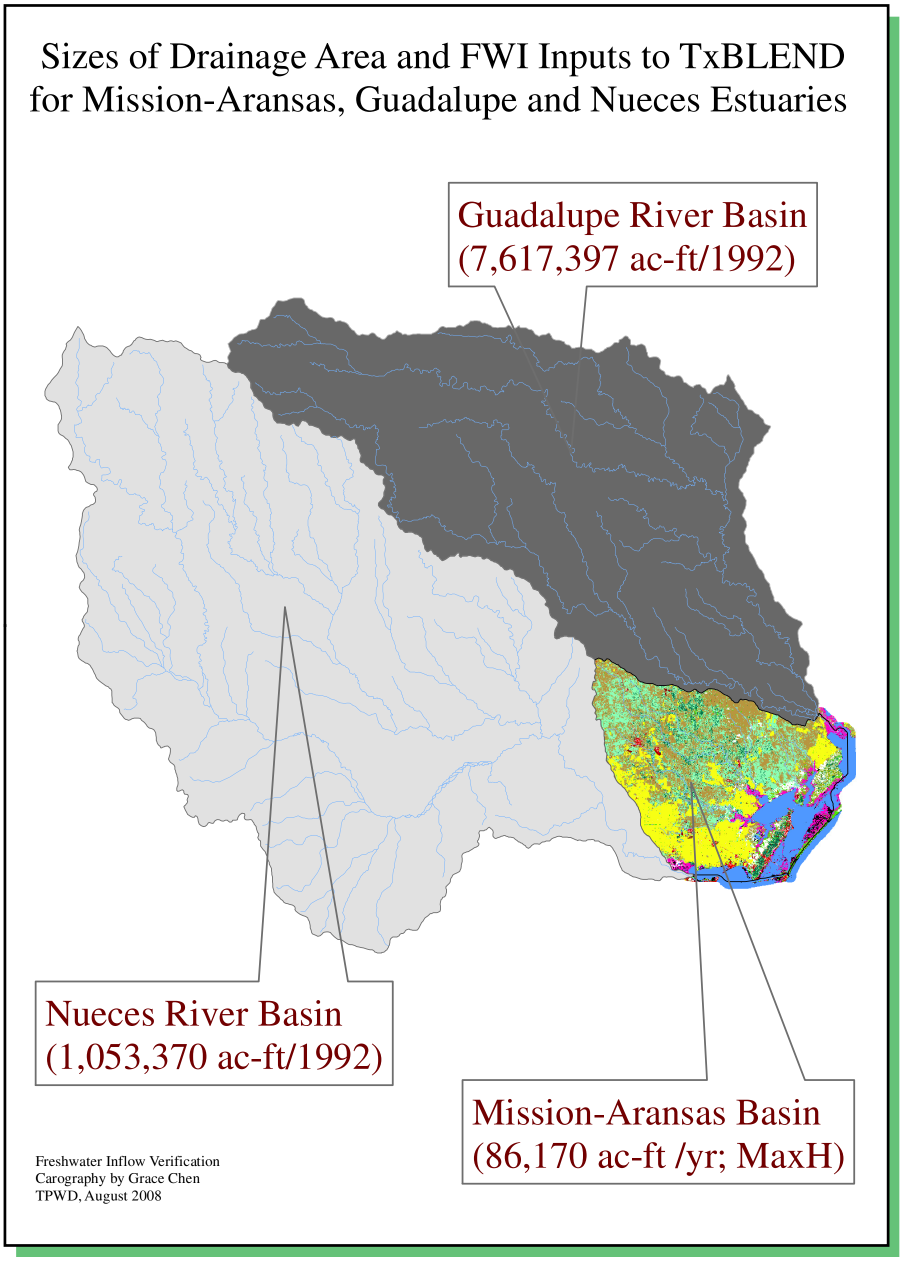


Figure 15. Comparisons of the size of drainage area between Mission-Aransas Estuary and neighboring estuaries as well as the volume between the MaxH inflow prescribed for the M-A Estuary and surface inflow entering the neighboring estuaries estimated for 1992 (wet year).

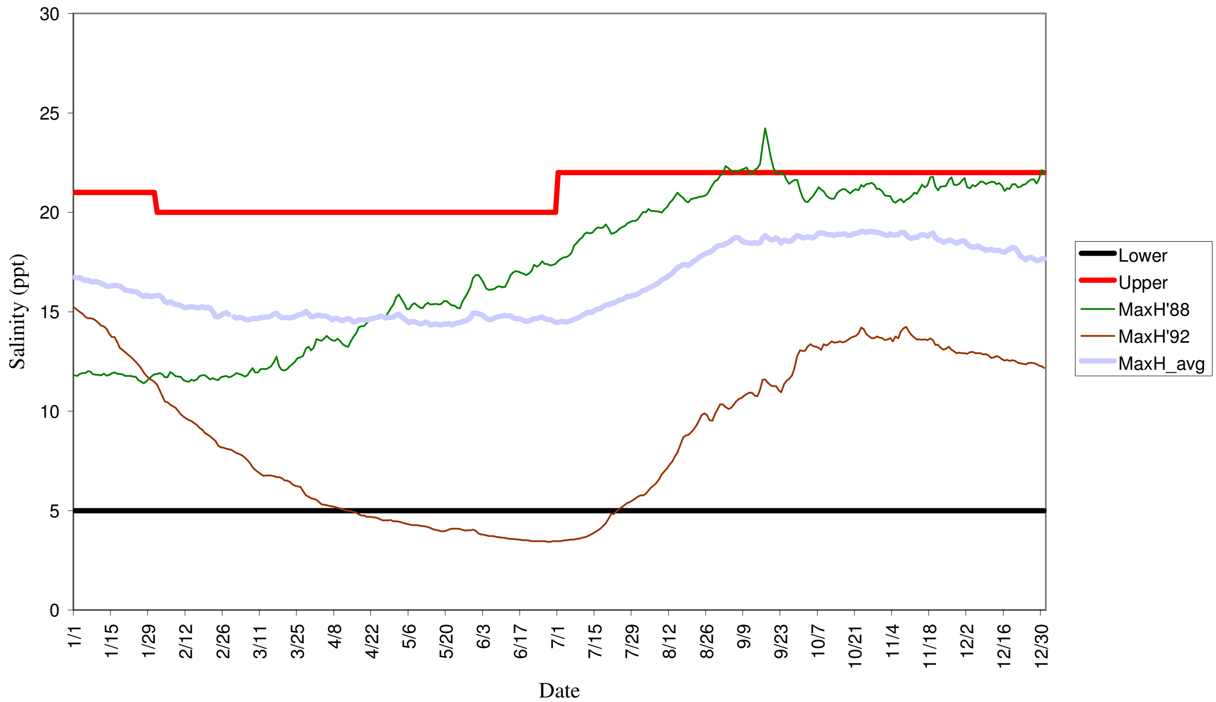


Figure 16. Daily mean salinities resulting from MaxH inflows at Copano-Southwest.

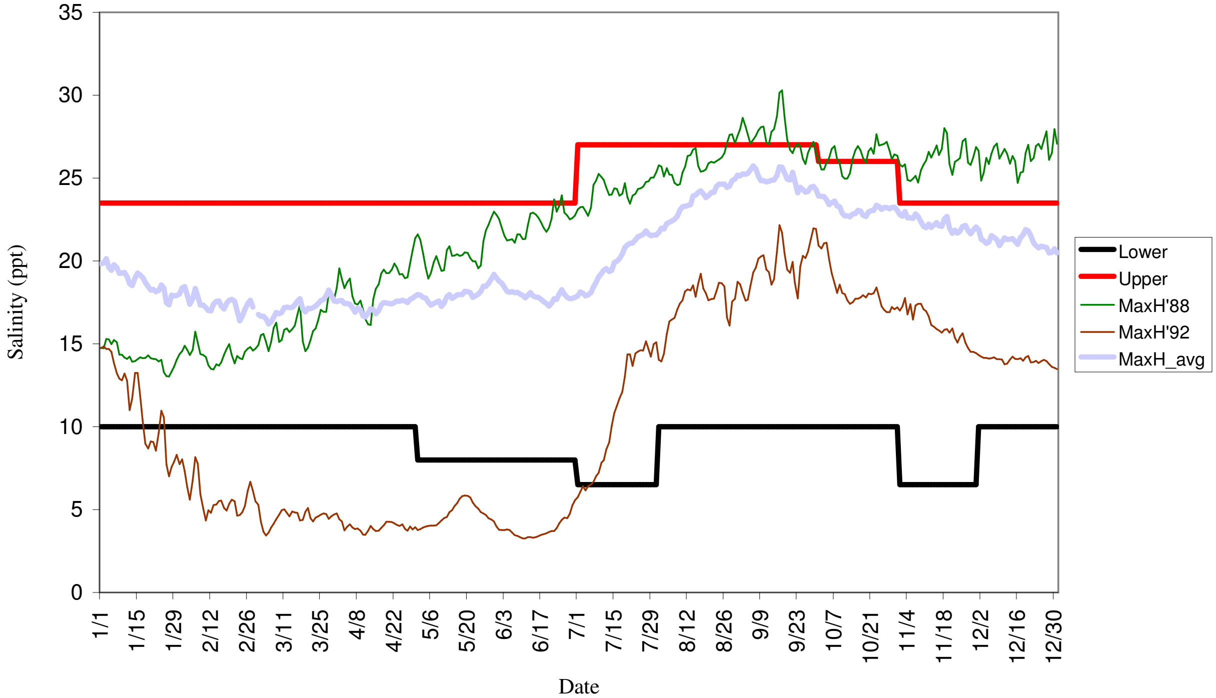


Figure 17. Daily mean salinities resulting from MaxH inflows at Copano-Causeway.

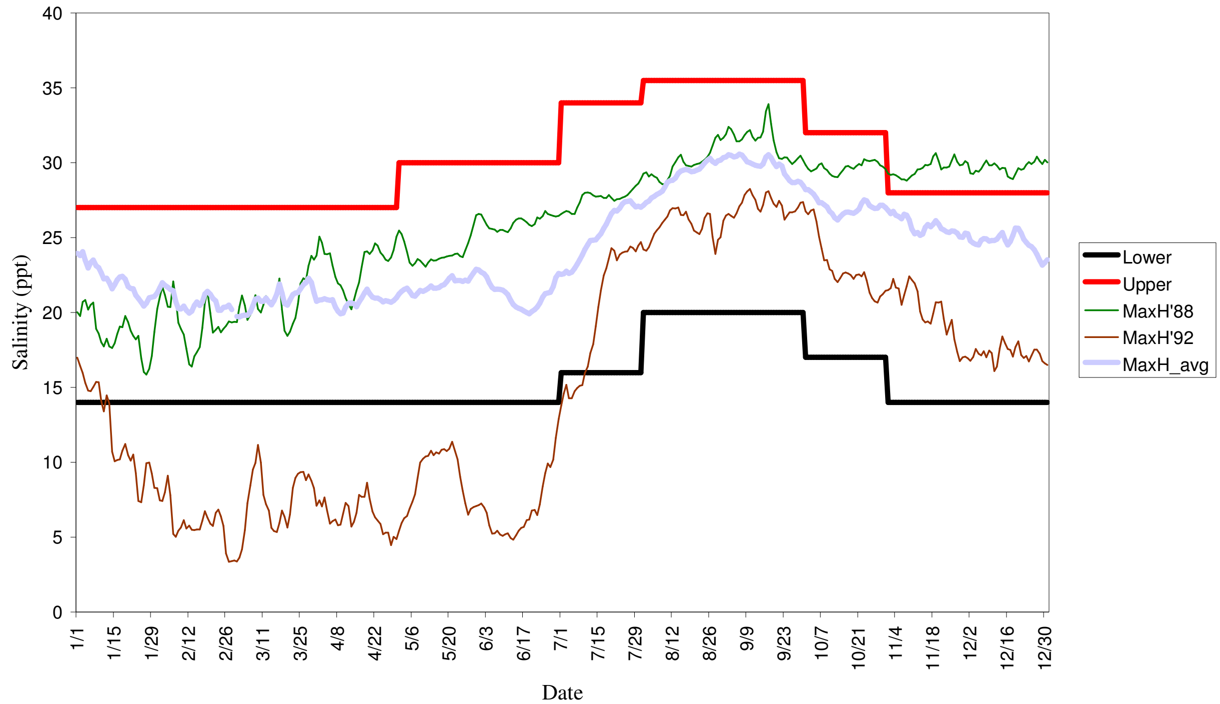


Figure 18. Daily mean salinities resulting from MaxH inflows at Mid-Aransas Bay.

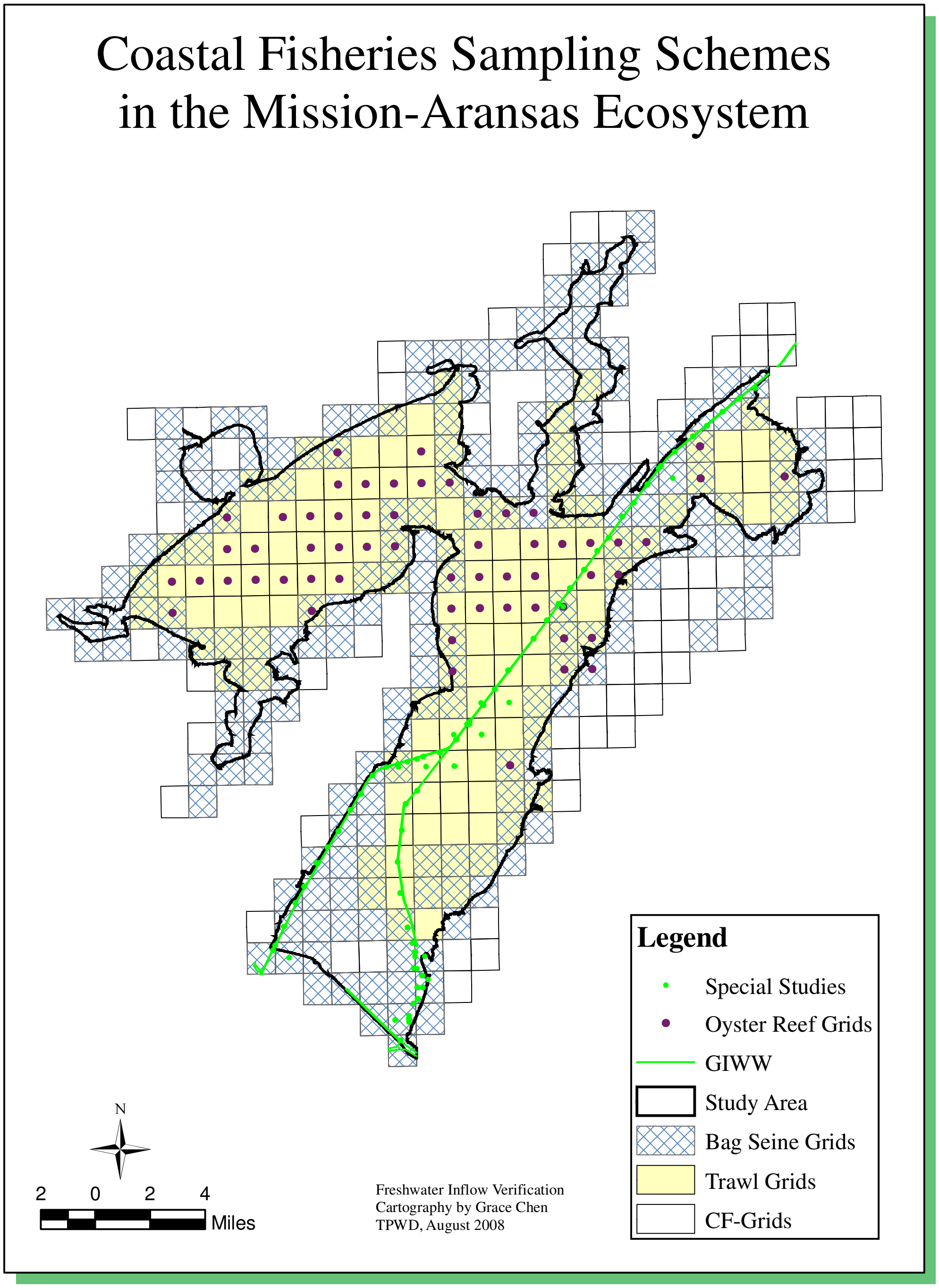


Figure 19. Spatial framework set up for the TPWD monitoring program implemented across the Mission-Aransas Ecosystem.

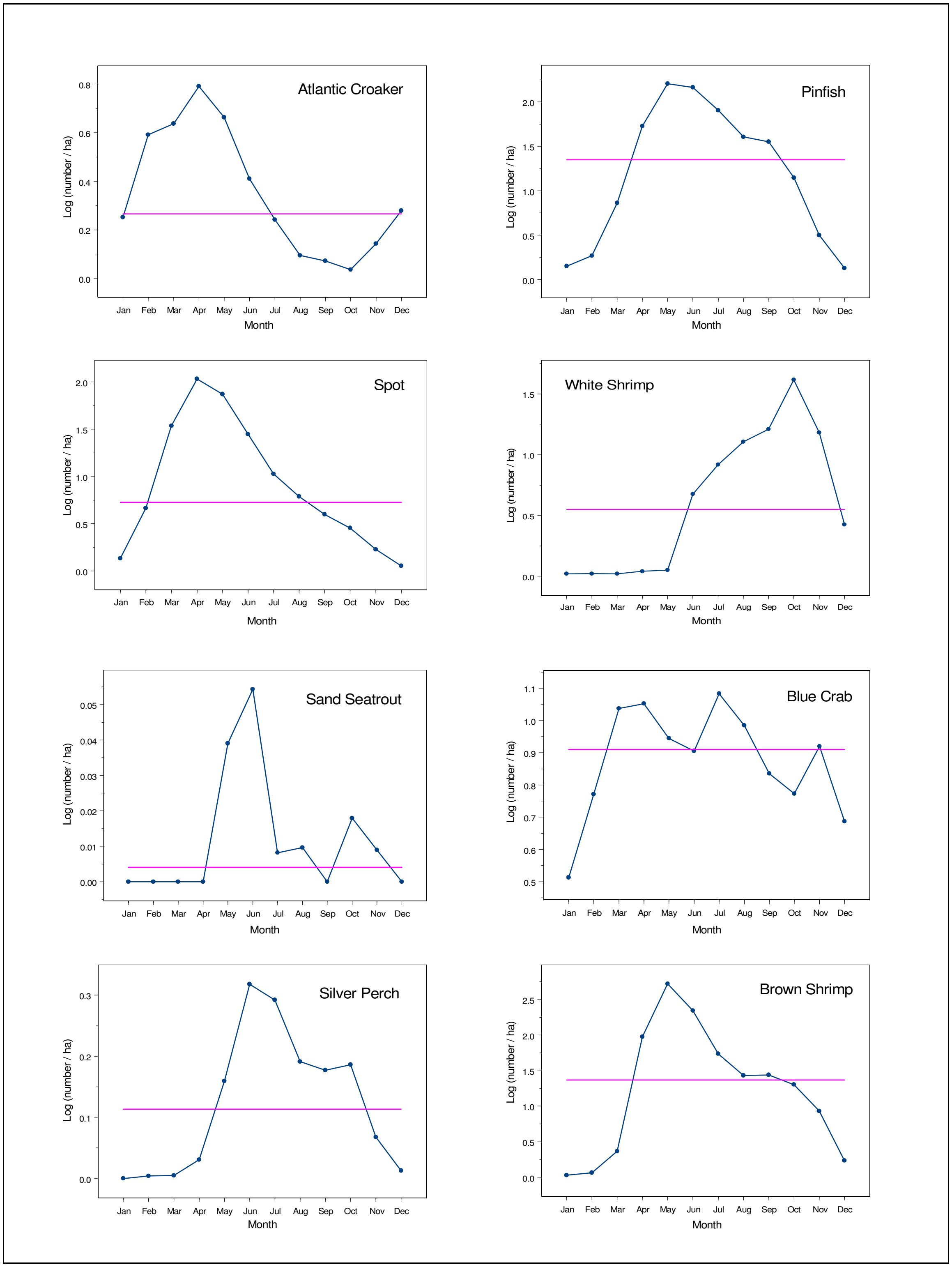


Figure 20. Log transformed abundance of key species caught with bag seines.

Notes: a) The pink line denotes the median of mean monthly log transformed CPUE.
b) Catch rates for sand seatrout and silver perch were low (see Table 8).

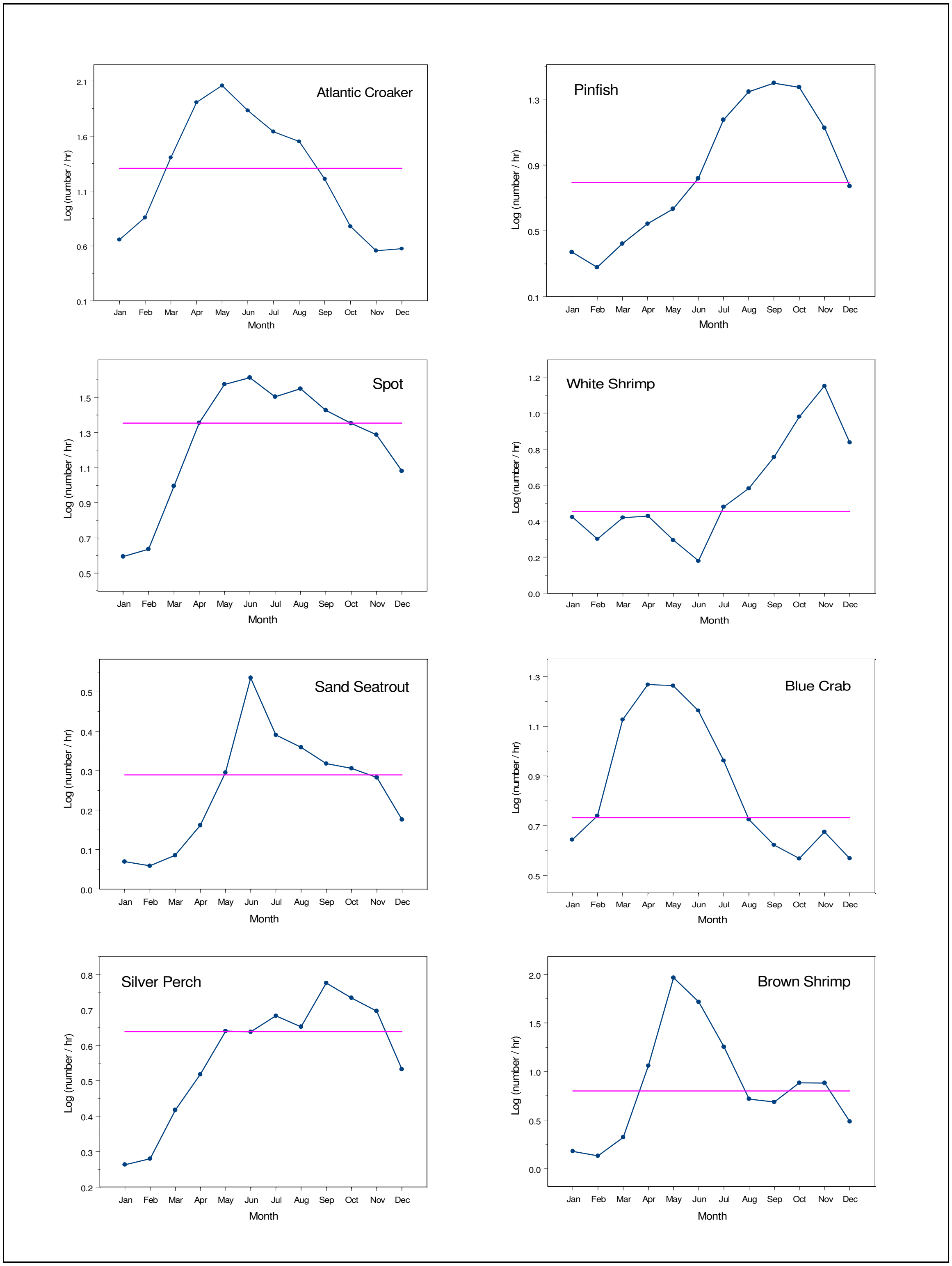


Figure 21. Log transformed abundance of key species caught with trawls.

Note: The pink line denotes the median of mean monthly log transformed CPUE.

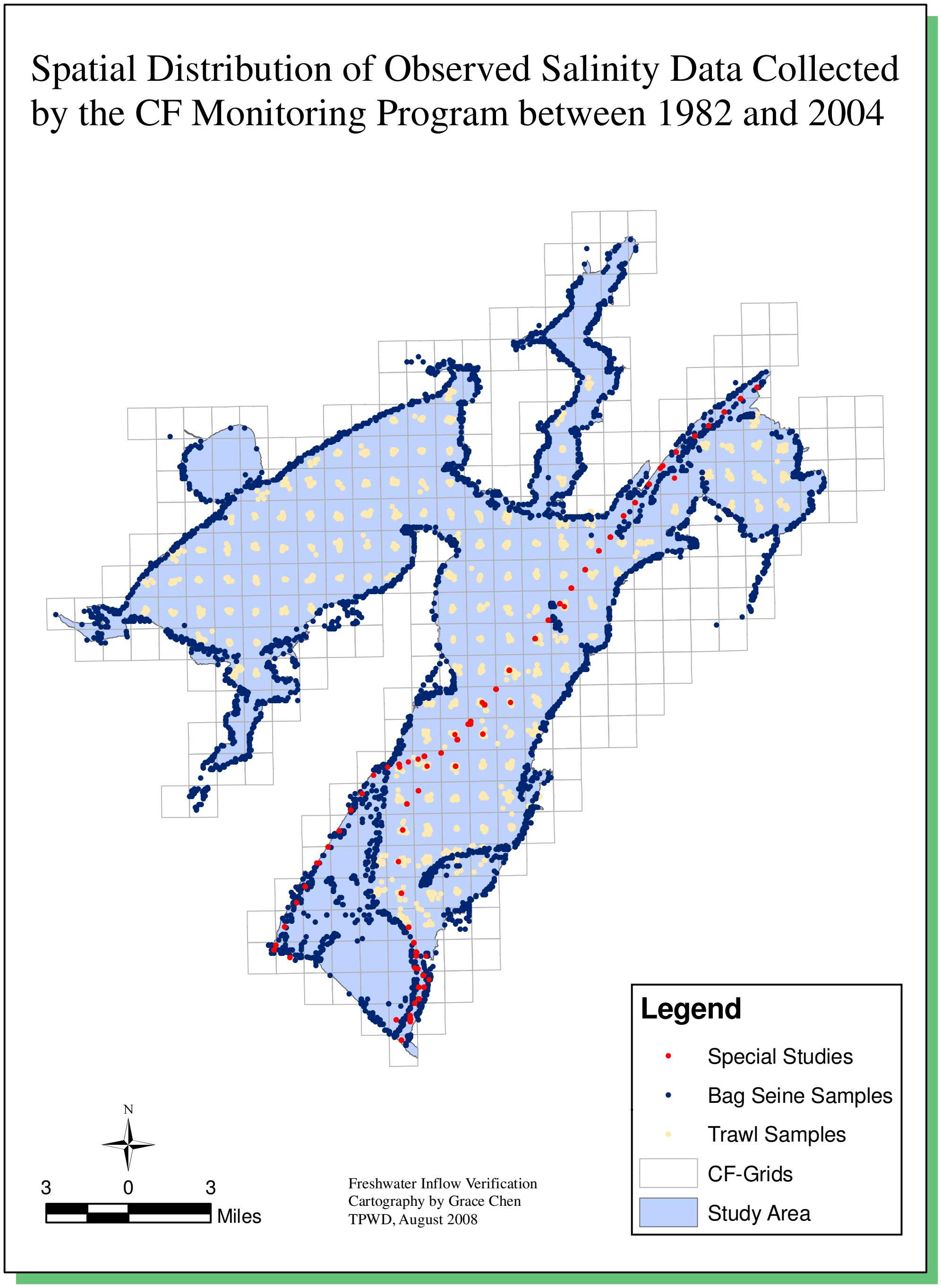


Figure 22. Spatial distribution of TPWD's observed salinity data (1982 – 2004).

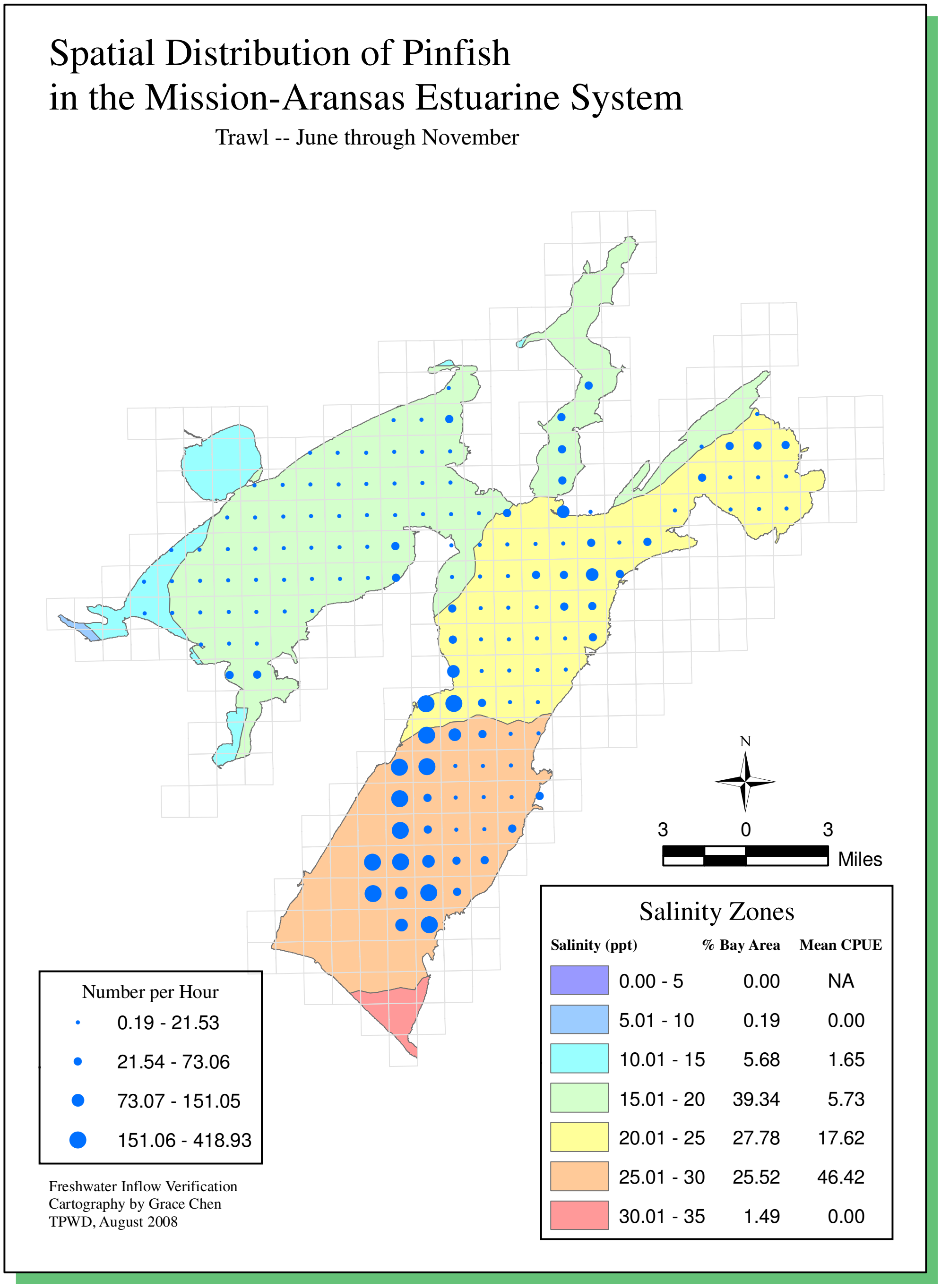


Figure 23. Spatial distribution of pinfish collected with trawls.

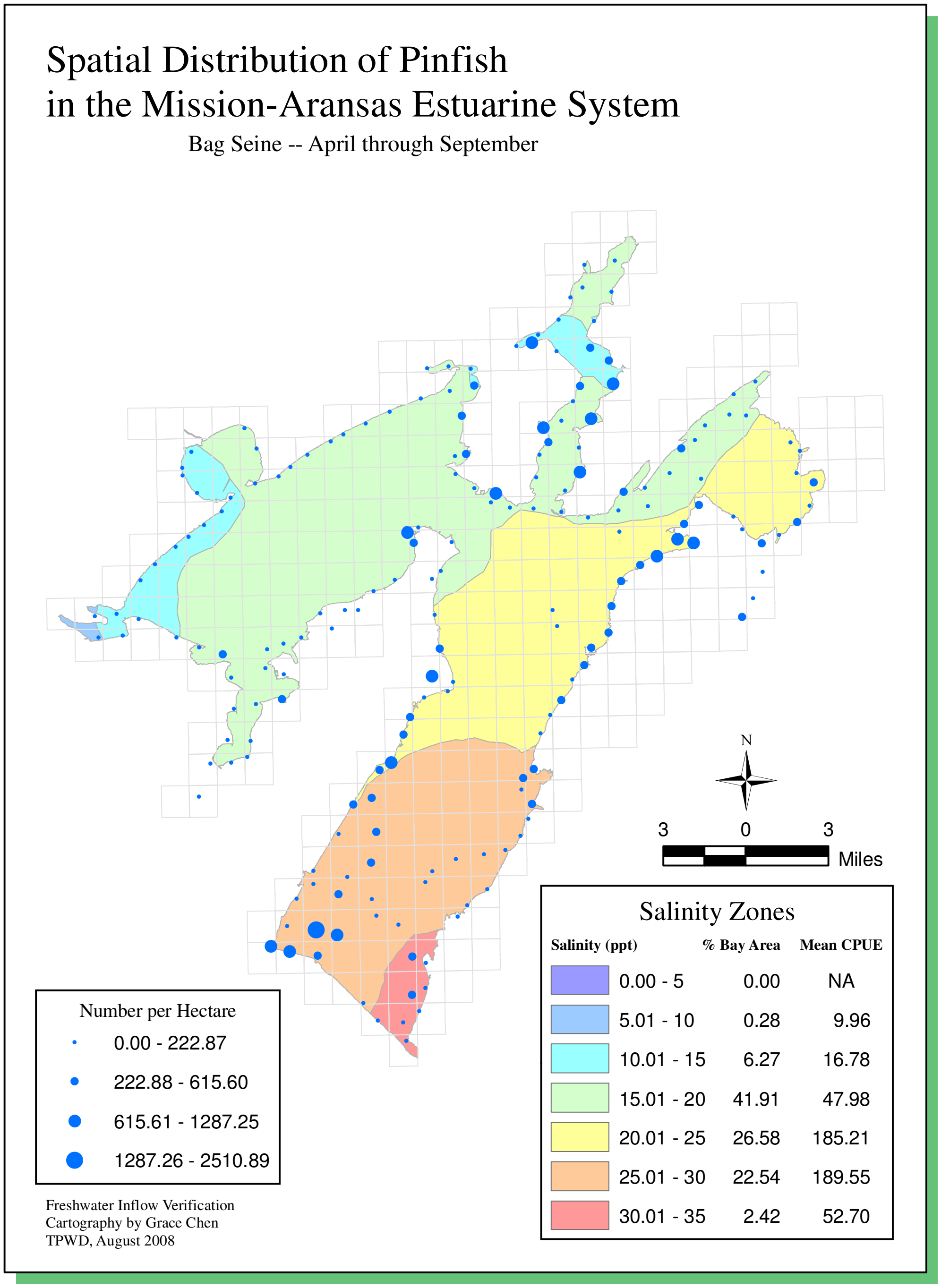


Figure 24. Spatial distribution of pinfish collected with bag seines.

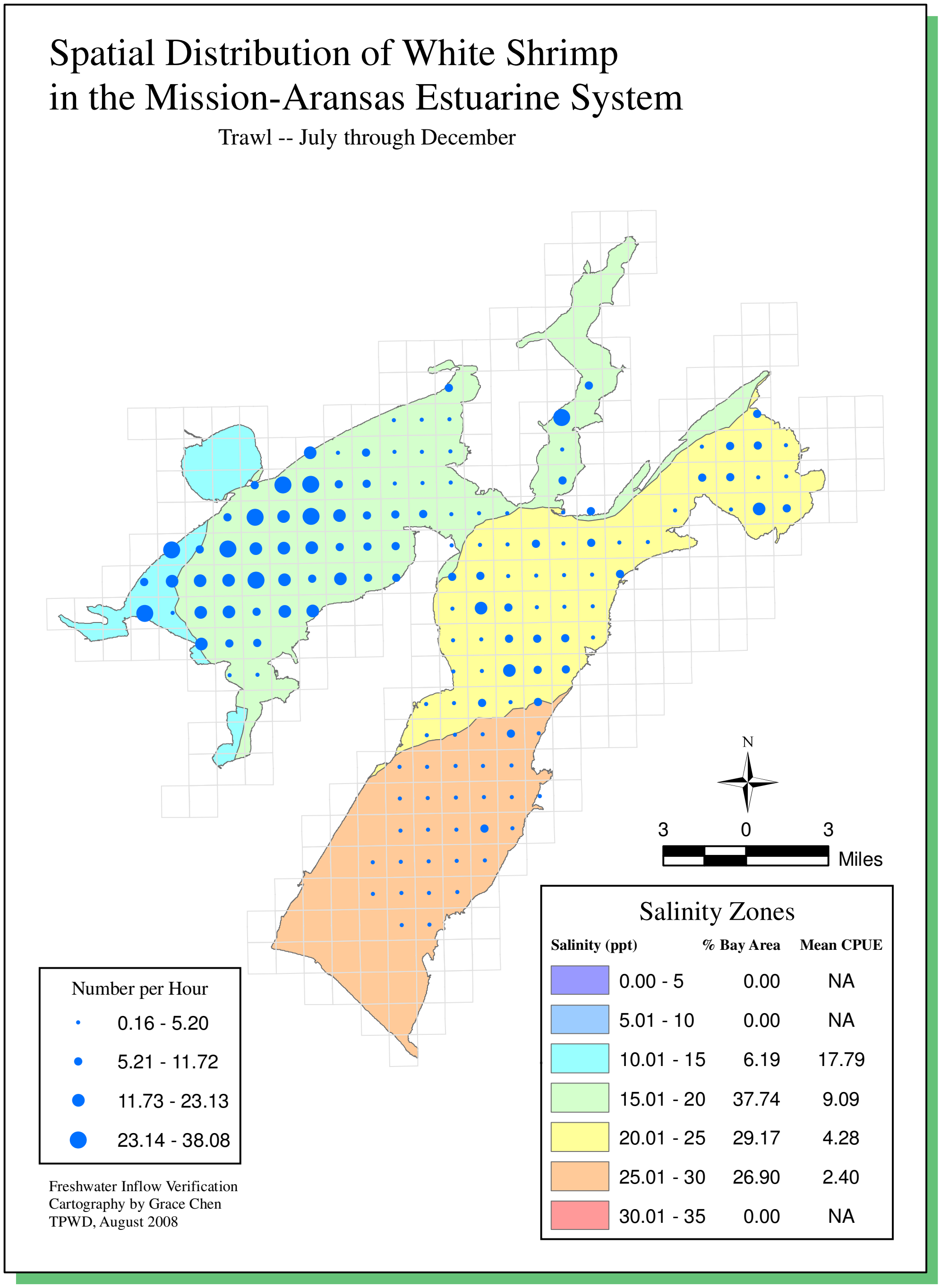


Figure 25. Spatial distribution of white shrimp collected with trawls.

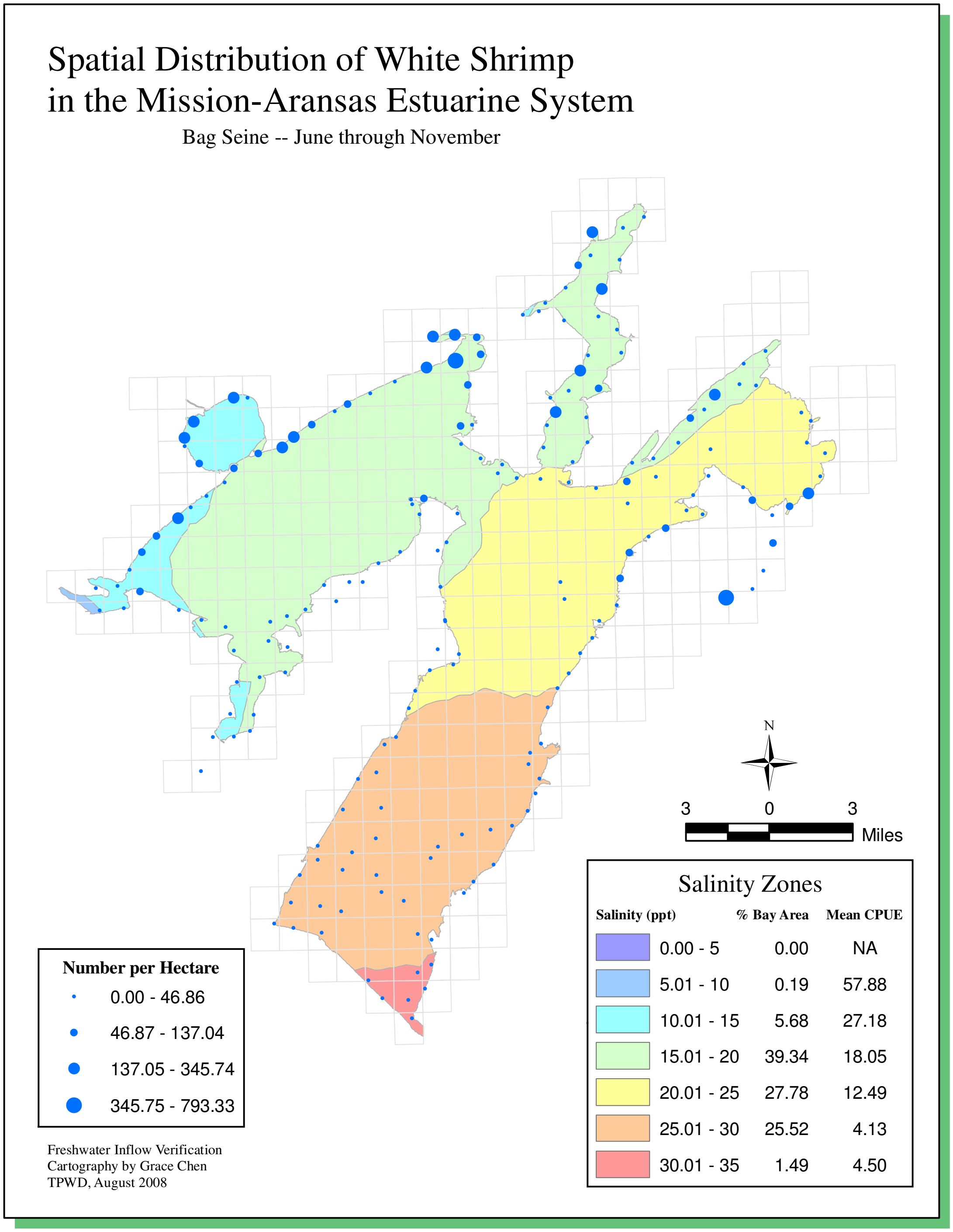


Figure 26. Spatial distribution of white shrimp collected with bag seines.

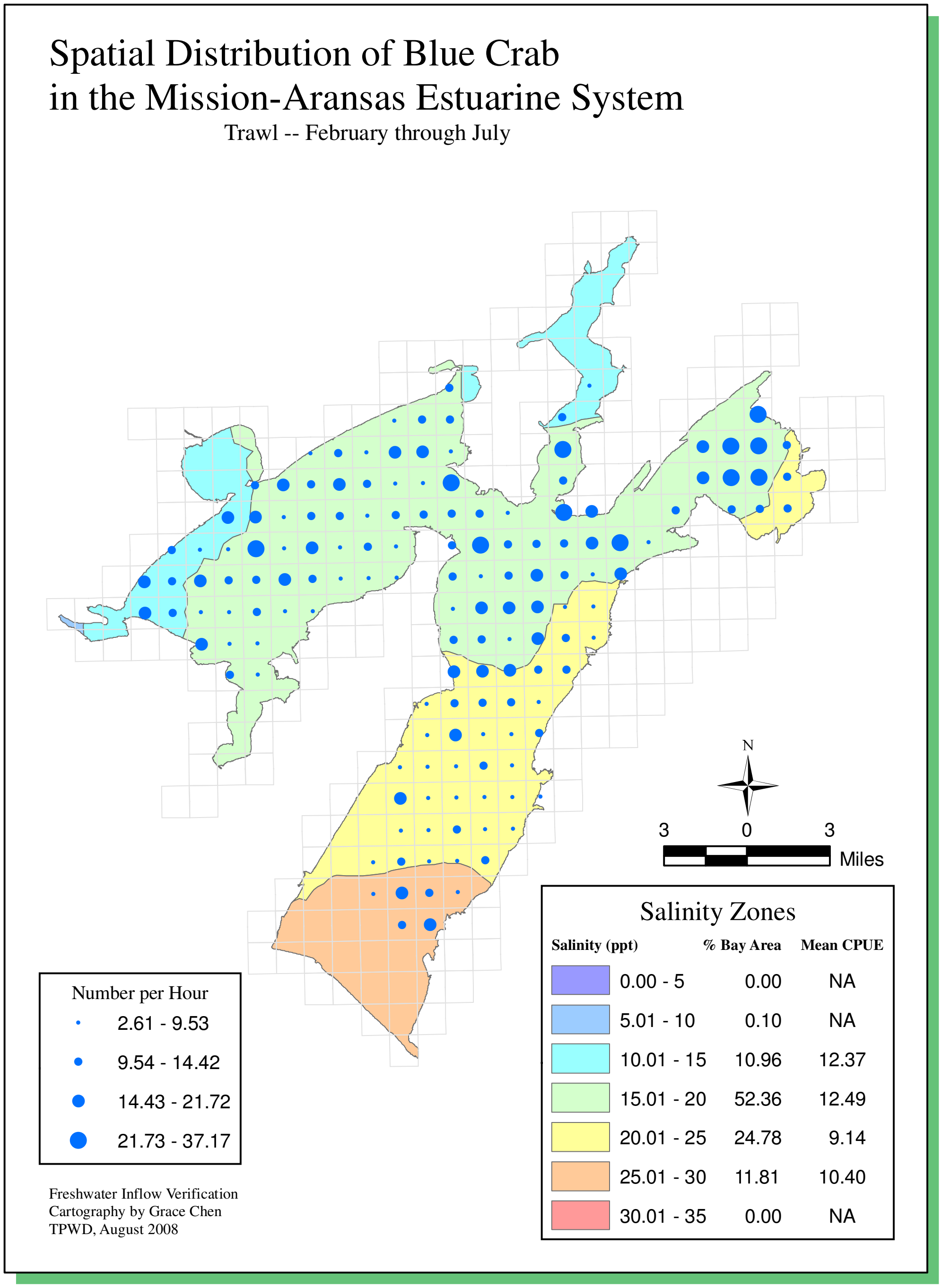


Figure 27. Spatial distribution of blue crab collected with trawls.

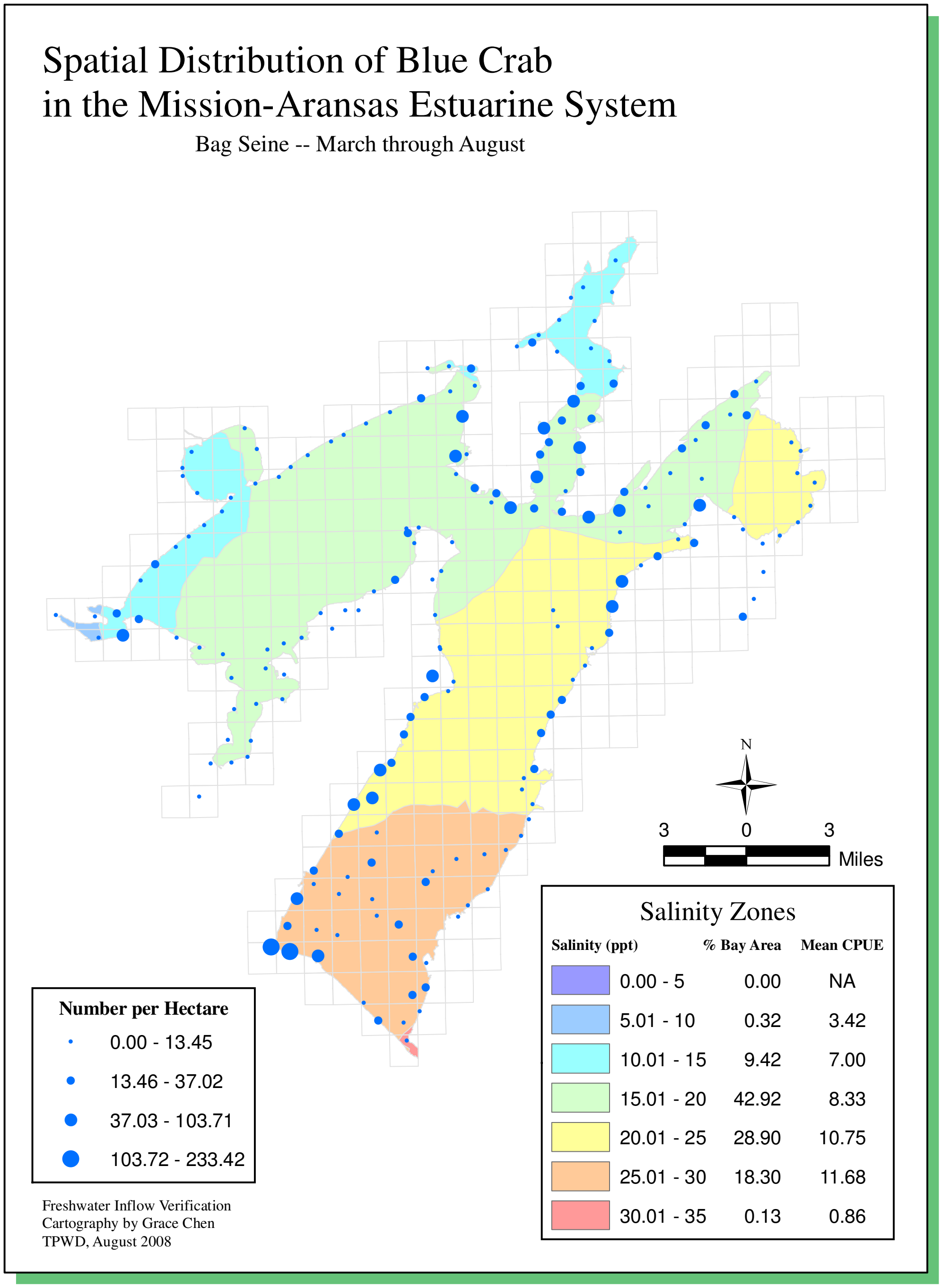


Figure 28. Spatial distribution of blue crab collected with bag seines.

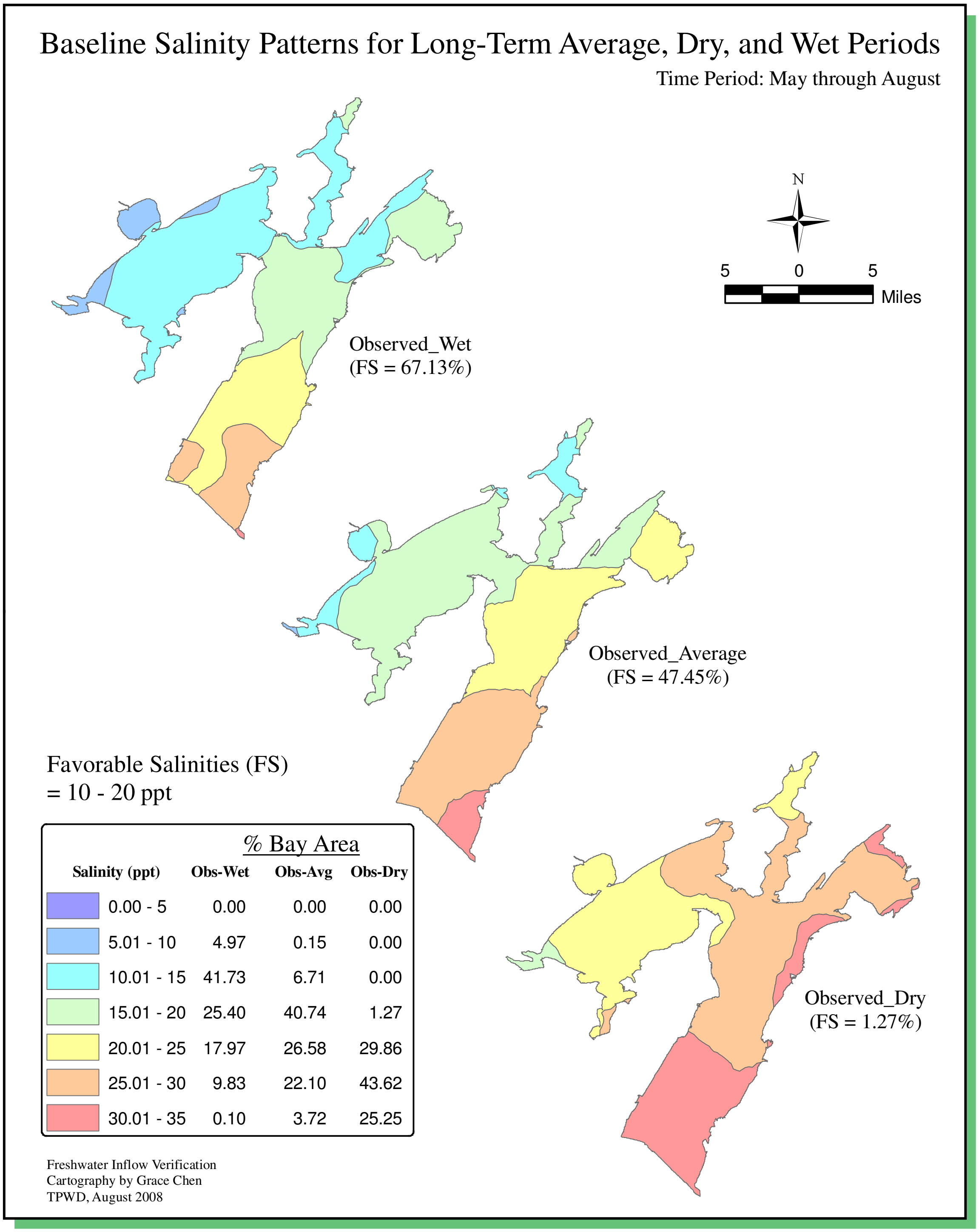


Figure 29. Baseline salinity patterns resulting from TPWD observed data.

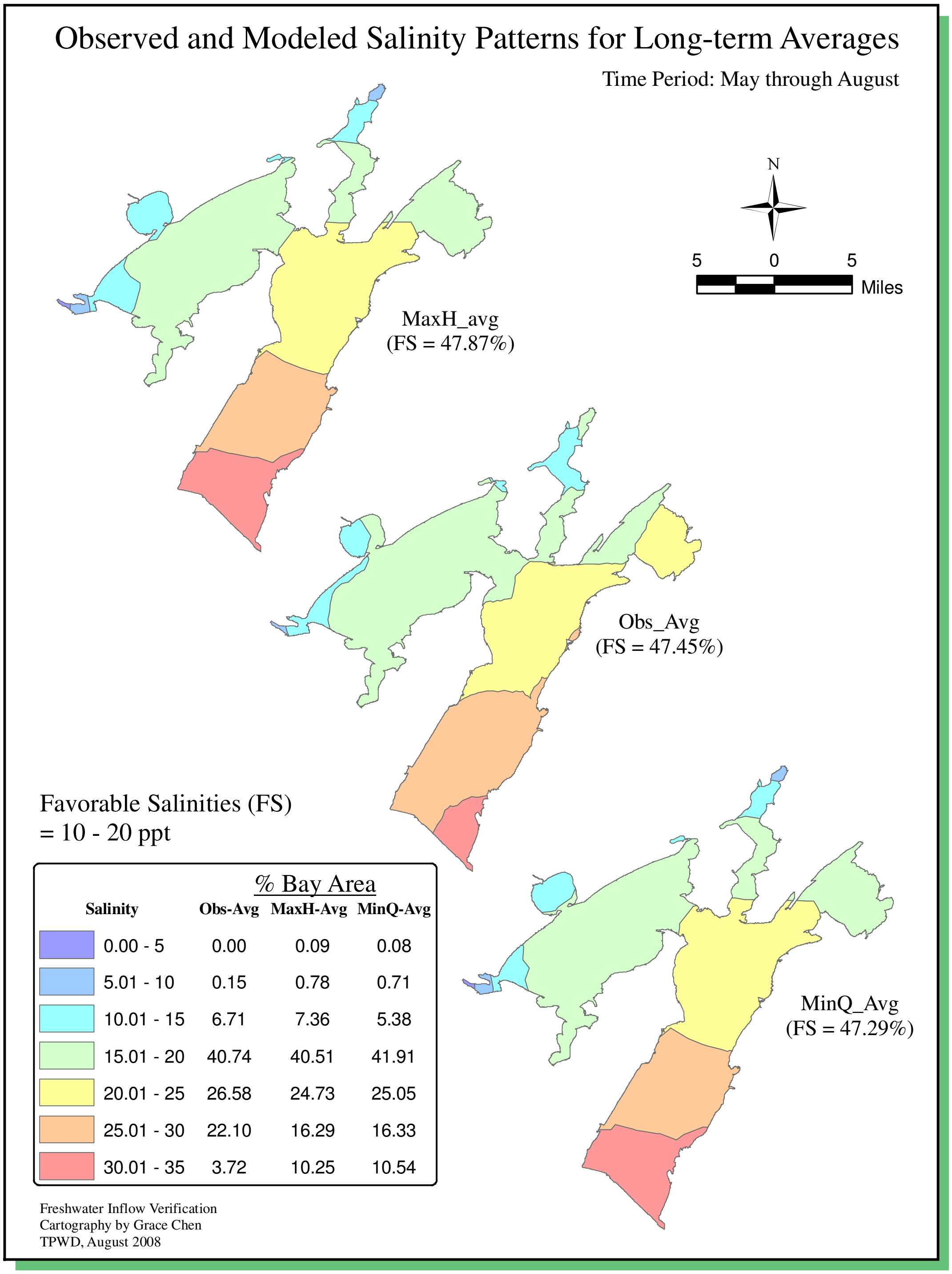


Figure 30. Comparisons of observed vs. modeled salinity patterns for long-term average conditions.

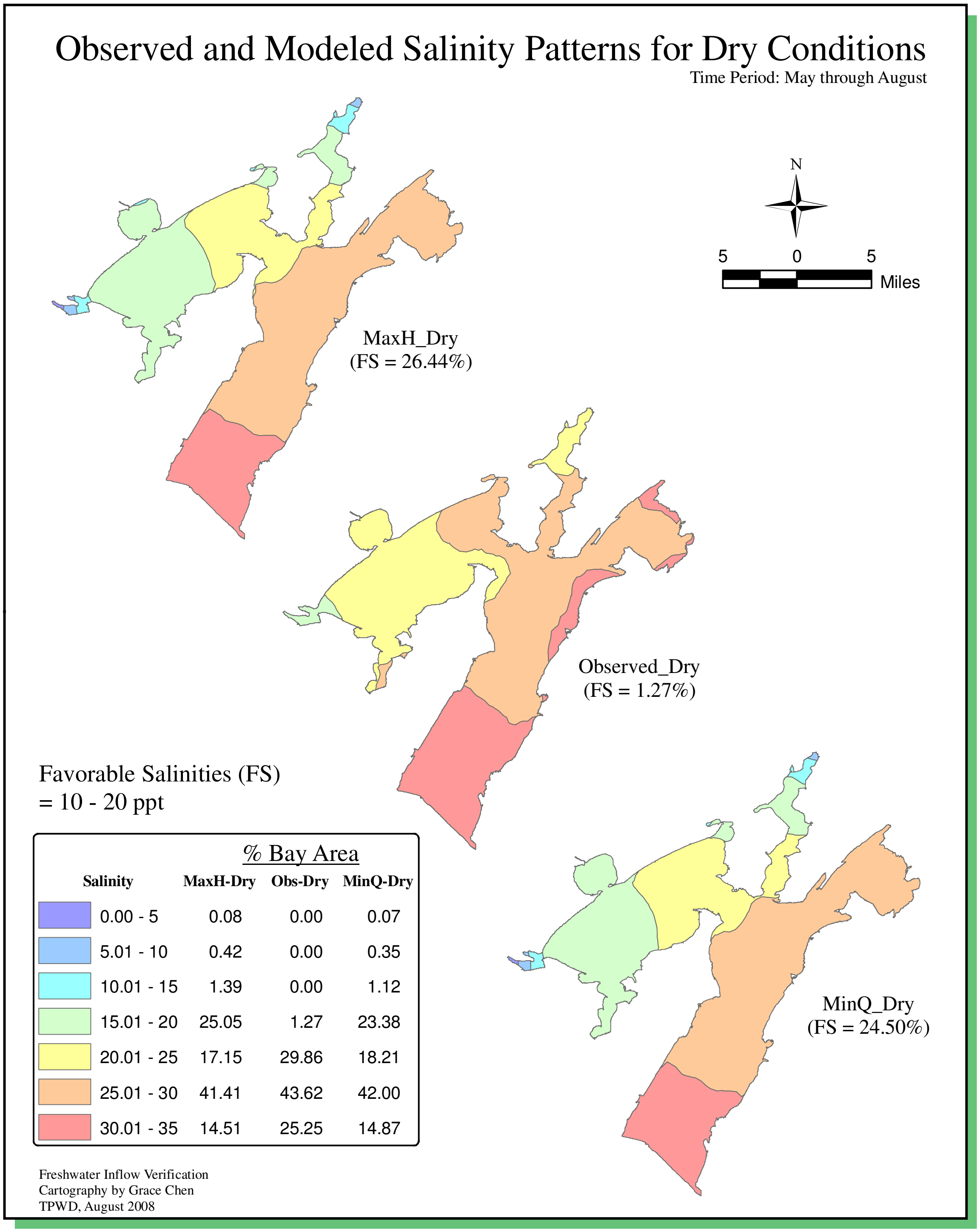
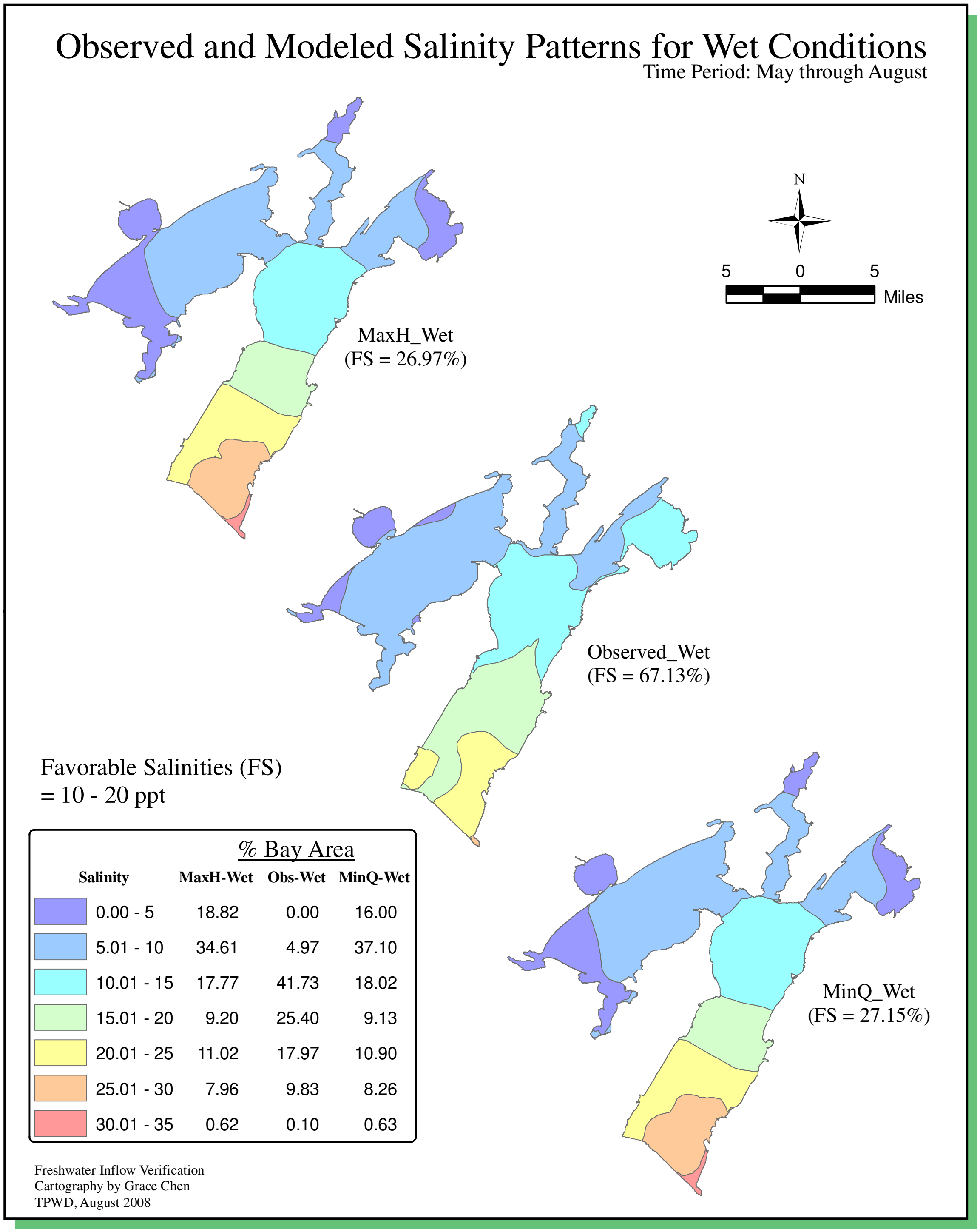


Figure 31. Comparisons of observed vs. modeled salinity patterns for dry periods.



Salinity	MaxH-Wet	Obs-Wet	MinQ-Wet
0.00 - 5	18.82	0.00	16.00
5.01 - 10	34.61	4.97	37.10
10.01 - 15	17.77	41.73	18.02
15.01 - 20	9.20	25.40	9.13
20.01 - 25	11.02	17.97	10.90
25.01 - 30	7.96	9.83	8.26
30.01 - 35	0.62	0.10	0.63

Figure 32. Comparisons of observed vs. modeled salinity patterns for wet periods.

APPENDIX

Values and Constraints for the TXEMP Model Used in the Freshwater Inflow Analysis of the Mission-Aransas Estuary

Technical Memorandum

By

David Brock

Mark Wentzel

Junji Matsumoto

Ruben Solis

Texas Water Development Board

Surface Water Resources Division

Bays & Estuaries Program

1700 N. Congress Avenue

P.O. Box 13231

Austin, TX 78711-3231

Performed in Cooperation with

Texas Parks and Wildlife Department

Coastal Fishery Division

4200 Smith School Road

Austin, TX 78744-3292

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Values and Constraints for the TxEMP Model Used in the Freshwater Inflow Analysis of the Mission-Aransas Estuary

Executive Summary

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

TxEMP accounts for biological needs and ecological requirements by incorporating regression equations linking historical salinity data with current and preceding monthly inflows. TxEMP also accounts for biological productivity by incorporating regression equations linking historical harvest data with corresponding bi-monthly inflows. Eight species were considered: blue crab, brown shrimp, white shrimp, oyster, red drum, speckled trout, black drum, and southern flounder. Historical freshwater inflow data were determined based on standard TWDB hydrology methods, and gaged flow at 5 stations on rivers and creeks flowing into the Mission-Aransas Estuary. Sediment and nutrient loads were also considered, though not included in the TxEMP model. Execution of TxEMP yielded minimum inflow (minQ) of 58,750 acre-ft/yr, maximum inflow (maxQ) of 95,190 acre-ft/yr, and maximum total harvest (maxH) at inflow of 86,170 acre-ft/yr. It is the consensus of the Bays and Estuaries teams from both the TWDB and TPWD that inflow between minQ and maxQ satisfy all constraints and produce biologically feasible results.

INTRODUCTION

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

SALINITY

Salinity zones

Eight areas with a substantial amount of salinity data were defined for the Mission-Aransas Estuary, four within Copano Bay and four within Aransas Bay (Table 1). From these eight areas, three were selected to represent the longitudinal salinity gradient from the river inflow points to the sea: southwest Copano Bay, Copano Causeway, and mid-Aransas Bay.

Table 1: Salinity (ppt) statistics for Mission-Aransas Estuary salinity zones.

Salinity Zone	Median	Mode	Mean	Std. Dev.	Range	N
Copano Causeway*	16.56	24.00	17.00	8.75	1.00 - 26.06	464
Copano Bay near Port Bay	15.00	22.00	14.76	9.13	0.00 - 40.00	397
Copano Bay SW*	13.99	20.00	14.14	9.63	0.00 - 37.00	430
Mid-Copano Bay	15.90	20.00	15.80	9.02	0.00 - 36.00	378
Mid-Aransas Bay*	22.50	24.00	22.36	8.76	0.33 - 40.00	684
North Aransas Bay	19.34	20.00	19.44	8.93	0.00 - 41.00	582
South Aransas Bay	25.00	25.00	24.66	8.72	0.00 - 47.40	629
Aransas Bay off St. Charles	17.73	20.00	17.42	8.35	0.00 - 38.00	504

"*" = zones used in TxEMP analyses.

Data

Salinity data were obtained from the Texas Water Development Board (TWDB) Coastal Data System and Bay and Estuary Datasonde programs, Texas Parks and Wildlife Department (TPWD) Fishery Monitoring Program, Texas Commission on Environmental Quality (TCEQ) Statewide Monitoring Network, and Texas Department of Health Shellfish Sanitation Monitoring Program. Data were available for years 1968-1996 and reported in parts per thousand (ppt). All data before December 1986, and some data after that date, came from measurements made during site visits at various times throughout the year. Beginning in late 1986, ambient water quality data were collected *in situ* with automated instruments (Hydrolab Datasondes) through a series of monthly deployments. Datasondes took measurements every 1 to 2 hours while deployed.

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

Salinity bounds

Salinity bounds were selected based primarily on salinity frequency distributions and biotic limits. Frequency distributions of salinity measurements for each month were examined for each zone to provide information about historical monthly ranges of salinity. The 25th and 75th percentiles were of greatest interest because salinity values in this interval represent half of all measurements, and fall in the mid-range 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 also used in the evaluation. With this information, the salinity bounds for the analysis were selected by TWDB and TPWD staff, and are presented in the tables below. In all cases, upper salinity bounds were set above the 75th percentile of the historical salinity distribution. In most cases, lower bounds were set below the 25th percentile of the historical salinity distribution.

Table 2: Salinity bounds (ppt) for the Copano Bay SW salinity zone.

Month	Lower Bound	Upper Bound
January	5.0	21.0
February	5.0	20.0
March	5.0	20.0
April	5.0	20.0
May	5.0	20.0
June	5.0	20.0
July	5.0	22.0
August	5.0	22.0
September	5.0	22.0
October	5.0	22.0
November	5.0	22.0
December	5.0	22.0

Table 3: Salinity bounds (ppt) for the Copano Causeway salinity zone.

Month	Lower Bound	Upper Bound
January	10.0	23.5
February	10.0	23.5
March	10.0	23.5
April	10.0	23.5
May	8.0	23.5
June	8.0	23.5
July	6.5	27.0
August	10.0	27.0
September	10.0	27.0
October	10.0	26.0
November	6.5	23.5
December	10.0	23.5

Table 4: Salinity bounds (ppt) for the mid-Aransas Bay salinity zone.

Month	Lower Bound	Upper Bound
January	14.0	27.0
February	14.0	27.0
March	14.0	27.0
April	14.0	27.0
May	14.0	30.0
June	14.0	30.0
July	16.0	34.0
August	20.0	35.5
September	20.0	35.5
October	17.0	32.0
November	14.0	28.0
December	14.0	28.0

Salinity chance constraint bounds

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

HARVEST TARGET

Data

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

Harvest targets and historical values

Harvest targets were defined for each species as 70% of mean historic harvest. The harvest target for each species is the value for which TxEMP must maintain a specific probability of achieving. This probability is defined by the harvest chance constraint, and is usually 50%.

Table 5: Mean, minimum, maximum and target values for species harvest (1000 lbs.).

Species	N	Mean	Min.	Max.	70% of Mean
Black Drum	32	78.02	2.10	286.9	54.62
Flounder	23	54.77	9.70	119.90	38.34
Blue Crab	31	1223.00	19.30	2716.10	856.10
Red Drum	20	159.52	28.40	484.30	111.66
Spotted Seatrout	20	181.40	40.90	360.7	126.98
Brown Shrimp	35	1846.90	12.70	4883.30	1292.83
White Shrimp	33	876.21	186.00	2726.90	613.35
Oyster	26	93.65	3.80	433.20	65.56

Harvest chance constraint bounds

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

INFLOWS

Data

The inflow bounds in the analysis represent statistical measures of the combined flow, also called surface inflow, of all runoff from the land to the estuary for the period 1941 to 1996. Combined flow is the sum of 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. USGS gages in the Mission-Aransas area used to determine inflows were: Chiltipin Creek at Sinton (id# 8189800), Aransas River near Skidmore (id# 8189700), Mission River at Refugio (id# 8189500), Medio Creek near Beeville (id# 8189300), and Copano Creek near Refugio (id# 8189200).

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

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

In the Mission-Aransas Estuary, annual inflows have ranged between 7,503 and 1,542,142 acre-ft/yr, with median inflow of 317,719 acre-ft/yr and mean inflow of 439,389 acre-ft/yr. Three different sets of flow bounds were defined to constrain the solution. Monthly flow bounds limited modeled flow in any monthly period. Seasonal bounds, based on 2-month seasons, corresponded with the 2-month seasonal periods used with the harvest equations. Annual bounds were used to limit modeled flows on an annual basis. All bounds were based on combined inflow statistics for the 56-year period 1941 to 1996.

Monthly upper and lower inflow bounds

In previous inflow studies, the lower monthly inflow bound was set to the 10th percentile of all inflow data used in analyses. For the Mission-Aransas Estuary, the lower monthly inflow bound was set to the 25th percentile of all monthly flows. A lower bound of 10th percentile was judged to be too low for July-August and consequently, all lower bounds were changed to the 25th percentile. The upper bound was set to the median of all monthly inflows for the same period in order to develop achievable recommended inflows. Consequently, inflow requirements, as calculated by the TxEMP model, can not exceed the median inflow for any month.

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

Month	Lower Boundary	Upper Boundary
January	0.85	2.94
February	0.97	5.02
March	1.24	3.05
April	1.41	2.95
May	3.61	21.76
June	1.90	18.03
July	1.41	3.91
August	1.88	5.27
September	2.75	17.65
October	1.83	10.31
November	1.42	3.76
December	1.41	2.78

Seasonal (2-month) upper and lower inflow bounds

The bounds for bimonthly (i.e., seasonal) flows constitute a separate set of constraints from monthly flow bounds. Both constraints must be satisfied for an optimum solution. Seasonal bounds were set close to the sum of monthly flow bounds for corresponding pairs of months. The sum of the January and February lower bounds totaled 1,800 acre-ft.; the sum of the upper bounds for the same period totaled 7,900 acre-ft. In the table below, the January-February seasonal lower bound was set to a value lower than the sum of the monthly bounds (600 acre-ft) while the January-February seasonal upper bound was set to a value slightly higher than the sum of the monthly upper bounds (8,000 acre-ft). The seasonal bounds are slightly wider than the sum of monthly flows to allow the TxEMP optimization model plenty of maneuvering room to search for an optimal solution.

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

Bi-month	Lower Boundary	Upper Boundary
Jan.-Feb.	0.6	8.0
Mar.-Apr.	1.0	6.0
May-Jun.	1.6	40.0
Jul.-Aug.	1.5	9.2
Sept.-Oct.	1.4	28.0
Nov.-Dec.	0.5	6.6

Annual upper and lower inflow bounds

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

HARVEST RATIOS

The TxEMP model permits harvest equations to be weighted for individual species in the calculation of the objective function. Weighting allows control of the relative importance of individual harvest equations in the optimization routine. If the weight of an equation were set to zero, that equation would not contribute to total harvest included in the objective function. Consequently, the optimization results would be independent of that species' contribution to harvest; TxEMP would calculate the harvest of that species but would not include the contribution of that species in optimization. In the same manner, the harvest equation of a species can be weighted to contribute more to the harvest total of the objective function than another species' equation. Originally, this was considered to be a convenient way to allow testing of different management options. Unfortunately, the nonlinear nature of some equations occasionally caused calculated harvest for some species to be greater than historically observed levels. To remedy this unrealistic tendency, which typically occurred at extremes of inflows, a new constraint was added to refine the optimization routine. The new constraint was designed to ensure that the harvest of any species compared to the total harvest of all species in the analysis remained within the bounds of a defined range. This constraint is called the harvest ratio and is based on historical harvest data from the estuary. The constraint guaranteed that the relative harvests of species from the optimization model remained within ranges that have been observed for the estuary. Using constraints reduces the problem of the model calculating a solution that provides exceptional harvest for one or two species to the detriment of others.

Data

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

Harvest Target Section. The biomass and harvest ratios differed greatly for brown shrimp and blue crab (Table 8). Biomass ratio values were 0.76 for brown shrimp and 0.05 for blue crab, whereas harvest ratio values were 0.42 for brown shrimp and 0.28 for blue crab. The two ratios are very different for the Mission-Aransas Estuary, but this has not been the case in other estuaries studied.

Harvest ratios were used in the execution of TxEMP because the harvest and biomass ratios were different, and biomass ratios for the Mission-Aransas system were very different in magnitude than that for other estuaries, especially with regard to brown shrimp. The lower and upper bounds for harvest ratio constraints were set at mean plus or minus 1.5 times the standard deviation. However, TxEMP was run with the lower and upper ratio bounds set to 0 and 1, respectively, for all species in order to avoid over-constraining the problem. The results were analyzed against the harvest ratio bounds.

Harvest ratio bounds

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

Species	Biomass Ratio	Harvest Ratio	Lower Bound	Upper Bound
Black Drum	0.021	0.012	0.000	0.029
Flounder	0.001	0.010	0.003	0.017
Blue Crab	0.054	0.281	0.059	0.504
Red Drum	0.007	0.031	0.000	0.076
Spotted Seatrout	0.014	0.026	0.001	0.051
Brown Shrimp	0.758	0.415	0.114	0.715
White Shrimp	0.145	0.206	0.020	0.391
Oyster	NA	0.020	0.000	0.052

NUTRIENT CONSTRAINT

A nutrient constraint was calculated for TxEMP to ensure that minimum recommended inflows were sufficient to supply nutrients necessary to support biological productivity in the estuary. For Mission-Aransas Estuary, a nutrient constraint was not included because of uncertainty in the value because of insufficient data. However, what follows is an estimate, based on a nutrient budget, of the amount of annual inflow that provides a target minimum nitrogen load. This estimate was used to evaluate TxEMP results in discussion of recommended inflow targets.

Nitrogen is generally the limiting nutrient in most estuaries (Whitledge 1989a and 1989b). This was supported for Mission-Aransas by preliminary analysis of water quality data collected between 1984 and 1989; dissolved inorganic nitrogen (DIN) concentrations were below detection limits nine times more often than dissolved phosphorus (DIP) concentrations. The tally of the nitrogen which helps fuel production in the system is based on total nitrogen (TN), which is TKN + NO_3 + NO_2 (total Kjeldahl N, nitrate N, nitrite N).

The steps involved in the development of the nitrogen loading constraint are not all presented here. The methodology for compilation of nitrogen loading to the estuary and the pieces of the estuary nitrogen budget follow what has been reported for the Nueces Estuary (Brock 2001). Details of loading and budget results will be presented elsewhere. Pertinent points are presented here from the loading data and from the budget analysis of sources and sinks. This information leads to the rationale and calculation of a recommended minimum nitrogen load and load-based minimum freshwater inflow.

Nitrogen to the Mission-Aransas Estuary and Nitrogen Budgets

The nutrients fueling estuarine production come mainly from the drainage basin of major tributaries, and from local coastal sources. The watersheds flowing to the Mission-Aransas Estuary are relatively small, some entirely coastal. Thus, the proportion of nutrients coming into the system from upstream sources, categorized here as gaged inflows, is relatively small. Ungaged coastal watersheds, including runoff from urban and semi-urban areas around the estuary are important contributors. Table 9 shows the contribution of total nitrogen to the estuary, averaged over 1977-1994.

Table 9: Total nitrogen loading (10^6 g N/yr) to the Mission-Aransas Estuary from major sources. Precipitation and deposition refer to nitrogen input from the atmosphere directly to the bay water surface.

	Gaged	Ungaged	Returns	Subtotal	Precipitation	Deposition	Total
Average	556	560	39	1155	251	251	1657
Median	443	408	39	960	235	235	1425

Water, total dissolved solids (TDS), and total nitrogen budgets were prepared for four annual periods, two low inflow years and two high inflow years, to test our understanding of nitrogen sources and sinks. The water budget combines the basic freshwater hydrologic data with net flows between bays from the TxBlend circulation model. TDS is assumed to act conservatively, with no diminution in the estuary from other than hydraulic processes. Thus, the TDS budget was developed to check on completeness of budget components. The TDS budgets required some adjustments to estimates of tidal mixing to achieve a balance. With adjustments, TDS balances were obtained, except for 1989, which had a 7% input deficit.

Annual nitrogen budgets were developed for 1988-1992 (Table 11) based on loadings (Table 9), flows, bay concentrations and biogeochemical processes, and other information (Brock 2001). Tidal flows and net flows between the Mission-Aransas Estuary and neighboring estuaries represent large components of the budget. Wastewater and harvest are comparatively small budget components.

Table 11: Total Nitrogen budget for Mission-Aransas Estuary, 10^6 g N/yr.

	1988	1989	1991	1992
Gaged Rivers	57	12	579	1421
Ungaged Inflows	77	142	596	1364
Wastewater Returns	32	29	34	44
From Gulf	1153	307	636	764
From Redfish Bay	463	139	325	458
From Mesquite Bay	982	563	554	920
Out to Gulf	-2828	-776	-2300	-3149
Out to Redfish Bay	-799	-281	-869	-966
Out to Mesquite Bay	-202	-59	-157	-216
Change in Storage	128	-115	-30	32
Wet & Dry Atmos. Deposition	425	386	894	695
Brine	0	0	0	0
N-Fixation	384	384	384	384
Burial	-158	-158	-158	-158
Denitrification	-3341	-3341	-3341	-3341
Harvest	-70	-30	-78	-56
Escapement	-252	-188	-242	-317
Grand balance	-3950	-2986	-3175	-2121

Nitrogen budgets do not balance for any of the study years. All years show that more nitrogen leaves the estuary than can be accounted for as inputs. Budget results indicate that either we do not have a complete picture of nitrogen sources and sinks, or the data available for construction of nitrogen budgets are not adequate.

There are a number of possible explanations for budget deficits. The largest sinks in the budget involve processes for which there is scant hard data. Denitrification rates were assumed similar to those in neighboring bays, and assumed to be constant regardless of loading. Both assumptions might not be true. Also the extrapolation of the rate across the whole estuary might not be valid. Inputs from, and losses to, the Gulf of Mexico depend on poorly known concentrations and rates of tidal mixing with the near-coastal Gulf.

In spite of the lack of satisfactory balance, the information in the budgets is still useful. It shows that the nitrogen economy of this estuary is substantially influenced by the net flows from the Guadalupe system and toward the Nueces Estuary.

Mission-Aransas Estuary Nitrogen Status

The Mission-Aransas Estuary receives the least loading (1.93 $g/m^3/yr$) of the estuaries of the Texas coast with the exception of Laguna Madre. However, when residence time is also considered, the loading available for production is more medial. There are indications that productivity in the estuary is not limited by nitrogen supply. Monitoring data from Texas Commission on Environmental Quality (TCEQ) do not show dissolved inorganic nitrogen concentrations to be routinely lower than levels required for planktonic productivity. The Mission-Aransas Estuary may exceed the threshold for a eutrophic estuary (Nixon, et al. 1996). This assessment is based on total organic carbon loading into the estuary being 17 g $C/m^2/yr$ (Table 4.3.1, Longley, 1994), and average phytoplankton carbon production being roughly 300 $g/m^2/yr$ (assuming similarity with Corpus Christi Bay levels from Stockwell, 1989; Flint, et al., 1986). The Mission-Aransas Estuary has been listed as a system susceptible to eutrophication and showing symptoms of moderate eutrophication (NOAA, 1989; Bricker, et al. 1999).

Mission-Aransas Estuary Recommended Nitrogen Input

The purpose of the nutrient budget is to determine the magnitude of nutrient inputs that promote, or are consistent with, characteristic system productivity. It may not be appropriate to assume that maintenance of present nutrient loading rates is consistent with desirable productivity levels, given concerns with eutrophication cited above. Several methods to determine a minimum nitrogen-loading rate were considered. However, the problems revealed in the budget exercise prevent adequate implementation of some methods.

The determination of the minimum nitrogen load necessary for the continuance of characteristic productivity can start with the early historical nitrogen loading to the system. It is assumed that the estuary was healthy and productive under those pre-modern conditions. The nitrogen loading rate characteristic of those pre-modern conditions should serve as an appropriate minimal loading requirement. However, the estuary differed from its current state in other ways prior to regional development, and the influence of these changes can not be completely known. Nevertheless, this approach to estimate nutrient requirements is the basis for the recommendations presented here for the Mission-Aransas Estuary.

Prior to urbanization and extensive agricultural development in the basin, inflows to the estuary are expected to have carried nitrogen at concentrations lower than what we find today. Those pre-modern concentrations should be similar to concentrations now found in streams not impacted by man's activities. Data on concentrations in rangeland runoff in the Mission-Aransas and neighboring watersheds are available from Baird et al. (1996). In addition, Twidwell and Davis (1989) have documented nutrient concentrations in stream segments identified as relatively un-impacted. These data are similar to those compiled by Omernik (1976) for similar landuse categories. From these data, a reasonable estimate of natural stream concentrations is roughly 0.7 mg/l N, as opposed to the flow-weighted average near 1.55 mg/l N for all Mission-Aransas Estuary tributaries.

An un-impacted inflow TN concentration was combined with average inflow volume to produce an estimate of non-anthropogenic nitrogen load to the Mission-Aransas Estuary. Based on a rangeland stream concentration of 0.7 mg/l N and a median inflow--compensated for diversions, the annual TN load is $278 \cdot 10^6$ g/yr from the drainage basin. This rate is proposed as a target minimal nitrogen load, capable of supporting estuary productivity that is historically characteristic of the system.

The historical TN load from tributary inflow is translated to an inflow requirement by computing how much freshwater inflow (including wastewater inputs) would deliver the required nitrogen at today's actual concentrations of TN. A nitrogen loading of $278 \cdot 10^6$ g N /yr would be delivered by approximately 135,00 acre-ft/yr inflow, at present volume weighted average stream concentrations.

The nutrient budget presented above demonstrates that there is incomplete information on the magnitude of nitrogen inputs and/or loss rates for the Mission-Aransas Estuary. If drainage basin loadings are larger than reported, the recommended flow could be larger than actually required.

SEDIMENT CONSTRAINT

A sediment constraint is a means of considering the estuary's requirement for sediment input to maintain shallow water and marsh habitats. Salt marsh and shallow water habitats may decline with compaction of recently deposited sediments, local subsidence and sea-level rise. Shallow water habitats, especially those that are vegetated, provide nursery areas for important fish species. However, the sporadic nature of sediment delivery makes it difficult to determine the benefit or detriment to the bay and assign numerical constraints. The following is an investigation of the relationship between sediment load and historical flows in the Mission and Aransas Rivers.

Long-term sediment inflow data have not been collected for the Mission-Aransas Estuary; however, the USGS has collected some suspended sediment data at gage sites on the Mission and Aransas Rivers. Historical daily inflow data is also available for these sites. These sites are described in Table 12 below. Because there are no large diversions or regulation points on these rivers, their ability to carry sediment is not expected to have changed significantly from historical conditions.

Few sediment inflow studies have been completed for the Mission-Aransas Bay. Welborn and Bezent (1978) examined the suspended sediment data collected by the USGS for the Aransas River. They concluded that the suspended sediment load at Skidmore, TX was approximately 100 tons per square mile of watershed area per year. They also suggested that a significant amount of bed load could be carried by flows exceeding 1500 cfs.

Sediment Data Observed at USGS
189700 on the Aransas River.

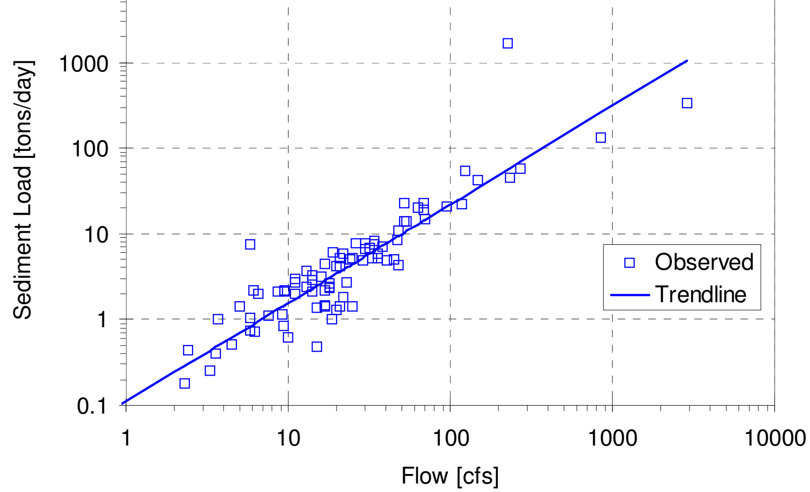

Figure 1. Sediment Data Observed at USGS
Gage # 08189500 on the Mission River.

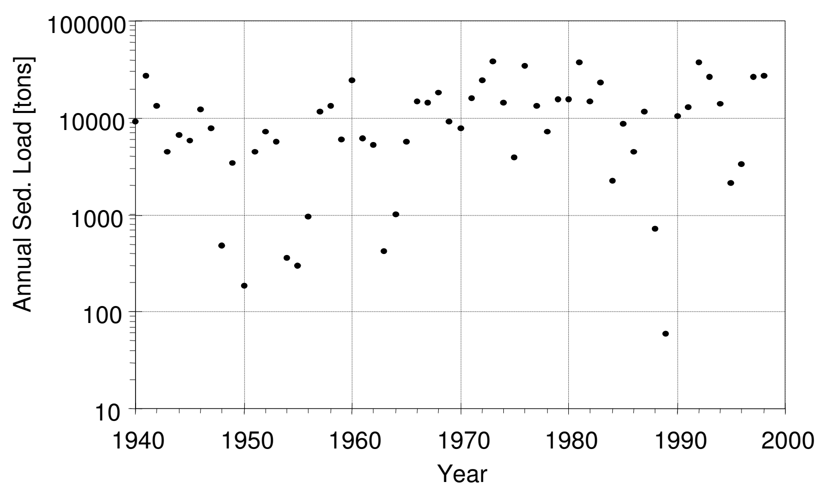

Figure 3. Estimated Yearly Sediment Loads at

Esti
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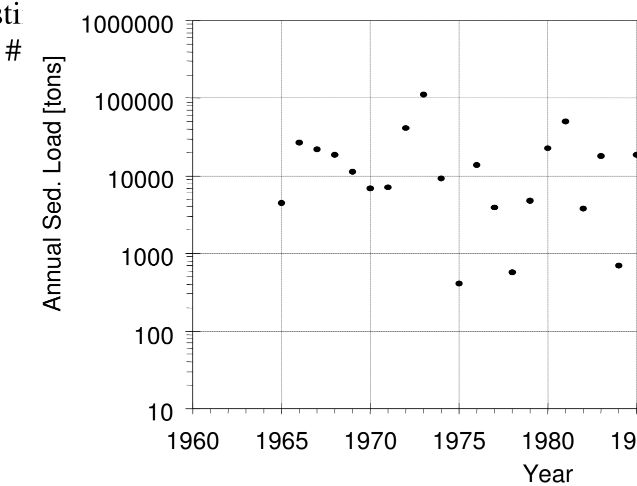

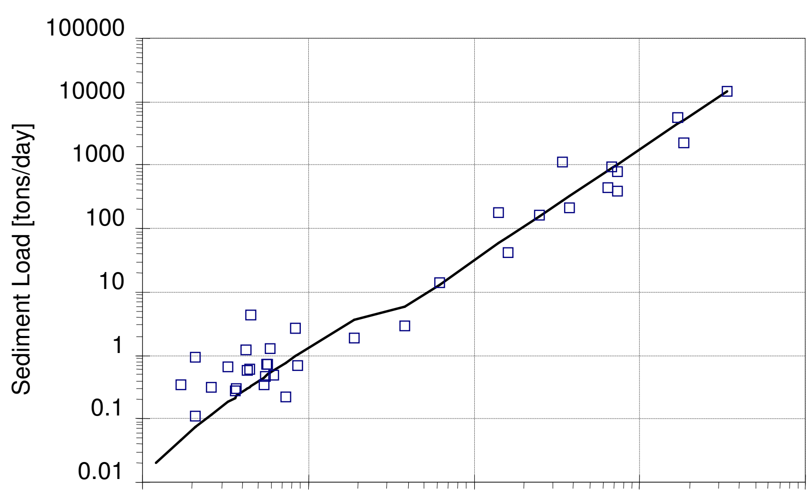

Table 12: Characteristics of Sediment Data Collection Sites.

	Mission River	Aransas River
USGS Gage #	08189500	08189700
Location	Refugio, TX	Skidmore, TX
Drainage Area	690 mi^2	247 mi^2
Flow Data	July 1929 to Present	March 1964 to Present
Average Daily Flow	125 cfs	35 cfs
Percentile Flow 90%	97 cfs	16 cfs
50%	11 cfs	4 cfs
10 %	2.3 cfs	0.7 cfs
Sediment Data	August 1973 to August 1993	February 1966 to May 1975

In the determination of recommended inflows for the Mission-Aransas Estuary, sediment data were examined in order to determine the relative relationship between flow rate and sediment for the Mission and Aransas Rivers. Sediment (tons/day) versus flow (cfs) relationships are shown in Figures 1 and 2. Sediment data from the Mission River was not well suited for analysis because only two of 89 samples represented flows above 300 cfs, making it difficult to estimate sediment loads of high flows. A power curve of the form $S = 0.1094\ Q^{1.1509}$, where S is the sediment load (tons/day), and Q is the average daily flow (cfs), was fit to the data. However, because of the lack of data at high flow rates, the shape of the curve may not accurately model sediment load for flows greater than 300 cfs. Daily flows exceed 300 cfs only 5 % of the time on the Mission River; sediment load at these flows may be over- or under-estimated.

Aransas River data were much better suited for development of a sediment load versus flow relationship. A total of 36 samples were available for this site, with nine data points in the flow range above 300 cfs. Yang's (1996) equation was used to estimate the daily sediment load as a function of variables such as the flow rate, water temperature, channel geometry and slope, and median particle size. All necessary input data were developed from discharge measurement, water quality, and sediment data obtained from the USGS. Yang's equation appears to provide a reasonable estimate of sediment load as a function of flow rate for this site (Figure 2).

Daily sediment loads were estimated for both the Mission and Aransas Rivers based on the sediment load versus flow relationships and daily flow records for each river. Flows above 10,000 cfs were ignored in the analysis because data were not available to determine the sediment load versus flow relationship at these flow rates. Average daily flows exceeded 10,000 cfs 26 times in 60 years on the Mission River, and 6 times in 36 years on the Aransas River. Daily sediment estimates were summed on a yearly basis (Figures 3 and 4). The average sediment load for the gaged period was roughly 12,000 tons/yr for the Mission River, and 19,000 tons/yr for the Aransas River. However, annual suspended sediment load varied significantly for both rivers from year to year (Figures 3 and 4). For the period 1966 to 1975, average suspended sediment load for the Aransas River was approximately 25,000 tons/yr, or 103 tons per square mile of watershed. This value compares quite well with the value of 100 tons per square mile obtained by Welborn and Bezent (1978) for the same time period.

The relationship of flow rate to suspended sediment load was compared between the Mission and Aransas Rivers (Figure 5). Relatively rare flow events (as demonstrated by their small exceedence values) contribute significantly to the suspended sediment load of both the Mission and Aransas Rivers. For the Aransas River, the largest one percent of flows (those greater than 500 cfs) contribute more than 90 percent of the total suspended sediment moved by the river. For the Mission River, the largest one percent of flows (those greater than 2,640 cfs) contribute almost half of the suspended sediment moved by the river. Results for the Mission River may be somewhat inaccurate because of the small amount of observed sediment data for flows above the 5% exceedence range (roughly 300 cfs). Nevertheless, results for the Aransas River clearly illustrate that large, infrequent flow events are responsible for most of the suspended sediment volume supplied by this watershed to Mission-Aransas Bay. A sediment constraint for the Mission-Aransas Estuary was deemed unnecessary because there are no dam structures along the Mission or Aransas Rivers, and because the inflows that bring sediment to the estuary are extraordinarily large and caused by natural events (e.g., tropical storms, hurricanes).

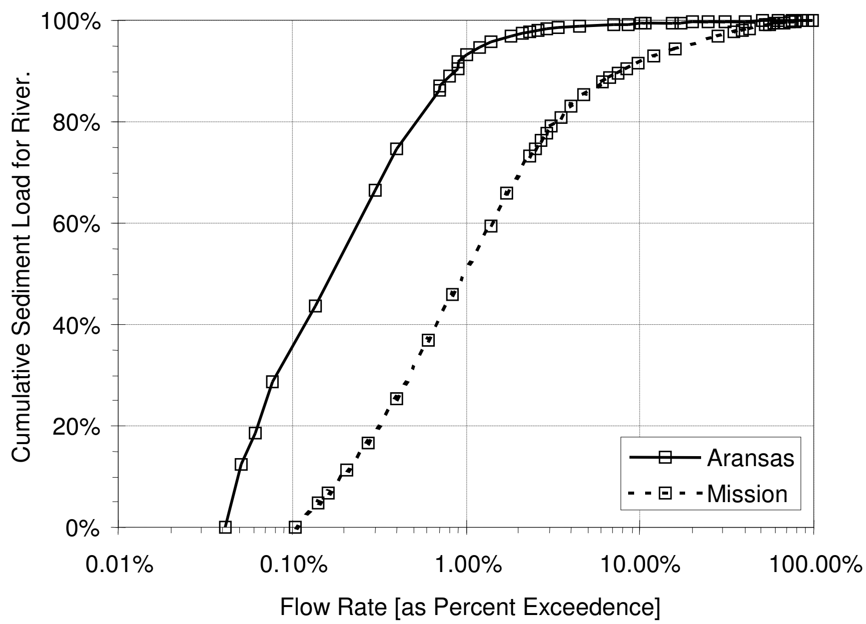

Figure 5. Cumulative Suspended Sediment Yield for Flow Rates on Mission and Aransas Rivers. Sediment load is provided as a percentage of the total suspended sediment load during the gaged period for each river. Flow rates are expressed in terms of the percent of time they are exceeded for each river.

SALINITY-INFLOW EQUATIONS

Salinity data for the period 1977 through 1996 were used to prepare the salinity-inflow equations. Salinity was calculated as a function of two values, the total of the inflows in the previous 30-day period before the salinity measurement (Q1) and the total of the inflow in the period 30 to 60 days before the salinity measurement (Q2). In the equations below, S is salinity in ppt, Q is the monthly combined inflow in 1000 acre-ft, and ln is the natural logarithm function.

Southwest Copano Bay: $S_{sw} = 24.85 - 2.395*\ln(Q_1) - 1.751*\ln(Q_2)$

Copano Causeway: $S_{cc} = 25.36 - 1.866*\ln(Q_1) - 1.625*\ln(Q_2)$

Mid-Aransas Bay: $S_{ma} = 30.03 - 1.967*Q_1 - 1.062*Q_2$

Table 13: Salinity-inflow statistics.

Salinity Zone	N	R^2	Adj. R^2	S.E.	p-value
Southwest Copano Bay	386	0.42	0.42	6.7313	< 0.0001
Copano Causeway	442	0.37	0.36	6.5026	< 0.0001
Mid-Aransas Bay	629	0.33	0.33	6.1979	< 0.0001

HARVEST-INFLOW EQUATIONS

Harvest and inflow data described above were used to prepare the harvest-inflow equations. In order to improve R^2, outliers were identified via Cook's distance, standardized residual, and Mehalanobis distance, and were omitted from regression analysis on a trial and error basis. No more than 10% of the data were omitted as outliers. Observations for which harvest was not reported were also omitted because no reported harvest is a function of effort rather than production. Trip (# trips/yr), an estimate of effort, was included as a variable for the brown shrimp harvest-inflow equation because otherwise Q_{MJ} and Q_{SO} values would negatively affect modeled harvest which is opposite of nature. The trip term in the optimization procedure was fixed at 16,562, the average number of brown shrimp trips per year for the past ten years (1987-1996). In the equations below, H is annual harvest in pounds (lbs.) and Q_p is the sum of combined inflows for a two-month period in 1000 acre-ft (P = SO for September-October, ND for November-December, JF for January-February, MA for March-April, MJ for May-June, and JA for July-August). "ln" is the natural logarithm function.

Blue Crab: $(H_{bc})^{1/2} = -2.989 + 7.401*\ln(Q_{JF}) - 3.252*\ln(Q_{MA}) - 2.995*\ln(Q_{MJ}) + 4.373*\ln(Q_{SO}) + 4.647*\ln(Q_{ND})$

Brown Shrimp: $H_{bs} = -491.97 - 1.555*Q_{MJ} + 2.596*Q_{JA} + 0.5370*Q_{SO} + 0.2056*trip$

White Shrimp: $\ln(H_{ws}) = 5.019 + 0.2491*\ln(Q_{JF}) - 0.1376*\ln(Q_{MA}) + 0.1464*\ln(Q_{MJ}) + 0.1893*\ln(Q_{ND})$

Oyster $\ln(H_{oy}) = 5.250 + 0.9656*\ln(Q_{JF}) - 0.6514*\ln(Q_{MA}) - 0.5711*\ln(Q_{MJ}) - 0.3363*\ln(Q_{JA}) + 0.4186*\ln(Q_{ND})$

Red Drum: $\ln(H_{rd}) = 5.193 - 0.3610*\ln(Q_{JF}) + 0.4479*\ln(Q_{MA}) - 0.5077*\ln(Q_{JA}) + 0.2663*\ln(Q_{SO})$

Spotted Seatrout: $\ln(H_{st}) = 5.846 - 0.0722*(Q_{JF})^{1/2} - 0.1637*(Q_{JA})^{1/2} + 0.0173*(Q_{SO})^{1/2} + 0.0701*(Q_{ND})^{1/2}$

Black Drum: $H_{bd} = 73.716 + 0.331*Q_{JF} - 0.571*Q_{MA} - 0.647*Q_{JA} + 0.075*Q_{SO} + 0.907*Q_{ND}$

Flounder: $\ln(H_{fl}) = 1.183 - 0.1042*\ln(Q_{JF}) + 0.1132*\ln(Q_{JA}) + 0.2868*\ln(Q_{SO}) + 0.3539*\ln(Q_{ND})$

Table 14: Harvest-inflow equation statistics.

Species	N-used	N-deleted	R^2	Adj. R^2	S.E.	p-value
Black Drum	32	1	0.51	0.41	47.90	0.0017
Flounder	23	12	0.59	0.50	0.3951	0.0019
Blue Crab	31	2	0.65	0.58	8.8078	<0.0001
Red Drum	20	0	0.68	0.59	0.4293	0.0013
Spotted Seatrout	20	0	0.71	0.63	0.3065	0.0006
Brown Shrimp	35	0	0.78	0.75	668.8	<0.0001
White Shrimp	33	2	0.56	0.50	0.5072	0.0001
Oysters	26	7	0.60	0.50	0.9085	0.0016

RESULTS

The performance curve generated by TxEMP demonstrates a slow harvest increase to maxH, followed by a rapid decrease to maxQ. Execution of TxEMP yielded minimum inflow (minQ) of 58,750 acre-ft/yr, maximum inflow (maxQ) of 95,190 acre-ft/yr, and maximum total harvest (maxH) at inflow of 86,170 acre-ft/yr. It is the consensus of the Bays and Estuaries teams from both the TWDB and TPWD that inflow recommendations between minQ and maxQ satisfy all constraints and produce biologically feasible results. The following table presents MinQ, MaxH and MaxQ from the solution set, and also presents MinQsal, which is the result of running TxEMP with only salinity contraints.

Table 14: TxEMP Model Solutions for the Mission-Aransas Estuary (in Acre-Feet).

Month	MinQsal	MinQ	MaxH	MaxQ
Jan	2,940	2,940	2,940	2,940
Feb	4,100	5,010	5,010	5,010
Mar	3,040	3,050	3,050	3,050
Apr	2,950	2,430	2,430	2,430
May	3,850	12,860	19,120	21,760
Jun	2,340	10,660	15,830	18,030
Jul	1,910	1,410	1,410	2,390
Aug	1,880	2,200	1,880	5,080
Sep	2,750	7,360	17,650	17,650
Oct	1,830	4,290	10,310	10,310
Nov	2,180	3,760	3,760	3,760
Dec	2,780	2,780	2,780	2,780
Total	32,550	58,750	86,170	95,190

INFLUENCE OF GUADALUPE RIVER

The salinity regression equations developed for use in TxEMP, and ultimately the flow recommendations proposed for the Mission-Aransas Estuary are based on the assumption that inflows remain unchanged into San Antonio Bay (Guadalupe Estuary), the major bay north of the Mission-Aransas Estuary. This appendix tests the sensitivity of salinity conditions in Aransas and Copano Bays to reduced inflows on the Guadalupe River. Because Guadalupe River inflows are significantly greater than flows into the Mission-Aransas Estuary, and because these systems are hydraulically connected, changes in Guadalupe River flows do affect the Mission-Aransas Estuary. This sensitivity analysis attempts to establish the magnitude of that effect.

While not all flows entering the Guadalupe Estuary move southward into the Mission-Aransas Estuary, it is still useful to compare the magnitude of those flows to flows entering the Mission-Aransas Estuary. The mean annual surface inflow into the Guadalupe Estuary is 2.37 million ac-ft (1941-1999, TWDB), of which a significant fraction (about 2.0 million ac-ft/year) comes from the Guadalupe River. (For clarity, this also includes flows from the San Antonio River.) Flows entering the Mission-Aransas Estuary directly from its drainage basin are less than one fifth as much, totaling only 0.44 million ac-ft (1941-1999, TWDB). Figure 6 compares inflows from the Guadalupe River to total inflows into the Mission-Aransas Estuary for the 6 year period from 1987 -1992. It graphically exhibits the large difference between inflows from the Guadalupe River to those into the Mission-Aransas Estuary (note the ordinate is a logarithmic scale).

It is likely that average flows on the Guadalupe River will change in the future. Freshwater inflow studies conducted on the Guadalupe Estuary (TPWD 1998) called for MaxH inflows of 1.15 million acre-feet/year, while Water Availability Modes Simulation (WAMS) runs indicate future flows between 1.9 (WAMS Run3) and 1.6 (WAMS Run8) million acre-feet/year.

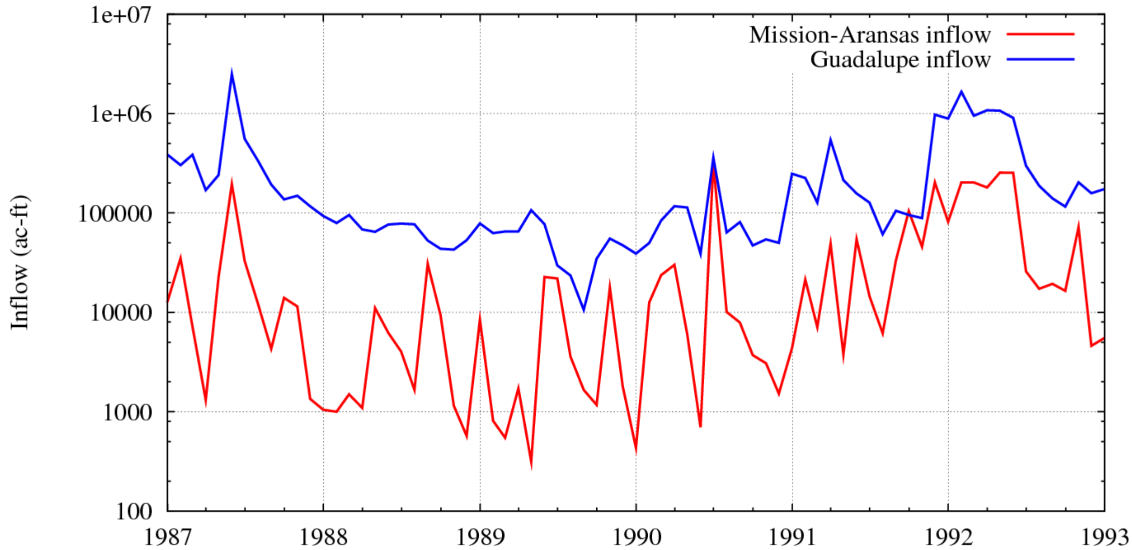

Figure 6. Comparison of monthly inflows to the Guadalupe Estuary and to the Mission-Aransas Estuary.

The sensitivity analysis was conducted by running three simulations of the TxBLEND hydrodynamic model in which daily historical Guadalupe River inflows were reduced. The six-year simulation period from 1987 to 1992 encompassed both dry (1989) and wet (1992) years. The base condition used full, or 100% of Guadalupe River inflows. Daily flows in subsequent simulations were reduced to 80% (i.e. a 20% reduction), and 60% of their full values. Daily inflows from other sources into the Guadalupe Estuary and the Mission-Aransas Estuary were kept at their full values. Three locations were selected for salinity comparisons - mid San Antonio Bay, mid Aransas Bay and mid Copano Bay (Figure 7).

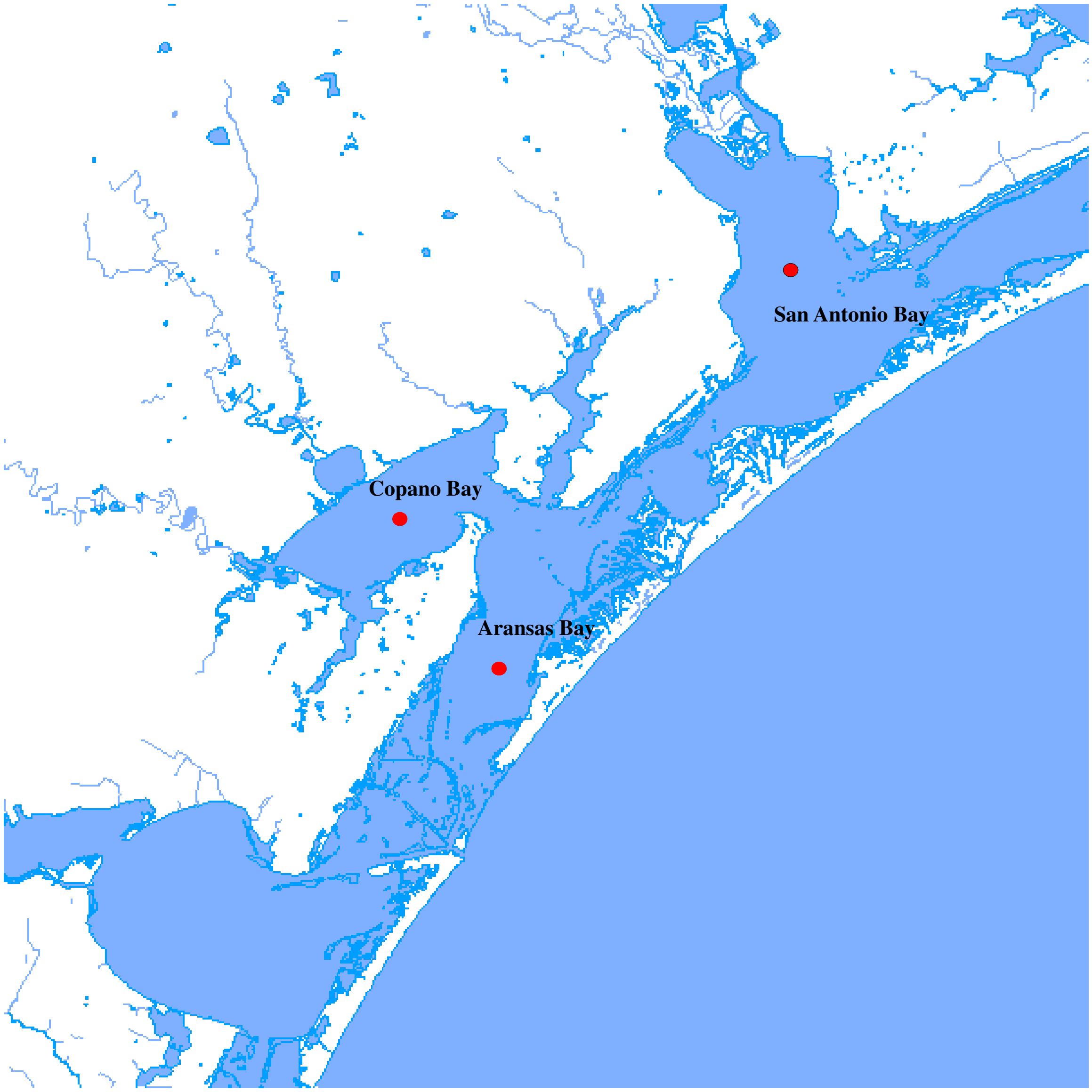

Figure 7. Three locations selected for comparison of salinity values following reductions in inflows from the Guadalupe River.

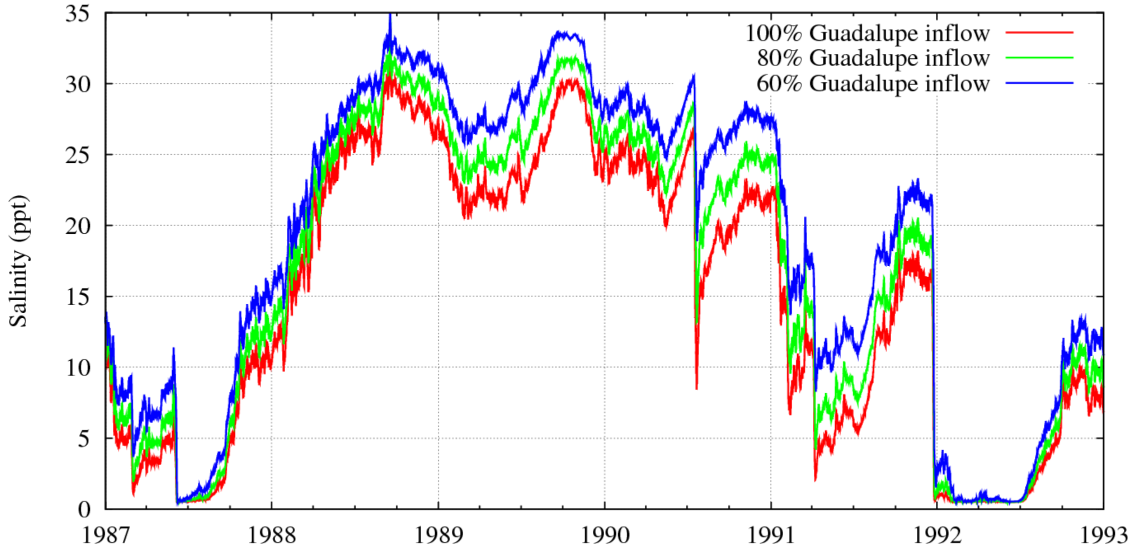

Figure 8. Simulated salinities at mid San Antonio Bay under three scenarios: 100% of observed Guadalupe River inflows (red), 80% of Guadalupe River inflows (green), and 60% of Guadalupe River inflows (blue).

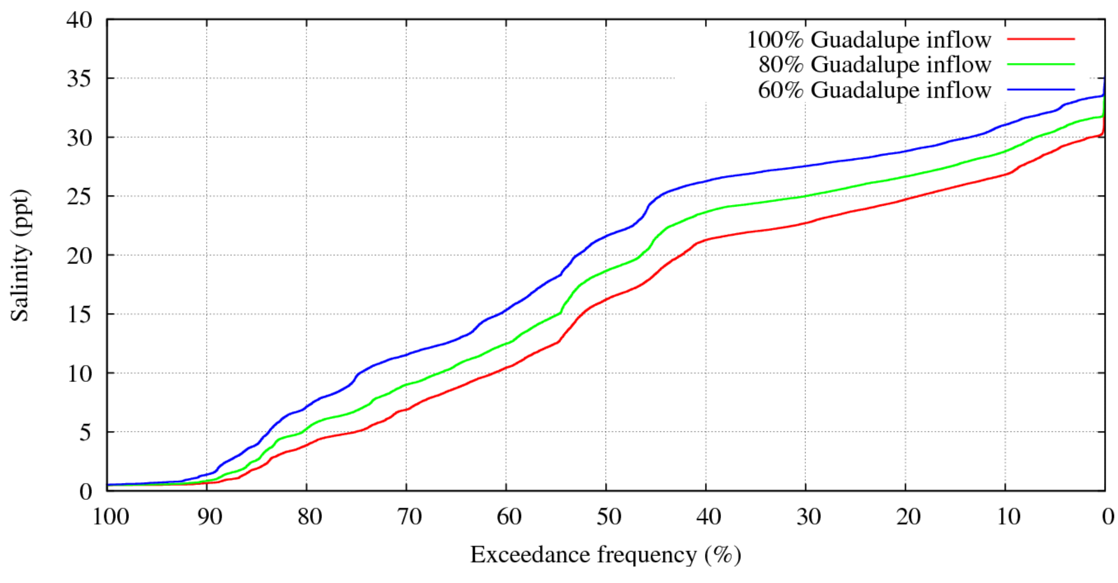

Figure 9. Exceedance frequency vs. simulated salinity at mid San Antonio Bay under three scenarios: 100% of observed Guadalupe River inflows (red), 80% of Guadalupe River inflows (green), and 60% of Guadalupe River inflows (blue).

Figure 8 compares salinities in mid San Antonio Bay for the three simulations. As expected, it shows high salinities during the 1989 low flow period and low salinities in the first part of 1992 following a flood event. Of the three comparison sites, observed salinity increases with flow reductions are largest due to the proximity to the inflow source. Using the daily salinity data shown in Figure 8, an exceedance frequency curve was developed for the mid San Antonio Bay (Figure 9). Although the six-year period used to develop the curve is too short to fully describe salinity characteristics, the figure nonetheless indicates the difference that might occur due to reduced inflows. Figure 9 indicates that at the 50'th percentile, salinity would increase by 6 ppt if inflow is reduced to 60% (i.e. reduced by 40%) of historical levels.

Figures 10 and 11 show similar comparisons for mid Aransas Bay, and Figures 12 and 13 show comparisons for Copano Bay. In both of these cases, changes in salinity due to flow reductions are less than observed in mid San Antonio Bay. For the Aransas Bay site, this is probably due to the proximity of the site to the Gulf. The smaller differences are clearly exhibited by the exceedance curves in Figure 11. At the 50th percentile the 60% flow (i.e. 40% reduction) would increase salinity by about 2 ppt.

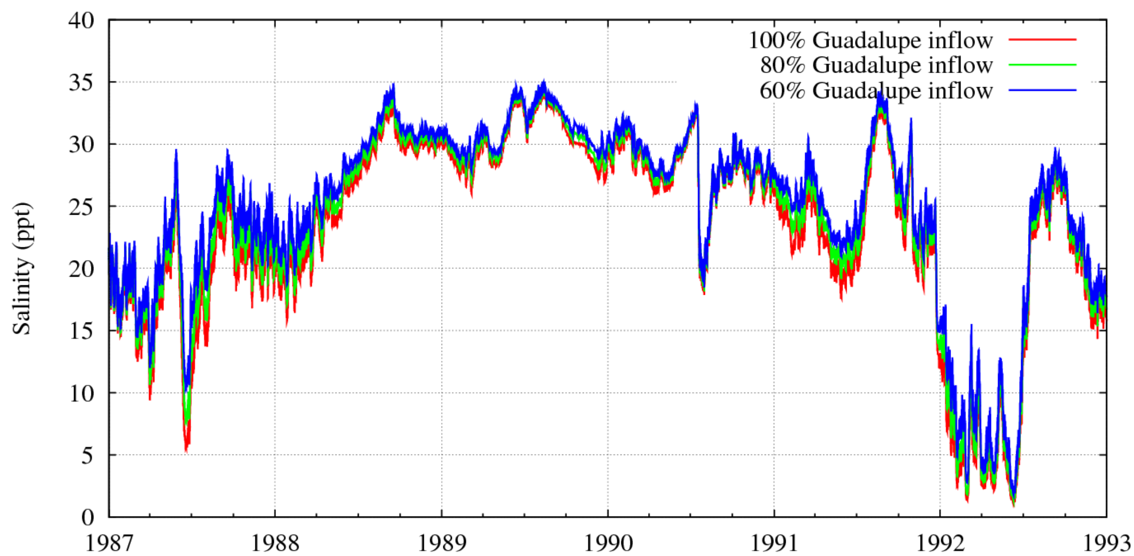

Figure 10. Simulated salinities at mid Aransas Bay under three scenarios: 100% of observed Guadalupe River inflows (red), 80% of Guadalupe River inflows (green), and 60% of Guadalupe River inflows (blue).

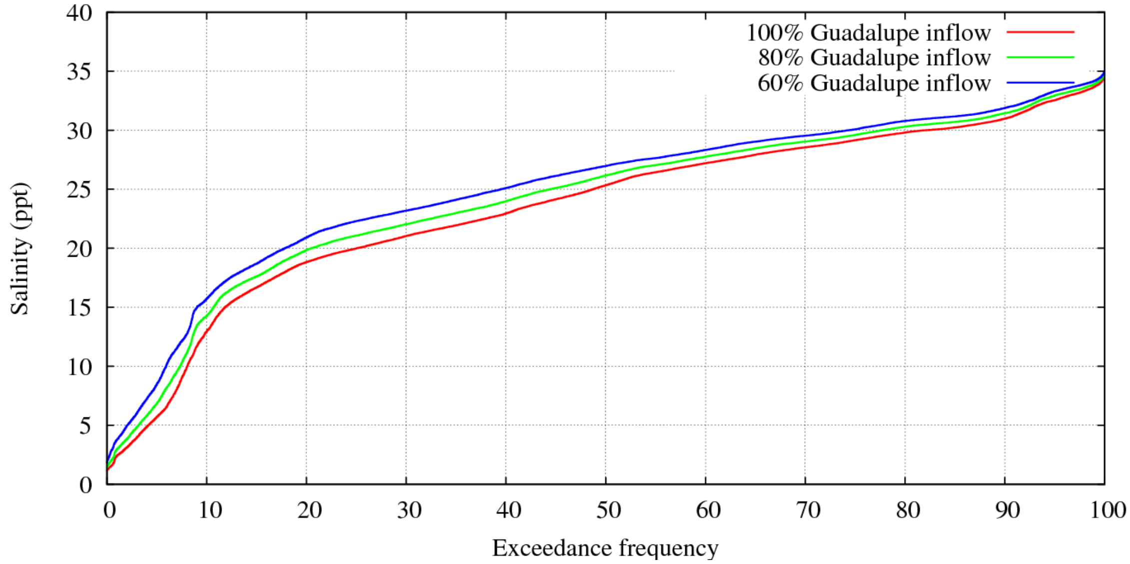

Figure 11. Exceedance frequency vs. simulated salinity at mid Aransas Bay under three scenarios: 100% of observed Guadalupe River inflows (red), 80% of Guadalupe River inflows (green), and 60% of Guadalupe River inflows (blue).

Figure 12, for mid Copano Bay, shows a similar pattern as seen for mid Aransas Bay. However, the daily variation is much smaller because the flow velocity is much smaller in Copano Bay than in Aransas Bay. Figure 13 shows exceedance frequency curves for mid Copano Bay. It exhibits a similar difference as mid Aransas Bay; it would be about 2 ppt higher if the Guadalupe inflow is reduced by 40%.

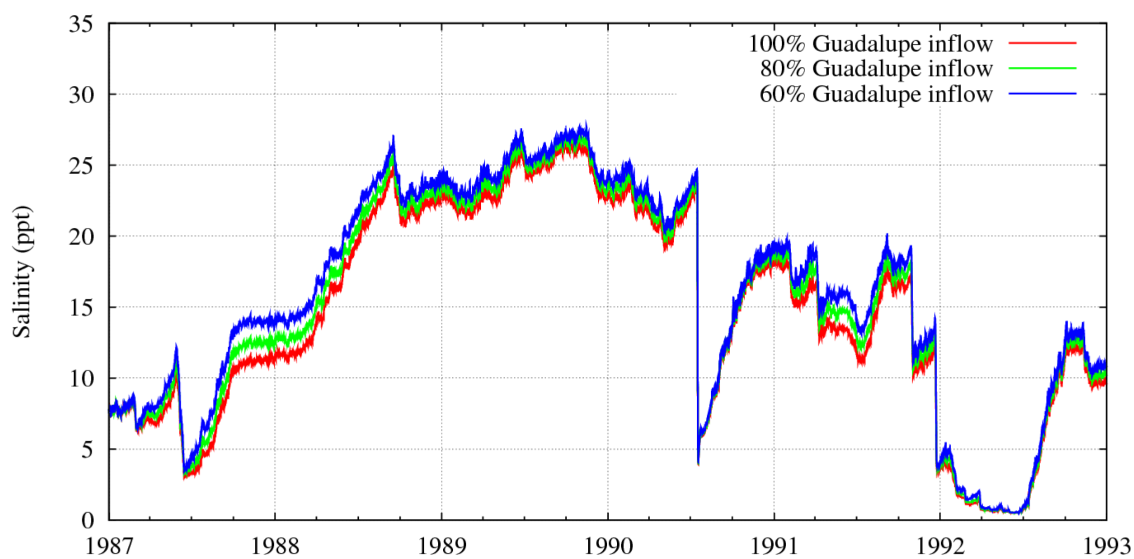

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Figure 12. Simulated salinities at mid Copano Bay under three scenarios: 100% of observed Guadalupe River inflows (red), 80% of Guadalupe River inflows (green), and 60% of Guadalupe River inflows (blue).

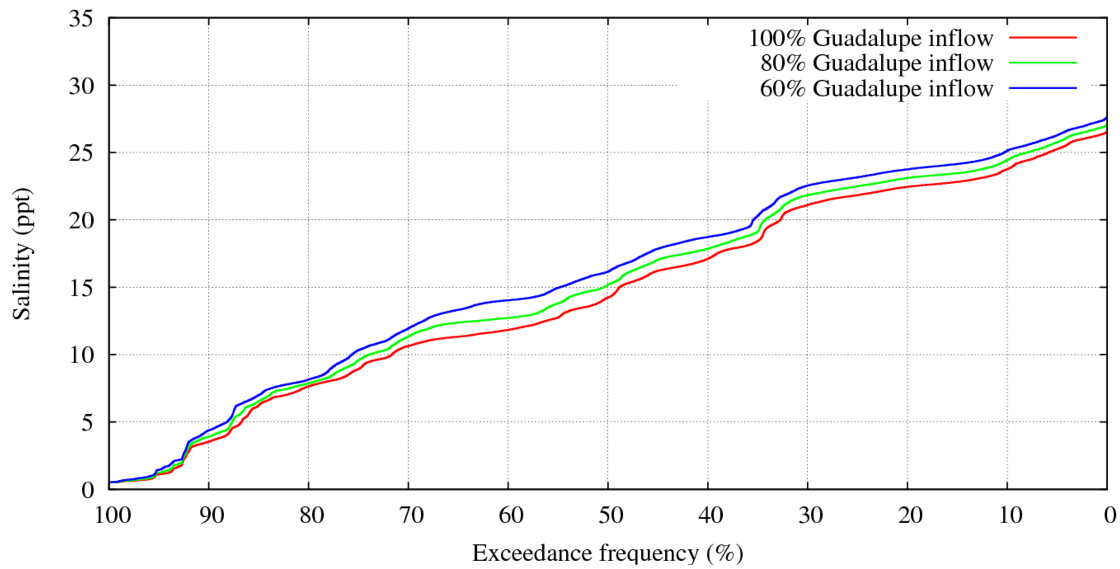

Figure 13. Exceedance frequency vs. simulated salinity at mid Copano Bay under three scenarios: 100% of observed Guadalupe River inflows (red), 80% of Guadalupe River inflows (green), and 60% of Guadalupe River inflows (blue).

A simple comparison of the MaxH inflow to the mean historical inflow indicates that the Guadalupe inflow is reduced by about 50% under MaxH target inflow. However, actual implementation of the MaxH inflow would be unlikely to lead to that great a reduction in mean flow because the mean flow is strongly influenced by large inflows or floods and they will occur no matter what target inflow is set. By comparison, WAMS model output for 1941-1989 simulation for Run3 (full use of appropriated water) shows a reduction of Guadalupe River inflow from about 2.0 million acre-feet/year to 1.6 million acre-feet/year, or a 20 % reduction in flow. In summary, reductions in flow are likely to occur although the magnitude of the reduction is not certain.

This sensitivity analysis indicates the reduction of Guadalupe River inflows to 60% of their historical values will lead to increases in salinity of about 2 ppt in Aransas and Copano Bays. Future analyses of the Mission-Aransas system should consider this influence in refinements to inflow recommendations for this system.

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